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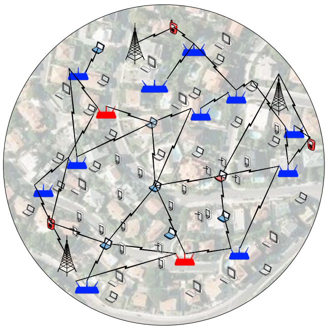

Radio Resource Management of Wireless Mesh Networks

Lúcio Miguel Studer Ferreira

Supervisor: Doctor Luís Manuel de Jesus Sousa Correia

Thesis approved in public session to obtain the

Ph.D. Degree in Electrical and Computer Engineering

Jury final classification: Pass with Merit

Jury

Chairperson: Chairman of the IST Scientific Board

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Doctor Roberto Verdone

Doctor Luís Manuel de Jesus Sousa Correia

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2013

To my beloved

Filipa, Aurora and João.

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Abstract

This thesis addresses the management of multi-radio Wireless Mesh Networks (WMNs). An organisational framework for their opportunistic management is proposed. Nodes' heterogeneous resources are explored opportunistically by a manager suggesting network functionalities. To support the implementation of communication functionalities in nodes, an Open Connectivity Service (OConS) architecture is proposed for the flexible orchestration of both legacy and novel connectivity mechanisms. Two novel radio resource management strategies are also proposed. A fair and efficient resource allocation strategy combines multiple mechanisms that efficiently optimise radio resources (rate, power and channel) to guarantee a max-min fair share of capacity. On the other hand, supported by OConS and the organisational framework, an opportunistic resources allocation service is presented, which exploits network conditions and nodes' heterogeneous capabilities to improve connectivity. The performance of these two strategies is evaluated through simulation for regular and random WMNs deployments, with a single and multiple Internet gateways, considering also a flash crowd of nodes. Compared with other strategies, the proposed ones increase by more than 3.2 times the offered capacity, guaranteeing low delay and packet losses, independently of the number of hops. They explore fully, fairly and efficiently the capacity of the used systems, increasing WMNs' coverage, connectivity and capacity.

Keywords

Wireless Mesh Networks. Radio Resources Management. Capacity. Efficiency. Fairness. Multi-radio. Multi-channel. Self-organisation. Opportunism. Heterogeneity.

Resumo

Esta tese aborda a gestão de recursos de redes em malha sem fios (WMNs) multi-rádio. É proposto um enquadramento organizacional para a sua gestão. Os recursos heterogéneos dos nós são explorados por um gestor para oportunisticamente explorar as funcionalidades de rede. Este é suportado por uma arquitetura de serviços de conectividade aberta (OConS) para a orquestração de mecanismos de conectividade. São também propostas duas estratégias inovadoras para a gestão de recursos rádio. Uma serve para a otimização eficiente de recursos rádio (débito, potência e canal), garantindo uma distribuição de capacidade entre os nós *max-min* justa. É também proposto um serviço OConS para a gestão oportunista de recursos que explora as condições da rede e as capacidades dos nós para melhorar a conectividade, baseado no enquadramento organizacional. O desempenho destas estratégias é avaliado em simulação, para cenários de distribuições regulares e aleatórias de nós, com um ou múltiplos nós com acesso à Internet, assim como perante um agrupamento repentino de nós. Quando comparadas com outras estratégias, estas aumentam até 3.2 vezes a capacidade oferecida, garantindo atrasos e perdas mínimos, independentemente do número de saltos. Exploram totalmente e de forma justa a capacidade do sistema usado, aumentando a cobertura, conectividade e capacidade.

Palavras-chave

Redes em Malha sem fios. Gestão de Recursos Rádio. Capacidade. Eficiência. Equidade. Multi-rádio. Multi-canal. Auto-organização. Oportunismo. Heterogeneidade.

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List of Acronyms

2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	3^{rd} Generation Partnership Project
4G	4^{th} Generation
4WARD	Architecture and Design for the Future Internet
AC	Access Category
ACK	Acknowledgement
AE	Access Element
AIFSN	Arbitration Interframe Space Number
AMCP	Asynchronous Multi-channel Coordination Protocol
AP	Access Point
ARPANET	Advanced Research Projects Agency Network
ATIM	Announcement Traffic Indication Message
BAT	Block Addressing Table
BER	Bit Error Ratio
BS	Base Station
BSS	Basic Service Set
CA	Channel Assignment
CC	Common Control
CCA	Clear Channel Assessment
CCF	Common Channel Framework
CCW	Channel Coordination Window
CDMA	Code Division Multiple Access
CF	Coordination Function
CFP	Contention-Free Period
CL	Controlled Load
CRRM	Common Radio Resource Management
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CTX	Clear To Switch

CW	Contention Window
DCA	On-Demand Channel Assignment
DCF	Distributed Coordination Function
DE	Decision Element
DFS	Dynamic Frequency Selection
DIFS	DCF Interframe Space
DL	Down Link
DSDV	Destination Sequence Distance Vector
E2E	End-to-End
EDCA	Enhanced Distributed Channel Access
EE	Enforcement Element
eNB	evolved-UTRAN Node B
ESS	Extended Service Set
EU	European Union
E-UTRAN	Evolved UTRAN
FBN	Fixed Backhaul Network
FERA	Fair and Efficient Resources Allocation strategy
FFT	Fast Fourier Transforms
FMC	Fixed-Mobile Convergence
FWA	Fixed Wireless Access
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HMCP	Hybrid Multi-Channel Protocol
HR	High Rate
HSDPA	High-Speed Downlink Packet Access
HSUPA	High-Speed Uplink Packet Access
HWMP	Hybrid Wireless Mesh Protocol
ICSMA	Interleaved Carrier Sense Multiple Access
ID	Identity
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
INC	Inter- and Intra- Node Communication
IP	Internet Protocol
IPC	Inter-Process Communication

ISP	Internet Service Provider
KPI	Key Performance Indicator
LACA	Load-Aware Channel Assignment
LAN	Local Area Network
LR	Low Rate
LTE	Long Term Evolution
MAC	Medium Access Control
MAN	Metropolitan Area Network
MAP	Mesh Access Points
MAS	Medium Access Slots
MBS	Mesh BS
MCS	Modulation-Coding Scheme
MDA	Mesh Deterministic Access
MDAOP	MDA Transmission Opportunity
MesTiC	Mesh based Traffic and interference aware Channel assignment
MIMO	Multiple-Input Multiple-Output
MMAC	Multi-channel MAC
MMR	Mobile Multi-hop Relay
MP	Mesh Points
MPDU	MAC Protocol Data Units
MPNC	Mesh-PNC
MPP	Mesh Point Portals
MR-LQSR	Multi-Radio Link-Quality Source Routing
MRS	Mesh Routing Strategy
MSDU	MAC Service Data Units
MSH	Mesh
MSH-CSCH	Mesh Centralised Schedule
MSH-DSCH	Mesh Distributed Schedule
MSH-NCFG	Mesh Network Configuration
MSH-NENT	Mesh Network Entry
MSS	Mesh SS
MT	Mobile Terminal
MTr	Mesh Traffic
MUP	Multi-radio Unification Protocol
NAV	Network Allocation Vector

NIC	Network Interface Card
OConS	Open Connectivity Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLSR	Optimised Link State Routing
OR	Orchestration Register
OSAP	Orchestration Service Access Point
OWROS	Opportunistic WMN Resources management OConS Service
PAN	Personal Area Network
PCS	Physical Carrier Sensing
PER	Packet-Error-Ratio
PHY	Physical
PMP	Point to Multipoint
PN	Piconet
PNC	Piconet Coordinator
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RA	Rate Adaptation
RAN	Radio Access Networks
RA-OLSR	Radio Aware Optimised Link State Routing
RAT	Radio Access Technology
RBN	Radio Backhaul Network
RM-AODV	Radio Metric Ad-hoc On Demand Distance Vector
RRM	Radio Resource Management
RTS	Request To Send
RTX	Request To Switch
SAIL	Scalable and Adaptive Internet Solutions
SIFS	Short InterFrame Space
SINR	Signal to Interface and Noise Ratio
SON	Self-Organised Network
SOP	Service Orchestration Process
SS	Subscriber Station
SSCH	Seed-Slotted-Channel Hopping
STA	Station
TCP	Transmission Control Protocol

TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TPC	Transmitter Power Control
TTL	Time To Live
UCG	Unified Channel Graph
UDP	User Datagram Protocol
UE	User Equipment
UL	Up Link
UMTS	Universal Mobile Telecommunications System
UTRAN	Universal Terrestrial Radio Access Network
VCS	Virtual Carrier Sensing
VoIP	Voice over IP
WDS	Wireless Distribution System
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WIP	All-Wireless Mobile Network Architecture
WLAN	Wireless Local Area Network
WM	Wireless Medium
WMAN	Wireless Metropolitan Area Network
WMC	Wireless Mesh Client
WMN	Wireless Mesh Network
WMR	Wireless Mesh Router
WPAN	Wireless Personal Area Networks
WWAN	Wireless Wide Area Networks
WWW	WWW World Wide Web

List of Symbols

γ	Path loss exponent
δ_{packet}	Percentage of dropped packets
η_{energy}	WMN energy efficiency
η_{phy}	Bandwidth usage efficiency
$\eta_{spectrum}$	WMN spectrum efficiency
ρ	Signal to interference plus noise ratio
ρ_{min}	Signal to interference plus noise ratio threshold
$\tau_{packet\ gen}$	Average generated packets inter-arrival time
τ_{packet}	Time needed to cross the WMN
B	Channel bandwidth
$\mathcal{C}$	Set of orthogonal channels
c	Speed of light
C_c	Channel c
CW_{min}	Congestion window minimum size.
d_{cs}	Carrier sensing range
$d_{i\ max}$	Range within which a node may interfere
d_i	Interference range
d_{map}	Distance between communicating nodes
d_{max}	Communication range
f	Frequency
$f_{max-min}$	WMN max-min fairness of flows throughput
$\mathcal{I}$	Set of interferer MAPs
K_{packet}	Packet size
$l_{m,n}$	Link between M_m and M_n
$\mathcal{L}_{m,r}$	Set of links of radio $M_{m,r}$
K_{ack}	ACK packet size
K_{data}	Data packet size
K_{ip}	IP header size

K_{mac}	MAC header size
K_{packet}	Packet size
K_{queue}	Channel queue size
L_0	Free-space propagation loss at 1 m
L_p	Path loss
$L_{p\,max}$	Path loss of the most attenuated link
$\mathcal{M}_{m,r}$	Branch of $M_{m,r}$, set of MAPs with flows crossing $M_{m,r}$
$M_{m,r}$	Radio r of MAP M_m
M_m	MAP m
$N_{\mathcal{M}c_i}$	Total number of non-interfering sets of parent-radios
N_{ch}	Number of available orthogonal channels
N_{dy}	Number of dynamic-radios
$N_{hop}(M_m)$	Distance in hops from M_m to the nearest MPP
$N_{flw}(M_{m,r})$	Number of flows crossing $M_{m,r}$
$N_{flw}(l_{m,n})$	Number of flows crossing link $l_{m,n}$
$N_{links}(M_{m,r})$	Number of links/children of $M_{m,r}$
N_{map}	Number of MAPs
N_{gw}	Number of MPP gateways
N_{ptx}	Number of transmission power levels
N_{radios}	Number radios for mesh backhaul per node
N_{rphy}	Number of physical rates
N_{rings}	Number of rings around MPP
N_{st}	Number of stable-radios
P_{cs}	Carrier sensing power threshold
P_N	Additive white Gaussian noise power
P_{oper}	Baseline power consumption of a MAP, for operation
P_{rx}	Received power level
$P_{rx\,min}$	Receiver sensitivity
$P_{rxi\,max}$	Maximum supported interference
P_{tx}	Transmission power level
$\wp_{tx}$	Set of transmission power levels
r	Radio of a given MAP
r_{ap}	MAP coverage radius

R_{app}	Maximum achievable application-layer throughput of a given physical rate
R_{ctrl}	Max-min fair aggregated traffic capacity of a given MAP
R_{fair}	Max-min fair aggregated traffic capacity of a given MAP
$R_{link\ max}$	Maximum link throughput
R_{ll}	Maximum link-layer throughput (capacity)
R_{load}	Load of offered aggregated traffic by a given MAP
$\mathcal{R}_{phy}$	Set of physical bit rates
R_{phy}	Physical bit rate
R_{thr}	Achieved throughput of aggregated traffic by a given MAP
r_{wmn}	Scenario radius
R_{wmn}	WMN throughput
$T_{BO\ CH\ switch}$	Back-off time after switching channel
T_{dy}	Maximum time the dynamic radio is allowed to stay on a given channel without checking if there is another channel with traffic to send
T_{Hello}	Periodicity of *Hello* packets broadcast
T_{ack}	Transmission time of an acknowledgement message
T_{data}	Transmission time of the payload
T_{ip}	Transmission time of the TCP/UDP and IP headers
$T_{link\ min}$	Minimum link delay
T_{mac}	Transmission time of the MAC header
T_{phy}	Transmission time of the PHY header
T_{pmb}	Transmission time of the physical preamble
$T_{p\ ack}$	ACK transmission delay
$T_{p\ data}$	Data packet transmission delay
T_{prop}	Propagation delay.
T_{slot}	Slot duration.
T_{sym}	Transmission time for a symbol.
$T_{packet}(M_m)$	Time instant a which a packet arrives to node M_m
T_{prop}	Propagation delay
$U(M_i, C_c)$	Utilisation of channel C_c by node M_i
$\mathcal{U}(\mathcal{X}_m, C_c)$	Utilisation of channel C_c within $\mathcal{X}_m$

$\mathcal{X}_m$	M_m's interference neighbourhood

List of Programs

OPNET Modeler Wireless Suite 15.0	Opnet is used (a) to implement the proposed multi-radio mesh nodes and developed strategies and algorithms, (b) to develop a complete description of a wireless mesh network according to various scenarios, and (c) to evaluate the performance of the proposed enhancements.
MS Excel 2007	Excel is used for implementing analytical models and to process results.
MS Word 2007	Word is used to edit this thesis and associated documents, such as publications and projects' technical reports.
MS Visio 2003	Visio is used to edit the figures presented in this thesis.
LaTeX	LaTeX is used to edit several publications and projects' technical reports.

Chapter 1

Introduction

Chapter 1 provides an introduction to the thesis, presenting, in Section 1.1, a brief history of wireless mesh networks. In Section 1.2, the thesis motivation and objectives are presented, and in Section 1.3, the novel aspects and concepts explored in the thesis are highlighted. Section 1.4 provides an overview on the pursuit research strategy, where projects contributions and published work are identified. Finally, the dissertation contents are defined in Section 1.5.

Key concepts: WMN History; motivation; objectives; novelty; impact; overview.

1.1 Brief History

Seamless communication has become an elementary building-block of modern society. Mobile and wireless communications highly enabled such paradigm, providing seamless connectivity. In the last decades, such networks experienced an extraordinary evolution in terms of technological capabilities, worldwide used by billions of users to connect anywhere, anytime, and at an acceptable cost. This has had an enormous impact in the daily life of users, establishing communication links to their families, work colleagues, Internet services, emergency services, health care, etc.

Current mobile and wireless communication systems result from the convergence of two different evolutionary paths in telecommunication systems, drawn initially for different purposes. On the one hand, wireless telephony networks (also known as cellular networks), originally designed to provide voice services via mobile and wireless phones, supported by operators network infrastructures. On the other, computer networks, designed to provide packet data services through computers, supported by the Internet. Nowadays, the separation of these two worlds is almost indistinguishable. The distinction between a phone and a computer becomes difficult to determine, when we observe for example the communication and computing capabilities, size and portability of smartphones and tablets. These terminals are able to operate both in "computer" and "telephony" networks, evolving to be supported by the same network. Below, the evolution of these two paths towards this convergence is shortly described.

The first generation of wireless telephony systems was launched in the 1980s, analogue ones designed for voice services and with limited capacity and portability. They evolved in the 1990s to digital, with the 2nd Generation (2G) Global System for Mobile Communications (GSM) [MoPa92], enabling voice and data over circuit switching, and later the support of packet switching with General Packet Radio Service (GPRS) [VrLa02]. The Universal Mobile Telecommunications System (UMTS) brought the 3rd Generation (3G) [3GPP03] in the 2000s, increasing services bit rates, allowing better Internet access, video calls, besides the important capacity to integrate legacy generations (GSM). Mobile terminals started to come equipped with photo and video cameras, keyboards, touch displays and audio players. This turned users into "prosumers" of information, not only consuming but also producing data. Machine to machine wireless communications also raise, as an important part of data traffic. Flat rates offered by operators led to an exponential increase of data traffic worldwide. In the last years, the 4th Generation (4G), so called Long Term Evolution (LTE) [3GPP08b], compatible with legacy systems, enables even higher bit rates and lower latencies. Its architecture is simpler, and is based on the Internet Protocol (IP) [TaWe10], originally designed for computer networks. Cellular systems created new communication "needs", where users want to have connectivity anytime, anywhere, and in any form. Although providing high revenues, the deployment of these networks represents an enormous investment, requiring large and expensive cabling infrastructures for the interconnection of all base stations.

On the other side, the first packet switched network started in the early 1960s in the USA, the Advanced Research Projects Agency Network (ARPANET) [Salu95], being a progenitor of what was to become the global Internet. It was initially for use by research projects. In 1982, the Internet Protocol Suite (TCP/IP) [Stev94] was standardised, and the concept of a world-wide network of fully interconnected TCP/IP networks, called the Internet, was introduced. Commercial Internet Service Providers (ISPs) began to emerge in the early 1990s, starting a rapid expansion to Europe and Australia. Since the mid-1990s, the Internet has had an enormous impact worldwide on commerce and culture, including the rise of near instant communication by email, Voice over IP (VoIP) and the World Wide Web (WWW). The Internet continues to grow, driven by ever greater amounts of online information and knowledge, commerce, entertainment and social networking. It is estimated that in 1993 the Internet carried 1% of the information flowing through two-way telecommunication networks, this figure having grown to 51% by 2000, and by 2007 more than 97% [HiLo11]. It is a prime example of a large-scale, highly engineered, yet highly complex system.

The Internet is heterogeneous; for instance, data transfer rates and physical characteristics of connections vary widely. The principles of routing and addressing methods for traffic in the Internet reach back to their origins in the 1960s, when the eventual scale and popularity of the network could not be anticipated. Thus, the possibility of developing alternative structures is currently under investigation [SAIL13]. Still, the Internet structure was found to be highly robust to random failures, and very vulnerable to high degree attacks. Several types of computer networks were developed around the Internet, such as Local, Metropolitan and Wide Area Networks (LANs, MANs and WANs, respectively). A LAN interconnects computers in a limited area, such as a home, school or office building. Their cabling is based on coaxial and fibre-optic cables. In the 1990s, Wireless LANs (WLANs) started to become a reality, based on IEEE 802.11 standards [IEEE07b], to enable wireless Internet connectivity to mobile laptops and smartphones. Since then, they evolved largely, with standards that increase bit rates, extend coverage and quality of service guarantees, enabling a variety of services. Modern implementations of WLANs range from small in-home networks to large, campus-sized ones to completely mobile networks on airplanes and trains. Users can access the Internet from WLAN hotspots in restaurants, hotels, with tablets and smartphones with heterogeneous capabilities, including WLAN, 3G and 4G. Oftentimes these types of public access points require no registration or password to join the network. Others can be accessed once registration has occurred and/or a fee is paid. Still, they are much more cost-effective, compared to cellular networks, having helped to increase their extensive deployment and intensive use. They provide higher bit rates than cellular networks, although quality of service guarantees are inferior. Initially seen as a competitor of cellular networks, they are nowadays allies, for example, enabling traffic offload when cellular networks are heavily loaded.

WMNs are an interesting evolutionary path of wireless networks, a wireless backhaul of self-organised mesh nodes, providing wireless access connectivity to end-users, and needing only some gateways to the Internet [HoLe08]. WMNs extend the use of the wireless medium from access towards backhaul networks. They rise from the challenging combination of cellular networks, multi-hop ad-hoc networks and fixed backhaul networks. Both the wired Internet and the Public Switched Telephone Network (PSTN) are essentially mesh networks that have long been present. In the 1970s, the development of a packet radio network known as ALOHAnet [Abra70] developed methods to arbitrate access to a shared radio channel by network nodes. It allowed stations to automatically repeat packets and extend the range of transmitters, resulting in the first ad-hoc, decentralised networks without pre-existing infrastructure. In the late 1970s, DARPA create a packet radio network called PRNET [JuTo87] to conduct a series of experiments to verify the use of ARPANET over packet radio links between mobile and fixed network nodes. These researches lead to commercial operations of packet radio networks, as well as amateur networks. In the 1990s, Mobitex launched Ricochet Internet service [Cher02], deployed with success in many cities, and working as a WMN. Packets were forwarded by small repeaters until reaching a wired Internet access point. Throughput was similar to the standard telephone modem, and could be treated as an “always-on” connection. It was marketed for a flat monthly fee, adopted by many users as home Internet connections.

In 2000, Roofnet was launched [BBAM05], an experimental IEEE 802.11b/g mesh network, the software being available free as open source. Since then, several proprietary solutions were developed, e.g., [Trop13] or [Nort05], starting from single-radio nodes to multi-radio solutions, deployed with success in many campi and cities. Still, they present limited performance, and the fact that they are proprietary slows their worldwide adoption. In parallel, effort on standardisation of WMNs has been lead mostly by IEEE, already existing mesh standards for Wireless Personal

Area Networks (WPAN) [IEEE06] and Wireless Metropolitan Area Networks (WMAN) [IEEE01], although their adoption is poor. For Wireless Local Area Networks, the 802.11s standard was launched in September 2011 [IEEE11], seen as a potential boost for worldwide adoption of WMNs if all manufacturers start to integrate it in their equipment. WMN deployments are already available in many cities. For example, in Taipei [Nort05], a deployment of 10 000 nodes equipped with two radios (an IEEE 802.11a for backhaul and an IEEE 802.11g for access) is available, a proprietary solution from Nortel, supporting a maximum of two hops to the gateway.

WMNs are usually built to allow many users to share few wired Internet connections with minimal up-front investment, and being easily adjustable and expandable. Their advantage is the rapid, flexible robust and self-organised deployment of a mesh of hotspots, extending Internet service provisioning without the need of an expensive infrastructure, requiring ripping apart buildings and tearing up streets to wire miles of copper or fibre cables. WMNs provide flexible coverage in areas beyond the reach of other wired or wireless technologies, satisfying requirements of various consumers, large or small, and opening a world of possibilities. They may enable a burgeoning market in a foreseeable future, even though considerable research efforts are still needed.

1.2 Motivation and Objectives

The core technology of current Internet was designed more than thirty years ago. Although it has proved to be successful, some voices have recently claimed that its principles are no longer valid, and that a redesign is deemed necessary [Day07]. It is true that up to now the patches that have been added have been enough to cope with the incremental new challenges. Still, these might not be enough to tackle the requirements that are posed by the appearance of new services and paradigms, requiring an appropriate combination of different mechanisms. This is the case of WMNs, for their disruptive and sometimes clean slate requirements to achieve optimum functioning. WMNs need delicate cross-layering that breaks basic rules of the classical IP layered network architecture, where each layer is independent and isolated of each other. WMNs are seen by many as one of the “black sheep” of communication networks, possibly being one of the reasons for its slow evolution, standardisation and deployment of WMNs, compared to other type of networks. On the other hand, as they easily enable to extend the wireless Internet access of a few gateways, this is seen by many ISPs as a menace to their business models based on individual monthly subscriptions.

WMNs rise from the challenging combination of radio access networks, multi-hop ad-hoc networks and fixed backhaul networks. This leverages critical and unique design factors from very different domains, ranging from physical aspects, such as the wireless multi-hop communication paradigm, passing by the challenge of multiple concurrent accesses to the wireless medium, up to routing and security aspects. In particular, classical single-radio nodes have poor performance, multi-radio nodes able to overcome limitations being needed due to the multi-hop nature of WMNs, by simultaneously transmitting and receiving mesh traffic as well as communicating with the end-users they provide connectivity to.

This thesis has two main objectives:

- to propose novel frameworks for the flexible and opportunistic management of WMNs and for the flexible orchestration of connectivity services integrating legacy and novel mechanisms;
- to propose strategies for the efficient and fair management of radio resources of multi-radio nodes (addressing channel assignment, transmission power control, rate adaptation and flow control) and for the opportunistic management of self-organised and heterogeneous WMNs.

In the traditional model for WMNs, a two-tiered architecture classifies nodes as mesh routers or clients. Such an approach, based on this strong separation of roles, is interesting when an administrative entity deploys and controls the network. Nevertheless, in spontaneous and self-organised networks, where there is no administrative entity behind the network formation, this model does not hold anymore. In such scenario, the heterogeneity of nodes should be fully exploited in order to increase as much as possible network availability and usability. This is a motivation for one of the objectives of this thesis, to propose novel frameworks for the flexible and opportunistic management of WMNs, supporting the integration of novel mechanisms.

On the other hand, WMNs face numerous challenges related to the intrinsic characteristics of the wireless medium and traffic flow. Sharing the wireless medium for multi-hop raises interference and contention challenges. WMNs confront a sensitive trade-off between maximising connectivity (only possible by using a common channel), and minimising interference between transmissions (using different channels). Additionally, WMNs enable the exchange of aggregated traffic between end-users and gateways to the core network, where typically all traffic of the WMN flows through the gateways. Typically, these nodes become bottlenecks, limiting the WMN capacity. Although being a mesh, where every mesh node may communicate with its neighbour, traffic flows typically as a fat-tree, ramified into links of decreasing throughput towards destination mesh nodes, which present poor fairness properties, as contention, delay, and packet losses are incremental with the number of hops. Mesh nodes nearer the gateway are in natural advantage relatively to farther ones, starved when the traffic load increases beyond a certain limit. In this sense, an equal share of capacity among all aggregating mesh nodes is a requirement for fair network performance. These aspects drive to the second objective: to propose a strategy that manages efficiently radio resources (channels, transmitted power levels and bit rates) in order to guarantee fair share of resources among WMN's nodes, both in structured and random deployments, with a single or multiple gateways, taking opportunistically advantage of the available resources of nodes with heterogeneous communication capabilities.

1.3 Novelty

This thesis claims novelties in two fields, within the scope of management of WMNs. On the one hand, a framework, a functional architecture and an opportunistic service for the management of WMNs are proposed. On the other hand, a strategy, integrating multiple mechanisms, is proposed for the efficient, fair and opportunistic management of radio resources.

An organisational framework for the flexible and opportunistic formation and maintenance of WMNs is proposed, relying on the concept of self-organisation and collaboration. The main idea is to make the network take advantage of the specific characteristics and capabilities (communication, computing, and storage) of heterogeneous nodes in an opportunistic fashion. In our vision, any wireless node (either a classical mesh router or client) can perform any network functionality, if they can and if they wish. They may collaborate in a self-organised network, where they share duties by taking tasks according to their capabilities, all having one common objective: make the network working as efficient as possible. By introducing this flexibility, spontaneous networks are likely to respond better to the expected services. An opportunistic resources manager is proposed that gathers information relative to the different network functionalities and task requirements. It then suggests specific functionalities and/or tasks that the nodes are free to accept or not.

The above framework needs an architecture and communication protocol to support the flexible and dynamic implementation of legacy and novel communication functionalities in nodes. For it, an Open Connectivity Service (OConS) architecture is proposed, flexible and modular in the description of connectivity resources and mechanisms, based on the identification of functional entities and their interfaces. It enables the orchestration of both legacy and enhanced connectivity mechanisms, which can be dynamically adapted and orchestrated into OConS Services offered to the network.

This thesis also claims two strategies for the management of WMNs radio resources: a novel Load and Fair and Efficient Resource Allocation strategy (FERA) and an Opportunistic WMN Resources allocation OConS Service (OWROS). These strategies are supported by a multi-radio node model, with a virtual Medium Access Control (MAC) supporting multiple radio interfaces (MAC & PHY), an abstraction layer representing to higher layers (IP) the abstraction of a single radio. It enables the transparent management of multiple radios, where radio resource management strategies can be implemented. It is modelled using the proposed OConS functional architecture. A hybrid channel management policy is also proposed, flexibly guaranteeing connectivity with any neighbouring node.

FERA is designed for efficient and fair mesh forwarding in multi-radio WMNs. It combines multiple mechanisms that efficiently optimise radio resources (rate, power and channel) to guarantee a max-min fair capacity to every node. FERA's rate adaptation mechanism, sensitive to traffic specificities of WMNs, uses the highest bit rates at mesh gateways, while, for the ramified links, minimum rates that satisfy their capacity needs are used. This enables to efficiently minimise the transmitted power and interference, advantageous for channel reutilisation. FERA also integrates a load and interference aware channel assignment mechanism, allowing the simultaneous operation of all links without interference. When this is not achievable, two auxiliary mechanisms of capacity sharing and capacity reduction can be subsequentially used, reducing the capacity of certain MAPs to guarantee fairness to all nodes. FERA's gateway flow-control mechanism guarantees that all MAPs respect the allocated capacity, guaranteeing that every MAP is able to operate at its max-min fair capacity. Several network and usage evaluation metrics are defined and used to evaluate performance, namely throughput, delay, max-min fairness, capacity usage efficiency, energy efficiency, and spectrum efficiency.

Supported by the proposed opportunistic organisational framework and the OConS architecture, an OWROS service is proposed, which exploits opportunistically network conditions and multi-radio node capabilities to improve connectivity through the orchestration of adequate connectivity mechanisms, such as "legacy" client access or Internet gateway provisioning mechanisms, as well as the novel FERA mesh forwarding one. In a WMN scenario of randomly deployed mesh nodes and end-users equipped with heterogeneous terminals, this service aims to improve the network performance, increasing overall coverage, connectivity and capacity.

1.4 Research Strategy and Impact

The work developed in this thesis was done within different research European frameworks and projects, such as the Sixth and Seventh Framework Programme (FP6-IST and FP7-ICT), and also the Co-operation in the field of Scientific and Technical Research (COST), namely IST-NEWCOM [NEWC07], IST-WIP [WIP09], ICT-4WARD [4WAR10], ICT-SAIL [SAIL13], and COST Actions 2100 [COST11] and IC 1004 [IC1013]. Although all these projects had a considerable work overhead beyond this thesis, they enabled sharing knowledge, visions and experience with multiple researchers of international institutions, namely networks' manufactures, cellular operators, research centres and universities, resulting in multiple cooperative activities and publications. Besides this, technical reports for Optimums, Vodafone and TMN mobile operators were edited, as well as for ANACOM Portuguese national regulator.

In the development of this thesis, these projects naturally had a considerable influence over many decisions taken. Reciprocally, the impact of the research activity carried within this thesis had impact on these projects. This thesis proposes an organisational framework for the opportunistic management of self-organised WMNs, which was adopted within the IST-WIP project, and presented as one of its key results. This thesis proposes an OConS functional architecture, which opened new potentialities for the integration of novel mechanisms in a modular approach. It was widely adopted within the ICT-SAIL project, to integrate several novel mechanisms, which were evaluated and demonstrated as a key result of the project. The proposed opportunistic service for management of connectivity in WMN, enabled to evaluate and validate within the ICT-SAIL project, the proposed OConS architecture. Besides this, the self-organised RRM strategy, implemented in a virtual MAC supporting multiple radio interfaces, was used within the IST-4WARD project to demonstrate the capabilities of the Generic Path architecture.

The definition of common reference scenarios is a key issue in cooperatively unifying research. They allow presenting complementary studies around a common scenario, permitting also to compare and evaluate different solutions for the same technical problem. The COST2100 Special Interest Group (SIG) "COST2100 Reference Scenarios" [SIGA11] was chaired by the author of this thesis. It involved contributions from multiple European research institutions towards the definition and publication of 4 canonical scenarios, which were used within the working groups of COST 2100. A scenario of interest for wireless challenged networks with a flash crowd of end-users was defined, and used within IST-WIP and ICT-SAIL projects for the integrated evaluation of mechanisms proposed by various projects' partners.

The work presented in this thesis was disseminated in several papers that have been published or submitted to various conferences and journals:

- Book contributions:
  - L.S. Ferreira and L.M. Correia, "Services and Traffic Modelling", in *Luis M. Correia (ed.), Mobile Broadband Multimedia Networks. Techniques, Models and Tools for 4G*, Academic Press, London, UK, 2006.
- International Journals:
  - L.S. Ferreira and L.M. Correia, "An Efficient and Fair Strategy for Radio Resources Allocation in Multi-Radio Wireless Mesh Networks", submitted to *Wireless Personal Communications*, Oct. 2012.
  - L.S. Ferreira, M.D. Amorim, L. Iannone, L. Berlemann and L.M. Correia, "Opportunistic Management of Spontaneous and Heterogeneous Wireless Mesh Networks", in *IEEE Wireless Communications* , Vol. 17, No. 2, Apr. 2010, pp. 41-46.
  - L.S. Ferreira, A. Serrador and L.M. Correia, "Concepts of Simultaneous Use in Mobile and Wireless Communications", in *Wireless Personal Communications*, Vol. 37, No. 3/4, May 2006, pp. 317-328.
- International Conferences:
  - L.S. Ferreira, R. Agüero, L. Caeiro, A. Miron, M. Soellner, P. Schoo, L. Suciu, A. Timm-Giel and A. Udugama, "Open Connectivity Services for the Future Internet", in *Proc. of WCNC 2013: IEEE Wireless Communications and Networking Conference*, Shanghai, China, Apr. 2013.
  - L.S. Ferreira and L.M. Correia, "Efficient and Fair Radio Resources Allocation for Spontaneous Multi-Radio Wireless Mesh Networks", in *Proc. ISSSE 2012: International Symposium on Signals, Systems and Electronics*, Potsdam, Germany, Oct. 2012.
  - L.S. Ferreira and L.M. Correia, "OConS Service for Management of Connectivity in Spontaneous Community-Based Wireless Mesh Networks", in *Proc. of MONAMI 2012: 4th ICST International Conference on Mobile Network Management*, Hamburg, Germany, Sep. 2012.
  - L.S. Ferreira and L.M. Correia, "Radio Resource Management for Optimising Wireless Mesh Networks Deployments ", in *Proc. of WPMC 2011: 14th International*

Symposium on Wireless Personal Multimedia Communications, Brest, France, Oct. 2011.

- L.S. Ferreira and L.M. Correia, "Energy-Efficient Radio Resource Management in Self-Organised Multi-Radio Wireless Mesh Networks", in *Proc. of PIMRC 2011: 22nd IEEE Symposium on Personal, Indoor, Mobile and Radio Communication*s, Toronto, Canada, Sep. 2011.
- R. Agüero, L. Caeiro, L.M. Correia, L.S. Ferreira, M. García-Arranz, L. Suciu and A. Timm-Giel, "OConS: Towards Open Connectivity Services in the Future Internet", in *Proc. of MONAMI 2012: 3rd ICST International Conference on Mobile Network Management*, Aveiro, Portugal, Sep. 2011.
- M. Sifalakis, C. Tschudin, S. Martin, L.S. Ferreira and L.M. Correia, "A Generic Service Inteface for Cloud Networks", in *Proc. of CLOSER 2011: 1st International Conference on Cloud Computing and Services Science*, Noordwijkerhoud, The Netherlands, May 2011.
- L.S. Ferreira, L. Caeiro. M. Ferreia and A.S. Nunes, "QoS performance evaluation of a WLAN mesh versus WIMAX network for an isolated village scenario", in *Proc. EuroFGI Workshop on IP Quality of Service and Traffic Control*, Lisbon, Portugal, Dec. 2007.
- L.S. Ferreira and R. Rocha, "Multi-Channel Clustering Algorithm to Improve Performance of WSNs," in *Proc. of ConfTele'07 – VI Conference on Telecommunications*, Peniche, Portugal, May 2007.
- L.S. Ferreira, B.W.M. Kuipers, C. Rodrigues and L.M. Correia, "Characterisation of Signal Penetration into Buildings for GSM and UMTS", in *Proc. of ConfTele'07 – VI Conference on Telecommunications*, Peniche, Portugal, May 2007.
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- A. Serrador, G. Galvano, L.S. Ferreira and L.M. Correia, "Parameters for the Definition of Scenarios for CRRM Performance Evaluation", in *Proc. of MELECON'2006 - 13th IEEE Mediterranean Electrotechnical Conference*, Málaga, Spain, May 2006.

The main contributions made within the European research projects were the following ones:

- Scalable and Adaptive Internet Solutions (ICT-SAIL) [SAIL13], an FP7-ICT Large-scale integrating project (2010-2013):
    - Architectural concepts of connectivity services [Suci11], [SuTi12].
    - Architecture and mechanisms for connectivity services [TiSu13].
    - Applications for connectivity services and evaluation [MiSu13].
- Architecture and Design for the Future Internet (ICT-4WARD) [4WAR10], an FP7-ICT Large-scale integrating project (2008-2010):
    - Mechanisms for Generic Paths [Rand09].
    - Evaluation of Generic Path architecture and mechanisms [Woes10].
    - In Network Management for Generic Path [Ferr10].
- An All-Wireless Mobile Network Architecture (IST-WIP) [WIP09], an FP6-IST specific targeted research project (2006-2008):
    - Architectural requirements for the Radio Internet: addressing, routing, design strategies [DuMa06].
    - Detailed Objectives of Radio Internet [AmFl06].
    - Applicability of Current PHY and MAC Algorithms and Techniques to the WIP Global Architecture [Ibar06].
    - Design of the lower layer techniques for WIP Advanced Wireless Infrastructure [Ferr07].
    - Solutions: mesh networking, multi-hop relaying, cross-layer design, communities, operator/cellular assistance [Tass07].
    - Performance evaluation of the low layer techniques and integration in the WIP global architecture [Ibar08].

Additionally, most of the relevant work was presented in regular meetings of the COST Actions 2100 [COST11] (2006-2011) and IC 1004 [IC1013] (2011-2015).

Besides this research work, three M.Sc. thesis proposals were elaborated under the supervision of Professor Luis M. Correia on WMN topics, with the collaboration of the author of this thesis:

- Dominik Sarapata, "RRM strategies for WMN" [Sara10].
- Emanuele Tidó, "Performance evaluation of a WMN in a Residential Scenario" [Tido08].
- Salvatore Messina, "Performance Evaluation of a WMN in a Campus Scenario" [Mess08].

1.5 Contents

This thesis is structured in 8 chapters including this one, and 5 appendixes. Their content is summarised below.

Chapter 1 provides an introduction to the thesis, presenting, in Section 1.1, a brief history of wireless mesh networks. In Section 1.2, the thesis motivation and objectives are presented, and in Section 1.3, the novel aspects and concepts explored in the thesis are highlighted. Section 1.4 provides an overview on the pursuit research strategy, where projects contributions and published work are identified. Finally, the dissertation contents are defined in Section 1.5.

Chapter 2 provides an overview of Wireless Mesh Networks and its challenges. In Section 2.1, basic concepts around WMNs are presented. In Section 2.2, typical services and scenarios for WMNs are highlighted. In Section 2.3, critical design and performance issues of WMNs are identified. In Section 2.4, advances in MAC for multi-channel multi-radio nodes are identified. Section 2.5 addresses resource management in multi-radio WMNs, namely channels, transmission power and rate. Finally, in Section 2.6 novel self-organisation and community-centric WMN concepts are highlighted.

Chapter 3 proposes novel frameworks for the management of WMNs. In Section 3.1, an organisational framework for opportunistic formation and maintenance of self-organised WMNs is presented. To support it, a functional open connectivity services architecture is presented in Section 3.2. It enables to offer novel connectivity services flexibly orchestrating legacy and novel mechanisms.

Chapter 4 proposes novel strategies to manage WMNs' radio resources. Section 4.1 describes design guidelines and assumptions. A set of models supporting the proposed strategies is presented in Section 4.2. In Section 4.3, the FERA strategy is proposed for the efficient and fair management of radio resources. In Section 4.4, the OWROS service is presented, an OConS service for opportunistic WMN resources allocation. In Section 4.5, network and usage evaluation metrics are presented.

Chapter 5 describes the implementation of strategies and scenarios for evaluation. In Section 5.1, the implementation of a multi-radio mesh node and the proposed strategies in OPNET Modeler simulation platform are described. Then, input configuration parameters and output evaluation metrics are identified in Section 5.2. Finally, Section 5.3 describes a set of scenarios for evaluation of the proposed strategies.

In Chapter 6, the evaluation of performance results is presented for the FERA strategy and the OWROS service proposed in Chapter 4. Section 6.1 presents a preliminary discussion, identifying coverage, throughput and delay bounds, as well as general considerations on the proposed FERA strategy. In Section 6.2, an evaluation of FERA for the reference scenario is done. In Section 6.3, the performance of FERA for different scenarios is compared, varying the number of mesh nodes and size of the scenario. In Section 6.4, a more challenging random WMN deployment scenario is evaluated. Finally, in Section 6.5, the performance of OWROS is evaluated for a random residential neighbourhood scenario with a flash crowd.

Chapter 7 presents the main conclusions of the thesis. Section 7.1 presents a summary of the thesis. Section 7.2 presents the main findings and results. Section 7.3 provides some considerations about future work.

Appendix A presents an overview of existing WMN standards for Wireless Personal, Local Metropolitan and Wide Area Networks. Appendix B characterises various scenarios where WMNs are likely to provide a more versatile or affordable solution than other wired or wireless technologies. Appendix C presents an overview of channel assignment strategies. Appendix D presents some considerations on routing for WMNs. Appendix E describes the impact on throughput and delay of the overhead introduced by protocols. Appendix F presents the assessment of the implementation of the proposed multi-radio nodes and RRM strategy in OPNET Modeler simulation platform.

Chapter 2

WMN Overview and Challenges

Chapter 2 provides an overview of Wireless Mesh Networks and its challenges. In Section 2.1, basic concepts around WMNs are presented. In Section 2.2, typical services and scenarios for WMNs are highlighted. In Section 2.3, critical design and performance issues of WMNs are identified. In Section 2.4, advances in MAC for multi-channel multi-radio nodes are identified. Section 2.5 addresses resource management in multi-radio WMNs, namely channels, transmission power and rate. Finally, in Section 2.6 novel self-organisation and community-centric WMN concepts are highlighted.

Key concepts: scenarios; radio resources; design challenges; multi-radio; multi-channel.

2.1 Basilar Concepts

WMNs are an emerging network architecture with two fundamental objectives, Figure 2.1: (a) to form a self-organised multi-hop wireless backbone; (b) to offer connectivity to end-users. WMNs comprise two types of nodes: Wireless Mesh Routers (WMRs), which build the multi-hop backbone; Wireless Mesh Clients (WMCs), classical end-user terminals.

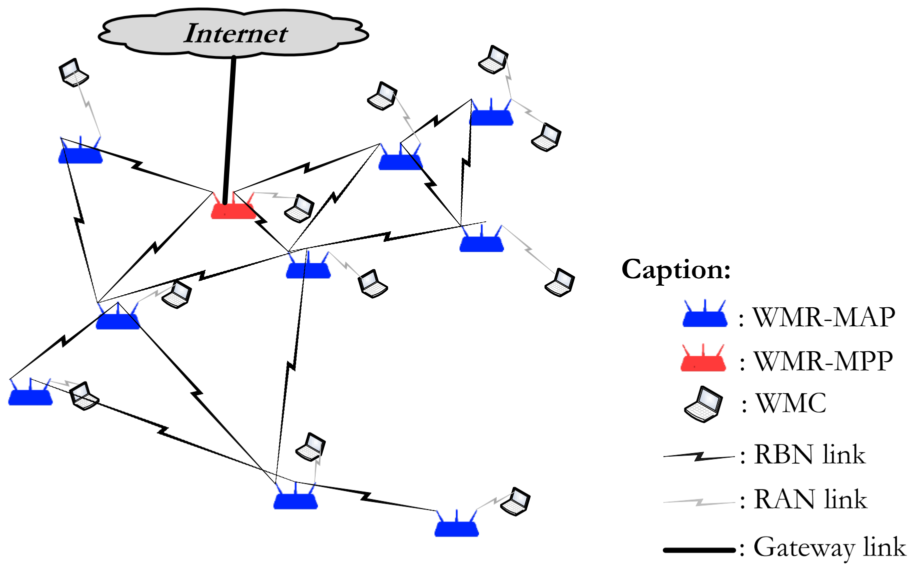


Figure 2.1 – Wireless Mesh Network.

WMRs may be equipped with multiple radio interfaces (so-called radios) built on either the same or different wireless access technologies, supporting simultaneous operation on various radios. Each radio has its own MAC and physical layers (transceiver), able to communicate on one configured channel. WMRs act as radio backhaul routers, supporting mesh networking, able to discover their peers and associate to them, and cooperating in a self-organised way to create a Radio Backhaul Network (RBN). WMRs are able to select an optimal path through the WMN to forward traffic. They can be of several types: Mesh Points (MPs), Mesh Access Points (MAPs) or Mesh Point Portals (MPPs). A MAP is a WMR that participates in the mesh, forwarding frames on behalf of other WMRs, collocated with an AP, covering a region where they offer connectivity to end-users' WMCs, building a Radio Access Network (RAN). RBNs and RANs are typically supported by different physical layer technologies, each multi-radio MAP having dedicated radios for RAN and RBN mesh functionalities. WMCs associate to MAPs, not requiring new functionalities, and communicate by means of the RBN. The RBN can be a self-standing network, simply offering inter-user connectivity. Otherwise, if connection is available through one or more WMRs acting as gateways, so-called MPPs, the RBN might be considered as a local wireless extension of the Internet, so-called Fixed Backhaul Network (FBN). Some WMCs may also provide peer to peer communication among clients, forwarding traffic or even performing routing and self-configuration functionalities, like typical ad-hoc networks.

A WMN is an intermediary network that exchanges aggregated traffic between RANs' WMCs and the FBN, as illustrated in Figure 2.2. It may be considered as a three-layered network, where WMRs congregate functionalities of three networks:

- providing gateway connectivity between the RBN and FBN (MPPs), as FBN elements;
- forwarding traffic between WMRs, as RBN elements;
- providing connectivity to end-users' WMCs (MAPs), as RAN elements.

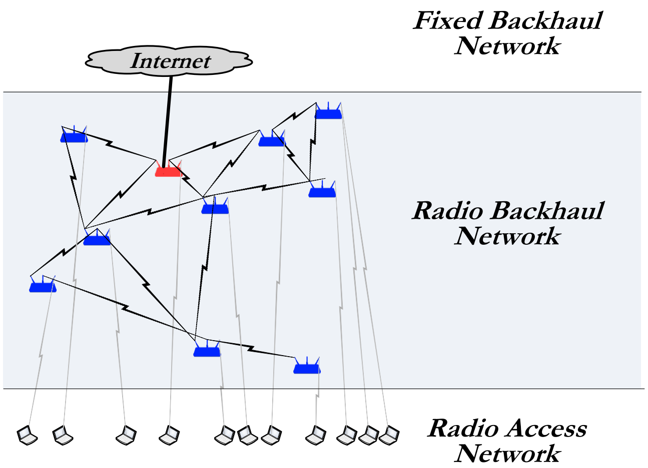


Figure 2.2 – WMN, an intermediary radio backhaul network between fixed backhaul and radio access networks.

Some characteristics of WMNs are listed below:

- A WMN is a multi-hop wireless backbone of WMRs of limited mobility, powered, and acting as an access network. In this sense, a WMN can be seen as a wireless concatenation of hotspots, or an infrastructured ad-hoc network.
- WMNs are self-organised, having the capability of self-forming, self-organising and self-healing, enhancing system resilience and reliability.
- The mesh topology extends the network coverage with reduced deployment costs and fast and flexible network configuration.

- WMNs explore short range communications with neighbours, enabling high transmission rates, low power levels, and short frequency reuse distance.
- Power-consumption constraints are different for WMRs and WMCs.
- Only a few mesh routers are connected to the Internet. Traffic flows mainly between users and these gateways to the internet.
- Since there are several routes to the same destination, WMN is a robust, more reliable and available topology than hierarchical or star topologies, essential when node or link failures occur, or when channel conditions are poor. With an adequate routing protocol, the traffic can be routed to avoid congested areas, resulting in an efficient traffic distribution within the network, enhancing load balancing and throughput.
- In a WMN, WMCs access is typically infrastructured, being possible in certain cases that WMCs have mesh forwarding functionalities, but without the possibility of providing end-connectivity to users. Mobility of WMCs is supported by the WMN infrastructure.
- WMNs are not stand-alone and need to be compatible and interoperable with other networks, to be able to provide WMCs' connectivity on the one hand, and Internet gateway access on the other.
- WMRs may integrate heterogeneous networks, including both wired and wireless, ones used for mesh forwarding, Internet gateway access or access provision.

They are also designated as infrastructured ad-hoc networks, where mesh nodes constitute an ad-hoc network that provides infrastructured access to end-users. Still, the tiered architecture of WMNs differentiates them from ad-hoc networks, characterised by a flat architecture. The existence of one or several MPP nodes drastically extends the scope of mesh from ad-hoc networks, where traffic travels mostly between MPP gateways and aggregating MAPs. Also, contrarily to WMNs, in ad-hoc networks, routing has to face the high mobility of all nodes by assuming that the topology is highly dynamic, links are fragile, and no dedicated infrastructure components are present. WMNs have also no energy constrains, by opposition to ad-hoc networks. These differences make protocols and architectures designed for the ad-hoc wireless networks perform very poorly when applied in WMNs. Both the wired Internet and the PSTN are essentially mesh networks that have long been present. The advantage of the wireless mesh technology is to allow the easy deployment of networks without the need of a fixed costly infrastructure. It provides flexible coverage, and can reach areas beyond the reach of other wired or wireless technologies.

WMNs are seen by many as the evolutionary path for wireless networks in general. Within several existing standards addressing specific communication's scenarios and applications, task groups have been already established to address the wireless mesh paradigm. In Appendix A, an overview of existing WMN standards for WPANs, WLANs, WMANs, and Wireless Wide Area Networks (WWANs) is presented.

2.2 Scenarios and Applications

Although the wireless mesh technology is still in its infancy, its potential to likely transform our world appears enormous. Some of the scenarios where it is likely to provide a more versatile or affordable solution than other wired or wireless technologies include the following ones [LZKS06]:

- Extensive coverage areas, e.g., offices, campus, stadiums, or spanning a sprawling facility.
- Areas that are unwired, under-wired, or hard to-wire, such as highways, conduits or farmlands.
- Emergency situations, such as fire fighting, disaster recovery, and military operations.

Given their unique characteristics, WMNs have a wide range of potential applications as presented below [AkWa05], characterised in detail in Appendix B:

- Broadband home networking – The deployment of a WMN in a home environment can easily reduce zones without service coverage. Network capacity is also better, compared to the traditional solution of having APs connected to an access modem or hub via wire.
- Community and neighbourhood networking – Mesh networks can simplify the connectivity of users inside a community allowing direct links (or indirect via multiple hops) among them. Applications such as distributed file access and video streaming are then facilitated.
- Enterprise networking – The traditional application of WLANs in such scenarios is the use of APs providing isolated "islands" of wireless access, connected to the wired enterprise networks. The replacement of this topology by a mesh network presents several advantages, e.g., the elimination of most Ethernet wires and the improvement of network resource usage.
- Metropolitan area networks – Considerations on this scenario are similar to the previous ones related to enterprise networking, taking into account that a much larger area is covered, and that scalability requirements assume an important role during network configuration.
- Transportation systems – Mesh networks support convenient passenger information services, remote monitoring of in-vehicle security video and driver communications.
- Building automation – Equipment, like elevators, air conditioners, electrical power devices,

etc., need to be controlled and monitored, thus, connected among themselves and to some sort of central controller. This task can be greatly improved, and deployment costs greatly reduced if mesh networks are used.

- Health and medical systems – For several purposes, there is the need to transmit broadband data from one room to another. Transmission of high resolution medical images and various periodical monitoring signals can generate a large volume of data, which can be handled by a mesh network.
- Security surveillance systems – Similar to the two previous applications, mesh networks are adequate to connect security surveillance systems in buildings, shopping malls, stores, etc.

2.3 Design and Performance Issues

WMNs rise from the challenging combination of wireless access networks, multi-hop ad-hoc networks and fixed backhaul ones. This leverages critical and unique design factors from very different domains, ranging from physical aspects, such as the wireless multi-hop communication paradigm, passing by the challenge of multiple concurrent accesses to the wireless medium, up to connectivity, topology and routing aspects [PaDu11]. Besides challenging by their own, these aspects are tightly interconnected, requiring a delicate cross-layering that breaks basic rules of the classical IP layered network architecture, where each layer is independent and isolated of each other. With respect to radio resources' management, c*apacity*, *scalability* and *fairness* are sensitive issues in WMNs that must be understood and addressed jointly, when developing solutions. Several associated performance issues are presented next.

The wireless medium is a scarce resource, the efficient access to the medium being a key issue. When all transmitters are within range of each other, it is easy to provide fair access opportunities to all flows. Still, in dense multi-hop topologies, where nodes share the same wireless medium but not all are within the range of each other, various spatial positions of nodes may lead to different views of the channel state, Figure 2.3. This leads to several *unfairness* and *starvation* situations [LiWa07]. Some of these problems are identified below.

The *hidden node* problem refers to a scenario, Figure 2.3, with an on-going transmission from *A* to *B* in the period of 1 to 5 s (referred in the figure as $t_{[1\text{-}5]}$). Hidden node *C* is within the range of receiver *B*, but not in the range of sender *A*; since it senses the medium free, it may commence transmission at instant 4 s, producing a collision in *B*. Nevertheless, the transmitter is not aware of the collision. Another problem is the *exposed node* D that wants to transmit to E at instant 2 s; since it is in deferral period, due to the transmission from A to B, it cannot transmit. However, there is no reason to defer its transmission, since B is out of D's range. A third problem is the *deaf node* D, which during his deferral period 1-5 s did not hear the announcement of the beginning of a transmission from F to E at instant 2 s. When D's deferral period is over, and since it senses the channel idle, it starts to transmit at instant 6 s, producing a collision in E. All these collisions require retransmissions that result in delays.

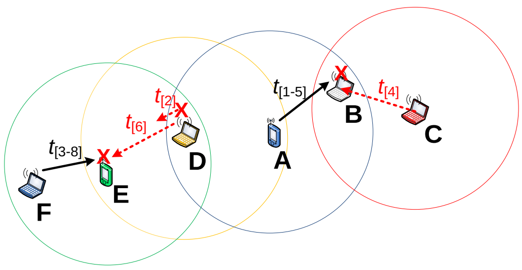
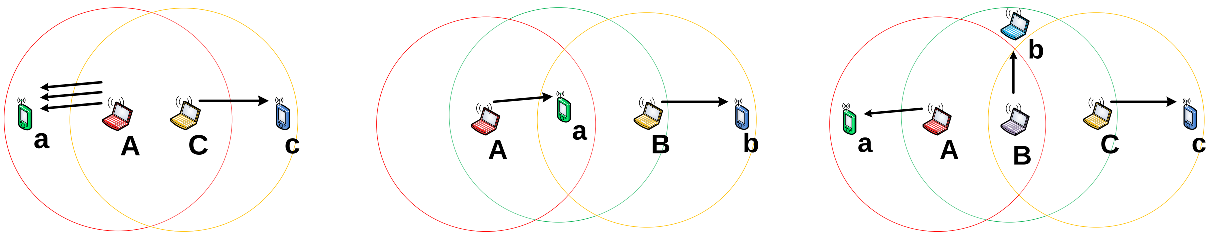


Figure 2.3 – Examples of Hidden (C), exposed (D) and deaf (D) nodes.

An *unfair channel sharing* problem [ZhLH07] also occurs when two nodes contend to the medium, one with a higher number of flows than the other, Figure 2.4 (a). Typically, a MAC allocates an equal number of packet transmissions to two contending flows on the same channel, not hidden from each other. Nevertheless, these links may be operating at very different data rates, e.g., 1 and 11 Mbit/s. In this case, the effective throughput of 11 Mbit/s link becomes limited by that of 1 Mbit/s. If instead the MAC layer allocates equal channel time to the links, the 11 Mbit/s link would no longer be limited by the 1 Mbit/s one.



(a) Unfair channel sharing. (b) Information Asymmetry. (c) Flow-in-the-middle problem.

Figure 2.4 – Examples of communication problems in a shared wireless medium.

The *information asymmetry* problem [ShSK06], Figure 2.4 (b), arises when the senders of two contending flows are not within radio range, and have an asymmetric view of the channel state where transmitter B of flow Bb is within radio range of receiver a of flow Aa. If both flows have packets to transmit (backlogged), flow Bb will receive significantly higher throughput than Aa, because B knows exactly when to contend for the channel, thanks to the control packets it can hear from receiver *a*. Nevertheless, since *A* is hidden from *B*, it has to discover an idle period only through random back off. Since, in a backlogged *Bb* flow, idle periods are short, compared to data transmission periods, most of the attempts of *A* to transmit occur during *B* transmission, resulting in collisions at receiver *a*. Repeated collisions trigger timeouts at sender *A*, which increases the backoff period. As a result, the collision probability of *Aa* is close to 1, while for *Bb* it is close to 0. This *starvation* problem occurs typically in nodes in a chain willing to communicate to a gateway, Figure 2.5. This is not only due to having a different number of contenders for each flow, which is natural in a multi-hop topology, rather, it is due to coordination problems in Carrier Sensing Multiple Access (CSMA).

The *flow-in-the-middle* problem [ShSK06] arises when the sender of a flow senses the activity of neighbouring nodes that are not within range with respect of each other, Figure 2.4 (c). If all flows are backlogged, the middle flow *Bb* will receive very low throughput, while outer flows will receive maximum one, due to lack of transmission opportunities of flow *Bb*. When *A* captures the medium, *B* will sense and will defer, but *C* will contend and initiate transmission. The misaligned concurrent transmissions of outer flows may be long, being only possible for *B* to transmit when both outer flows are in back-of phase. This occurrence shall become increasingly rare, as the ratio of data transmission interval to back-off interval increases. These two problems suffer from the inability of identifying an idle interval because transmissions are generally misaligned and their duration is much larger than the back-off interval. Starvation would be eliminated if all transmissions occurred on orthogonal channels, but could result in network partitions.

Transmissions occurring on different channels can still be misaligned. When a node communicates on a channel, it is not aware of the state on other channels. Hence, when it finishes communication it may attempt to exchange information with its neighbours while they are currently on other channels. One of the problems is the *multi-channel hidden terminal* [ShSK06], where control packets sent on a certain channel fail to inform neighbouring nodes currently communicating on a different channel. Observing again Figure 2.4 (b), consider that nodes *A* and *a* exchange control packets on a control channel, failing to inform the reservation of channel 1 to neighbouring node *B* currently communicating to *b* on channel 2. During flow *Aa* transmission, flow *Bb* will return to the control channel. Since it has not heard the reservation of channel 1 by flow *Aa*, it may select data channel 1. In this case, flow *Aa* will experience a collision, while the transmission of *Bb* succeeds. Flow *Aa* can be starved if there are many advantaged flows within its radio range.

The *missing receiver* problem [ShSK06] arises when control packets sent on a certain channel to access an intended receiver fail, because this node is currently on a different channel (acting either as transmitter or receiver). Consider a simple three-node scenario, where node *A* transmits to node *B* and node *B* transmits to node *C*. An access attempt of *A* for *B* on channel 1 will fail if *B* is on channel 2. A will perform random back-off and retry on channel 1, causing large packet delay for flow *AB* and decrease its throughput.

In a WMN scenario where all nodes operate over the same channel, substantial *flow interference* is observed between transmissions within the same path and between paths. As an example, in the scenario depicted in Figure 2.5, when node 4 is transmitting to node 5, no other node can transmit. This effect highly reduces the End-to-End (E2E) capacity of the network.

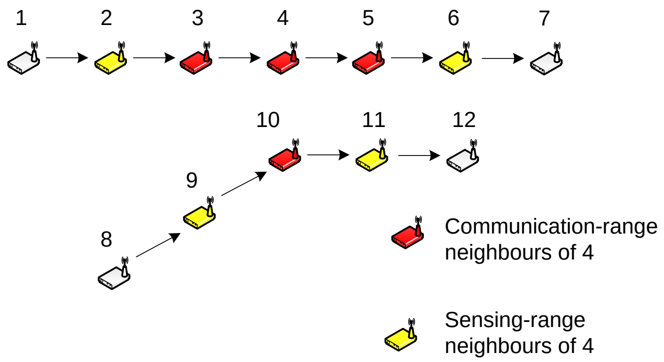


Figure 2.5 – Interference between nodes within the same and between different paths.

The *fat-tree traffic flow* effect results from the fact that in WMNs almost all traffic flows towards gateways connected to the Internet. The consequence is a concentration of traffic around gateways, as illustrated in Figure 2.6, where every MAP injects a load *G* in the WMN. Also called *bottleneck effect* [RaCh05], this leads to strong unfairness problems. Packet loss, contention and delay become incremental with the number of hops. When developing solutions for WMNs, equal share of throughput must be ensured to users, independent of their spatial location.

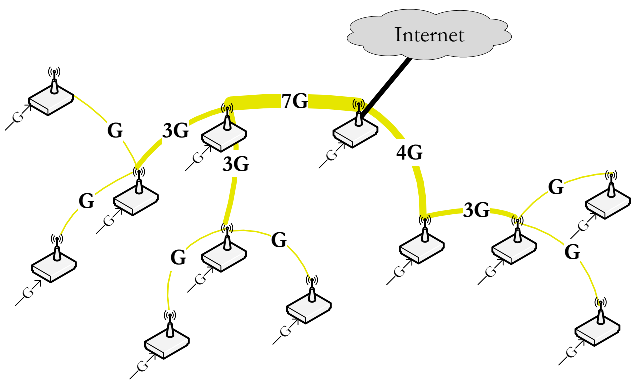


Figure 2.6 – WMN fat-tree traffic flow effect.

The maximum link-layer data rate falls down quickly with increasing distance between the transmitter and receiver due to *path loss*, which increases exponentially with distance. Another fundamental reason for the low network capacity of single-radio WMNs is that radio interfaces are *not relay-oriented*, and cannot transmit and receive at the same time (half-duplex). Consequently, the forwarding capacity of relay nodes is halved. For example, on a string topology of n single-radio nodes using CSMA Collision Avoidance (CSMA/CA) MAC, the throughput degrades approximately to $1/n$ of the raw channel bandwidth, while on a bi-dimensional network, the throughput can be as small as $1/n^2$ [GuKu00]. Although there are several factors that contribute to throughput degradation, such as the MAC protocol, the so-called coordination problems associated to flow unfairness are the ones that aggravate it the most. Also associated to not being relay-oriented, communication from one terminal to the gateway suffers from *cumulative delays* associated to each hop. To support delay sensitive applications such as voice, the number of hops must be limited.

In all communication systems, large *protocol overheads* are introduced by packet headers associated to the different layers of the protocol stack (IP/TCP/MAC/PHY). Also, wireless medium access mechanisms introduce large overheads; contention based ones, for example, introduces large overheads due to backoffs and handshake mechanisms. The advertised peak data rates by systems correspond to the link-level data rate. By considering the overheads up to the application layer, the actual throughput available to applications is highly reduced.

A limiting factor on network capacity is the *ineffective congestion control*, the interaction between network congestion and the sub-optimal backoff algorithms in both lower-layer MAC and higher-layer transport protocols. Protocols like TCP [Stev94] rely on segment losses to detect network congestion, invoking mechanisms to reduce data transmission rate. Nevertheless, in wireless networks, losses are also due to high Bit Error Ratios (BERs) of the lossy wireless channel (BER in wired networks is around 10^{-8} - 10^{-10} vs. 10^{-3} - 10^{-5} in wireless) or contention on the access to the wireless channel. TCP is unable to distinguish between losses induced by network congestion and other types of losses. Invoking congestion control mechanisms in these cases will lead to a considerable drop in throughput, when in fact there is no congestion, yielding to underutilisation of the network. Table 2.1 shows, on an IEEE 802.11a-based one-hop network under various channel conditions, the conditions difference of performance between TCP and UDP, which has no congestion control, but is not reliable. In fact, when a packet is lost in an intermediate hop, TCP's E2E strategy requires the retransmission to traverse the entire path all over again. This leads to a waste of bandwidth on all preceding hops where the prior transmissions were successful. Also, TCP exacerbates the starvation problem [ZhLH07], because TCP senders further back-off when their packets take a long time to get through the inhibited links. As a result, TCP flows traversing on an inhibited link could be completely suppressed in the worst case.

Another fundamental limitation of current solutions is their *ineffective use of spectrum*, as they operate over only a small portion of the available spectrum [ABPW04]. Although multiple non-interfering channels are available, standards are designed to use only a single frequency channel at any given time. To use the entire spectrum without incurring the cost of switching delays, one would have to use multiple radios tuned to specific channels.

Finally, network *scalability* [ZhLH07] is one of the most important problems of large-scale WMNs. The main reasons are: (i) half-duplex character of single-radio nodes, (ii) inefficient congestion control, (iii) collisions due to hidden node problem, (iv) resources wasted due to exposed node problem, and (v) the difficulties in handling multi-channel systems. Scalability is addressed more in detail further.

Table 2.1 – Throughput degradation for a one-hop IEEE 802.11a (extracted from [ZhLH07]).

Channel Condition	**TCP Throughput [Mbit/s]**	**UDP Throughput [Mbit/s]**	**TCP Underutilisation [%]**
Very bad	0.1	0.9	90.8
Bad	3.4	6.1	44.5
Average	14.5	18.6	22.0
Good	26.9	32.9	18.2

2.4 Multi-Radio and Multi-Channel Nodes

Although WMNs can be built up based on existing technologies, their performance is still far below expectations. In the wireless medium, there are big differences between single- and multi-hop paradigms. Section 2.3 raises several challenges that must be solved to achieve high performing WMNs. As stated before, a limitation of single-radio nodes is that they operate in half-duplex mode. On the contrary, multi-radio nodes enable full duplex operation, able to simultaneously receive in one channel and transmit in another, doubling the node throughput. On the other hand, using multiple channels increases the capability of isolation between links, allowing the increase of aggregate throughput. Thanks to the decrease of interference with distance, spatial reuse of channels becomes possible. Thus, any E2E path in a multi-hop network should utilise all the available orthogonal channels in a manner that maximises spatial reuse, i.e., maximises the number of simultaneous transmissions in the network area [ZhLH07]. Multi-radio meshes are expected to be a key component in achieving such scalability.

A naive strategy would be to equip each node with the number of radios equal to the number of orthogonal channels [RABB06]. However, this strategy is economically prohibitive due to the significant number of non-overlapping channels. Furthermore, small form-factor embedded systems used for manufacturing routers support only a limited number of radios. It is possible to do an evaluation of WMNs mesh nodes with respect to the number of radio interfaces they are equipped with, Table 2.2 [WaMB06]. Single radio interface nodes, responsible for dealing with both access and backhaul traffics, present severe limitations. Nodes equipped with two radio interfaces employ one for backhaul and the other for access. Although there is a slight improvement in performance, it still presents severe limitations due to the half-duplex relaying of traffic, one of the key functionalities of these nodes. Nodes equipped with three or more radio interfaces present high potentialities. Interfaces can be dedicated each to specific functions; one can be for client access; two others for backhaul ingress and egress traffics (full-duplex), or for control and traffic functionalities, depending on the MAC protocol. This approach enables scalability of WMNs, presenting low latency and high throughput over hops, supporting real time applications, one of the challenges for WMNs.

Table 2.2 – Evaluation of WMN multi-radio nodes (extracted from [WaMB06]).

	Single Radio	**Double radio**	**Multi-radio**
Number of radio interfaces	1	2	3 or more
Scalability	Very Limited	Limited	High
Latency over hops	High	Medium High	Low
Throughput over hops	Very Low	Low	High
Real time applications support	Limited	Limited	High

WMNs are characterised by a sensitive trade-off between maximising connectivity and minimising interference. On the one hand, a mesh node needs to share a common channel with each of its neighbours to be able to communicate. On the other, to reduce interference, it should minimise the number of neighbours with which it shares a common channel. To understand this trade-off, two scenarios, of single- and multi-radio nodes, are presented next. First, the connectivity of a network of single-radio nodes is illustrated in Figure 2.7, where all nodes except M_a and M_c are in communication range. When all nodes use the same channel C_1, connectivity between nodes is maximised, as depicted in (a). Still, only one node may transmit at each time, otherwise interference occurs. Consider now that multiple channels are available, as illustrated in (b). M_a may transmit to M_b on C_1 simultaneously as M_c transmits to M_d on C_2. If channels are fixed, the two links can be fully utilised without interference. Still, the network is partitioned (M_a and M_b cannot communicate with M_c and M_d). On the other hand, if nodes have channel-switching capabilities, negotiation of traffic channels may be possible in a common control channel, or to have transmissions carefully scheduled between various node-pairs.

(a) Connectivity maximisation. (b) Interference minimisation.

Figure 2.7 – Trade-off between connectivity and interference in single-radio nodes.

As shown in Table 2.2, a promising solution to reduce interference and increase capacity of WMNs is to equip mesh nodes with several radios, enabling them to work simultaneously on multiple channels. Still several challenges remain open. Figure 2.8 illustrates a multi-radio scenario. In Figure 2.8 (a), the assignment of channels aims to maximise connectivity with three assigned channels; still, the three links sharing C_2 cannot be active simultaneously. On the other hand, Figure 2.8 (b) shows how interference can be completely eliminated, and the represented links can be simultaneously active; still, the compromise is that there is no link between M_b and M_d as in (a). In this case, even with multiple radios, network partitions may arise if channel assignment is not carefully done. Another possibility is the hybrid channel assignment, keeping one radio of each node fixed, while the other can switch among channels, any node being reachable via its fixed radio. This guarantees connectivity, overcoming the network partition problem. The ideal approach is to break each collision domain into as many channels as possible, while maintaining the required connectivity among neighbouring nodes.

These examples show how the goal of channel assignment is to achieve a balance between minimising interference and maximising connectivity, which can be viewed as a topology control problem [MaDa05]. The perfect balance is the one whose connectivity is sufficient to enable maximum capacity. This evidences the need for multi-radio and multi-channel solutions, requiring the dynamic management of resources, in particular of channels for communication between nodes, as well as an efficient management of multiple radios resources, such as transmission power and bit rates.

(a) Connectivity maximisation. (b) Interference minimisation.

Figure 2.8 – Trade-off between connectivity and interference in multi-radio nodes.

In a multi-hop, multi-radio and multi-channel environment, the MAC protocol is a key element. MAC protocols for WMNs are typically TDMA or CSMA based. Scheduled TDMA access requires global timeslot synchronisation among a network with a large number of hops and nodes, which is difficult to achieve. Contention-based CSMA access results in an easier implementation, showing close to optimal performance for radios with adaptive bit rate mechanisms [JiPs12], [BrMo09]. Different approaches may be developed for multi-channel MACs, depending on hardware platforms:

- *Multi-channel single-transceiver MAC:* with a single radio, only one channel is active at a time per node, although over time an interface can switch among different channels. To coordinate transmissions between nodes, protocols such as Interleaved Carrier Sense Multiple Access [JaMM03], Multi-channel MAC [SoVa04], Seed-Slotted-Channel Hopping [BaCD04] or Asynchronous Multichannel Coordination Protocol [ShSK06] are used (see Appendix C).
- *Multi-channel multi-transceiver MAC*: In this case, a radio includes multiple parallel transceivers, supporting simultaneous operation on several channels, increasing network capacity. On top of this physical layer, a single MAC coordinates the functions of multiple channels. However how to design an efficient MAC for coordination of multiple parallel transceivers is still an open research topic.
- *Multi-radio MAC*: In this case, a node has multiple radios, each with its own MAC and PHY layers. Communication in these radios is totally independent. Thus, a virtual MAC is required on top of MACs to coordinate communications in all channels. This approach enables nodes to operate simultaneously on different channels, increasing the network capacity. Examples of existing protocols are On-Demand Channel Assignment [WLTS00],

Receiver-Based Channel Selection protocol [JaDa01], Multi-radio Unification Protocol [ABPW04], Hybrid Multi-Channel Protocol [KyVa06], and Common Channel Framework [BeTa06] (see Appendix C). It enables integration of different systems, such as IEEE 802.11, 802.16, 802.15.

As evidenced along this section, the multi-radio MAC is the most adequate approach to follow.

2.5 Management of Radio Resources

The inherent limitations of WMNs raise several challenges in the management of the resources of these networks, since issues such as channel allocation, power control, rate adaptation, connectivity, topology, load balancing and routing are tightly interconnected, requiring joint optimisation [PaDu11]. Some examples are presented next:

- *Connectivity and channel assignment.* A node needs to share a common channel with each of its communication-range neighbours with which it wishes to set up connectivity. On the other hand, to reduce interference, a node should minimise the number of neighbours with whom to share a common channel. One should break each collision domain into as many channels as possible, while maintaining the required connectivity among neighbouring nodes, thus, channel dependency among nodes is an important issue.
- *Channel assignment and topology.* The channel assignment strategy and associated rate and transmission power affect the topology of the network. The goal is to achieve a balance between interference and connectivity to achieve maximum capacity. Tuneable parameters, such as channel selection and associated transmission power, and bit rate, determine the network's topology, since certain nodes when using the same channel may communicate/interfere or not, depending on the used power levels and receiver and interference sensitivities associated to the used rates.
- *Channel assignment and routing.* A routing protocol determines a path for any packet from its source to destination. Channel allocation and associated rate adaptation and power control will determine the allocated capacity to each link, tightly related with routing. Thus, dynamic optimisation of both radio resources and routes is important.
- *Load-aware channel assignment.* Radio resources should be distributed among links in a way that they match the expected traffic loads, i.e., the available capacity on each link is proportional to the load it needs to carry. Since capacity of a resource is affected by the collision domain,

a lower number of interfering nodes sharing the same channel results in higher available capacity per link. Thus, a channel selection criterion has to be based on the measured channel throughput and usage.

The current work focuses on the management of radio resources – channels, transmission power levels and bit rates – leaving the selection of optimum paths to routing protocols that work independently. Considerations on routing for WMNs are available in Appendix D. The WMNs' Radio Resource Management (RRM) paradigm aims to support the interference-free operation of multiple simultaneous wireless links (pre-identified by a routing protocol) exploring the entire capacity of the network. Radio spectrum is divided into a set of non-interfering disjoint channels, enabling node pairs to communicate simultaneously without interference, if using different channels. Because of the scarcity of the radio spectrum, there is a limited number of channels, thus, the reuse of channels is necessary. Therefore, co-channel interference is thus the most restraining factor on system capacity. Channel assignment in WMNs deals with the minimisation of co-channel interference, by adjusting the distance between co-channels, tightly dependent on the transmitter power levels, the communication bit rates and sensitivity [KiLH06]. In this sense, an efficient and combined management of these resources is essential to achieve WMNs exploring the entire capacity fairly. An overview of strategies and mechanisms optimising these resources is presented next.

In order to support efficient wireless communications between multiple nodes, a wide-range set of radio resources may be managed and configured in multiple ways. Nodes' management can be coordinated by a single centralised entity, needing to have the knowledge of the entire network to optimise resources, such as channels [RaGC04], [SGDL07] and rates [AvAV09]. In opposition to these approaches, management of resources can be distributed, done at each node and based on local information, being more flexible and enabling self-organisation of nodes [FAIB10].

Several multi-radio operation policies are possible, determining which radio a node uses to transmit to a particular neighbour, and when to bind the radio to a particular channel. The fixed allocation of channels to radios, used in Load-Aware Channel Assignment (LACA) [RaGC04] and Mesh based Traffic and interference aware Channel assignment (MesTiC) [SGDL07], is the simplest policy, but it has the disadvantage of biasing topology, only enabling communication with neighbours sharing the same channel, and requiring an extra radio for control. Another option is a dynamic channel allocation policy, enabled by channel-switching capabilities of radios. Nevertheless, proposed solutions require tight time synchronisation between nodes [ChHa11], changes in the IEEE 802.11 MAC protocol [BeTa06], or dynamic modification of certain MAC parameters, such as contention windows [LeYY10]. The mixture of these policies results in the Hybrid Multi-Channel Protocol (HMCP) [KyVa06], a hybrid multi-radio operation policy where some radios are fixed on given channels, the others dynamically switching among the remaining ones. Connectivity with any neighbouring node is guaranteed, not forcing any topology. All radios are used for data communication, and no changes on the MAC are required. Communication channels are a scarce resource; hence, their use must address the trade-off between maximising connectivity and minimising interference. Channel assignment addresses the issue of which particular channel to use for transmission and reception. It has been proven that the Channel Assignment (CA) problem in a WMN topology is NP-hard [RaGC04], heuristic techniques being employed to assign channels to radios. Some strategies base channel selection on heuristics that minimise interference [RABB06], others weight traffic load and topology to rank nodes and then assign channels that minimise a heuristic interference [SGDL07], and several studies propose still a joint optimisation of CA and routing [RaGC04], [AvAV09]. Interference and load aware strategies, working with any routing protocol, in particular multi-path ones, are needed. A detailed overview of CA strategies is presented in Appendix C, describing their characteristics, identifying pros and cons and ideas of interest for the current work. A detailed taxonomy according to key identified characteristics is also presented, enabling the comparison among existing CA strategies.

Due to the topology and traffic specificities of WMNs, multi-rate solutions are of key importance. On the other hand, physical data-rate is tightly connected with communication and interference ranges, as the higher the data-rate the shorter the corresponding communication range and the larger the interference one. This requires an integrated management of resources, in particular of channels and power. Many solutions exist at various levels. At the MAC layer, link adaptation solutions are proposed [HoVB01], [SKSK02], where the sender adaptively changes its data rate based on the history of successful transmissions, or the proper data rate is indicated by the receiver via a control packet by measuring the channel condition. At network layer [DABM03], a routing metric is proposed to choose a high-rate path or less delay path over multi-hop wireless networks. In [AvAV09], a solution is proposed for balancing rate selection with channel assignment. Nevertheless, it is centralised and of complex implementation. Many multi-rate solutions address the unfair channel sharing problem, where the achievable throughput of a high-rate link is critically affected by neighbouring low-rate links when they share the same channel. A centralised rate-based CA algorithm is proposed in [KiSu08], which replaces low-rate links by multi-hop paths, formed by multiple high-rate links of orthogonal channels. A utility-based framework for joint channel assignment and topology control in multi-rate WMNs is proposed, balancing load among multiple gateways [DiSS10]. In [StSP10] an effective link rate assignment is proposed using lower rates for increasing the spatial reuse and throughput. A distributed rate-loss CA strategy [LiSC10] is proposed, where each mesh node selects the channel less affected from this problem. Nevertheless, no considerations are done with respect to the combined control of transmission power levels of nodes, essential for realistic and energy efficient results. In fact, the achievable physical bit rate is tightly connected to communication and interference ranges, as the higher the bit rate the shorter the corresponding communication range and the larger the interference one. Thus, when addressing rate-adaptation solutions, an integrated management of resources is required, in particular of channels and transmission power.

Energy efficiency [AMHM11] is an important topic where the extraordinary flexibility of WMNs provides large potentials for reducing energy consumption. Transmission power control is a key issue in wireless multi-hop environment that should be dynamically adapted to guarantee connectivity, but also to minimise interference and energy consumption. An overview of Transmitter Power Control (TPC) approaches for WMN is presented in [OlWy10]. Most approaches are simplistic and unrealistic, considering an optimal common transmission power level and associated communication range for all nodes [SGDL07], nevertheless, these conditions do not hold for non-homogeneous nodes' spatial distributions and bit rates, an efficient TPC mechanism being essential. Some suggest creating clusters of neighbouring nodes using the same power and channel, using different channels for communications between clusters [KaKu03]. Many MAC level solutions suggest the use of control packets at maximum power level to eliminate collisions [DoYM06], still others introduce modifications in the MAC [MoBH01] integrating a power controlled collision avoidance mechanism. Although reducing interference, these solutions result however in high contention, an undesired effect in networks where traffic flows should perform fluidly.

Another key issue for WMNs is to guarantee that MAPs are receiving a fair share of system resources. The concept of max-min throughput fairness is an allocation of resources where no rate can be increased without a lesser rate being reduced [TaSa02]. A fair share of the available capacity of the WMN shall be guaranteed to every MAP. This does not necessarily mean an equal distribution of resources. Depending on the topology and propagation conditions, the guaranteed capacity can be different. Still, to every MAP is guaranteed an aggregate traffic that fully explores the assigned capacity. If any MAP is favoured, increasing its load and associated throughput beyond is assigned capacity, resulting in the decrease of throughput of other MAP(s) that become disfavoured, then fairness decreases. In [StSP09], the use of lower rates is studied to reduce interference, by evaluating max-min fair WMN throughput under different link rate assignment strategies. In a network where offered traffic load varies, flow control mechanisms are needed to guarantee max-min fairness conditions. A source-rate-limiting mechanism, implemented by a flow admission control mechanism, is proposed in [NiHo07], while in [RaLi09] it is done by direct policing at the source, requiring telling the sources what their fair share is [RGGP06]. A gateway-enforced rate limit mechanism is proposed in [JaLW06], anticipating that the sources will react to limit their traffic, while a gateway-assisted max-min rate allocation is proposed in [JaWa09]. A distributed source rate limiting mechanism is proposed in [SaSh11] for WMNs, guaranteeing a max-min fair rate allocation. An elastic rate-limiting mechanism is proposed in [MGKK10], which partitions the airtime of the gateway, being sufficient to rate limit the nodes one-hop distant from the gateway to give transmission opportunities to all other nodes.

2.6 Self-Organisation and Community-centric WMNs

Recent advances in communication technologies are opening new ways for mobile users to get connected to each other. In addition to the traditional wired infrastructure, which is characterised by a static and relatively centralised management model, users will have the possibility to spontaneously establish Self-Organising Networks (SONs). Ad-hoc, wireless sensor, and mesh networks are examples of such networks. The main characteristics of a SON that set it apart from a traditional network are the lack of a management infrastructure (requiring minimal human involvement in the network planning and optimisation tasks) and the dynamics of the network. These two main characteristics impose two fundamental requirements on the design/operation of a SON: (a) all nodes in the SON may be required to assume the same management responsibilities, and (b) any network operation (e.g., management of the addressing space) should be inherently distributed. Additional peculiarities include the possible lack of geographic positioning infrastructure, the limited and variable capacity of wireless links, and the energy-constrained nature of some nodes.

Self-organisation encloses the concepts of self-configuration, self-optimisation and self-healing, Figure 2.9 [BLEA08]. Newly added heterogeneous mesh nodes self-configure in a "plug-and-play" fashion, while existing nodes continuously self-optimise their operational algorithms and parameters in response to changes in the network, traffic and environmental conditions. The adaptations are performed in order to provide the targeted service availability and quality as efficiently as possible. In the event of a node failure, self-healing mechanisms are triggered to alleviate the performance effects due to the resulting gap of connectivity, coverage and capacity, by appropriately adjusting radio parameters in surrounding nodes. As key gains of employing self-organisation are performance enhancements in network optimisation and spontaneous deployment, and reduction of operational deployment, planning, and monitoring costs.

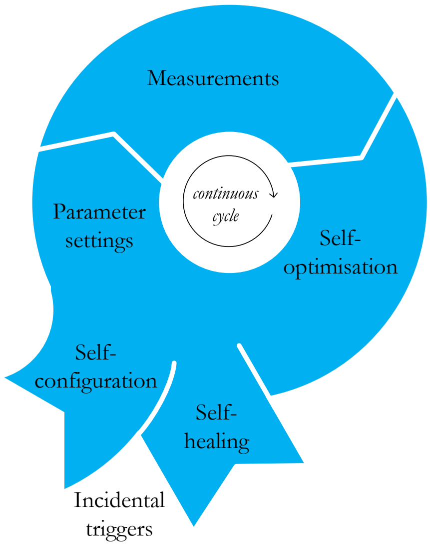


Figure 2.9 – Vision on self-organisation (adapted from [BLEA08]).

Based on the SON concept, community-based networking is definitely one of the major recent curious aspects of the Internet. Many applications found tremendous success based solely on the participation of users in social groups of interest or acquaintances [Stro08]. A natural evolution is that, besides social motivations, communities may also be inspired by technical reasons. One of the drivers of future technological developments is the increasing pervasiveness of wireless technologies. The appearance of a variety of spontaneous wireless networks is then expected, where "communities of users" will originate the formation of "communities of wireless nodes". One example of a community based on this technical motivation is FON [FON13], where each member shares the home *Wi-Fi* AP with the entire community, getting extended access to hotspots of other members around the world. This community has already reached considerable success, as members have strong incentives for cooperating. Nevertheless, in this solution, each AP needs to be connected to the fixed Internet infrastructure to provide connectivity, not directly communicating with each other. It is intuitive that, if these APs had cooperation capabilities through wireless links, users would themselves establish new means of interactions and find new motivations for building brand new types of communities.

In this context, the WMN paradigm seems the most appropriate solution to enable the spontaneous formation of such community-centric wireless networks, Figure 2.10. The classical WMN architecture achieves its maximum utility when deployed in a quite organised way within a specific area, adequately providing connectivity to users. This is confirmed by the fact that most of the initiatives toward the deployment of WMNs are orchestrated by some administrative entity, [Seat13], [Mesh08b]. By opposition to the traditional centrally-managed WMNs, a challenging architecture to support community building over WMNs consists of a self-organised and opportunistic architecture [FAIB10].

Figure 2.10 – Community building over neighbourhood WMNs (extracted from [AGST08])

Key issues to be addressed are:

- *Self-organisation*. In spontaneous community-based networks there is no central authority that is, by default, responsible for their formation and maintenance. Users must find a way to organise themselves, cooperating to provide means for the network to survive. A community-based architecture must enable integration and self-organisation of nodes.
- *Heterogeneity*. In spontaneous networks, it is likely that joining equipments be heterogeneous in many aspects – communication and computational capabilities, location and visibility from other nodes, persistence, and mobility pattern, to cite a few. Heterogeneous resources of each node must be explored, exploiting the nodes' ability to execute network functionalities.
- *Availability*. Because of the unpredictable nature of the network, it is difficult to guarantee coverage and connectivity among all nodes. Indeed, one never knows where and when WMRs join the network. Simply hoping that WMRs will, by themselves, provide the expected coverage and related functionalities is not realistic. Collaboration of nodes into the mesh infrastructure is needed, where appropriate network functionalities are assigned to specific nodes, enhancing network availability.

- *Opportunism*. In such a spontaneous network within a community of users, nodes are willing to cooperate as they can. An opportunistic approach must be supported, exploring the dynamic conditions and properties of the network, where specificities of each node and the ones in their vicinity are explored in order to enhance the network.

The previous points leverage the need for *adaptive* and *flexible* solutions for network formation and maintenance. The scenario addressed requires more than a simple two-tiered architecture in which nodes are *either* routers *or* clients. As previously introduced, the inherent strength of a community lies in the collaboration of its members. On the one hand, incentives have to be explored to foster users to adequately cooperate and share their resources for supporting the network [AGST08]. On the other, it must rely on mechanisms that help the decision of the different roles and responsibilities of the nodes.

Several proposals identify the limitations of the traditional wireless mesh architecture, when full exploitation of the space of possibilities is a requirement. OverMesh [VRDK07] is a platform that pushes the concept of network-centric computing to its maximum, since users become an integrating part of the network and contribute with services and resources. However, the problem is addressed from a different viewpoint. First, it does not adopt a user-centric strategy, fundamental in community networks. Second, modifications are done only as overlays, not tackling the problem as a network architecture issue. Finally, it assumes managed deployment. Another interesting study focuses on WMNs troubleshooting [QBRZ06], towards the support of efficient and reliable network operation. Although applying the concept in the mesh backbone would bring some gain, their full exploitation would be obtained when deployed in the entire network, including clients. In [LiKG06], the concept and challenges of so-called opportunistic networks (oppnets) is presented. In oppnets, nodes dynamically join the network to perform certain tasks in which they have been called to participate, expanding the network and leveraging the wealth of available pervasive resources and capabilities. In [AkWa08] it is stated that the conventional layered-protocol architecture of WMNs does not provide optimal performance, presenting several motivations for cross-layer design in WMNs. In [BrCG05], WMNs are discussed as a commodity multi-hop ad-hoc network and address the possibility to extend the backbone using heterogeneous technologies, such as IEEE 802.16 WiMax. There is also an on-going effort to define a new architecture based on relay stations (RSs) [PaWS04], expressed, for the IEEE 802.16 standard, by the IEEE 802.16j Relay Task Group [IEEE10]. Still, the purpose of RSs is to relay traffic between end-users and gateway BSs. It is statically configured and concerns only packet forwarding.

Chapter 3

Novel Frameworks to Manage WMNs

Chapter 3 proposes novel frameworks for the management of WMNs. In Section 3.1, an organisational framework for opportunistic formation and maintenance of self-organised WMNs is presented. To support it, a functional open connectivity services architecture is presented in Section 3.2. It enables to offer novel connectivity services flexibly orchestrating legacy and novel mechanisms.

Key concepts: framework; self-organisation; opportunism; connectivity; service; architecture.

3.1 Organisational Framework for Opportunistic WMNs

3.1.1 Flexible and Spontaneous WMNs

A community-based network is understood as a spontaneous and self-organised network of collaborating nodes, as defined in Section 2.6. It must be flexible, admitting new members and allocating tasks according to their capabilities. As previously introduced, the inherent strength of a community lies in the collaboration of its members. On the one hand, incentives have to be explored to foster users to adequately cooperate and share their resources for supporting the network. On the other, it must rely on mechanisms that help the decision of the different roles and responsibilities of nodes. This can be interpreted as a cross-layer concept, applicable from the application layer down to the network one. Terminals are heterogeneous and have a large variety of configuration possibilities. The need for explicit cooperation at the physical layer becomes essential. At the network layer, there is an even stronger need, where users' available bandwidth is used on behalf of other nodes. In this way, the network formation procedure is an inherent part of the creation and operation of a social user community. An example can be a WMN neighbourhood community, Figure 3.1, supported by the equipment of users living in the same neighbourhood.

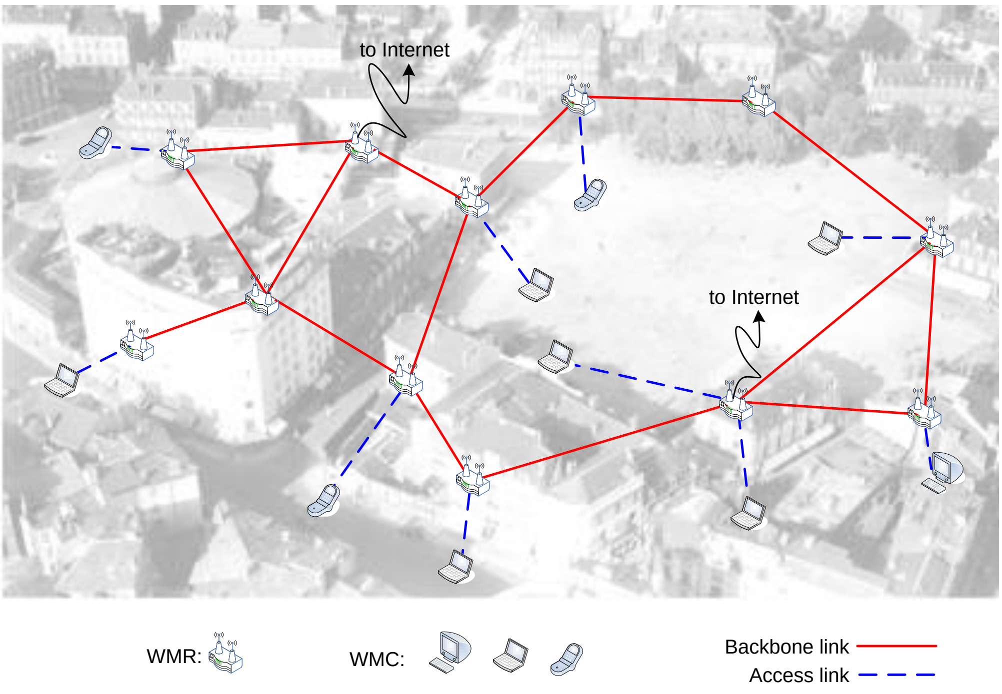


Figure 3.1 – Example of a WMN neighbourhood community.

The traditional WMN architecture follows a two-tiered architecture, where the first layer is composed of Wireless Mesh Routers (WMRs), forming a self-organised backbone, and the second layer consists of Wireless Mesh Clients (WMCs), which are basically end-user terminals. A novel flexible organisational framework for the opportunistic WMN formation and maintenance is proposed, breaking the rigidness of the traditional WMN architecture where nodes are categorised as either WMRs or WMCs, Figure 3.1. This strict and limitative node's role separation constraint is relaxed, and the case of spontaneous network formation, relying in the concept of opportunistic management of resources, is considered. The main idea is that the network takes advantage of the specific resources and characteristics of the nodes in an opportunistic way, where any node (WMRs and WMCs) can perform any network functionality, if it *can* and if it *wishes*. For this, it is proposed that nodes are assigned tasks based on what they really are.

It is advocated to separate the logical two-tiered architecture of WMNs from the physical nodes that incarnate this architecture. In this approach, the two-tiered architecture is kept, but one changes the way roles are assigned to nodes, with the objective of increasing network availability and usability. The idea is to create new logical spaces, where users offer services or perform useful tasks; they become more than a simple passive WMC, but less than a WMR, which plays a central role in the backbone architecture. Note that nothing avoids nodes to occupy more than one logical space. Also note that this approach is in accordance with the natural evolution of networking, where ubiquity is a keyword and end-users become more and more an integrated part of the network architecture.

The above definition comes out from the relatively simple observation that the operation of a network is the result of the composition of tasks and services performed by different nodes. These nodes can be considered as members of a community, in which they self-organise, sharing duties, by taking tasks according to their capabilities, having all one common objective: make the network working. Evidently, it is fundamental that the network is configured in such a way that the overall behaviour of the system is coherent (i.e., at least one node is responsible for each task). Such an allocation task is a key and difficult issue in spontaneous self-organising networks, because it is hard to know a priori which node will be able to perform which task. In other words, the fundamental "task assignment" mechanism must be adaptive. On the one hand, there must be some organisation in order to guarantee the execution of a task by at least one of the nodes; on the other, such an organisation may lead to poor adaptability.

It is proposed that nodes be assigned tasks based on what they really are, by decomposing the assignment of tasks into two main spaces:

- *Physical space*. It is composed of all nodes willing to participate in the community, identifying their characteristics and resources.
- *Functional space*. It identifies the minimum set of tasks that guarantee the proper operation of the network. Note that in this space there is a notion of requirement, which specifies the characteristics of the nodes that should perform the tasks. It is seen later that this space can be further subdivided into different layers, depending on the tasks to be performed.

These two spaces are regulated by an *opportunistic resources manager*, which identifies the set of nodes in the physical space that, due to their characteristics, will perform, in the most efficient way, tasks identified in the functional space. Below, these two spaces are presented more in detail, while the opportunistic resources manager is presented in Section 3.1.2.

Given the spontaneous nature of self-organising community-based networks, a keyword that must be carefully addressed is *heterogeneity*. Since, in this context, the network is formed by equipments provided by the users themselves, it can be assumed that equipments will present different characteristics one from another. Node heterogeneity will make the physical space a rich palette of characteristics, from which the opportunistic resources manager identifies specific roles for each node. Furthermore, the building process of the physical space goes through a bootstrap phase, where the characteristics of the initial community members are collected. In the following, a number of resources and characteristics of nodes are identified as having an impact on their ability to perform a given task:

- *Communication capabilities*. In the traditional mesh architecture, nodes of the wireless backbone are assumed to have all the same radio interface. Nevertheless, heterogeneous nodes may be equipped with one or several radio interfaces, of similar or distinct standards. They may also have a fast Ethernet connection, having the possibility to act as gateways. These resources of different nodes can be jointly explored to enable simultaneous independent communications, increasing the efficiency of the backhaul network.
- *Surrounding environment*. The geographic position of the node and its surrounding, the propagation environment and the number of nodes in communication range, are examples of important surrounding indicators to be evaluated when considering the promotion of a node to perform networking functionalities.
- *Mobility pattern*. Mobility of WMCs might help performing network tasks (e.g., information dissemination). It can be seen in its largest definition, including both continuous displacements and joins/leaves. This is one of the key characteristics that has an influence on

the role played by a node.

- *Persistence*. This is related to the confidence one may have on a node to remain connected to the network. There may be mobile nodes that are permanently connected, as well as static ones that are connected only during certain hours of the day. Various aspects have influence on persistence, related, e.g., to the behaviour of the user owning the node.
- *Position-awareness*. Some of the nodes participating in a community may be equipped with positioning capabilities, e.g., through Global Positioning System (GPS), which may be used in different building blocks of the architecture, like routing, service discovery, and community management.
- *Energy*. Since, in the considered networks, nodes are potentially mobile, the autonomy of a node is an important characteristic, if one wants it to perform certain tasks in the network.
- *Computational capability*. One of the main effects of heterogeneity is on the computational capabilities of nodes, a fundamental resource for estimating the ability of a node to perform some tasks.
- *Memory*. Memory availability is an important resource, since some tasks can be efficiently performed only in the presence of sufficient amount of memory (e.g., routing tables, and caches).
- *Storage space*. As in the previous case, nodes' storage availability is an important parameter for the network, since some tasks may require significant storage capabilities (e.g., databases containing authentication information).

As already mentioned, the functional space identifies the set of tasks that make a network fully operational. This space can be further decomposed into smaller subsets, or "planes", each one related to a particular function. Hereafter, several classes of network functions are identified whose efficiency can be influenced by the characteristics of the nodes performing them (this list does not intend to be exhaustive in a more general context):

- *Resources management*. In a spontaneous network, nodes are self-configurable. Nevertheless, some information should be conveyed to them about the global status and requirements of the network in order to configure the node's resources properly. Management of several functions is needed (evaluation of incoming nodes, monitoring of the network, suggestion of functionalities to nodes), requesting collection and maintenance of information from the entire network. Several nodes should support this task, in a distributed way, for robustness and efficiency purposes. Nodes suitable for this task include persistent nodes with a low degree of mobility, no energy constrains, and high connectivity.

- *Network access connectivity.* This is the basic goal of a wireless mesh network, to have a functionality in certain nodes that provides network connectivity to WMCs. This is usually reserved to WMRs, and typically requests the nodes to be equipped with at least two wireless interfaces, one working as an AP and another as part of the backbone. However, nodes with sufficient network interface resources can provide such functionality, improving coverage and connectivity.
- *Forwarding.* This is a key functionality within the wireless backhaul network, where traffic streams are forwarded through WMRs towards their destination. In traditional WMNs, it is only performed by WMRs, which clearly leads to under-utilisation of the existing communication possibilities of certain nodes. Client terminals could help increasing the capacity of the network by providing opportunistic forwarding. Nodes that participate in a community in general are consenting to contribute. Why should these nodes be prevented from forwarding messages? In order to perform such a task, nodes should be able to forward packets between at least two different neighbours, have a favourable surrounding environment, and not be energy constrained. Mobility of nodes is also beneficial, where nodes may opportunistically benefit from temporarily available nodes to increase localised capacity of the network. Furthermore, other approaches investigated in the area of disruption-tolerant networks could be included as an improvement mechanism. Forwarding by WMCs can be seen as an opportunistic functionality that, when available, improves connectivity and capacity of the network, without the need of participating to the routing task, but rather using some simplified forwarding rules.
- *Location service.* This is a fundamental building block of any self-organising network. Some nodes have to be responsible for continuously storing the location information (geographical or topological) of other nodes in the topology. In the traditional mesh approach, this function is only performed by WMRs; at the best, clients store location information in caches, but do not participate in the location service itself. If WMCs can help on this function, better knowledge of the network topology and infrastructure is reached, helping in the efficiency of the network. Desired characteristics are position-awareness, persistence and low mobility, storage space.
- *Address assignment.* Some nodes can be qualified to be responsible for assigning addresses and names to other nodes joining the network. This, however, is not just a matter of having sufficient amount of resources to perform the task; it involves issues related to security, trust, and availability, to cite a few, being also related to the characteristics of the nodes willing to execute this task. For example, nodes that show little persistence should not be responsible

for executing such a task, and this is not a matter of being a mesh router or a client. Desired characteristics are persistence, position-awareness (in case addresses are geographic positions), energy availability, and be equipped with the wireless technology of the backbone.

The above identification of functionalities shows that different tasks require different abilities from nodes. The ultimate question aimed to be answered is: *which nodes in the network should perform these functionalities*? As shown in the next section, the opportunistic resources manager mechanism addresses this issue.

3.1.2 Opportunistic Resource Management

The physical and functional spaces introduced above are complementary parts of the same system. The basic infrastructure of this network is provided by the interconnection of some WMRs forming the core of the network. In order to join this infrastructure, and also extend it, it is assumed that nodes run minimal communication protocol allowing them to exchange information on their capacities and characteristics. This information is collected by the opportunistic resources manager that, besides general information, gathers information relative to the different network functionalities and task requirements. It suggests specific functionalities and/or tasks that the nodes are free to accept or not.

In such a context, three basic types of nodes can be identified and defined:

- *WMR*. Nodes whose main purpose is to form the core infrastructure and perform all the tasks necessary for minimal network functioning and provide the primary community services. These nodes correspond to the traditional definition of WMRs, yet, they are able to hand out some tasks to other nodes on request of the opportunistic resources manager.
- *SuperWMC*. Nodes that are WMCs, but that have enough resources (communication capabilities, memory, persistence, etc.) to actively contribute in enhancing the core infrastructure. These nodes reply to the opportunistic resources manager entity, accepting to perform tasks that are useful to the community, thus, improving the existing network.
- *WMC*. Nodes that do not fulfil the requirements to contribute in enhancing the infrastructure, or are not willing to do it. These are conform to the traditional definition of WMCs.

Nodes can change their status depending on the evolution of the network, following the indications of the *opportunistic resources manager*. The latter is a (centralised or distributed) virtual entity that has the knowledge of (i) the physical space of existing nodes in the network with their characteristics and resources, and (ii) the functional space of network functionalities and associated requirements. It has the ability to maintain the state of resources and the network operation and performance.

The final organisation of the network should be similar to the example shown in Figure 3.2. On the left-hand side of the figure, the physical space can be observed, represented by the wireless devices with different characteristics. On the right-hand side of the figure, the functional space can be seen, where functionalities have been grouped into few sub categories called "planes". In these planes, beside the classical WMRs, SuperWMCs are placed, showing how different planes have different organisations of nodes. In the middle, the opportunistic resources manager is represented, responsible of dynamically binding entities placed in these two spaces, identifying the set of nodes that would perform efficiently tasks present in the functional space. Such a dynamic binding between the two spaces provides an adaptive and flexible solution for spontaneous, self-organised and community-centric networks. In Figure 3.2, it can be seen that when the physical nodes are architecturally separated from roles, more possibilities can be obtained from the network.

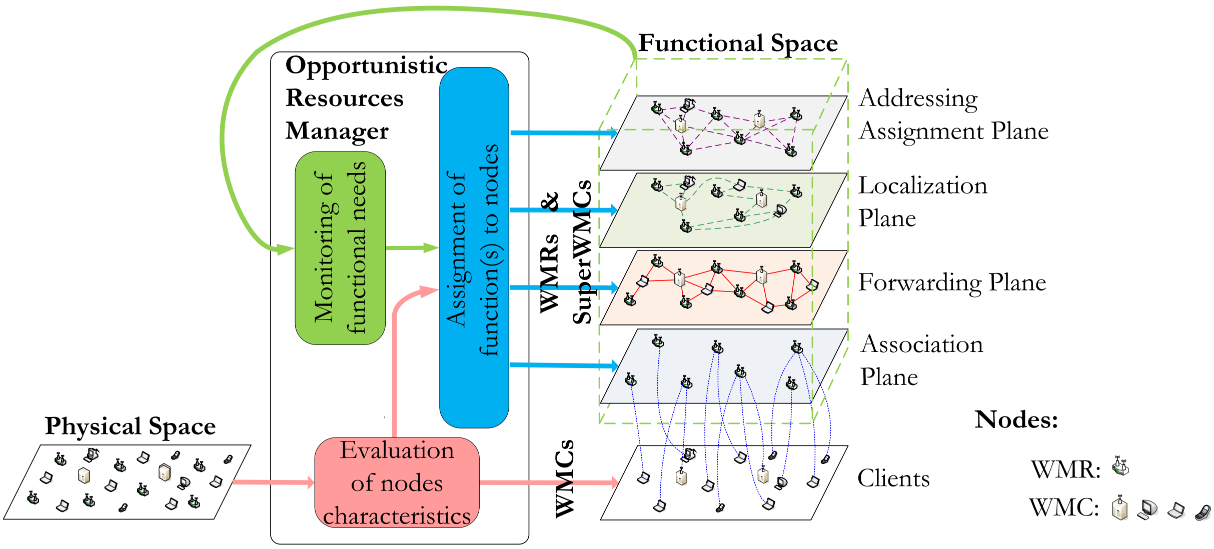


Figure 3.2 – Opportunistic resources manager, for flexible organisation of a WMN.

The reconfiguration and assignment of tasks is done dynamically during the operation of the network through a "promotion" strategy supported by the opportunistic resources manager, depending on the functional plane and on the node characteristic under monitoring. At the bottom of the right-hand side of Figure 3.2, one can see the classical two-tier organisation of WMNs. Note that all nodes that are not part of the core infrastructure join the network as normal WMC. Later on, after negotiation with the opportunistic resources manager, they join one or more functional planes, upgrading to the role of SuperWMC. Nevertheless, it is always the node that decides to cooperate or not.

The resource manager is central to the architecture, as it is responsible for assigning roles to clients. The first question is who should host the opportunistic resource manager. It can be a single node in the neighbourhood, previously elected by the members of the community. What is important in this case is that this node be one of the WMRs belonging to the core tier 1 nodes (and not a SuperWMC). The opportunistic resource manager can also be distributed on several WMRs. Thus, WMCs that agree to serve as SuperWMCs announce their availability, and declare the resources and capabilities they wish to share. The resource manager should also be responsible for checking whether the SuperWMC does respect the role for which it applied. On the one hand, the assignment of roles could be done through some negotiation mechanism (leading to a sort of service level agreement). On the other, the behaviour of the SuperWMC can be monitored both spontaneously (i.e., the SuperWMC announces it cannot respect the agreement) and through measurement mechanisms (performed by the resource manager). If a SuperWMC is declared unable to perform its role, it is downgraded to a WMC and possibly removed from the list of potential SuperWMCs. A specific implementation of an opportunistic manager is addressed in Section 4.4.

It is important to note that this approach follows additive principles – without any change, the network will work like any other "traditional" WMN. But if some nodes are able and willing to contribute, they can perform other tasks and become SuperWMC. The presence of such SuperWMCs, under the coordination of the opportunistic resources manager, improves network performance. The network (community) will be the greatest beneficiary of this approach.

3.1.3 An Example: Neighbourhood Scenario

In this section, an example of a neighbourhood scenario is presented, where collaborative users wish to form a spontaneous and self-organised community-based WMN. The goal of this example is to evidence the differences of the resulting networks when a WMN is built following the classical principles of a two tiered architecture vs. the novel proposed principles of the organisational framework, illustrated in Figure 3.2. It is shown how some nodes with specific characteristics can play a crucial role creating a more efficient network.

The neighbourhood WMN scenario is constituted by a heterogeneous set of nodes from members of the community (powerful wireless routers, traditional PCs, mobile laptops, small devices, and servers with wireless access) with heterogeneous characteristics and resources; they are spontaneously (uncontrolled) geographically distributed. The first step is to identify the physical space of this network.

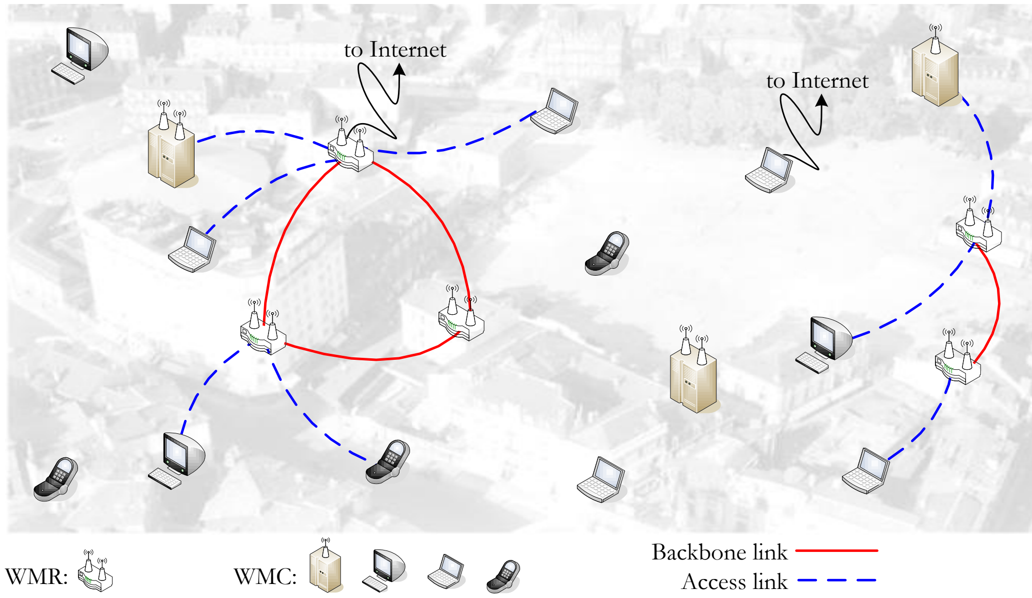
Nodes (WMRs and WMCs) start detecting the physical proximity with other community members. WMRs detect each other and automatically form the basic backbone, as in any WMN. In particular, WMRs are characterised by a profile that identifies them in the community. Authorised WMCs are now able to associate with a WMR. In the traditional two-tier WMN, no further improvements would be possible, except by adding new WMRs to the network.

Note that insofar were just listed the steps necessary to build a traditional two-tier WMN, but in the next steps the suggested proposal comes forward. First, WMRs should decide who should host the opportunistic resources manager; which can be done through some election mechanism; note that the opportunistic resources manager can also be distributed on several WMRs. Then, WMCs that agree to serve as a SuperWMC announce their availability and declare the resources and capabilities they wish to share. Finally, based on the network functionalities requirements, the opportunistic resources manager promotes some of these SuperWMCs to perform certain functionalities, enhancing the network availability and efficiency.

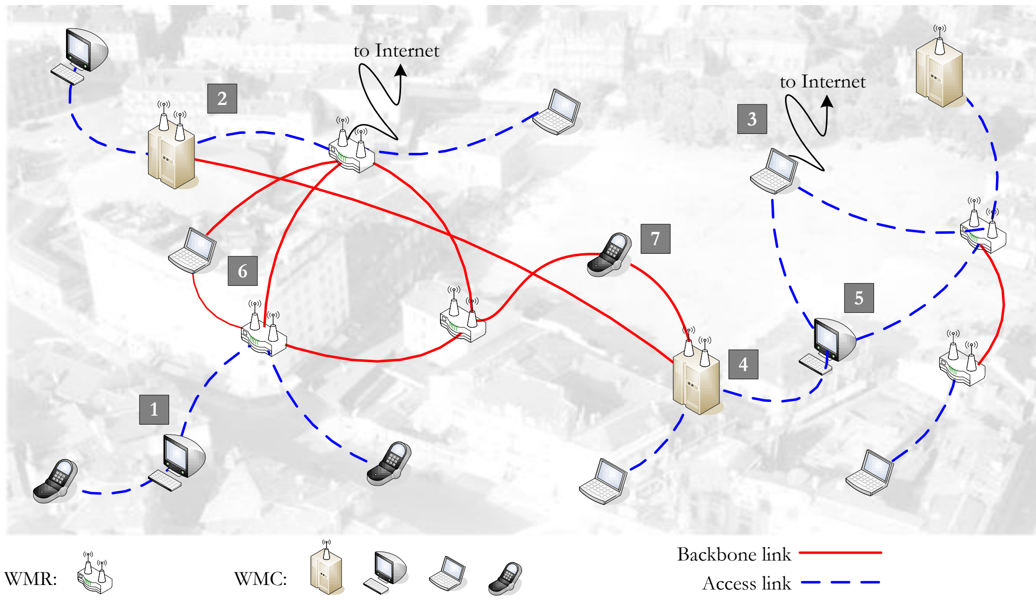
In Figure 3.3, one compares the two approaches (traditional vs. flexible) in terms of achieved functionalities. Following the traditional approach, Figure 3.3 (a), it can be seen that many nodes have no connectivity, the network being partitioned in two, one of the parts not having access to any gateway. This is due to the rigidness of the two-tier architecture, as evidenced.

The proposed approach, Figure 3.3 (b), has a very different outcome. Given the flexibility it introduces by assigning network functionalities to classical WMCs, the availability and performance of the network is improved. Let us now specify a bit more the characteristics of the WMCs, available to become SuperWMCs, that made the opportunistic resources manager attribute them key functionalities. Several cases, identified in Figure 3.3 (b) by a case number, are explained in detail below:

- Case 1. Certain SuperWMC nodes can be configured to forward traffic of neighbouring nodes, extending the overall connectivity of the network to nodes that in the traditional approach would be without connection. Such task can be performed relying on the same wireless technology used to access the backbone or, if the node has such capabilites, it can rely on different technologies (e.g., IEEE 802.11a, IEEE 802.11g, IEEE 802.16 and LTE). Compared to the original case Figure 3.3 (a), the coverage results extended.



(a) Traditional network.



(b) Flexible network.

Figure 3.3 – Comparing the resulting WMNs: traditional vs. flexible approaches.

- Case 2. One of the WMCs is a powerful and persistent server with a good wireless connection. The opportunistic resources manager suggests it to become a forwarder of traffic for a neighbouring node which has no connectivity. It suggests also to be co-responsible for the node location service functionalities, which currently is only performed by one WMR. If the WMC accepts the task, the traffic associated to the location service will be distributed in the network in a more efficient way.

- Case 3. One of the WMCs has a wireless connection to the internet and a wireless interface available for communication. In the traditional approach it would remain isolated, not needing to connect to the mesh backhaul since it has its own Internet access. Nevertheless, following the proposed flexible approach, the opportunistic resources manager asks it to become SuperWMC by serving as a gateway to the Internet, providing an Internet access to the nearby originally isolated backhaul network. Compared to Figure 3.3 (a), such a solution allows to avoid contention and congestion on single Internet gateways.
- Case 4. Some WMCs have, besides the common Wi-Fi radio interface, a WIMAX one. In a traditional two-tier mesh network the WiMax interface would not be used. In the flexible approach, the opportunistic resources manager suggests the creation of a high speed WIMAX forwarding link among these nodes with a WiMax interface, which will play in the community a key collaborative role in the network. It also suggests this node to perform address assignment task.
- Case 5. A new neighbour is willing to participate in the community with his wireless devices. His house is well covered by a WMR of a neighbour, being allowed to enter the network, but recommended to announce himself as willing to become SuperWMC and share his resources to allow him gain reputation in the network. In particular, he will forward traffic from the neighbouring nodes, connecting two initially partitioned segments of the network. Depending on the resources available on this node, it can participate to full routing, or it can just forward traffic between two different areas of the network.
- Case 6. A link between two WMRs is very week and intermittent, one of the nodes being an important gateway to the Internet. The opportunistic resources manager suggests to a WMC, equipped with the same radio interface than the backhaul and sensing good signal quality from both WMRs, to act as forwarder. The new SuperWMC accepts since, as incentive, it is allowed to also inject its own traffic directly into a high throughput backhaul link. The existence of these two redundant links will enable the use of link layer cooperative schemes that will help to improve the efficiency and to perform load balancing between the two WMRs.
- Case 7. A mobile node with a backhaul wireless interface, in idle mode, is temporarily in good communication range of two neighbouring nodes. Belonging to a member of the community, this node is available to opportunistically cooperate, whenever and wherever needed. The opportunistic resources manager suggests it to forward packets between the

two neighbouring nodes when possible, to help relieve a bottleneck on a link.

Conceptually, this approach, Figure 3.3 (b), could solve a number of limitations observed in the traditional context Figure 3.3 (a): it increases the connectivity of the network (no more partitions); it establishes extra paths to avoid low-quality links; it introduces more capacity for nodes to access the legacy Internet. In this way, the problem of flexibility in WMNs for spontaneous community-based networks is addressed. The argument that the traditional two-tiered architecture is too rigid to adapt to the heterogeneous nature of community nodes is supported. In order to solve this problem, the proposed organisational framework completely separates the functional plane from the physical one. The operation of the network is planned in such a way that it benefits from the opportunistic possibilities of the nodes instead of static role assignment.

3.2 Open Connectivity Services Architectural Framework

3.2.1 Overview and Components

A novel Open Connectivity Service (OConS) functional architecture is proposed. It is flexible and modular in the description of connectivity resources and mechanisms. It enables the orchestration (launch and monitor) of both legacy and enhanced connectivity mechanisms, running on one or more interconnected nodes, which can be dynamically adapted, integrated and orchestrated into OConS Services offered to the network. It supports the organisational framework for opportunistic management of WMNs proposed in Section 3.1. Following an object-oriented approach, the modular design of OConS allows the independent modification and enhancement of each mechanism, hiding their complexity, and providing a framework to ease the integration of different connectivity techniques, protocols and algorithms. This is achieved through an open environment, flexible enough to accommodate the currently available procedures and to adapt to the continuous evolution of the technological environment and of the end-users demands. In the proposed architecture, autonomous resource management mechanisms are aimed at, able to operate on a self-organised way, while supporting a distributed operation, and being able to share the decision processes with other peer-entities.

From a bird's eye view, most of the actions within a network can be characterised in three basic steps: (a) collecting the needed information; (b) taking the suitable decisions on the basis of such information; (c) enforcing the decisions, by instantiating the appropriate mechanisms. Following this observation, OConS mechanisms are modelled following a mechanism-level architecture that decomposes them into three clearly defined functional OConS entities:

- *Information Management Entity* (IE): It monitors and collects useful information and provides it to the decision making entities. The information gathered can be processed (e.g., abstracted, aggregated, filtered, and so on) by the IE before being transmitted to the entity requesting it or being subscribed to it. The IEs can be hosted on different devices in the network, such as routers, APs, BSs or on end-user terminals; they can also be hosted on a dedicated device, i.e., a specific monitoring device.
- *Decision Making Entity* (DE): It is the place where decision algorithms are implemented. A DE uses the information gathered by the IEs to make a decision accordingly. Likewise, a decision can be taken in one centralised location within the network, but it can also be made by a distributed decision mechanism.
- *Execution and Enforcement Entity* (EE): Once the decision is taken, the EE executes and enforces it. It may be located in a network element different from the one that made the decision.

In this sense, an OConS mechanism is a process made of one or multiple DEs, and zero or multiple IEs and EEs. The defining DE entity carries the mechanism's manifest, stating what it guarantees, its constraints (notably depending on the networking state), and so on. Any mechanism (legacy or novel) can be defined as an OConS mechanism, as long as it is modelled by the functional entities and OConS interfaces. The abstractions of the Functional Entities are independent from any layer or protocol. It is assumed that all entities have names, which can be resolved into the appropriate addresses and locators. These are pieces of software, available in an OConS node, enabling basic configuration functions, their interfacing among them supported by a specified intra-/inter-node communication process. Hence, this approach allows the implementation, instantiation and launching of any OConS mechanism, and its combination with other OConS mechanisms to form an offered OConS Service. Limiting the framework to only three functional entities, but allowing each of them to be placed onto one or distributed over several entities, enable us to support different configurations, topologies and scenarios. Because some of the functionalities can be realised on different layers (i.e., layer-independence), the proposed approach facilitates the endorsement of new layering models, as well as the support of legacy approaches.

An illustrative example of how a simple access selection mechanism can be modelled with the

OConS functional entities is presented in Figure 3.4. A Mobile Terminal (MT) is equipped with various interfaces able to access different Radio Access Technologies (RATs). It collects information available at the MT's IE and from the various access elements RAT IEs. Based on this information and user connectivity requirements possibly available in an IE, the DE on the MT takes the decision for one or several Access Elements (AEs). This is communicated to the MT's EE, which executes the required actions so as to initiate the flow through the selected RAT.

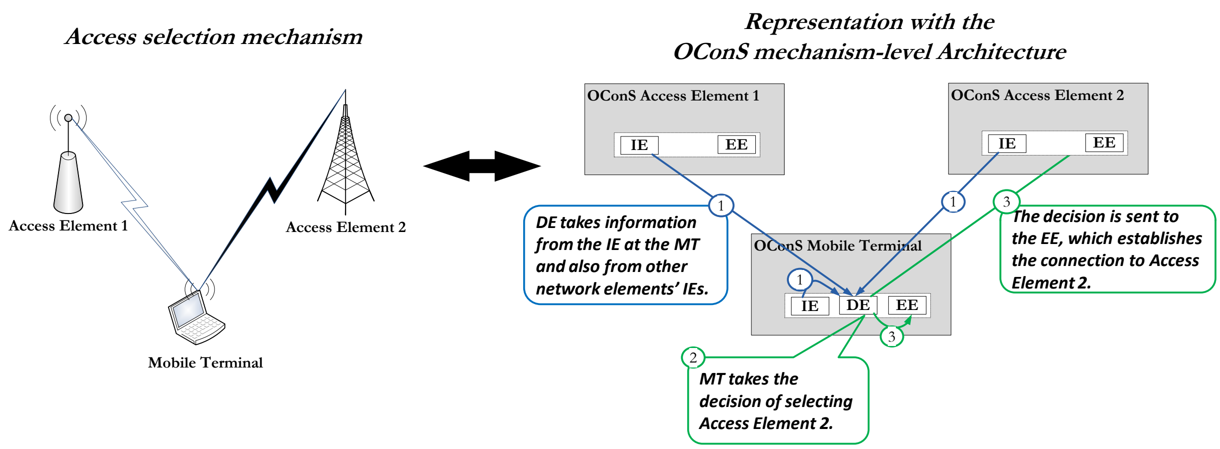


Figure 3.4 – Access selection mechanism modelled with OConS.

A node may have several OConS mechanisms. Several relations are possible among available OConS mechanisms: some of them are complementary; others can be combined, while others are conflicting. Nonetheless, one recognises that one can achieve potential synergies by combining existing mechanisms in more powerful and optimised solutions. Hence, the OConS mechanisms can be used as standalone or in relation with other mechanisms to form an *OConS Service*. An *OConS node* is an infrastructure node (e.g., end-user terminals, BSs, and routers) providing computing, storage, and networking resources to the OConS entities. It is the place where OConS entities are residing, instantiated and executed, enabling the launch of OConS services. It can be an OConS enabled node, or a node originally without OConS capabilities, upgraded with OConS-related software. An *OConS domain* is a set of OConS nodes. It provides connectivity services to applications, by implementing a given set of OConS services.

3.2.2 OConS Functional Architecture

The OConS functional architecture is represented in Figure 3.5 as a reference model. All architectural components and associated interfaces are described below.

The IEs, Des and EEs functional entities abstract/decompose the monitoring/information gathering, decision making and enforcement components available in OConS nodes. They enable to build OConS mechanisms, specified by DEs.

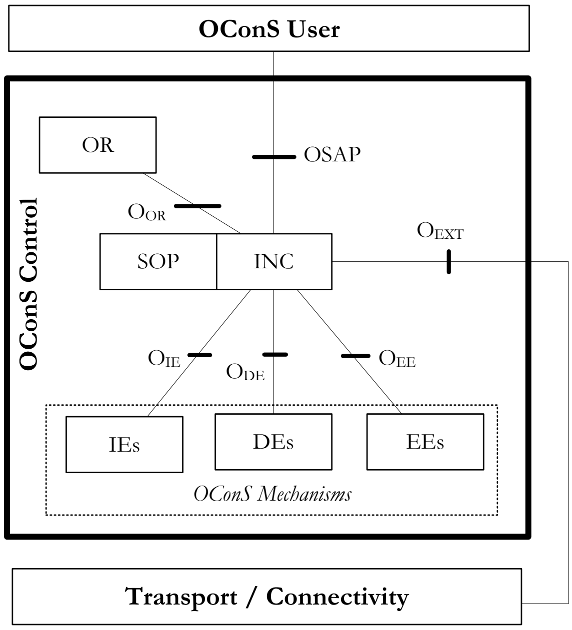


Figure 3.5 – OConS functional architecture.

The *Service Orchestration Process* (SOP) is the functionality that supports the OConS architecture. It is responsible for the discovery and validation of OConS mechanisms in a node and/or OConS domain. It serves an explicit connectivity request by an OConS user, or an implicit connectivity request triggered by a network state, Figure 3.6. From a set of available OConS mechanisms, it is able to select the most adequate ones, and instantiate and orchestrate an OConS Service. It is based on a set of rules, needed for mapping demand profiles, connectivity requirements, network states, and a selection of mechanisms to compose an OConS service. When orchestrating an OConS service, depending on the level of the activated mechanisms, SOP's orchestration may span a single link, a group of links and nodes, or affecting the complete E2E flow. SOP provides the following functionalities:

- Bootstrap, where available OConS entities and mechanisms are discovered, and default OConS services are launched.
- Launch or reconfigure an OConS service, composed of adequate OConS mechanisms, as a response to an OConS user connectivity request or to a change in the network state.
- Monitor launched OConS Services.

The *OConS Registry* (OR) is where data on the available OConS entities (OConS ID, type of entity, and capabilities) and mechanisms (mechanism ID, entities OConS ID, specifications how the mechanism should be built, and under which conditions it operates correctly or optimally), as well as on the created OConS services (service ID and IDs of associated active mechanisms, connectivity requirements, or the lifetime of the service) are registered. It is used by SOP to become aware of the existence of entities and mechanisms. Besides this, it can contain collected data on the network state and topology.

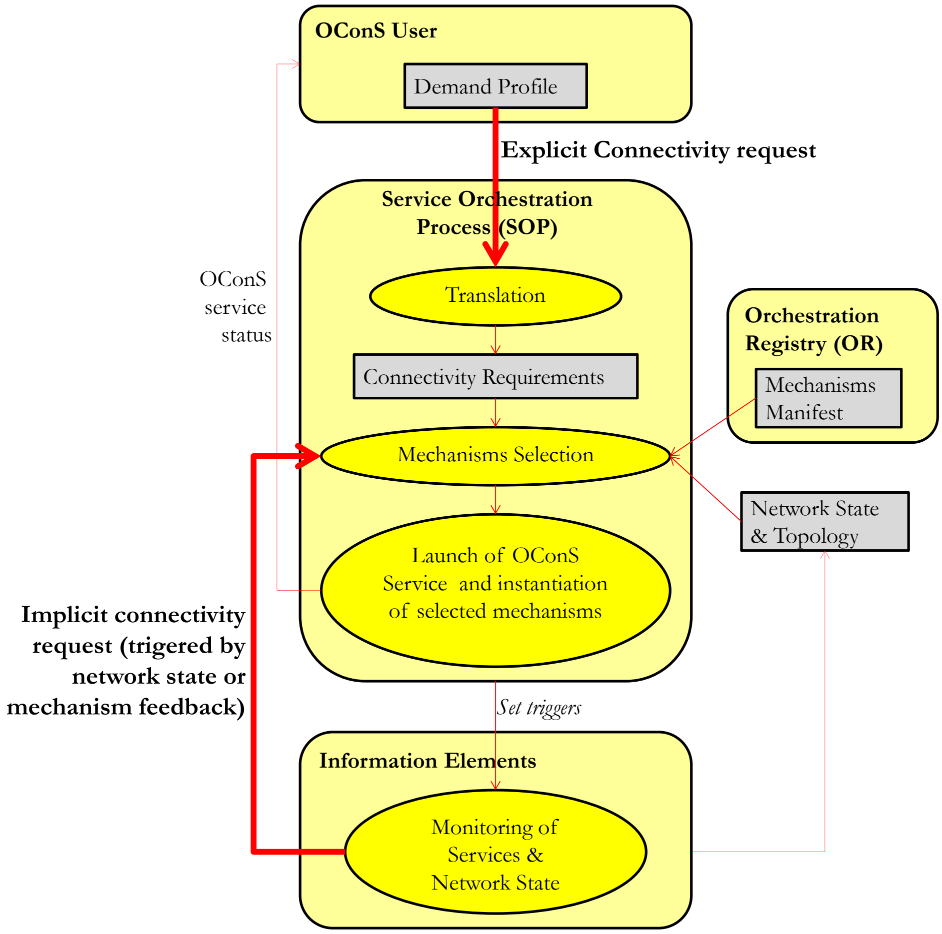


Figure 3.6 – OConS Orchestration.

The *Intra/Inter- Node Communication* (INC) supports the local and remote communications between the various architectural components. It is in charge of receiving OConS messages from local or remote components and forward them to their destination (either local in the OConS node, or remote in another node), and vice versa. The INC chooses whatever transport technology is deemed relevant for delivering the messages: it can be Inter-Process Communication (IPC) if the destination is internal to the same OConS node, or it can be an underlying transport communication, if the destination is remote. It is assumed that connectivity between nodes is available, nodes being reachable using existing forwarding schemes to deliver messages (e.g., IP connectivity, or "one hop connectivity" in a broadcast medium). OConS entities are agnostic of this communication method in use to carry their messages. The INC is in charge of resolving IDs into the relevant lower layer locator and the subsequent encapsulation and forwarding towards it.

The functional architecture described above can be the contained within an OConS node, or distributed through a group of OConS nodes within the OConS domain, where each node may contain a subset of these components. Still, as minimal components, an OConS node must have at least an INC, besides the existing functional entities. Within an OConS domain at least one SOP and one OR must exist. If no OR is available in an OConS node, registration of available entities and mechanisms is done remotely, supported by the INC. If there is no SOP in an OConS node, this means that it cannot launch by himself the orchestration of an OConS service. Nevertheless, an orchestrator OConS node may orchestrate remotely an OConS service in this node. Similarly, at the OConS mechanisms level, the functional entities that build a given mechanism can be all located within a single OConS node, or spread among several ones.

All above components communicate using the following *logical interfaces*:

- O_{IE}, O_{DE}, O_{EE}: interface to manage the functional entities. It enables the advertisement and discovery of entities, their registration, and configuration.
- *OSAP*: Orchestration Service Access Point external interface with OConS users (application/CloNe/NetInf), an Application Programming Interface (API) used to communicate user connectivity requirements to OConS through a demand profile, and also by the OConS system to communicate to the user the status of the requested OConS service (ready, error code).
- O_{OR}: interface to communicate with the OR. It enables to register entities, publish registered mechanisms, validate mechanisms, store network states, etc.
- O_{EXT}: interface to communicate with a remote OConS node's INC, over any-packet-based system able to encapsulate messages and carry them to other OConS nodes. Examples include UDP over Ethernet or 802.11.

The communication mode between OConS entities is in the form of requests and responses.

3.2.3 Enhancements provided by OConS

The OConS architecture enables the dynamic and flexible management of connectivity, rapidly reacting and adapting the network to changes (traffic, topology, application requirements). Its orchestration functionality provides an unified and abstract access to mechanisms, which can be combined and launched as an OConS service that explores the best as possible the particular conditions of the scenario. OConS is designed to coexist with legacy networking technologies. Non-OConS nodes, although not involved in the orchestration of an OConS service, can carry the data-stream which is controlled by an OConS service. Non-OConS nodes can also be upgraded to OConS nodes with OConS-related software. These are important characteristics in scenarios like a community-centric network of heterogeneous nodes, where heterogeneous nodes may join a network of enhanced capabilities and actively participate, by being assigned novel connectivity functions, if they can, as proposed in Section 3.1. The OConS architecture supports and explores the heterogeneity of joining nodes' capabilities and resources. Within OConS nodes, and thanks to the modularity of the orchestration and the well defined interfaces, it is easy to share and use both resources and capabilities to launch connectivity services adequate to the environment and network state.

The OConS architecture breaks the rigidness of classical architectures, supporting novel connectivity solutions, transport paradigms and communication protocols that explore the connectivity conditions. A classical adverse condition can be turned into an advantageous one, by launching adequate connectivity mechanisms. Thanks to the modularity of the OConS entities and its clear interfaces, OConS supports cross-layer optimisation, easily combining and exploring mechanisms that touch different layers of the classical protocol stack. Its well specified INC procedure and interfaces, supported by any transport paradigm, enables to easily establish a control plane among all OConS nodes. This enables the discernment of the most appropriate solutions to launch, localised or global ones, brought by link, network and flow level mechanisms. The combined support of both legacy and novel mechanisms is a strong characteristic, supporting solutions being built on existing Internet foundations, but enabling novel ones.

The OConS architecture is scalable, supported by a light control plane that enables to rapidly orchestrate, spread, launch and control adequate mechanisms in new-coming nodes. The open monitoring procedures brought by IEs, which can be re-used by multiple mechanisms, are capable of sharing within mechanisms network states, also helping in the scalability of the network. The OConS orchestration provides the possibility of a distributed or centralised management of connectivity, choosing what better fits in each situation. When nodes have no orchestration capabilities, a centralised solution is the best. In the opposite, in a community-centric network of highly capable nodes, distributed and autonomous orchestration enables to launch adequate localised solutions. In both cases, OConS takes the best of every node's capability, in terms of communication, but also processing (by implementation of orchestration functionalities) and storage (for storing monitoring information). OConS also supports opportunism, essential in community-centric networks, which are typically Wireless Challenged Networks (WCNs), where communication conditions are adverse, e.g., expectations of connectivity between certain nodes do no longer hold, or congestion is experienced on some links because of the multiple simultaneous requests from the crowd. OConS supports innovative techniques that explore resources and communication conditions in the best way to create and sustain the connectivity.

Finally, OConS provides enhanced and new connectivity mechanisms that are beneficial for the end-users and their applications, as well as for network operators. It supports both global networks, centrally supported by service providers, as well as self-organised community-centric ones, discussed in Section 2.6. A challenge for a community-centric network is a flash crowd scenario, an expected or unexpected large group of people with mobile devices with an increased demand for communications and services. Their requirements for communications services and content are dynamically changing, and have to be available for everybody and provided with the appropriate quality. The OConS architecture follows several design principles and presents several characteristics that enable the optimisation of connectivity in such challenging scenarios. End-users may enjoy better quality of service and experience with adapted connectivity, while network operators experience a more efficient usage of resources, higher throughput, and load balancing, which are collectively contributing to more satisfied users.

3.2.4 Example of OConS Services

A simple example of two OConS services in a generic network environment supported by OConS nodes of different characteristics is presented in Figure 3.7. OConS service A is provided to multiple users within a flash crowd WCN, which are all streaming the same music. The service is the composition of specific OConS connectivity mechanisms, such as mesh forwarding, access selection or gateway provisioning mechanisms, to guarantee the best connectivity. An OConS service for such a scenario is proposed in the next chapter. On the other side, OConS service B is an answer to a connectivity request of a user to access a file storage in the cloud. The result of this request is the orchestration of an access selection mechanism combined with a multipath routing mechanism, which provides the user with the optimal access network and, at the same time, with a multi-path connection in the backbone to the file storage, which provides better performance and reliability.

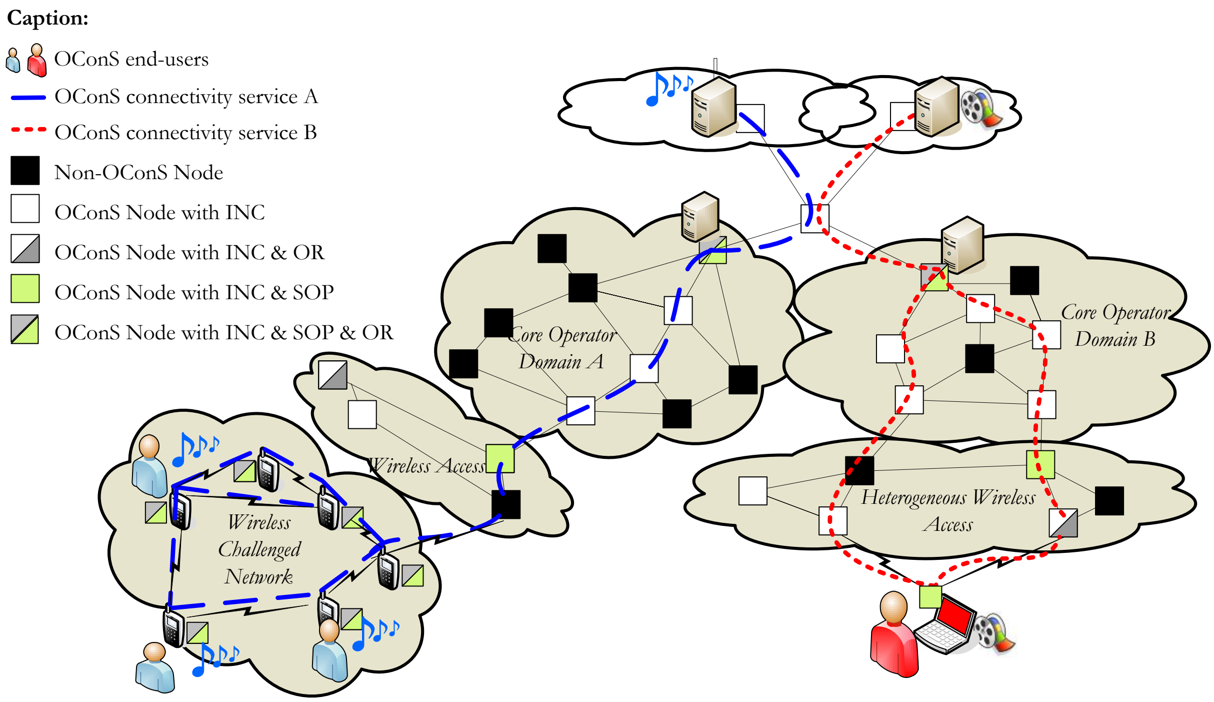


Figure 3.7 – Generic network environment with two orchestrated OConS services.

It is worth noting that different types of OConS nodes are represented in Figure 3.7. Any OConS-capable node has the basic capability to communicate with other peer OConS nodes via the INC functionality. In addition, nodes with a SOP are capable to orchestrate an OConS connectivity service within a set of OConS nodes. Certain nodes have an OR, storing information on available components (mechanisms and services), accessed locally or remotely by the SOP of the service orchestrator node. Other nodes with only an INC are remotely orchestrated by the orchestrator node and simply launch OConS mechanisms. The orchestration can be done either in a fully-distributed (e.g., OConS service A in the WCN) or in a domain-centralised manner (e.g., OConS service B in the wireless heterogeneous access network). OConS is designed to coexist with the current Internet. In fact, as shown in the above example, non-OConS nodes (i.e., those not upgraded with OConS-related software, intermediate or even end- nodes), although not involved in the orchestration of an OConS service, can carry the data-stream which is controlled by an OConS service.

Chapter 4

Novel Strategies to Manage WMNs' Radio Resources

Chapter 4 proposes novel strategies to manage WMNs' radio resources. Section 4.1 describes design guidelines and assumptions. A set of models supporting the proposed strategies is presented in Section 4.2. In Section 4.3, the FERA strategy is proposed for the efficient and fair management of radio resources. In Section 4.4, the OWROS service is presented, an OConS service for opportunistic WMN resources allocation. In Section 4.5, network and usage evaluation metrics are presented.

Key concepts: self-organisation; multi-radio; radio resources; fairness; efficiency; opportunism.

4.1 Design Choices

This chapter addresses the optimised operation of multi-radio multi-channel WMNs. To achieve it, the efficient management of radio resources, such as rates, transmitted power levels and channels, is required in order to minimise interference, and maximise connectivity and throughput via the communicating links. The management of resources must be aware of the neighbouring nodes' resources usage, the specificities of traffic flow in the WMN, and potential interference from neighbouring nodes. It will guarantee a max-min fair share of capacity among all nodes. The design choices for the proposed RRM strategies are summarised in Figure 4.1.

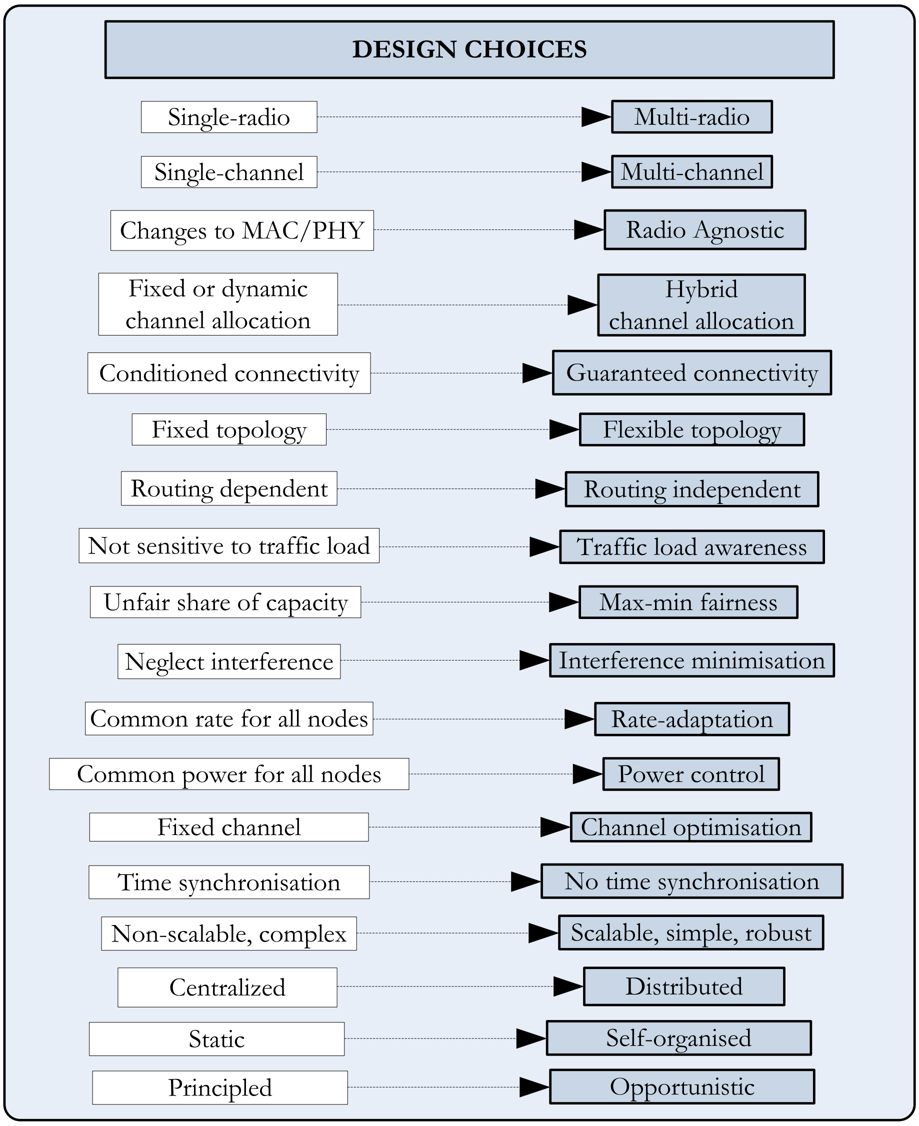


Figure 4.1 – Design choices for the proposed RRM strategies.

RRM strategies' design choices identified in Figure 4.1 are detailed below:

- *Multi-radio*: Optimisation of radio resources of nodes with multiple radios.
- *Multi-channel*: Support simultaneous operation, without interference, of each radio on an orthogonal channel.
- *Radio agnostic*: Implemented on top of the MAC layer, a virtual MAC controls the resources of multiple MACs below, not requiring changes of MAC or PHY protocols. This, by opposition to existing standards that require changes in the MAC. The virtual MAC is transparent to higher layers, representing the abstraction of a single radio.
- *Hybrid channel allocation*: Hybrid channel management of multi-radio nodes.
- *Guaranteed connectivity*: Guarantee connectivity with all neighbouring nodes. Still, connectivity shall only be optimised for the sub-set of links through which traffic flows.
- *Flexible topology*: Support any topology. The typical physical topology for a WMN is a partial mesh network topology (by opposition to a full mesh, where every node has a connection to every other node in the network). Still, the logical topology, which shows how data flows in the WMN (specified by a routing algorithm), is composed by a sub-set of links, which can dynamically change. The resources shall be self-optimised, for the optimal operation of resultant communication links through which packets flow.
- *Routing independent*: The proposed strategy shall be able to work with any routing protocol. It is assumed that the routing protocol balances the flows between the available gateways, determining the paths through which the various aggregated traffic flows shall travel. Based on these paths, radio resources shall be optimised. This does not prevent to have a dynamic routing algorithm that may recompute regularly paths. The proposed RRM mechanisms will be able to dynamically self-optimise the resources of the links crossed by traffic paths.
- *Traffic load awareness*: Optimisation of the radio resources exploring traffic specificities of WMNs (fat-tree traffic flow).
- *Max-min fairness*: Optimisation of nodes' radio resources with the goal to offer a max-min fair share of capacity to every aggregating node.
- *Interference minimisation*: Optimisation of the resources aiming at the minimisation of interference, as a mean to improve capacity.
- *Rate adaptation*: Adaptation of physical data-rate, sensitive to traffic load of links.
- *Power control*: Efficient control of transmitted power, guaranteeing connectivity but minimising interference, articulated with channel assignment and rate adaptation.

- *Channel optimisation*: Efficient channel assignment, optimising connectivity and minimising interference, aware of the traffic load of links.
- *No time synchronisation required between nodes*: The strategy must not request tight time synchronisation between mesh nodes.
- *Scalability*: Strategy that scales with the increasing number of nodes.
- *Simplicity*: Strategy of simple implementation and fast convergence.
- *Robustness*: Robust solution that takes care of possible changes in the network (appearance of new mesh nodes in the network and disappearance of others).
- *Distributed strategy*: Distributed strategy supported by an information exchange mechanism with neighbouring nodes.
- *Self-organised*: The strategy will self-configure, -optimise and -heal the radio resources.
- *Opportunistic*: Available radio resources will be explored opportunistically.

The following assumptions are considered. Although a node is able to communicate with all its neighbours, it is considered that a routing algorithm (out of the scope of the present study) pre-computes paths of aggregated traffic flows. Only the associated links will be optimised. It is also assumed that flows of aggregated traffic travel between MPPs and MAPs. A tree based topology is assumed, alternative paths only providing resiliency and load balancing, but not additional capacity. This is supported by a routing algorithm that guarantees a balance of load across all nodes.

In the present study multi-radio nodes have two radios for RBN connectivity and a third one for RAN. The strategy may be nevertheless applied to nodes with a larger number of RBN radios.

It is considered that a multi-radio node is able to operate simultaneously and without interference on one orthogonal channel per radio, although it is known that current available equipment (e.g. WLAN) does not fully guarantee such "orthogonal" operation within all channels [ShVa08]. It is also considered that channel switching delay is minimal, although it is known that current equipment presents delays between 0.1 and 2 ms [WuSC08].

The present study is focused on the optimisation of the meshed RBN. The main constrains to be considered in the optimisation are a fixed number of available channels, physical data-rates and transmission power levels on which nodes may operate to forward traffic. For it, only the resources of MAPs' RBN radios are optimised, the optimisation of the RAN radio not being addressed. This simplification is done since the optimisation of the infrastructured RAN, built by MAPs, may be considered independent of the mesh RBN, representing a different area of research – the optimisation of a cellular RAN deployment. MAPs are assumed as aggregating points of traffic (APs) from end-users they provide connectivity to, representing the end-users they aggregate traffic from/to MPP gateways that provide connectivity to the Internet. The performance of the network is evaluated in terms of the capacity each MAP has in aggregating traffic. This performance may be mapped to end-users as long as there is an optimised cellular planning of the RAN that guarantees no interference between RAN cells, and that each MAP is able to offer to RAN's end-users the RBN capacity it is optimised to aggregate.

4.2 Models

4.2.1 WMN Model

A formal description of a WMN is presented next. Consider a WMN composed of N_{map} multi-radio MAPs, set $\mathcal{M}$, providing Internet connectivity to End-User (EU) terminals via MPP gateways, as illustrated in Figure 4.2 for one MPP. Each MAP has 3 radios, two for mesh forwarding, and a third one to provide end-users RAN connectivity in a covered region designated cell. Neighbouring MAPs are able to communicate with each other via RBN connectivity's links, as illustrated in Figure 4.2, forming a partial mesh. For example, M_4 is able to communicate with M_0, M_1, M_3, M_6 and M_8.

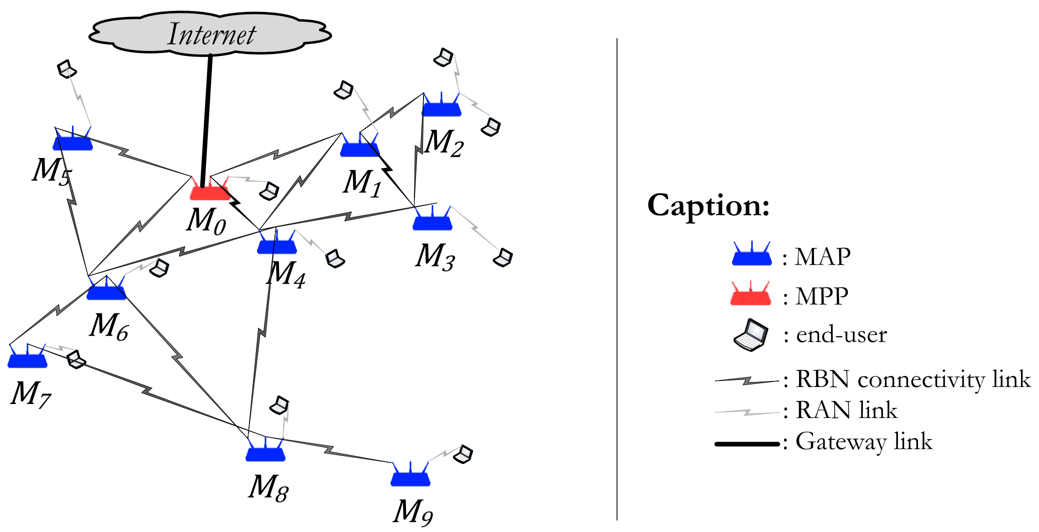


Figure 4.2 – Multi-radio WMN, representing the RBN connectivity's links.

A routing protocol computes the paths through which traffic flows travel, only a sub-set of links being used, as illustrated in Figure 4.3. For example, the routing algorithm determines that M_4 has only a link with M_0. These resulting path's links (from now on called links) are optimised by the proposed strategy. During simulation, the routing protocol may change the paths, the RRM strategy dynamically self-optimising the radio resources associated to the corresponding links to guarantee max-min fair share of capacity.

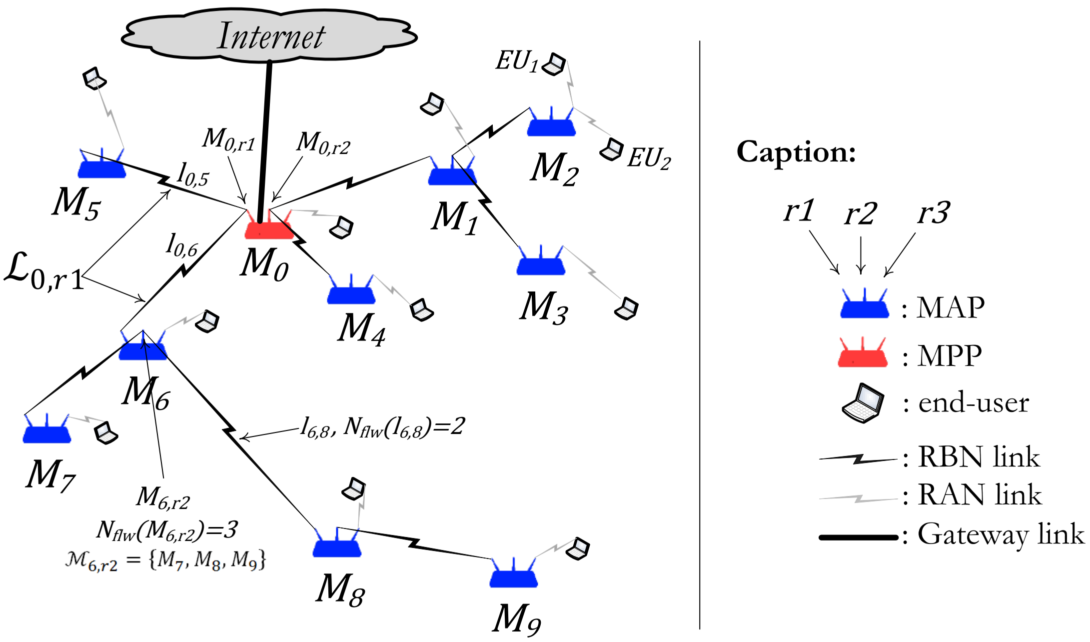


Figure 4.3 – Multi-radio WMN, illustrating the RBN traffic flow links.

The optimisation and configuration of the RAN radio of each MAP, to provide end-users access, is not addressed in this work (although some aspects are discussed in [FeCo11b]), being assumed that there are enough RAN resources in each MAP to offer the assigned capacity to the end-users it provides connectivity to without interference from neighbouring APs.

The aggregated traffic flow of a MAP (also designated simply as MAP's flow) is the aggregated traffic from end-users it provides connectivity to, exchanged between the MPP gateway and the MAP, and travelling through the WMN. For example, M_2's flow corresponds to the traffic aggregated from end-users EU_1 and EU_2. An MPP is itself also a MAP, and can aggregate traffic; still, its flow is not considered by the FERA strategy, as it is not forwarded by the WMN, having direct gateway access. MPPs' Internet gateway capacity is considered unlimited.

To characterise a WMN, the following parameters are defined, Figure 4.3:

- $M_{m,r}$: radio r of MAP M_m ($r1$ and $r2$ are for mesh, $r3$ for RAN end-users connectivity).

- $N_{flw}(M_{m,r})$: number of flows crossing $M_{m,r}$.
- $l_{m,n}$: link between M_m and M_n. The MAP nearest to MPP is the parent, communicating via its parent-radio with its child. Once paths are computed, a MAP has typically one single parent.
- $\mathcal{L}_{m,r}$: set of links of radio $M_{m,r}$, while $\mathcal{L}_m$ is the set of links of MAP M_m.
- $N_{links}(M_{m,r})$: number of links/children of $M_{m,r}$.
- $\mathcal{M}_{m,r}$: branch of $M_{m,r}$, set of MAPs with flows crossing $M_{m,r}$.
- $N_{flw}(l_{m,n})$: number of flows crossing link $l_{m,n}$.
- $N_{hop}(M_m)$: distance in hops from M_m to the nearest MPP.

As an example from Figure 4.3, branch $\mathcal{M}_{0,r1}$ is composed of MAPs M_5, M_6, M_7, M_8 and M_9. One can see how traffic ramifies as a fat-tree, as parent-radio $M_{0,r1}$ has $N_{flw}(M_{0,r1}) = 5$ flows, while $M_{6,r2}$ has 3 flows (of M_7, M_8 and M_9), and $M_{8,r2}$ only 1. This is an important property, explored by the proposed strategy for optimisation of radio resources.

The WMN deployment designates the position and distances of MAPs. It can be random, as in Figure 4.3, or hexagonal, Figure 4.4 (a typical cellular networks' deployment, which covers optimally a given scenario area). A hexagonal WMN deployment is characterised by:

- r_{wmn} [m]: WMN deployment radius.
- d_{map} [m]: distance between MAPs.
- r_{ap} [m]: MAP RBN's cell radius, where connectivity is provided to end-users.
- N_{rings}: number of rings around the MPP.
- $WMN_{x\ Ring}$: WMN hexagonal deployment composed of x rings around MPP.
- $\mathcal{M}_{xhop}$: set of MAPs' radios involved in the x hops links of the WMN.

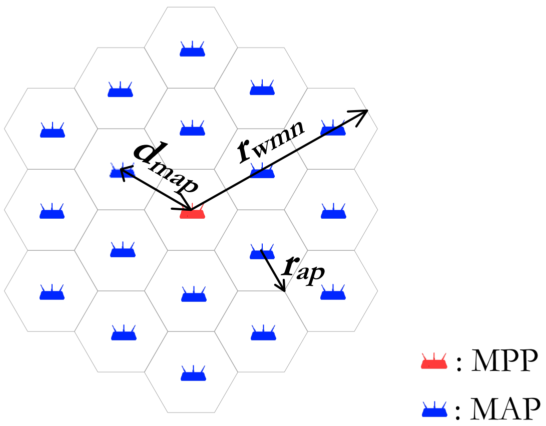


Figure 4.4 – WMN_{2Ring} hexagonal deployment.

In each MAP's radio, the following radio resources are configurable:

- P_{tx} [dBm]: transmission power level, from a set $\wp_{tx} = \left\{P_{tx\,1}, P_{tx\,2}, \dots, P_{tx\,N_{ptx}}\right\}$ of N_{ptx} levels.
- R_{phy} [Mbit/s]: physical bit rate, from a set $\mathcal{R}_{phy} = \left\{R_{phy\,1}, R_{phy\,2}, \dots, R_{phy\,N_{rphy}}\right\}$ of N_{rphy} available rates.
- C_c [Hz]: channel, from a set $\mathcal{C} = \left\{C_1, C_2, \dots, C_{N_{ch}}\right\}$ of N_{ch} available orthogonal channels.

To have a communication link established between two radios, both must have the same configuration of resources. For example, in Figure 4.3, $M_{6,r2}$, $M_{7,r1}$ and $M_{8,r1}$shall have their P_{tx}, R_{phy} and C similarly configured (this is achieved once resources are optimised).

Regarding traffic, various parameters are considered:

- R_{phy} [bit/s]: physical layer bit rate, number of bits that can be transmitted at a specific Modulation-Coding Scheme (MCS).
- R_{app} [bit/s]: maximum achievable application-layer throughput or capacity (number of bits successfully received per second) for a given R_{phy}, given by

$$R_{app_{[\text{Mbit/s}]}} = R_{phy_{[\text{Mbit/s}]}} \cdot \eta_{phy}\left(R_{phy}\right) , \tag{4.1}$$

  where η_{phy} is the bandwidth usage efficiency, weighting the IP/MAC/PHY overhead, depending on the system and packet size, besides R_{phy}.

- $R_{load}(M_m)$ [bit/s]: application-layer load of offered aggregated traffic by M_m, defined as:

$$R_{load\,[\text{Mbit/s}]} = \frac{K_{packet\,[\text{Mbit}]}}{\tau_{packet\,gen\,[\text{s}]}} , \tag{4.2}$$

  where:

  - K_{packet} [Mbit]: Packet size, at the application layer.
  - $\tau_{packet\,gen}$ [s]: Average generated packets inter-arrival time, following a specific distribution.

- $R_{thr}(M_m)$ [Mbit/s]: achieved application-layer throughput (number of bits successfully received) of aggregated traffic by M_m. When smaller than R_{load}, it means that some data packets have been dropped due to collisions or buffer overflow.
- $R_{fair}(M_m)$ [Mbit/s]: max-min fair capacity of M_m, the maximum load that guarantees max-min fairness in the whole WMN.

The proposed strategy guarantees to every MAP M_n a max-min fair capacity, $R_{fair}(M_n)$. This does not necessarily mean an equal distribution of resources. Depending on the topology and propagation conditions, R_{fair} can be different from MAP to MAP. Still, it is guaranteed that all MAPs may operate at their maximum throughput, with $R_{thr} = R_{fair}$. If any MAP is favoured, increasing its R_{load} and associated R_{thr} beyond R_{fair}, resulting in the disfavoured decrease of R_{thr} of other MAP(s), then fairness decreases.

4.2.2 Radio Propagation Aspects

Next, some propagation aspects useful to present the proposed strategies are described. Consider M_t transmitting packets to M_r. Considering the use of isotropic antennas and free-space conditions at 1 m [Rapp96], the received power level at node M_r is given by

$$P_{rx\,[\mathrm{mW}]} = \frac{P_{tx\,[\mathrm{mW}]}}{L_0 \cdot \left(\frac{d_{map\,[\mathrm{m}]}}{1\,[\mathrm{m}]}\right)^{\gamma}}, \tag{4.3}$$

where:

- P_{tx}: transmitted power level from node M_t.
- L_0: free-space propagation loss at 1 m [Rapp96], given by $(4 \cdot \pi \cdot f/c)^2$.
- d_{map}: distance between communicating nodes M_t and M_r.
- γ: path loss exponent, dependent on the propagation environment.

This is a simple and useful model for estimation of link performance. More sophisticated models have been developed to take into account other important factors such as terrain, urban clutter, antenna heights and diffraction. For a detailed description of these models, refer to [Rapp96]. In the present work the channel conditions are considered time invariant and known. The propagation environment is only characterised by γ. Specific scenario aspects which would, e.g., introduce extra attenuations for certain directions (e.g., shadowing due to obstruction of buildings or trees) are not characterised. Nevertheless, if realistic propagation conditions are available, the proposed strategy considers them. In fact, to configure P_{tx} for a given link, the proposed strategies measure the path loss of the link by comparing known P_{tx} and P_{rx} of signalling packets exchanged with the communicating neighbour, realistic propagation conditions being extrapolated. For these calculations, the path loss, L_p, is given by

$$L_{p\,[\mathrm{dB}]} = P_{tx\,[\mathrm{dBm}]} - P_{rx\,[\mathrm{dBm}]}\,. \tag{4.4}$$

The goal of a communication system is the reception, with an acceptable error rate, of packets at a receiver node from a transmitter one. The aggregate energy detected by a receiver consists of signal from the intended transmitter, co-channel interference from unwanted transmitter(s) and background noise. A receiver can only decode correctly a packet if the two following conditions are satisfied,

$$P_{rx\,[mW]} \geq P_{rx\,min\,[mW]}(R_{phy}) \tag{4.5}$$

$$\frac{P_{rx\,[mW]}}{P_{N\,[mW]} + \sum_{M_i \in \mathcal{I}} P_{rxi\,[mW]}} \geq \rho_{min}(R_{phy}) \tag{4.6}$$

where:

- $P_{rx\,min}(R_{phy})$: receiver sensitivity, minimum received power level to correctly sense and decode a received signal (R_{phy} and equipment dependent).
- ρ_{min}: SINR threshold, guaranteeing a maximum tolerable Packet-Error-Ratio (PER), for a specific MCS associated to an R_{phy}.
- P_N: additive white Gaussian noise power, given, for a signal transmission bandwidth, B, in a room temperature of 25 ºC (an ideal situation of null noise figure is considered), by

$$P_{N\,[\mathrm{mW}]} = -174 + 10 \cdot \log_{10}(B_{[\mathrm{Hz}]}) \tag{4.7}$$

- $\mathcal{I}$: set of interferers, MAPs simultaneously transmitting over the same channel.
- P_{rxi}: received power at M_r from an interfering node M_i.

From (4.5) the receiver sensitivity range (or maximum communication range) can be inferred, d_{max}, maximum distance at which the received signal is still above the minimum equipments receiver sensitivity, $P_{rx\,min}$, the receiver being able to correctly decode the packet. It depends on R_{phy} and P_{tx}, being given by

$$d_{max\,[\mathrm{m}]} = \left(\frac{P_{tx\,[\mathrm{mW}]}}{L_0 \cdot P_{rx\,min\,[\mathrm{mW}]}(R_{phy})}\right)^{1/\gamma} \tag{4.8}$$

On the other hand, from (4.6) the interference range, d_i, can be determined as the minimum interferer's distance at which the transmission from a neighbouring node is successfully received, when the interferer is simultaneously transmitting with the same P_{tx}. From (4.6) and (4.3), its expression can be deduced as

$$d_{i\,[\mathrm{m}]} = \left(\frac{P_{tx\,[\mathrm{mW}]}}{\frac{P_{tx\,[\mathrm{mW}]}}{d_{map\,[\mathrm{m}]}{}^{\gamma} \cdot \rho_{min}} - L_0 \cdot P_{N\,[\mathrm{mW}]}} \right)^{\frac{1}{\gamma}} \tag{4.9}$$

Considering in (4.6) that $P_N \ll P_{rxi}$, the following approximation can be also considered

$$d_{i\,[m]} \approx d_{map} \cdot \left(\rho_{min}\left(R_{phy}\right)\right)^{1/\gamma}, \text{ for } P_{tx}(M_t) = P_{tx}(M_i) \text{ and } P_N \ll P_{rxi}\,. \tag{4.10}$$

When nodes use different transmission powers, the above expressions are no longer valid. Considering that a receiver is receiving at the minimum supported power level, $P_{rx} = P_{rx\,min}\left(R_{phy}\right)$, the maximum supported interference is given from (4.6) by

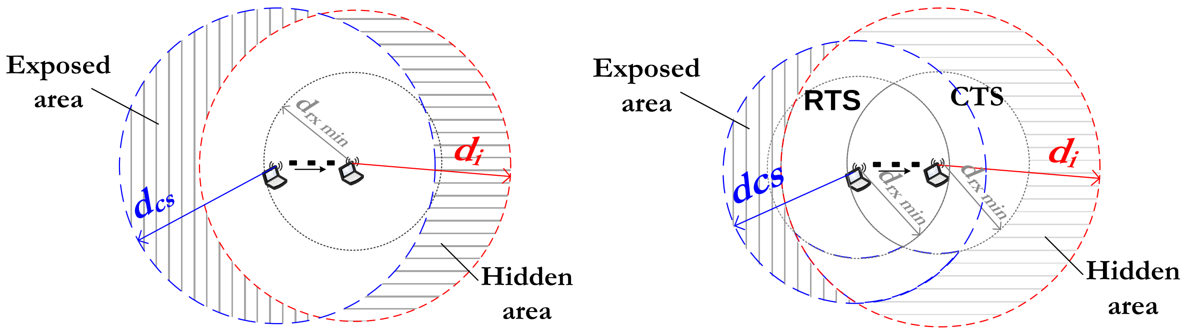
$$P_{rxi\,max\,[mW]} = \frac{P_{rx\,min\,[mW]}\left(R_{phy}\right)}{\rho_{min}\left(R_{phy}\right)} - P_{N\,[mW]}\ , \tag{4.11}$$

which is approximately invariant with R_{phy}, for typical $P_{rx\,min}$ and ρ_{min} values. Considering in (4.6) that $P_{rx} = P_{rx\,min}$ and $P_{rxi} = P_{rxi\,max}$, the maximum range within which a node may interfere is given by

$$d_{i\,max\ [m]} \approx \left(\frac{P_{tx\ [mW]}}{L_0 \cdot \left(P_{rxi\,max\,[mW]} + P_{N\,[mW]}\right)} \right)^{1/\gamma} \tag{4.12}$$

When a transmitter chooses a given P_{tx}, this interference range upper bound is a useful indicator.

The carrier sensing power threshold, P_{cs}, is the minimum received power level above which the medium is considered busy by a node willing to transmit. To be noted that the P_{cs} is different from $P_{rx\,min}$: $P_{rx\,min}$ is the power threshold above which a signal can be decoded; P_{cs} is the power level above which the channel is considered to be busy. P_{cs} should be sufficiently low, to detect on-going transmissions within its interference range. A proposed configuration is $P_{cs} = P_{rxi\,max}$, i.e., $d_{cs} = d_{i\,max}$. As depicted in Figure 4.5 (a), this guarantees *maximum* spatial reuse without permitting packet collisions, achieving a good trade-off between hidden terminals and exposed terminals so as to obtain high aggregate throughput. In fact, a correct configuration of P_{cs} is essential. When properly tuned, Physical Carrier Sensing (PCS) based on P_{cs}, Figure 4.5 (a), is more robust than Virtual Carrier Sensing (VCS), Figure 4.5 (b), not requiring either Request or Clear To Sent control packets to be exchanged (RTS and CTS respectively), which create overhead. PCS is flexible, as d_{cs} can be adjusted by tuning the P_{cs} threshold.



(a) Physical carrier sensing. (b) Virtual carrier sensing.

Figure 4.5 – Carrier sensing mechanisms.

4.2.3 Multi-Radio Node Model

To implement a multi-radio mesh node, a radio agnostic abstraction-layer is proposed on top of the Data-Link one. It is a virtual MAC that supports multiple radio interfaces (MAC & PHY), to higher layers representing the abstraction of a single one, Figure 4.6. The abstraction-layer enables:

- The operation of multiple radios in a node.
- The transparent implementation and management of RRM strategies for the joint optimisation of resources of the multiple radios.
- The implementation of a hybrid channel management policy.

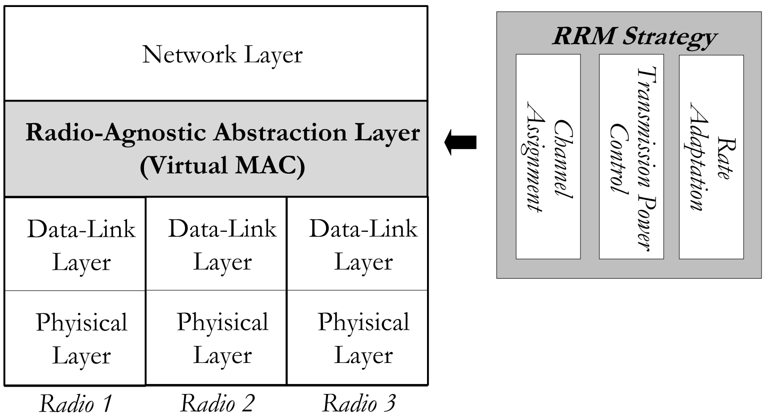


Figure 4.6 – Multi-radio node model.

The implementation of an RRM strategy is supported by a distributed procedure for monitoring and sharing resources between nodes, modelled using the OConS mechanism-level architecture presented in Section 3.2. It enables the distributed and self-organised optimisation and operation of nodes, as depicted in Figure 4.7. This procedure is detailed by the following steps:

- *Step 1*: The IE of each node M_m monitors various resources, storing information of the following Key Performance Indicators (KPIs):
  - $\mathcal{L}_m$: identification of the set of links established with M_m.
  - $L_p(l_i),\ l_i \in \mathcal{L}_m$: path loss of every existing link established with M_m, being obtained by comparing P_{tx} and P_{rx} of received packets.
  - $A(C_c)$, $C_c \in \mathcal{C}$: activity of M_x in C_c, being 1 if active and 0 if not.
  - $N_{hop}(M_m)$: obtained from neighbours information sharing mechanism.
  - $N_{flw}(l_i),\ l_i \ \in \mathcal{L}_m$: measured by inspecting the exchanged packets and identifying the number of MAPs whose flows cross l_i.
  - $R_{phy}(M_{m,r})$, $P_{tx}(M_{m,r})$, $R_{fair}(M_{GW,r})$.
- *Step 2*: Periodically, each IE broadcasts (on all channels) a *Hello* message advertising the node and its resources with several information: node ID, geographic positioning and KPIs. The *Hello* also contains similar information from nodes of its neighbourhood (the size of the neighbourhood corresponds to the interference range of the maximum received rate). This procedure enables the discovery of the local neighbourhood within a given number of hops.
- *Step 3*: When receiving a *Hello* message, the node's IE builds or updates its neighbourhood table with information of neighbour resources and KPIs.
- *Step 4*: Periodically, the DE receives from the IE the neighbourhood resources table.
- *Step 5*: Based on the neighbourhood resources table, the DE optimises the radio reources of each radio (operating physical data-rate, transmission power level and channel) recurring to the RRM strategy, consisting of rate adaptation, transmission power control and channel assignment mechanisms.
- *Step 6*: The EE enforces, on the various radios of the node, the decisions coming from DE. The EE is itself the operational part of the node, dealing with the reception and forwarding of packets.

This approach is adequate for spontaneous and opportunistic WMNs, where nodes join and leave the network dynamically, nodes' resources being dynamically optimised. The nodes' operation follows self-organisation principles:

- Self-configuration: newly added MAPs self-configure their resources automatically and independently as soon as they are plugged in (plug-and-play), and announce themselves to the neighbourhood. At this stage the nodes' resources are not yet optimised, but the node manages already to communicate with neighbouring nodes, whose resources are discovered thanks to the received *Hello* broadcasts of neighbours. Once the MAP begins to forward traffic, KPIs start to be updated and broadcasted to its neighbours (steps 1, 2 and 3).

- Self-optimisation and self-healing: Based on the compiled neighbourhood resources information (step 4) the DE regularly self-optimises its resources using the RRM strategy (steps 5 and 6) in response to changes in the network. In the event of a node failure, self-healing mechanisms are triggered in the surrounding nodes to alleviate gaps of connectivity, coverage or capacity. The whole WMN converges in an optimum solution after a transitory period, fairly maximising the throughput of every aggregating MAP.

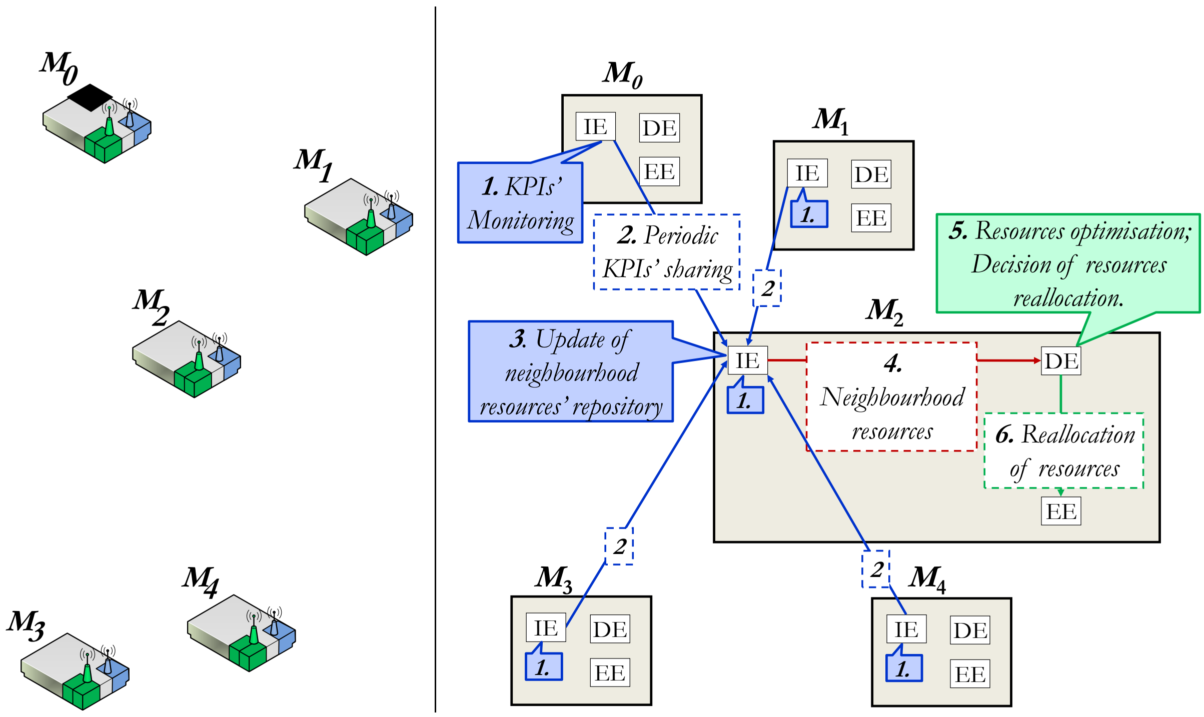


Figure 4.7 – Modelling a distributed RRM strategy for WMNs as an OConS mechanism.

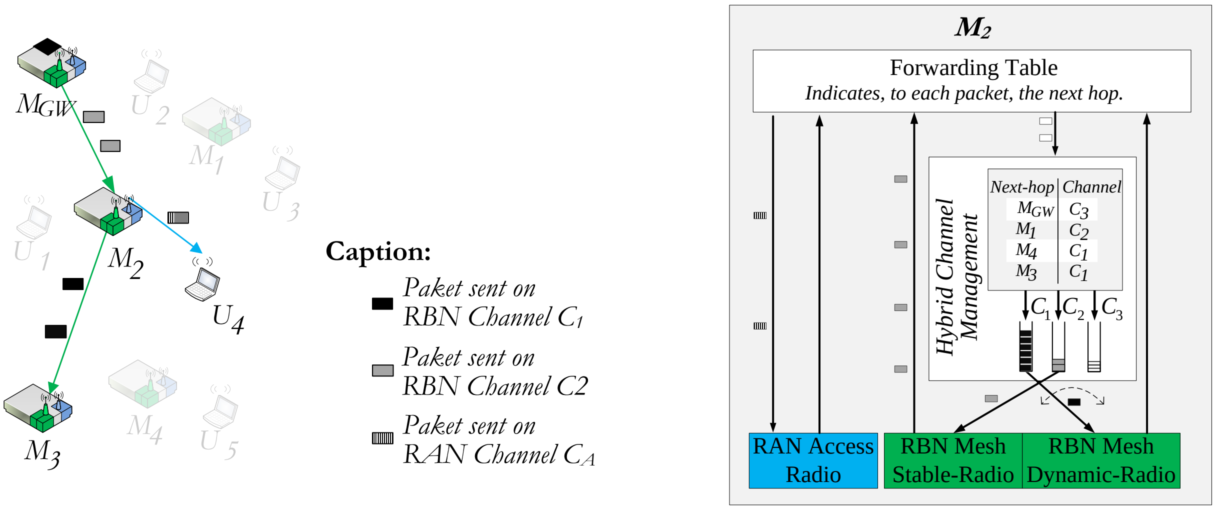
4.2.4 Hybrid Channel Management Policy

The capability of dealing simultaneously with multiple flows arriving from different channels, as illustrated in Figure 4.8 (a), is supported by the existence of multiple radios. A hybrid channel management policy is used for their control, Figure 4.8 (b). It is a distributed operation and guarantees connectivity with neighbouring nodes, not requiring synchronisation between them. Each node operates the channels of the various radios following a hybrid approach, as proposed in the HMCP strategy [KyVa06], described in Appendix C. Consider that every mesh node is equipped with N_{radios} radios, enabling it to operate simultaneously on N_{radios} different channels. These radios are divided into two groups:

$$N_{radios} = N_{st} + N_{dy} \,, \tag{4.13}$$

where:

- N_{st}: set of stable-radios, each having allocated a stable channel.
- N_{dy}: set of dynamic-radios, dynamically switchable between the remaining channels.



(b) M_2's simultaneous reception and transmission. (a) Hybrid channel management.

Figure 4.8 – Snapshot of operation of a multi-ratio mesh node at a given instant, simultaneously transmitting and receiving in multiple radios.

Each node advertises its stable-channel(s) as its receiving channel(s), always available for reception of packets. The other radio-channel is dynamic, periodically switching among the remaining channels that have packets to be transmitted, following a Round-Robin procedure. To forward data to a neighbouring node, the dynamic-radio is switched to the stable-channel of the corresponding receiving node. These aspects are further studied in the coming sections. This approach addresses an important trade-off between maximising connectivity and minimising interference. On the one hand, connectivity is guaranteed with the dynamic-radio, enabling to communicate with any neighbouring node; on the other, the allocation of stable-channels can be strategically done in order to minimise interference and optimise throughput. The choice of the stable-channel is periodically optimised by a channel assignment mechanism, presented in Section 4.3. One has to take into consideration the particularity of the received and forwarded traffic, and the proximity to gateway nodes, among other aspects. On stable topologies, if resources are adequately optimised, dynamic radios may remain stable on a channel during long periods of time, shortly switching only to broadcast packets.

The scenario depicted in Figure 4.8 (a) illustrates a node M_2 with $2+1$ radios. It manages simultaneously to receive RBN packets from M_{GW} on channel C_2, while forwarding on channel C_1 packets to M_3, forwarding also at the same time RAN packets to end-user U_4 on channel C_A (the configuration of the RAN channels is out of the scope of the present work, which focuses on the RBN). In Figure 4.8 (b), the operation of node M_2 is depicted, where the EE element summarises the steps of reception/transmission of packets. It receives packets from M_{GW} on channel C_2. The *RoutingTable* indicates the next node to which each packet must be forwarded. If the next-hop of a given packet is M_3, *next-hop–channel* table specifies that it shall be placed in packet-queue C_1 (the stable-channel of M_3, used for reception). Packets to be sent through the stable-channel are placed in the corresponding queue and sent briefly. Packets to be sent on remaining channels are placed on the corresponding packet queue, and transmitted when the dynamic radio is transmitting on that channel.

The components and functionalities of the hybrid channel management policy are detailed next:

- *NeighbourTable*: Each node maintains a table containing the list of its one-hop neighbours and their corresponding stable-channel(s), enabling to communicate to any neighbour by switching the dynamic-radio to the neighbour's stable-channel.
- *ChannelUsageTable:* Each node also maintains a table of its extended neighbourhood, used for the periodic decision of re-assignment of new stable-channel(s). For each node it contains its geographic location and, for each operating channel (in the stable- and dynamic-radios), the data-rate, average received/transmitted power and several KPIs, as discussed previously.
- *Channel-queue*: For each channel of the *NeighbourTable* exists a packet queue. If a unicast packet is received from the higher layer for transmission, the stable channel of the next-hop node is looked up in the *NeighbourTable*, and the packet is queued into the corresponding channel-queue. Replies (e.g., CTS and ACK) are managed by the MAC layer and done in the same channel as RTS and data packets are received.
- *Switching the channel of a dynamic-radio*: The dynamic-radio is switched to the channel with the oldest queued data, ensuring fairness. It changes channels only when there are packets queued for another channel, and the dynamic-radio is on a channel for more than T_{Dy}, the maximum time a dynamic-radio may transmit on a certain channel. This condition prevents starvation of other queues. When a radio-channel is switched to a new channel, and in the case where RTS-CTS handshaking is enabled, the node may have missed earlier RTS-CTS

transmissions, thus, deferring the time for one maximum sized packet transmission, $T_{BO\ CH\ switch}$. This guarantees avoidance of multi-channel hidden terminal. This strategy ensures that on-going transmissions are protected from interference. If RTS-CTS is not enabled, then, the radio-channel has to only defer until the channel is idle.

- *Hello messages broadcast*: Periodically, each T_{Hello} seconds, a node broadcasts on every channel a *Hello* packet containing its stable-channel(s) together with its *ChannelUsageTable* (geographical position, channel utilisation and other parameters of use for the proposed mechanisms). The frequency of *Hellos* depends on the magnitude of average node mobility, on the variation of the conditions of traffic or availability of nodes. *Hello* packet exchange is used by many routing protocols, such as Ad-hoc On Demand Distance Vector (AODV) [PeBD03]. In this sense, link layer *Hello* information could be merged with messages from routing layers.
- *Updating NeighbourTable and ChannelUsageTable*: When a node receives a *Hello* packet from a neighbour, it updates its *NeighbourTable* if a new stable-channel was allocated to that neighbour. It also updates information of its *ChannelUsageTable* using the *ChannelUsageTable* received in the *Hello*. An entry that has not been updated for a specified maximum lifetime is removed. This ensures that out of date entries of nodes that have moved away are removed from the *NeighbourTable* and *NeighbourUsageTable*.
- *Stable-channel selection*: Initially, when a mesh node joins the network, it chooses randomly a stable-channel. After a period T_{Hello}, it consults its *ChannelUsageTable* that was built meanwhile. If the stable-channel has a higher utilisation, $U(M_m)$, in its neighbourhood than other channels, according to some probability it changes its stable-channel to a less used one. After this, the node broadcasts a *Hello* packet informing neighbours of its (possibly new) stable-channel. This procedure is supported by a CA strategy described in Section 4.3.
- *Gateway announcement function*: The gateway announces itself through a broadcast message, this message being subsequently forwarded by each node that receives it. It has a hop counter field that enables to acknowledge each node the number of hops it is from the gateway.

4.3 Fair and Efficient Resource Allocation Strategy

4.3.1 Overview

A Fair and Efficient Resource Allocation (FERA) strategy is proposed for the optimisation of multi-radio MAPs' radio resources – bit rate, transmitted power level and channel – to efficiently guarantee a max-min fair capacity to every aggregating MAP. FERA is sensitive to the traffic load of the node and its links, being max-min fair in the share of capacity among nodes. The transmission power control mechanisms are energy-efficient in addressing the non-homogeneity of nodes' rates. A load-aware channel assignment mechanism guarantees interference-free connectivity among forwarding nodes. FERA makes WMNs flexible and dynamic, by the exploitation of nodes resources with the objective of increasing as much as possible network availability and usability, maximise network performance, minimise interference and contention among co-channel mesh nodes, providing scalable capacity with increasing number of nodes, and increase the overall energy and spectrum efficiency. To support the above functionalities, FERA is composed of the following mechanisms, detailed in the following sections:

- A combined Rate Adaptation (RA) and Transmitter Power Control (TPC) mechanism that optimises, for a given MAP, the operating physical bit rate and transmitted power level of the links with its children.
- A Channel Assignment (CA) mechanism that optimises, for a given MAP, the operating channel of the links with its children.
- An auxiliary mechanism to share capacity, when the available channels are not sufficient to avoid interference between certain links.
- An auxiliary mechanism to reduce the bit rate of the gateway, when the overall interference among links occurs due to a reduced number of available channels.
- A flow-control mechanism that continuously monitors and controls MAPs' aggregated throughput to guarantee max-min fair share of capacity among WMN's nodes.

FERA is implemented in the radio agnostic abstraction-layer, as presented in Section 4.2.3. The multi-radio node model and the hybrid channel management policy enable nodes to communicate with each other even without optimised resources. FERA is a self-organised strategy, supported by a distributed procedure for resources' monitoring and sharing. They exchange *Hello* messages with nodes information and KPIs, detailed in Section 4.2.4, essential for the optimisation mechanisms.

The MPP gateway, M_{GW}, is the first node to have optimised its resources, then each of its children, $M_m \in \mathcal{M}_{GW\ chd}$, and so on. FERA can be hierarchically-distributed, run by each MAP, the ordered sequence of optimisation being guaranteed by messages broadcast, once a given node configures its resources. Another possibility is to run FERA centrally on each gateway, which will collect all relevant information from all associated nodes (topology, propagation conditions, aggregating MAPs), optimise their resources, and communicate them the resulting configurations. The mechanism can be run periodically, or only triggered when changes are detected (e.g., topology changes).

It is considered that each traffic flow travels between a gateway and an aggregating MAP. Each MAP is able to identify the various flows (of specific MAPs) it forwards. In the case of the existence of multiple gateways, each one triggers FERA independently, being assumed that the routing protocol has defined the links between MAPs to be used for forwarding traffic flows. It is also assumed that the routing balances the flows between the available gateways. In the present study, one considers MAPs with 2 mesh-radios, although FERA is applicable to MAPs with more radios.

4.3.2 Rate Adaptation and Transmitted Power Control Mechanisms

A combined RA and TPC mechanism is proposed, sensitive to the traffic and topology specificities of WMNs. It assigns a max-min fair capacity to every MAP. It uses the highest possible bit rates for the gateway links to make available the highest possible capacity to the WMN. For the remaining MAPs, as traffic ramifies, lower bit rates are used, still satisfying the links' throughput needs, to distribute fairly the capacity assigned to each aggregating MAP. This enables to efficiently reduce P_{tx} and interference range, enabling channel reuse among links. If certain links do not support the assigned capacity, the unused capacity is redistributed. The MPP gateway, M_{GW}, is the first node to have optimised its resources, then each of its children, $M_m \in \mathcal{M}_{GW\ chd}$, and so on.

For M_{GW}, the mechanism is as follows. The set of links, $\mathcal{L}_{GW}$, that M_{GW} has with its children (through which flows are exchanged) has to be distributed between $M_{GW,r1}$ and $M_{GW,r2}$ radios. For it, links are ordered by the decreasing number of flows

$$\{l', l'', l''' \dots\}, \text{where } N_{flw}(l') \geq N_{flw}(l'') \geq N_{flw}(l''') \dots \tag{4.14}$$

Starting from l', each link is assigned to the radio with less flows,

$$l^i \in \mathcal{L}_{GW,r}\colon\ \forall\, x \in \{r1, r2\},\ N_{flw}\left(M_{GW,r}\right) \ \leq N_{flw}\left(M_{GW,x}\right). \tag{4.15}$$

Each radio $M_{GW,r}$ configures then its R_{phy} and P_{tx}, used to communicate with all its children. It first computes the path loss of the most attenuated link of $\mathcal{L}_{GW,r}$, given by

$$L_{p\,max}\left(\mathcal{L}_{GW,r}\right) = max\left\{L_p(l_i),\ l_i \in \mathcal{L}_{GW,r}\right\}. \tag{4.16}$$

For the maximum transmitted power level, $P_{tx\,max}$, R_{phy} is chosen as the maximum bit rate that satisfies (4.5) for all links $\mathcal{L}_{GW,r}$, given by

$$R_{phy}\left(M_{GW,r}\right) = \\ max\left\{R_{phy} \in \mathcal{R}\colon \forall l_i \in \mathcal{L}_{GW,r},\ P_{tx\,max} - L_{p\,max}\left(\mathcal{L}_{GW,r}\right) \geq P_{rx\,min}\left(R_{phy}\right)\right\}. \tag{4.17}$$

This maximum rate is supported by the child with worse propagation conditions (typically the farthest one). The minimum transmission power level, which still guarantees communication at $R_{phy}\left(M_{GW,r}\right)$ rate with all children of $M_{GW,r}$, is given by

$$P_{tx}\left(M_{GW,r}\right) = \\ min\left\{P_{tx} \in \wp : \forall l_i \in \mathcal{L}_{GW,r},\ P_{tx} - L_{p\,max}\left(\mathcal{L}_{GW,r}\right) \geq P_{rx\,min}\left(R_{phy}\left(M_{GW,r}\right)\right)\right\}. \tag{4.18}$$

The capacity of each gateway radio $M_{GW,r}$ determines the total capacity available for its branch $\mathcal{M}_{GW,r}$. FERA aims to guarantee a max-min fair throughput to every aggregating MAP, equally distributing the capacity among all flows. The max-min fair aggregated throughput per aggregating MAP of branch $\mathcal{M}_{GW,r}$ is given by

$$R_{fair\,[\text{Mbit/s}]}\left(M_{GW,r}\right) = \frac{R_{phy\,[\text{Mbit/s}]}\left(M_{GW,r}\right)\ \cdot\ \eta_{phy}\left(R_{phy}\left(M_{GW,r}\right)\right)}{N_{flw}\left(M_{GW,r}\right)}. \tag{4.19}$$

The optimised bit rate and transmitted power levels are enforced in the radios and a *Hello* message (with the optimised parameters) is broadcast, so that the children use the same configuration for communication with its parent. The steps that summarise the RRM strategy for M_{GW} are provided in Figure 4.9. To be noted that M_{GW} may also aggregate traffic, although not using WMN resources as it is directly connected to the Internet.

Looking for example at gateway radio $M_{0,r2}$ of Figure 4.3, used for the links with M_1 and M_4, its resources are computed as follows. The maximum capacity, $R_{app} = \eta_{phy} \cdot R_{phy}\left(M_{0,r2}\right)$, is equally shared among the $N_{flw}\left(M_{0,r2}\right) = 4$ flows of aggregating MAPs of this branch (M_1, M_2, M_3, M_4), the max-min fair capacity assigned to each being given by (4.19).

input:

$M_{GW,r}, \quad r = 1, \dots, N_{radios}$

$\mathcal{R}_{phy}$, $\mathcal{P}_{tx}$, $P_{rx\,min}(\mathcal{R}_{phy})$ table

$\mathcal{L}_{GW} = \{l_1, l_2, \dots, l_{N_{links}}\}$

$L_p(l_i),\ l_i \in \mathcal{L}_{GW}$

$N_{flw}(l_i),\ l_i \in \mathcal{L}_{GW}$

ordered set $\{l', l'', l''' \dots\}$, where $N_{flw}(l') \geq N_{flw}(l'') \geq N_{flw}(l''') \dots$

$\mathcal{L}_{GW,r} = \emptyset,\ r \in \{1, \dots, N_{radios}\}$

for $i = 1; N_{links}$

$\quad l_i \in \mathcal{L}_{GW,r} : \forall x \in \{1, \dots, N_{radios}\},\ N_{flw}(\mathcal{L}_{GW,r}) \leq N_{flw}(\mathcal{L}_{GW,x})$

end for

for $r = 1;\ N_{radios}$

$\quad L_{p\,max}(\mathcal{L}_{GW,r}) = \max\{L_p(l_i),\ l_i \in \mathcal{L}_{GW,r}\}$

$\quad i = N_{rate}$

$\quad$ **while** $\left(P_{tx\,N_{ptx}} - L_{p\,max}(\mathcal{L}_{GW,r}) \geq P_{rx\,min}(R_{phy\,i})\right)$ and $(i \geq 1)$ **do**

$\quad\quad i = i - 1$

$\quad$ **end while**

$\quad R_{phy}(M_{GW,r}) = R_{phy\,i+1}$

$\quad j = N_{ptx}$

$\quad$ **while** $\left(P_{tx\,j} - L_{p\,max}(\mathcal{L}_{GW,r}) \geq P_{rx\,min}\left(R_{phy}(M_{GW,r})\right)\right)$ and $(j \geq 1)$ **do**

$\quad\quad j = j - 1$

$\quad$ **end while**

$\quad P_{tx}(M_{GW,r}) = P_{tx\,j+1}$

$\quad R_{fair}(M_{GW,r}) = \frac{R_{phy}(M_{GW,r}) \cdot \eta_{phy}(R_{phy}(M_{GW,r}))}{N_{flw}(M_{GW,r})}$

end for

output:

$R_{phy}(M_{GW,r}), P_{tx}(M_{GW,r}), R_{fair}(M_{GW,r}) \quad r = 1, \dots, N_{radios}(M_{GW})$

Figure 4.9 – Algorithm for RA and TPC of M_{GW}.

For a MAP $M_m \neq M_{GW}$, the combined RA and TPC mechanism is as follows. M_m has two radios, $M_{m,r1}$ to communicate with its parent, while $M_{m,r2}$ is used to communicate with M_m's children. M_m knows the number of flows crossing it, knows R_{fair}, and the characteristics of the link with its parent radio $M_{p,r}$ (R_{phy} and P_{tx}). $M_{m,r1}$ is configured similarly to its parent radio, with $P_{tx}(M_{m,r1}) = P_{tx}(M_{p,r})$ and $R_{phy}(M_{m,r1}) = R_{phy}(M_{p,r})$, as both radios of any link must be similarly configured. If M_m aggregates traffic and belongs to the branch of gateway radio $M_{GW,r}$, its max-min fair capacity is $R_{fair}(M_{GW,r})$, similarly to its children. Regarding $M_{m,r2}$ radio, resources are configured to support the $N_{flw}(\mathcal{L}_{m,r2})$ flows of its children, each at $R_{fair}(M_{GW,r})$, so that each child's flow can achieve its fair capacity. The minimum bit rate that supports these $N_{flw}(\mathcal{L}_{m,r2})$ flows with its children is given by

$$R_{phy}(M_{m,r2}) = \min\{R_{phy} \in \mathcal{R}: \forall l_i \in \mathcal{L}_{m,r2}, \eta \cdot R_{phy} \geq N_{flw}(\mathcal{L}_{m,r2}) \cdot R_{fair}(M_{GW,r})\}. \tag{4.20}$$

Reducing R_{phy} results in a lower receiver sensitivity, $P_{rx\,min}$, enabling lower transmission power levels. $P_{tx}(M_{m,r2})$ is configured using (4.18), to enable communication with its children at $R_{phy}(M_{m,r2})$.

Similarly, the optimised bit rate and transmitted power levels are enforced in the radios and a *Hello* message (with the optimised parameters) is broadcast, so that the children use the same configuration for communication with its parent. The steps that summarise the RA and TPC algorithm for M_m are provided in Figure 4.10.

To exemplify this case, the configuration of radio $M_{1,r2}$ of Figure 4.3 is analysed. As it has only 2 children' flows instead of the 4 of $M_{0,r2}$, it can use a lower bit rate than $M_{0,r2}$.A lower P_{tx} is also used, an energy-efficient solution that reduces the interference range from transmissions of this link.

There may be cases where some of $M_{m,2}$'s children are too far away to satisfy (4.20), i.e., the propagation conditions do not enable to satisfy condition (4.5). In such case, $R_{phy}(M_{m,2})$ must be calculated using (4.17), and $P_{tx}(M_{m,2})$ obtained from (4.18). The set of aggregating nodes $\mathcal{M}_{m,r2}$ (children of M_m) will not be able to achieve $R_{fair}(M_m)$, a new smaller $R_{fair'}(M_m)$ needing to be computed from (4.19), for $M_{m,r2}$. As extra capacity of the associated $M_{GW,r}$ radio is not used (from the one allocated to $\mathcal{M}_{m,r2}$), it shall be distributed by the remaining aggregating MAPs of $M_{GW,r}$, resulting in a new $R_{fair'}(M_n)$, given by

$$R_{fair'\,[\text{Mbit/s}]}(M_n) = \frac{\eta \cdot R_{phy\,[\text{Mbit/s}]}(M_{GW,r}) + N_{flw}(M_{m,r2}) \cdot \left(R_{fair\,[\text{Mbit/s}]}(M_m) - R_{fair\,'[\text{Mbit/s}]}(M_m)\right)}{N_{flw}(\mathcal{L}_{GW,r}) - N_{flw}(\mathcal{L}_{m,r2})}, \quad (4.21)$$

where $M_n \in \frac{\mathcal{M}_{GW,r}}{\mathcal{M}_{m,r2}}$. This new $R_{fair'}(M_n)$ capacity requires to re-compute R_{phy} and P_{tx} of radios of $M_n \in \mathcal{M}_{GW,r} \setminus \mathcal{M}_{m,r2}$. In centralised FERA, this is easy to re-compute; for the hierarchical-distributed one, this optimisation procedure is supported by adequate message passing among nodes.

input:
$\mathcal{R}_{phy}$, $\mathcal{P}_{tx}$, $P_{rx\,min}(\mathcal{R}_{phy})$ table
$M_{p,r}$ parent radio of M_m
$R_{phy}(M_{p,r})$, $P_{tx}(M_{p,r})$, $R_{fair}(M_{GW,r})$
$N_{flw}(M_m)$
$L_p(l_i), l_i \in \mathcal{L}_m$
$P_{tx}(M_{m,r1}) = P_{tx}(M_{p,r})$
$R_{phy}(M_{m,r1}) = R_{phy}(M_{p,r})$
if (M_m aggregates traffic) **then** $R_{fair}(M_m) = R_{fair}(M_{GW,r})$
$i = 1$
while $\left(R_{phy\,i} \cdot \eta_{phy} \geq N_{flw}(\mathcal{L}_{m,r2}) \cdot R_{fair}(M_m)\right)$ and $(i \leq N_{rphy})$ **do**
$\quad i = i + 1$
end while
$R_{phy}(M_{m,r2}) = R_{phy\,i}$
$L_{p\,max}(\mathcal{L}_{m,r2}) = \max\{L_p(l_i),\ l_i \in \mathcal{L}_{m,r2}\}$
$j = N_{ptx}$
while $\left(P_{tx\,j} - L_{p\,max}(\mathcal{L}_{m,r2}) \geq P_{rx\,min}\left(R_{phy}(M_{m,r2})\right)\right)$ and $(j \geq 1)$ **do**
$\quad j = j - 1$
end while
$P_{tx}(M_{m,r2}) = P_{tx\,j+1}$
output:
$R_{phy}(M_{m,r})$, $P_{tx}(M_{m,r})$, $R_{fair}(M_{m,r})$

Figure 4.10 – Algorithm for RA and TPC of $M_m \neq M_{GW}$.

To exemplify this case, the configuration of radio $M_{6,r2}$ of Figure 4.3 is analysed. Due to maximum transmitted power level bounds, M_8 may be too far away to enable a bit rate high enough that supports the three flows of $R_{fair}(M_{0,r1})$ from M_7, M_8 and M_9. Only a lower $R_{fair'}(M_{5,r2})$ is possible for M_7, M_8 and M_9, dictated by the maximum possible $R_{phy}(M_{6,r2})$. This means that the capacity of $M_{0,r1}$ is not fully used, the unused one being redistributed by M_5 and M_6, which will have their max-min fair capacity increased.

4.3.3 Channel Assignment Mechanism

As described in Section 4.2.4, as soon as the mesh-node is plugged in, connectivity is guaranteed with every neighbour thanks to the hybrid channel management policy. The CA mechanism optimises, for each MAP parent-radio $M_{m,r}$, the channel to be used in the links with its children, selecting the one that will suffer less from interference, contention and channel switching. From the moment this channel is optimised, it is used for bi-directional communication with its corresponding children. The CA mechanism only makes sense to be launched after RA and TPC, as it is sensitive to load and interference (associated to nodes' transmission power level).

The CA mechanism can be synthesised as follows:

- Periodically, each mesh node computes the utilisation of each existing channel and broadcasts this information within its neighbourhood. Nodes also store and broadcast information from other nodes. Receiving nodes decide which information is of interest.
- Nodes collect neighbours information, based on which they run the CA mechanism.

The utilisation of a channel $C_c \in \mathcal{C}$ by a node M_x is given by

$$U(M_x, C_c) = \frac{A(C_c) \cdot N_{flw}(M_x)}{2^{N_{hop}(M_x)}}. \tag{4.22}$$

The utilisation weights the importance of M_x in forwarding traffic via C_c in the WMN. The nearest it is to a gateway (weighted by $2^{-N_{hop}(M_x)}$) and the more flows it has to forward (weighted by $N_{flw}(M_x)$), the more important M_x is in the use of C_c.

For the selection of the best channel for MAP M_m, the usage of every channel is evaluated within M_m's interference neighbourhood given by

$$\mathcal{X}_m = \left\{ M_x : \frac{P_{rx}(M_n)}{P_N + P_{rx}(M_x)} < \rho_{min}\left(R_{phy}(M_m)\right) \mid M_n \in \mathcal{M}_{m\,chd} \right\}, \tag{4.23}$$

where $P_{rx}(M_n) = P_{tx}(M_x) - L_p(M_x - M_n)$. The utilisation of C_c within $\mathcal{X}_m$ is weighted by the channel utilisation, given by

$$\mathcal{U}(\mathcal{X}_m, C_c) = \sum_{M_x \in \mathcal{X}_m} U(M_x, C_c). \qquad (4.24)$$

The best channel for $M_{m,r}$ is the one less used within $\mathcal{X}_m$, i.e., with the lowest utilisation,

$$C_{opt} = \{C_k \in \mathcal{C}: \mathcal{U}(\mathcal{X}_m, C_k) \leq \mathcal{U}(\mathcal{X}_m, C_i), \forall\, C_i \in \mathcal{C}\}. \qquad (4.25)$$

This channel is the one that creates less interference and may be less interfered. The CA strategy is summarised in Figure 4.11.

Looking at the example of Figure 4.3 and considering 4 available channels, $\mathcal{L}_{0.r1}$ will get C_1, $\mathcal{L}_{0.r2}$ will have C_2, $\mathcal{L}_{1.r2}$ and $\mathcal{L}_{8.r2}$ will get C_3, and $\mathcal{L}_{6.r2}$ will get C_4. The distance between $\mathcal{L}_{8.r2}$ and $\mathcal{L}_{1,r2}$, and the possibly low bit rates and power levels may prevent from interference. If not, the mechanism described in the next section is used.

input:
$\forall\, M_x \in \mathcal{X}_m: U(M_x)$
$P_{tx}(M_x)$
$L_p(M_x - M_m)$

for each $C_c \in \mathcal{C}$:

$\quad \mathcal{X}_m = \left\{M_x \in \mathcal{X}_m: \frac{P_{tx}(M_m) - L_p(M_x - M_m)}{P_N + P_{rx}(M_x)} < \rho_{min}\left(R_{phy}(M_m)\right)\right\}$

$\quad \mathcal{U}(\mathcal{X}_m, C_c) = \sum_{M_x \in \mathcal{X}_m^{C_c}} U(M_x)$

find $C_k \in \mathcal{C}: \mathcal{U}(\mathcal{X}_m^{C_k}) \leq \mathcal{U}(\mathcal{X}_m^{C_i}), \forall\, C_i \in \mathcal{C}$

output: C_k

Figure 4.11 – Channel assignment algorithm for M_m.

4.3.4 Capacity Sharing, Bit Rate Reduction and Flow-Control Mechanisms

A capacity sharing mechanism among interfering links is launched when the number of available channels is not sufficient to eliminate situations of interference. The idea is to use the same channel within a larger set of links, but increasing the bit rate sufficiently so that enough capacity is available for all to achieve their R_{fair} throughput. Considering $\mathcal{M}_c$ as the set of parent-radios that use channel C_c and have interfering links, their new bit rate is given by

$$R_{phy}(\mathcal{M}_c) = min \left\{ R_{phy} \in \mathcal{R} \colon \eta_{phy} \cdot R_{phy} \geq \left[\sum_{M_m \in \mathcal{M}_c} N_{flw}(M_m) \cdot R_{fair}(M_m) \right] \right\}. \qquad (4.26)$$

The power level that guarantees communication at $R_{phy}(\mathcal{M}_c)$ of each parent-radio with its children is given by (4.18). Still, there may be cases where there is no sufficiently high R_{phy} or P_{tx} to satisfy these conditions, this mechanism not being possible.

Looking at the example of Figure 4.3, if the nodes involved in $\mathcal{L}_{8.r2}$ and $\mathcal{L}_{1.r2}$ interfere, but are able to sense each others transmissions, a sufficiently high $R_{phy}(\mathcal{M}_c)$ will be selected to provide enough capacity to support all simultaneous flows, achieving their R_{fair} throughput.

In situations of scarce channels, a bit rate reduction mechanism is used when the number of available channels is still insufficient to avoid interference among multiple links. The R_{phy} of the M_{GW} radio with problems is configured to a lower rate, resulting from (4.19) in a smaller assigned R_{fair} per aggregating MAP. This will require links with less capacity, R_{phy} and P_{tx} being decreased. Ranges of interference will result shorter, enabling to reuse channels within shorter ranges. In this way, the new smaller R_{fair} is achievable by every MAP of $\mathcal{M}_{GW}$.

A flow-control mechanism, located at MPPs and/or at every aggregating MAP, is used to ensure fairness. It is aware of the R_{fair} capacity assigned to every MAP and is able to identify the flow of each aggregating. During operation, the traffic aggregated by each MAP M_m must respect the condition $R_{load} \leq R_{fair}$. The flow-control mechanism is continuously controlling this condition. If $R_{load} > R_{fair}$, packets start to be dropped to reduce the injected load, sources reacting and reducing their load. This guarantees a max-min fair usage of capacity among all nodes.

4.4 Opportunistic WMN Resources management OConS Service

An Opportunistic WMN Resources management OConS Service (OWROS), composed of various connectivity mechanisms, is proposed for enhancing connectivity in spontaneous community-based WMNs. It is based on the organisational framework for opportunistic management of WMNs, proposed in Section 3.1, its implementation being supported by the OConS architecture proposed in Section 3.2. OWROS implements the opportunistic resources manager depicted in Figure 3.2.

Consider several heterogeneous wireless nodes willing to build a multi-hop community-based WMN, in order to provide end-users with the connectivity between them and towards a fixed Internet infrastructure. Creating and sustaining the connectivity is a major challenge, due to the spontaneous nature of its deployment, where the communication environment is often under adverse conditions that do not guarantee full connectivity. Still, the heterogeneity of nodes (WMCs and WMRs) characteristics and resources (physical space) opens a wide set of connectivity possibilities that go much beyond the classical two-tier WMN architecture. OWROS is supported by the willingness of each joining WMC to collaborate in the improvement of the networking conditions of the community-based WMN. As depicted in Figure 3.2, OWROS evaluates, on the one hand, the capabilities of a given node (physical space) and, on the other, the network functional needs (functional space), launching one or multiple of the following OConS mechanisms in the node, to provide specific networking functions:

- *Internet gateway provisioning*: a legacy mechanism that enables the node to provide gateway connectivity to the WMN. It requires the node to have an interface (radio or fixed) with connectivity to the Internet.
- *Client access provisioning*: this is a classical mechanism, where the node acts as a classical radio access network, covering a region where it offers connectivity to WMCs. It optimises the operating bit rate, power and channel resources. To be triggered, the node needs to have an available radio interface capable to offer connectivity to end-users.
- *Mesh forwarding connectivity*: FERA mechanism for mesh connectivity, proposed and detailed in Section 4.3. This is a novel mechanism for multi-radio nodes that optimises the operating bit rate, transmission power level and channel of each radio and associated operating forwarding links. FERA guarantees a max-min fair capacity to all aggregating nodes. To be triggered, one or more radio interfaces must exist, capable of forwarding traffic. Details on this OConS mechanism are presented in Section 4.3, in the current one only being discussed its orchestration with the other two legacy mechanisms to build an OWROS service.

OWROS corresponds to a distributed version of the opportunistic resources manager, depicted in Figure 3.2, which is launched on every node of the WMN community, an OConS domain. In particular, it enables WMCs willing to collaborate in the WMN to take networking tasks according to their capabilities, becoming SuperWMCs. Depending on the nodes' capabilities, it might launch none, a subset or all three identified OConS mechanisms.

The orchestration of OWROS is described next. Every WMR of the OConS domain has the knowledge of the functional networking needs within its neighbourhood, see Figure 3.2. It has also registered, in its OR (so-called domain OR) the three above mechanisms that may compose OWROS (gateway, access, and forwarding), with the associated requirements. The service is offered to members of the community. Depending on the node's capabilities and functional network needs, the service suggests specific network functionalities that the node is free to accept or not; to be noted that in the classical WMN architecture, WMCs would never implement such functionalities.

For a new member of the community, two phases exist: bootstrapping, and orchestration of the OWRM OConS service. It is considered that the bootstrapping phase, consisting of the discovery of the node's OConS entities and discovery of neighbouring nodes, has been successful. A new member of the community that is not an OConS node is upgraded with OConS-related software by the SOP of a neighbouring WMR.

The orchestration of OWROS in a given WMC consists of a sequence of interaction procedures, as illustrated in Figure 4.12:

1. *Monitoring of functional needs*: the WMC requests network state information to a neighbouring WMR, which reports connectivity requirements and functional networking needs.
2. *Subscription of candidate OConS mechanisms*: the WMC's SOP subscribes, in a domain OR, to the OConS mechanisms available in the OConS domain, offered by OWROS. The domain OR publishes in the WMC's SOP the candidate OConS mechanisms (gateway, access, and forwarding ones), specifying for each mechanism the needed functional entities, together with the implementable algorithm that specifies the associated DE.
3. *Physical space characteristics request*: The WMC's SOP requests network state information from the IEs, as well as the capabilities of EEs. This information is used to specify the WMC's physical space characteristics, namely communication capabilities (one or several radio interfaces, of similar or different standards, Ethernet connection), surrounding environment (e.g., geographic position, propagation environment, nodes in communication range), mobility pattern, persistence, energy autonomy, and computational capabilities.
4. *Validation of OConS mechanisms*: the physical space characteristics and available OConS entities will validate which candidate OConS mechanisms are supported by the WMC.
5. *Selection of OConS mechanisms*: Within these OConS mechanisms, and based on a set of rules mapping connectivity requirements into mechanisms capabilities, the ones that satisfy the network connectivity requirements are selected.

6. *Composition and configuration of OConS service*: SOP creates and instantiates the DEs of the OConS mechanisms to be launched, and puts them in relation to work together and build the OConS service. Resources and some mechanisms may still need to be configured.
7. *Registration of instantiated OConS mechanisms and OConS service* in the OR.

These orchestration steps enable to implement OWROS in any OConS node, launching adequate OConS mechanisms that improve connectivity of the network.

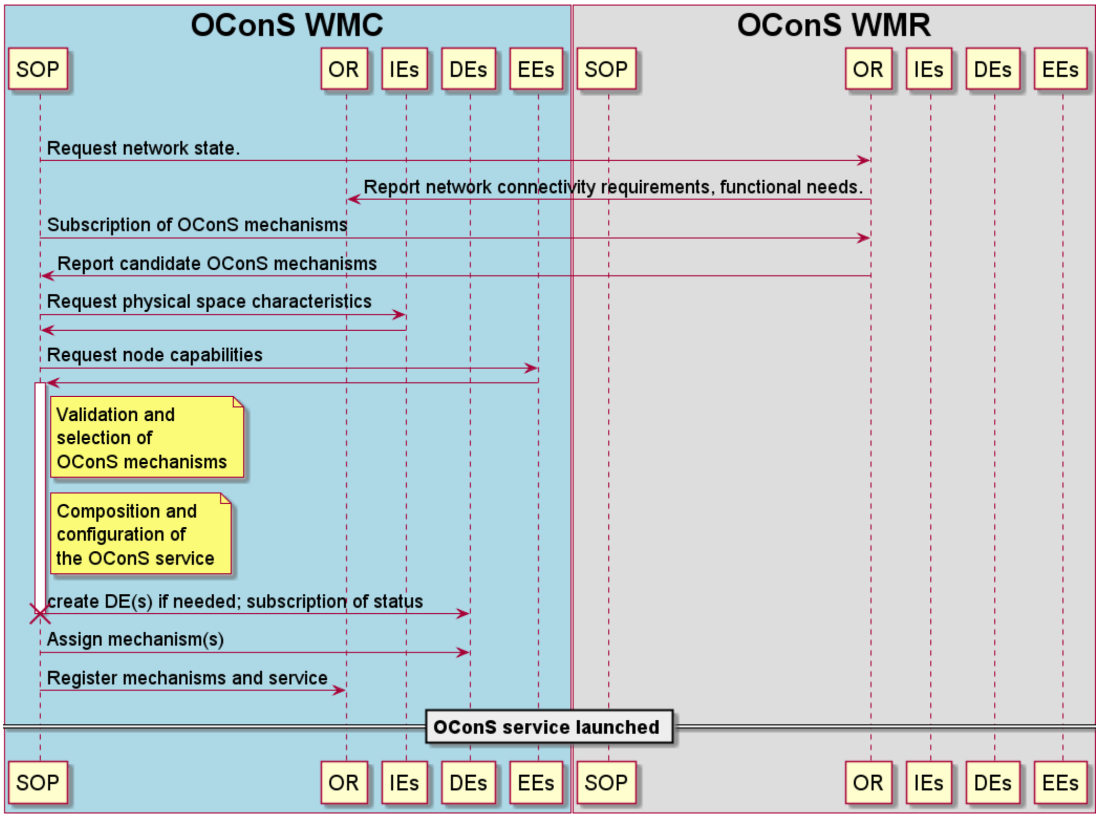


Figure 4.12 – Interaction procedure for the orchestration of OWROS in a WMC.

4.5 Evaluation Metrics

Several usage and network metrics are considered to evaluate the performance of a WMN.

Usage metrics evaluate the performance of the MAP's aggregated traffic flow, composed by:

- $R_{fair}(M_m)$ [Mbit/s]: max-min fair capacity of a given MAP, the maximum load that guarantees max-min fairness in the whole network.

- $R_{thr}(M_m)$ [Mbit/s]: throughput of M_m's flow, measured as the number of bits received per second.
- $\tau_{packet}(M_m)$ [ms]: WMN packet delay of M_m's flow (between the instant it passes the gateway and M_m, $T_{packet}(M_{gw})$ and $T_{packet}(M_m)$, respectively), given by

$$\tau_{packet}(M_m)_{[\mathrm{ms}]} = \left|T_{packet}(M_m)_{[\mathrm{ms}]} - T_{packet}(M_{gw})_{[\mathrm{ms}]}\right|, \quad (4.27)$$

- $\delta_{packet}(M_m)$ [%]: percentage of dropped packets, measuring the relation between load and throughput, given by

$$\delta_{packet}(M_m)_{[\mathrm{Mbit/s}]} = \frac{R_{thr}(M_m)_{[\mathrm{Mbit/s}]}}{R_{load}(M_m)_{[\mathrm{Mbit/s}]}}. \quad (4.28)$$

The performance of a WMN network is considered reliable in terms of packet delivery and providing satisfactory QoS if $\delta_{packet} < 10\%$ and $\tau_{packet} < 100$ ms. The estimation of the maximum R_{thr} at which the network is reliable is achieved by the gradual increase, in consecutive simulations, of the inter-arrival rate of packets, $\tau_{packet\ gen}$, until one of the two above conditions is no longer satisfied. The maximum value of $\tau_{packet\ gen}$ that guarantees the two above conditions determines the maximum reliable throughput.

Network metrics evaluate the performance of the network, given by:

- R_{wmn} [Mbit/s]: WMN throughput, amount of aggregated traffic per second, given by

$$R_{wmn\ [\mathrm{Mbit/s}]} = \sum_{n=1}^{N_{map}} R_{thr\ [\mathrm{Mbit/s}]}(M_n). \quad (4.29)$$

- $R_{wmn\ max}$ [Mbit/s]: maximum theoretical WMN throughput, given by

$$R_{wmn\ [\mathrm{Mbit/s}]} = \sum_{n=1}^{N_{map}} R_{fair\ [\mathrm{Mbit/s}]}(M_n). \quad (4.30)$$

- $f_{max-min}$: WMN max-min fairness of flows throughput, weighting if every flow achieves the allocated resource R_{fair}. Using Jain's fairness index [JaCH84], it is given by

$$f_{max-min} = \frac{\left[\sum_{n=1}^{N_{map}} x_n\right]^2}{N \cdot \sum_{n=1}^{N_{map}} {x_n}^2}, \text{ where } x_n = \frac{R_{thr}(M_n)}{R_{fair}(M_n)} . \quad (4.31)$$

  $f_{max-min} = 1$ means that all MAPs achieve their allocated R_{fair} capacity, the network being 100% max-min fair. If $f_{max-min} < 1$, there are unsatisfied MAPs.

- $\eta_{capacity}$ [%]: WMN capacity usage efficiency. It weights the throughput by the allocated physical layer bit rate. It is given by

$$\eta_{capacity\,[\%]} = \frac{\sum_{i=1}^{N_{ch}} \sum_{\mathcal{M}_{m,r} \in \mathcal{M}_{C_i}} \left(\sum_{M_n \in \mathcal{M}_{m,r}} R_{thr\,[\text{Mbit/s}]}(M_n) \right)}{\sum_{i=1}^{N_{ch}} \sum_{\mathcal{M}_{m,r} \in \mathcal{M}_{C_i}} \left(R_{phy\,[\text{Mbit/s}]}(\mathcal{M}_{m,r}) \right)}, \tag{4.32}$$

where $\mathcal{M}_{C_i}$ is the set of parent-radios sharing the capacity of a channel C_i (i.e., the set of links sharing a given channel). In $\mathcal{M}_{C_i}$, a single link can be active, its throughput and physical rate being accounted, and not of all possible links. If a channel is reused without interference by two sets of parent-radios, this is accounted as two different sets $\mathcal{M}_{C_i}$, as they are not sharing an available capacity. $\eta_{capacity}$ is bounded by η_{phy}.

- η_{energy} [Mbit/J]: WMN energy efficiency, weighting the achieved throughput by the needed power for transmission in the sub-set of links that can be simultaneously transmitting. It is given by

$$\eta_{energy\,[\text{Mbit/J}]} = \frac{R_{wmn\,[\text{Mbit/s}]}}{\sum_{i=1}^{N_{ch}} \sum_{\mathcal{M}_{m,r} \in \mathcal{M}_{C_i}} \left(P_{tx\,[\text{W}]}(\mathcal{M}_{m,r}) \right)}. \tag{4.33}$$

  The larger η_{energy} is the more bits are sent with less energy. For a given instant, it relates the energy spent by simultaneously active links forwarding the WMN capacity.

- $\eta_{total\ energy}$ [Mbit/J]: WMN total energy efficiency, weighting the achieved throughput by the needed power for transmission and operation of every MAP. It is given by

$$\eta_{total\ energy\,[\text{Mbit/J}]} = \frac{R_{wmn\,[\text{Mbit/s}]}}{\sum_{i=1}^{N_{ch}} \sum_{\mathcal{M}_{m,r} \in \mathcal{M}_{C_i}} \left(P_{tx\,[\text{W}]}(\mathcal{M}_{m,r}) \right) + N_{map} \cdot P_{oper\,[\text{W}]}}. \tag{4.34}$$

  where P_{oper} is the baseline power consumption of a MAP, for operation.

- $\eta_{spectrum}$ [bit/s/Hz]: WMN spectrum efficiency, weighting the needed bandwidth to achieve a given aggregated throughput by all MAPs of the WMN, given by

$$\eta_{spectrum\,[\text{bit/s/Hz}]} = \frac{R_{wmn\,[\text{Mbit/s}]}}{B_{[\text{Hz}]} \cdot N_{ch}}, \tag{4.35}$$

  where B is the bandwidth of a channel.

Chapter 5

Strategies Implementation and Evaluation Scenarios

Chapter 5 describes the implementation of strategies and scenarios for evaluation. In Section 5.1, the implementation of a multi-radio mesh node and the proposed strategies in OPNET Modeler simulation platform are described. Then, input configuration parameters and output evaluation metrics are identified in Section 5.2. Finally, Section 5.3 describes a set of scenarios for evaluation of the proposed strategies.

Key concepts: implementation; OPNET Modeler Simulation platform; scenarios.

5.1 Implementation

The self-organised formation and maintenance of multi-radio WMNs, optimising the available radio resources through the proposed RRM strategies presented in Chapter 4, was implemented in the OPNET Modeler Wireless Suite simulation platform [OPNT13], for evaluation of the overall performance of the proposed strategy and mechanisms. Modeler incorporates a vast suite of protocols and technologies, including a development environment to enable the modelling and analysis of various network types and technologies. The most important features of Modeler are pointed out below:

- Object orientation – Modeler adopts all the basic concepts of an objects programming language. All the developed systems are described in terms of objects, which are instances of models (the OPNET equivalent to classes). Models describe all the characteristics of an object in terms of its behaviour, and also provide them with a set of attributes that may have different values for each different instance. There is a vast number of already implemented models addressing several technologies, protocols and commercially available equipment from various suppliers. They provide the user with all the necessary means to develop a complete description of a communication network or an information system. In addition to this "ready to use" models, there is also the possibility to develop a completely new set of custom models using all the capabilities offered by the three modelling domains: network, node and process. All models have a hierarchical structure.
- Custom models development – Modeler provides a flexible, high-level development environment and programming language with extensive support for communications and distributed systems, having the flexibility to allow users to develop custom models. A vast suite of available protocols and technologies can be incorporated and combined in a clean object oriented approach to enable the modelling of any network type and technology.
- Discrete event modelling approach – a Modeler simulation run can be viewed as a sequence of events that represent specific action points, where a change in the system model can take place. Events are managed in an event list by the simulator kernel and are generated by the specific objects forming the simulation model.
- Application-specific statistics – Modeler provides several built-in mechanisms to collect and analyse data during a simulation. In addition, there is also the possibility for a user to enhance the available set of statistics by defining new ones.

- Integration with other simulation tools – it is possible to connect Modeler with other simulators, which can be interesting to exploit some specific feature of an available tool.

OPNET has specified single-radio nodes that can be configured to IEEE 802.11a. These nodes have all layers implemented in detail, from PHY, MAC, to IP, with routing capabilities. Based on this node, a multi-radio node is developed, as represented in Figure 5.1, following the specification presented in Section 4.2.3, and implementing the channel management policy described in Section 4.2.4. It is equipped with two radio interfaces for mesh backhaul communication managed from a new radio agnostic abstraction-layer, identified as *link_layer* in Figure 5.1, where the hybrid channel management policy and the proposed strategies are implemented. Each radio interface (MAC&PHY layers) is controlled by the abstraction-layer, which optimises their radio resources (operating channel, bit rate and transmitted power level). This abstraction-layer also controls the flow of packets between the IP layer and the two MACs, deciding through which channel and radio a given packet should be sent. The multi-radio node has a single IP address and two MAC addresses, of the corresponding radio interfaces. The abstraction-layer is responsible for the resolution of network layer (IP) addresses into link layer (MAC) addresses, replacing the Address Resolution Protocol (ARP). For each packet that it has to be sent (to a neighbouring node), the abstraction-layer identifies the MAC address of the radio through which it will be sent (source MAC address) as well as the next-hop node receiving radio's MAC address (destination MAC address). The two mesh radios follow the IEEE 802.11a standard [IEEE07a].

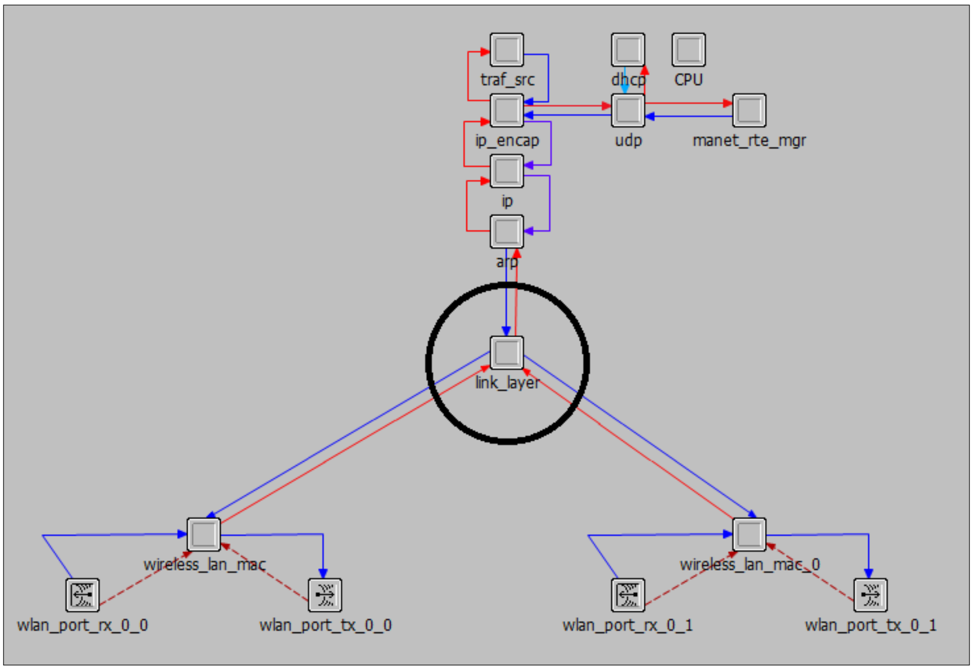


Figure 5.1 – Developed multi-radio mesh node model, visualised with OPNET model editor.

A new *link-layer* OPNET process model was created, Figure 5.2, between the IP process model and two MAC&PHY process models. It is a state transition diagram entirely implementing the abstraction-layer, the hybrid channel management policy and the proposed RRM strategies, not needing changes neither in the MAC nor in the IP layers.

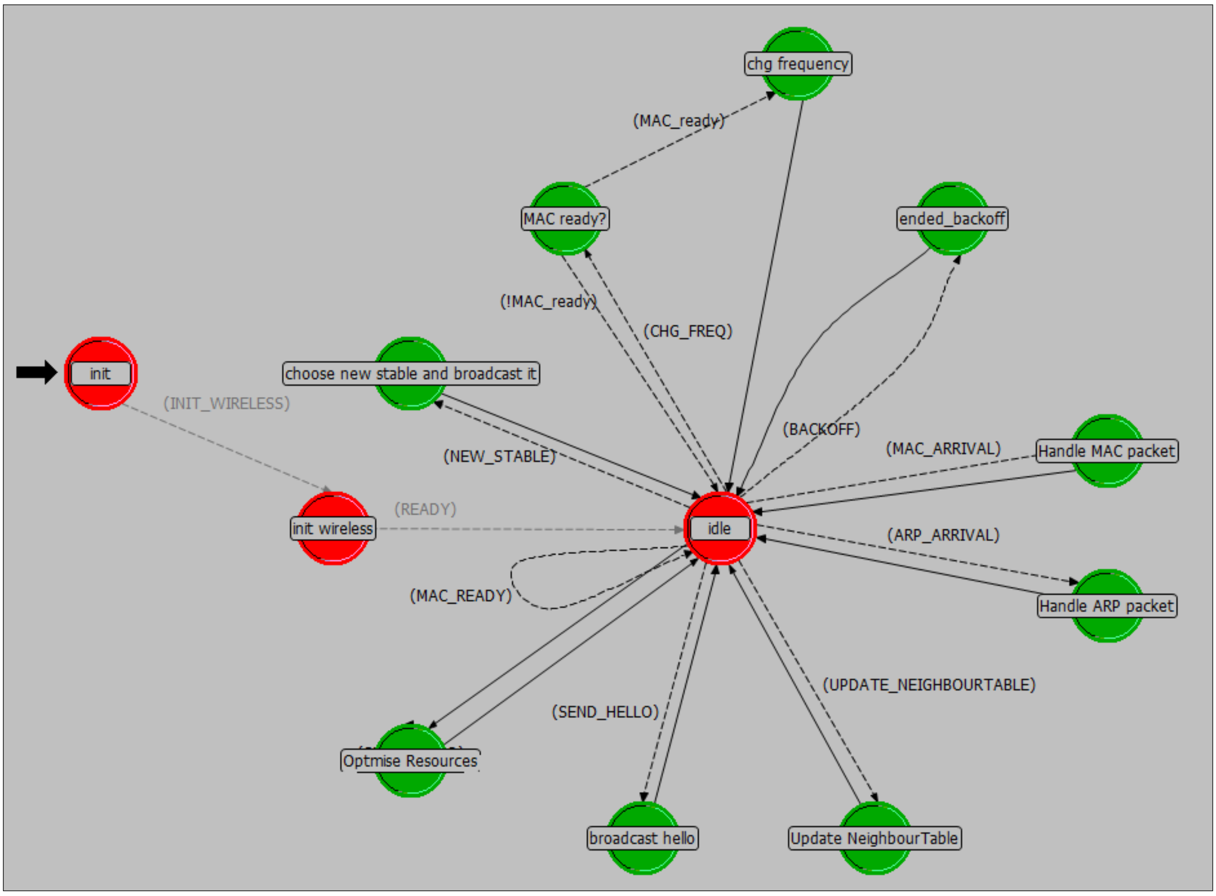


Figure 5.2 – OPNET process model (state transition diagram) of the Link layer module.

Link_layer state transition diagram's enter and exit executives as well as functions are specified in through more than 3000 lines of OPNET ProtoC code, exemplified in Figure 5.3. All the functionalities described in Chapter 4 are implemented. Besides this, probes and global variables enable to access and change parameters of MAC and PHY layers of each radio, such as the operating channel, transmission power level and rate.

In terms of packet flow, the *link_layer* receives/sends packets from/to IP and MAC layers, processing them according to the multi-radio node model described in Section 4.2.3. The *link_layer* process module has one queue per channel, where "packets to be sent through that channel" are queued, as illustrated in Figure 4.8. For each radio operating on a specific channel, the *link_layer* forwards the packets queued for that corresponding channel.

```
    /************************************************/
    /* get next hop IP address of packet           */
    /************************************************/

    op_ici_attr_get_ptr (mac_iciptr, "next_hop_ip_addr", (void**) &next_hop_ip_addr_inet);
    next_hop_ip_addr = inet_ipv4_address_get((*next_hop_ip_addr_inet));
    inet_address_print (next_hop_ip_addr_str, *next_hop_ip_addr_inet);

/**/    // PRINT INFORMATION
/**/    op_prg_text_output("\n%f s: %s (-> ", op_sim_time(), my_ip_address_str);
/**/    op_prg_text_output("%s): ", next_hop_ip_addr_str);
/**/    op_prg_text_output(" LL received from ARP packet ID %d ",op_pk_id(pkptr));
/**/    // PRINT INFORMATION

    /*******************************************************************************/
    /* get a pointer to the fields of the packet, for correction of src_internal_addr    */
    /*******************************************************************************/

    op_pk_fd_access_read_only_ptr (pkptr, ip_dgram_fields_index, (void**) &pkt_fields_ptr);

    if(!inet_address_ptr_compare(next_hop_ip_addr_inet, &Inet_Broadcast_Addr))
    {
        /*******************************************************/
        /* BROADCAST ADDRESS:            queue in all queues */
        /*******************************************************/

/**/    op_prg_text_output("(broadcast packet)\n");

        for(ch_number = 0; ch_number < number_of_channels; ch_number++)
        {

            /*************************************************************/
            /* replicate broadcast packet and ICI and store in queues   */
            /*************************************************************/

            if(ch_number == 0)
            {
                // corrects MAC source address in ICI and packet.
                if(ch_number == my_stable_channel)
                {
                    op_ici_attr_set_int64 (mac_iciptr, "src_mac_addr", my_stable_mac_address);
                    pkt_fields_ptr->src_internal_addr = my_stable_mac_address;
                }
                else
                {
                    op_ici_attr_set_int64 (mac_iciptr, "src_mac_addr", my_switchable_mac_address);
                    pkt_fields_ptr->src_internal_addr = my_switchable_mac_address;
                }

                // stores in queue
                insert_in_queue (ch_number, pkptr, mac_iciptr);
            }
            else
            {
                /*****************************************************************/
                /* need to create a copy of the packet and ICI for other queues  */
                /* since each ICI and packet is destroyed at the arrival in MAC  */
                /*****************************************************************/
                dup_iciptr = op_ici_create ("lsf_ip_mac_req");

                dup_pkptr = op_pk_copy (pkptr);
                op_pk_fd_access_read_only_ptr (dup_pkptr, ip_dgram_fields_index, (void**) &pkt_fields_ptr);

                // sets correct MAC source address in ICI and packet.
                if(ch_number == my_stable_channel)
```

Figure 5.3 – Example of ProtoC code.

A *Hello* packet is periodically broadcasted on all available channels with information of the node (IP & MAC addresses) and its resources, as well as information on neighbouring nodes (to enable broadcast information of nodes through multiple hops). When a node receives a *Hello* packet, information on the nodes of interest and their resources is extracted and updated in a *NeighbourTable*. When a packet is received in the *link_layer* from a MAC module, it is simply forwarded to the IP layer. When a packet is received from the ARP module, the *NeighbourTable* information is used to identify, through the next-hop address, the corresponding receiving channel of the next-hop node, being queued in the corresponding channel packet queue, as illustrated in Figure 4.8, where it waits to be sent. Packets are not queued in the MAC. A following packet is sent to the MAC only when the previous one is confirmed to have been transmitted. This enables to switch the channel on the MAC without loosing packets. In fact, if a packet would be queued in the MAC to be sent in channel C_i and suddenly the MAC's operating channel is switched to C_2, transmitting the packet in C_2 will not reach the intended node. The node has the capability to self-configure and self-optimise its radio resources regularly, using the proposed RRM strategy and information on its neighbourhood stored in the *NeighbourTable*. The stable-MAC operates on a stable-channel, and the switchable-MAC switches its operating channel in a round robin fashion among all the available channels if needed, as described in Section 4.2.4.

The simulation of a multi-radio WMN in OPNET consists of the deployment of a set of MAPs in a geographical area, their activation in random instants of time, and the posterior generation of aggregated traffic, exchanged between MPPs and MAPs through the meshed network. Each MAP self-configures and self-optimises individually its radio resources, based on exchanged information between neighbouring MAPs, using the RRM strategy. In Figure 5.4, an example of the OPNET simulation environment is presented, where performance results of some MAPs, in terms of measured throughput and delay, are plotted also by the simulation environment. Various evaluation metrics were built, measuring during simulation desired parameters.

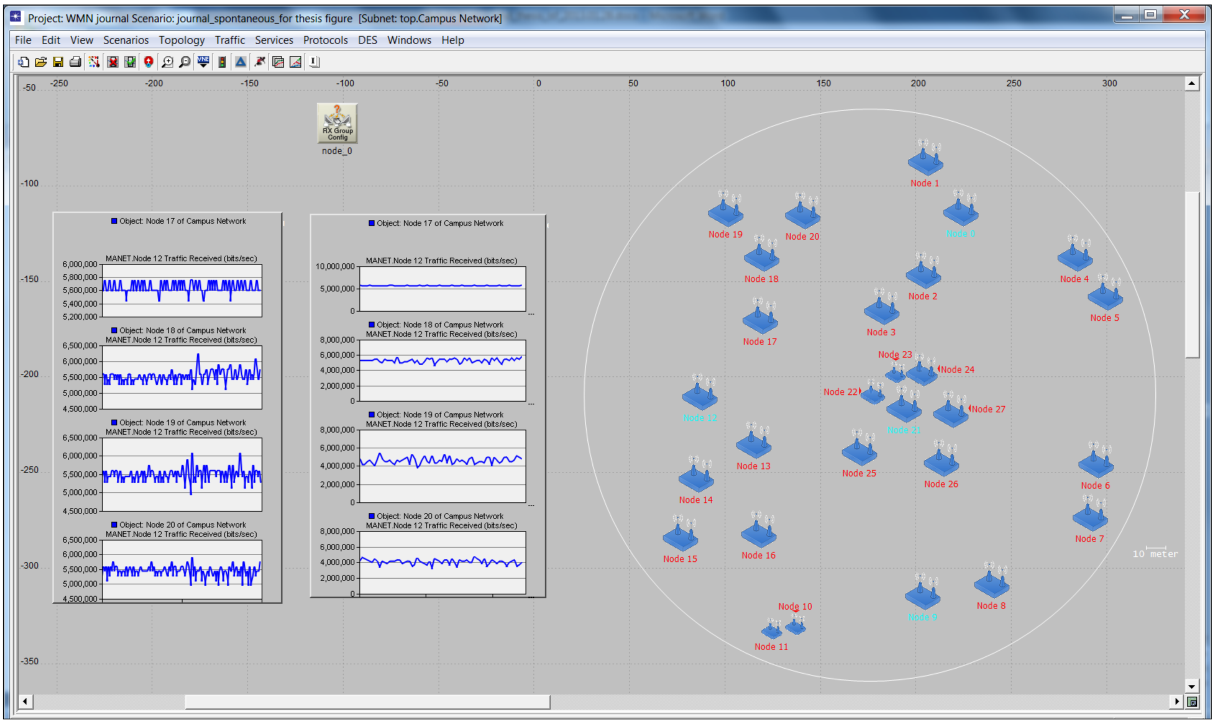


Figure 5.4 – Example of OPNET simulation environment.

Several corrections were done in the original MAC and PHY process models (*wireless_lan_mac* and *wlan_port_rx* and *wlan_port_tx*). Errors of processing of propagation signals were corrected, integrating a more realistic channel propagation model, and implementing correctly receiver sensitivity and carrier sensing power levels thresholds. Its implementation and performance is assessed in Appendix F. Simulation results of throughput, delay, coverage and interference match theoretical ones with errors below 2%, assessing the correct implementation and performance of multi-radio nodes in OPNET. On the other hand, regular OPNET nodes do not enable to change operating transmission rate, power and channel dynamically during operation. Changes in various modules were introduced to enable this dynamic operation.

5.2 Input and Output Parameters

This section identifies the set of parameters used to characterise a WMN scenario and to evaluate the impact of the RRM strategies in the performance of the network, as presented in Figure 5.5. Three categories of input parameters are defined, network, strategy and usage parameters. On the other hand, a set of network and usage evaluation metrics are defined to evaluate the performance of a scenario. Several of these parameters have already been defined or discussed, their organised compilation being presented here.

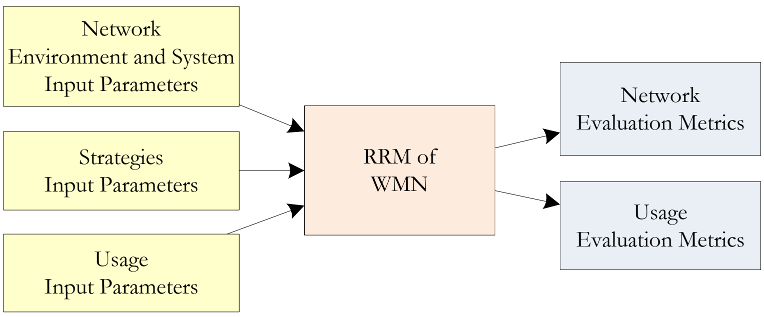


Figure 5.5 – Input and output parameters categories.

A wide set of input network parameters are needed to characterise and configure in detail a WMN scenario. These may be organised in two sub-categories:

- Environment parameters:
    - Scenario size;
    - Scenario radius (for circular scenarios), r_{wmn};
    - Number of MAPs, N_{map};
    - Number of MAPs that are MPP gateways, N_{gw};
    - Deployment type. For an hexagonal deployment:
        - Number of rings around MPP, N_{rings};
        - Distance between MAPs, d_{map};

        - MAP coverage radius, r_{ap};
    - Pre-computed paths;
    - Path loss exponent, γ.
- System parameters:
    - Number of radios for mesh backhaul per node, N_{radios};
    - Wireless communication standard(s);
    - Number of available orthogonal channels, N_{ch};
    - Set of orthogonal channels, $\mathcal{C}$;
    - Channel bandwidth, B;
    - Set of available physical bit rates, $\mathcal{R}_{phy}$.
    - Bandwidth usage efficiency, η_{phy};
    - Set of available transmission power levels, $\wp_{tx}$;
    - Receiver sensitivity power level, $P_{rx\,min}$;
    - SINR threshold, ρ_{min};
    - Carrier sensing power threshold, P_{cs}.
    - Baseline power consumption of a MAP, for operation, P_{oper}.

The mechanisms that compose the proposed strategies and the hybrid channel management policy have the following input parameters:

- Number of stable radio channels, N_{st};
- Number of dynamic radio channel, N_{dy};
- Maximum time the dynamic radio is allowed to stay on a given channel without checking if there is another channel with traffic to send, T_{dy};
- Back-off time after switching channel, $T_{BO\ CH\ switch}$;
- Periodicity of *Hello* packets broadcast, T_{Hello};
- Channel queue size, K_{queue}.

In terms of usage input parameters, traffic flows are exchanged, via the WMN, between each aggregating MAPs and MPPs. Each MAP has associated an aggregated traffic flow, belonging to the users it is providing connectivity, and is characterised by the following parameters:

- Packet size, K_{packet};
- Average generated packets inter-arrival time, $\tau_{packet\ gen}$;
- Distribution of inter-arrival time of generated packets;

- Load of offered aggregated traffic by MAP M_m, $R_{load}(M_m)$.

Several metrics are used to evaluate the performance of a WMN. The MAP's usage is evaluated according to the following metrics:

- WMN packet delay of M_m's flow, $\tau_{packet}(M_m)$;
- Percentage of dropped packets of M_m's flow, $\delta_{packet}(M_m)$;
- Throughput of M_m's flow, $R_{thr}(M_m)$;
- Max-min fair capacity of M_m's flow, $R_{fair}(M_m)$.

Network metrics evaluate the performance of the network, given by:

- WMN throughput, R_{wmn};
- Maximum theoretical WMN throughput, $R_{wmn\,max}$;
- WMN max-min fairness of flows throughput, $f_{max-min}$;
- WMN efficiency of usage of allocated capacity, $\eta_{capacity}$;
- WMN energy efficiency, η_{energy};
- WMN spectrum efficiency, $\eta_{spectrum}$;

5.3 Evaluation Scenarios

To evaluate the performance of the proposed RRM strategies in Chapter 4, and to understand dependencies and generalise as much as possible conclusions, a set of WMN scenarios is characterised, as specific configurations of a broad set of parameters organised in Section 5.2. Some of these parameters are fixed, while others may be varied.

5.3.1 Structured Reference Scenario

The reference WMN scenario covers a circular residential neighbourhood area of radius $r_{wmn} = 100$ m, Figure 5.6. To provide connectivity to indoor end-users, 19 MAPs are deployed outdoor, following a hexagonal topology of two rings around an MPP gateway (M_0) located at the centre. This typical cellular networks' deployment covers optimally the scenario. Environment parameters are characterised in Table 5.1. For the RBN (MAPs interconnection) the propagation environment is urban outdoor, characterised by $\gamma = 3.3$, while for the RAN (communication between MAPs and end-users) it is an outdoor-indoor one, $\gamma = 4$ [CRSK06].

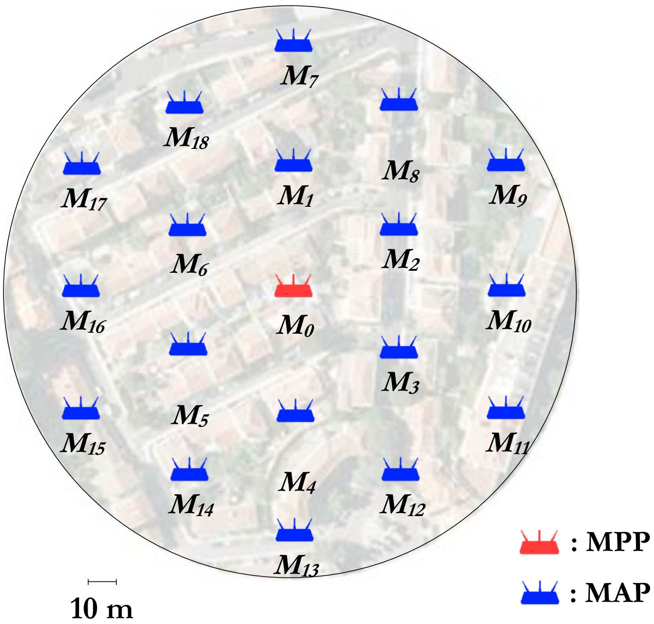


Figure 5.6 – Reference scenario.

Table 5.1 – Reference scenario network environment's parameters.

Degree of freedom	Value
r_{wmn} [m]	100
N_{map}	19
N_{gw}	1
Deployment	Hexagonal
Rings	2
d_{map} [m]	40
r_{ap} [m]	20
γ for RBN	3.3
γ for RAN	4

System parameters are characterised in Table 5.2. Each MAP has three radios: two IEEE 802.11a [IEEE07b] used to implement the meshed RBN, and the other IEEE 802.11b/g [IEEE07b] to provide RAN connectivity to end-users. In Europe, IEEE 802.11a has available, in the 5.5 GHz band, 11 orthogonal channels for outdoor communication for which P_{tx} can be up to 30 dBm ($P_{tx\,max}$), while IEEE 802.11g has available only 3 orthogonal channels, in the 2.4 GHz band, for which $P_{tx\,max} = 20$ dBm. Eight discrete P_{tx} levels are considered for both systems, with steps of 3 dB. All power levels are assumed to be available for all rates. The P_{oper} is set to 15 W, i.e., 41.8 dBm.

Table 5.2 – Reference scenario RBN and RAN system's parameters.

	RBN	**RAN**
Wireless communication standard	IEEE 802.11a	IEEE 802.11b/g
N_{radios}	2	1
N_{ch}	11	3
$\mathcal{C}$ [GHz]	{5.50, 5.52, 5.54, 5.56, 5.58, 5.60, 5.62, 5.64, 5.66, 5.68, 5.70}	{2.412, 2.437, 2.462}
B [MHz]	20 MHz	
$\mathcal{R}_{phy}$ [Mbit/s]	{6, 9, 12, 18, 24, 36, 48, 54}	{1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, 54}
$\wp_{tx}$ [dBm]	{9, 12, 15, 18, 21, 24, 27, 30}	{-1, 2, 5, 8, 11, 14, 17, 20}
$P_{tx\,max}$ [dBm]	30	20
P_N [dBm]	-101	
P_{oper} [dBm]	41.8	
P_{cs}, $P_{rxi\,max}$ [dBm]	-95	

Table 5.3 identifies values for η_{phy}, $P_{rx\,min}$ and ρ_{min} for the R_{phy} rates of the IEEE 802.11a standard used for the RBN. Values of η_{phy} are for UDP packets 1 500 bytes length. $P_{rx\,min}$ is taken 7 dB below the values specified by IEEE 802.11a and b/g standards [IEEE07b], and similar to the levels achieved by currently available equipment [CISC12], resulting in more realistic communication ranges. Values of ρ_{min} guarantee a PER below 10%. When estimating $P_{rxi\,max}$ with (4.11), $P_{rx\,min}$ and ρ_{min} values evidence that $P_{rxi\,max}$ is almost invariant with R_{phy} and equal to -95 dBm, with a standard deviation of 0.6 dB. Aiming at $d_{cs} = d_i$ [MVRZ09], P_{cs} is set equal to -95 dBm.

Table 5.4 presents usage and strategy parameters. Every MAP aggregates a flow of UDP (User Datagram Protocol) 1 500 bytes packets, a typical packet size found in Internet backbone networks, corresponding to the maximum size of Ethernet packets. The use of UDP enables the study of the network under stress conditions, not limited by congestion control mechanisms. Removing the UDP/IP headers (8 and 20 bytes, respectively), corresponds to an application layer packet size of 1 472 bytes. The offered load, R_{load}, is determined by the average inter-arrival time with which packets are generated, $\tau_{packet\,gen}$, which is uniformly distributed. Packets are sent downlink from the MPP gateway to each MAP. Regarding the strategy, mesh radio $r = 1$ is static while $r = 2$ is dynamic. During simulation, the dynamic radio stays on a channel a maximum of $T_{Dy} = 150$ ms, after which it changes to the next non-empty channel-queue. In case remaining channel-queues are empty, it does not switch channel. After switching, a back-off period $T_{BO\ CH\ switch}$ = 2 ms is established, to avoid multi-channel hidden terminal collisions. The periodicity of *Hello* messages is set to T_{Hello}= 1 s, for every node.

Table 5.3 – Reference scenario RBN system's parameters.

R_{phy} [Mbit/s]	η_{phy} [%]	R_{app} [Mbit/s]	$P_{rx\ min}$ [dBm]	ρ_{min} [dB]
6	88.9	5.3	-89	4.6
9	85.2	7.7	-88	6.6
12	82.1	9.9	-86	7.5
18	76.3	13.7	-84	9.6
24	71.2	17.1	-79	15.2
36	62.9	22.6	-77	16.9
48	56.6	27.2	-73	21.6
54	53.7	29.0	-72	22.4

Table 5.4 – Reference scenario usage and strategy parameters.

	Degree of freedom	Value
Usage	K_{packet} [byte]	1 472
	Inter-arrival time distribution	Uniform
Strategy	N_{St}	1
	N_{Dy}	1
	T_{Dy} [ms]	150
	$T_{BO\ CH\ switch}$ [ms]	2
	T_{Hello} [s]	1
	K_{queue} [byte]	30 000

5.3.2 Scenarios for WMN Deployments Optimisation

A set of scenarios for optimisation of WMN deployments is defined, by the variation of certain degrees of freedom (configurable parameters), for the study of specific dependencies. The variations, with respect to the reference scenario, are on the scenario size and number of MAPs and rings, as characterised in Table 5.5.

Table 5.5 – Scenario set for evaluation of different deployments.

Category	Degree of freedom	Scenario											
		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
Network Environment	r_{wmn} [m]	50				100				150			
	N_{map}	7	19	37	61	7	19	37	61	7	19	37	61
	Rings	1	2	3	4	1	2	3	4	1	2	3	4
	d_{map} [m]	33	20	14	11	67	40	29	22	100	60	43	33
System	All	Default settings											
Strategy	All												
Usage	All												

Table 5.5 – Scenario set for evaluation of different deployments. (cont.)

Category	Degree of freedom	Scenario											
		D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24
Network Environment	r_{wmn} [m]	200				300				400			
	N_{map}	7	19	37	61	7	19	37	61	7	19	37	61
	Rings	1	2	3	4	1	2	3	4	1	2	3	4
	d_{map} [m]	133	80	57	44	200	120	86	67	267	160	114	89
System	All	Default settings											
Strategy	All												
Usage	All												

5.3.3 Random Deployment Scenario

A random deployment scenario is also defined, as illustrated in Figure 5.7, challenging for the evaluation of the proposed strategies. In a larger circular area, r_{wmn} = 400 m, 28 MAPs are randomly deployed, 3 of which are MPP gateways. Comparing to the default settings of the reference scenario, the only difference is in the environment parameters, as defined in Table 5.6.

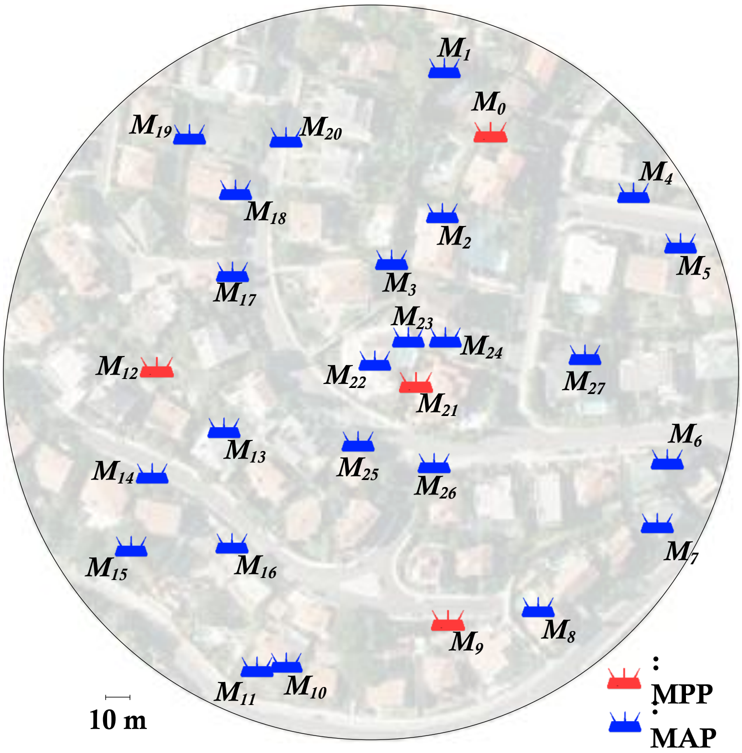


Figure 5.7 – Random deployment scenario.

Table 5.6 – Random deployment scenario parameters.

	Degree of freedom	Random Scenario
Network Environment	r_{wmn} [m]	400
	N_{map}	28
	N_{gw}	3
	Deployment	Random
System	All	Default settings
Strategy	All	
Usage	All	

5.3.4 Flash Crowd Community-Based Scenario

A residential neighbourhood scenario is also considered, as depicted in Figure 5.8, with an area of 300 × 200 m^2. A spontaneous community-based WMN, composed of 12 randomly deployed WMRs (MAPs and MPPs), provides connectivity to WMCs. Multi-radio WMRs are equipped with two IEEE 802.11a radios for mesh forwarding, one IEEE 802.11b/g radio for client access provisioning. Two WMRs are MPP gateways (M_9 and M_{10}), equipped with a fibre interface. This interface is considered of unlimited capacity, not to biase the evaluation of the maximum capacity of the WMN. WMCs have an IEEE 802.11b/g radio used to access the WMN. Urban outdoor propagation environment conditions are considered.

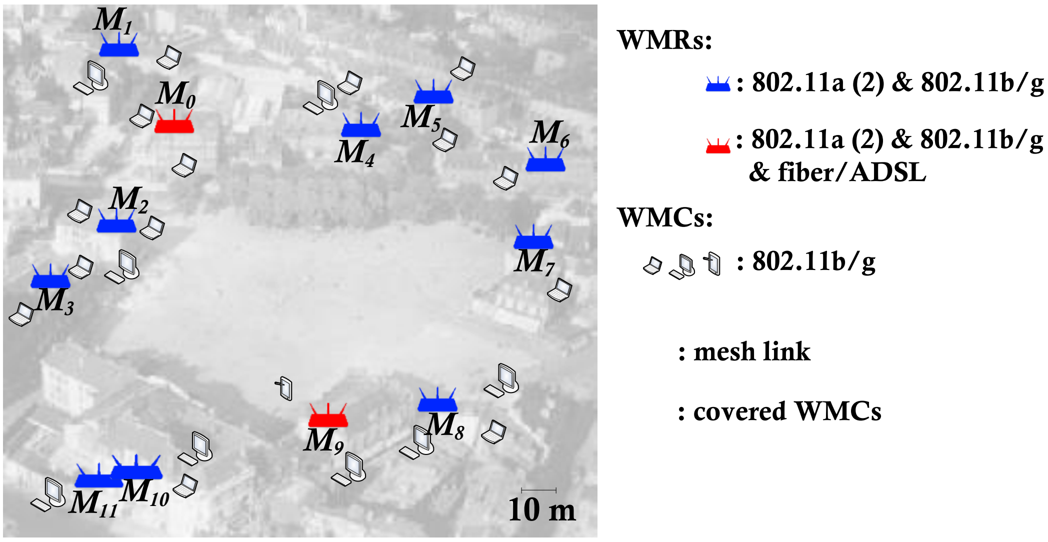


Figure 5.8 – Community-based WMN scenario, of heterogeneous nodes.

A flash crowd situation is considered, where a large number of end-users with heterogeneous multi-radio WMCs congregate suddenly, all willing to simultaneously access the Internet, as depicted in Figure 5.9. WMC terminals are of heterogeneous connectivity capabilities. All of them are equipped with an 802.11g radio, but many WMCs have two or more interfaces of other systems, such as 802.11a and LTE ones, as illustrated in Figure 5.9.

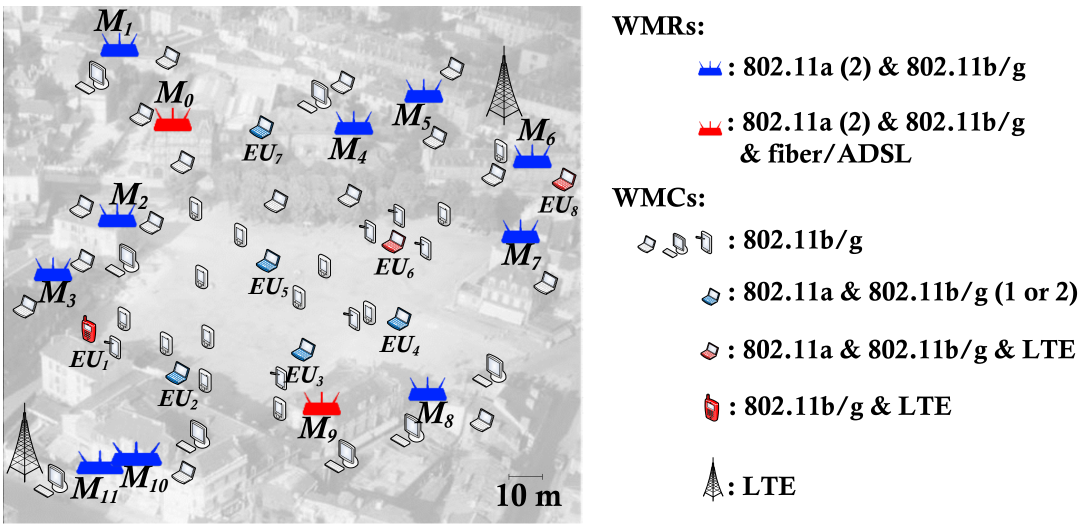


Figure 5.9 – Community-based WMN scenario with a flash crowd of heterogeneous WMCs.

Chapter 6

Performance Evaluation

In Chapter 6, the evaluation of performance results is presented for the FERA strategy and the OWROS service proposed in Chapter 4. Section 6.1 presents a preliminary discussion, identifying coverage, throughput and delay bounds, as well as general considerations on the proposed FERA strategy. In Section 6.2, an evaluation of FERA for the reference scenario is done. In Section 6.3, the performance of FERA for different scenarios is compared, varying the number of mesh nodes and size of the scenario. In Section 6.4, a more challenging random WMN deployment scenario is evaluated. Finally, in Section 6.5, the performance of OWROS is evaluated for a random residential neighbourhood scenario with a flash crowd.

Key concepts: results analysis; performance evaluation.

6.1 Preliminary Discussion

6.1.1 Coverage Bounds

Several propagation aspects condition the wireless communication between any pair of nodes. Transmission, receiver sensitivity, communication and interference ranges characterise key aspects that strongly influence the communication and overall performance of WMNs. They vary with R_{phy}, P_{tx} and the propagation environment. In this section, an analysis of these ranges and dependencies is presented.

The equipment sensitivity, $P_{rx\,min}$, increases with R_{phy}, as shown in Table 5.3, and determines the maximum range at which two nodes may communicate, d_{max}, using a given P_{tx}. For the propagation conditions of the reference scenario, described in Section 5.3.1, d_{max} dependency on R_{phy} and P_{tx} is plotted in Figure 6.1. Lower R_{phy} or larger P_{tx} result in larger d_{max}. For example, at $R_{phy} = 6$ Mbit/s, d_{max} is almost three times larger than at 54 Mbit/s. The communication range is limited by $P_{tx\,max} = 30$ dBm, as given in Table 6.1. For the reference scenario, neighbouring MAPs are 40 m distant, the maximum rate $R_{phy} = 54$ Mbit/s being supported. Comparing with the simulation results, presented in Section F.1, the deviation from these theoretical results is below 2 %, assessing the correct implementation and performance of the developed multi-radio nodes in OPNET.

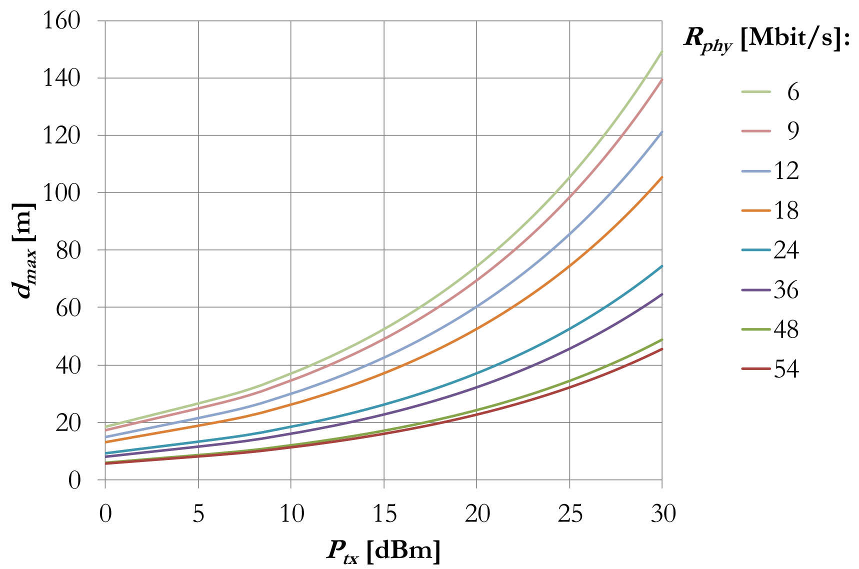


Figure 6.1 – Communication range in an urban outdoor environment.

Table 6.1 – Communication ranges for various rates, using maximum transmitted power level.

R_{phy} [Mbit/s]	d_{max} [m]
6	149
9	139
12	121
18	105
24	74
36	65
48	49
54	46

The dependencies illustrated in Figure 6.1 are explored by FERA. First, it is observed that for a given d_{map}, there is a maximum supported R_{phy}, the maximum one that guarantees $d_{max}(R_{phy}, P_{tx\,max}) \geq d_{map}$. For example, for d_{map} = 40 m, R_{phy} = 54 Mbit/s is supported when P_{tx} = 30 dBm, as d_{max}(54 Mbit/s, 30 dBm) = 43 m. This rationale is followed by the RA and TPC mechanisms in (4.17) and (4.18) to optimise MPP gateways' resources. Secondly, it can be seen that for a given link, if R_{phy} decreases, a lower P_{tx} level may be used. For example, for d_{map} = 40 m, R_{phy} = 12 Mbit/s is supported with P_{tx} = 15 dBm, as d_{max}(12 Mbit/s, 15 dBm) = 42 m. This rationale is followed by the RA and TPC mechanisms in (4.20) and (4.18) to optimise the resources of remaining non MPPs' radios. Besides energy efficient, neighbouring nodes' interference is reduced, allowing reusing channels within shorter distances.

These characteristics also evidence the advantage of multi-hop communication. In the example of Figure 6.2, M_3 must exchange packets with M_0. M_3 could exchange them directly as, within $d(l_{0,3})$ = 90 m range, communication is possible at R_{phy} = 18 Mbit/s and P_{tx} = 30 dBm. Still, if packets are exchanged via M_1 and M_2 intermediary nodes, the inter-node distance is reduced to 30 m, and packets can be sent at R_{phy} = 54 Mbit/s and P_{tx} = 25 dBm. With two radios per MAP and adequate channel assignment, this solution is more performing and efficient than a single-hop.

a) Single-hop. b) Multi-hop.

Figure 6.2 – Modes of communication.

When no interferer exists, the transmission range, d_{tx}, gives the maximum range within which SNR is above ρ_{min}, its dependency on R_{phy} and P_{tx} being plotted in Figure 6.3, for the reference scenario. Still, this range is much larger than the receiver sensitivity one. Thus, the maximum range at which communication is possible, even without interference, is limited by d_{max} and not d_{tx}.

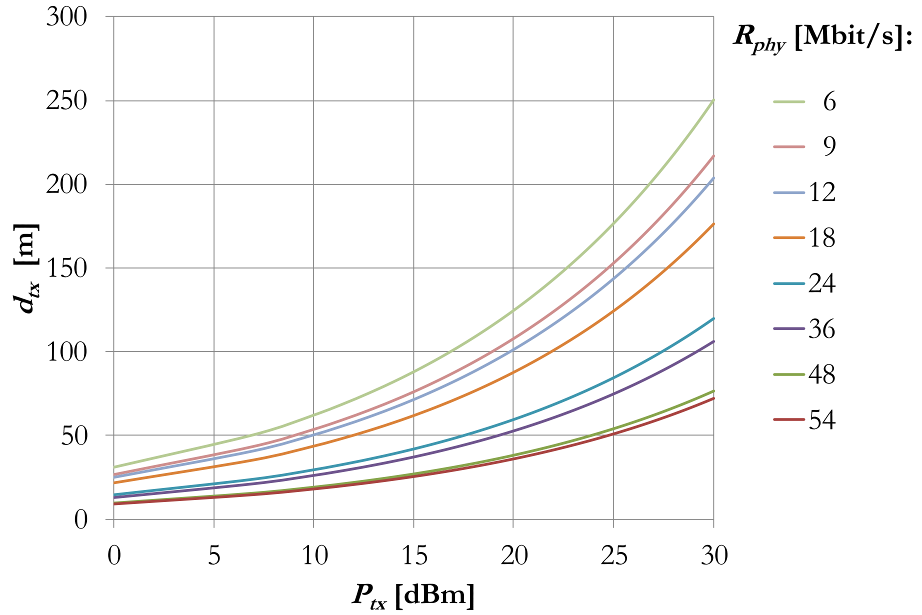


Figure 6.3 – Transmission range for the reference scenario.

When a third node transmits simultaneously on the same channel as the receiver is receiving, interference may not affect communication, as long as $\rho \geq \rho_{min}$. The threshold ρ_{min} increases with R_{phy}, Table 5.3, as modulation and coding schemes become less robust to interference. Consider two node pairs M_a, M_b and M_x, M_y simultaneously transmitting on the same channel C_1, Figure 6.4. The interference range of M_b, $d_i(M_b)$, is the minimum distance $d(l_{b.x})$ at which M_x does not interfere in the reception of M_b.

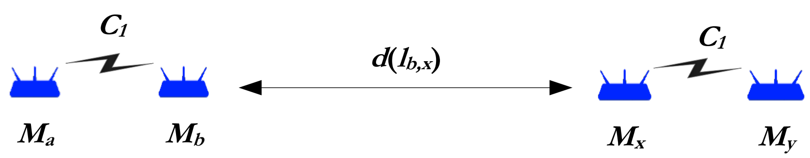


Figure 6.4 – Interference range between two communicating node-pairs.

Figure 6.5 plots the relation between $d(l_{a,b})$ distance (d_{map}), and $d(l_{b,x})$ distance (d_i), for γ = 3.3, considering that M_a and M_x use the same transmission power level, P_{tx} = 30 dBm, R_{PHY} = 54 Mbit/s; d_{max} and d_{tx} are also represented. d_i increases with d_{map}, as the received power level at M_b from M_a decreases, and the received signal becomes more vulnerable to interference. When $d_{map} \rightarrow d_{tx}$ then $d_I \rightarrow \infty$; any concurrent transmitter (at whatever distance from the reference receiver) will cause the packet to be dropped as the receiver SINR drops below the threshold needed for packet decoding. Still, the communication is limited by d_{max} (smaller than d_{tx}), a condition that must be satisfied, independently of the existence of an interferer. When $d_{map} \leq d_{max}$ and the interferer is not closer than d_i, communication is possible. From Figure 6.5, communication is possible when $d(l_{a,b}) = d_{map} \leq d_{max} = 46$ m and $d(l_{b,x}) = d_i \leq 5.2 \cdot d(l_{a,b}) = 239$ m.

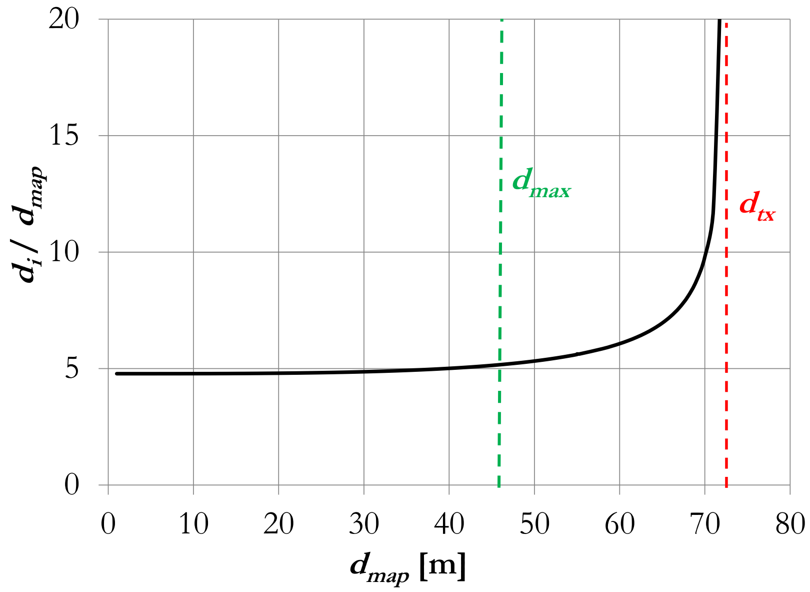


Figure 6.5 – Example of relation between nodes' distance and interference ranges.

The two conditions that must be satisfied to have communication, $d_{map} \leq d_{max}$ and the receiver-interferer distance greater than d_i, are expressed by the interference range curve of Figure 6.5 truncated at d_{max}. Figure 6.6 synthesises these conditions, for various R_{phy}. Using a lower R_{phy} enables a smaller d_i/d_{map}, as the associated ρ_{min} decreases, and enables also larger communication ranges, d_{max}.

In Figure 6.6, it can be seen that d_i/d_{map} does not vary much with d_{map}, approximation (4.10) being valid for most of the truncated curves. In Table 6.2, the ratios for both outdoor and indoor environments ($\gamma = 3.3$ and 4) are presented. Indoor environments, characterised by higher attenuations than outdoor ones, have smaller d_i/d_{map}, being more robust to interference. Still, the communication range is also smaller, as exemplified in Table 6.2 for $P_{tx} = 20$ dBm.

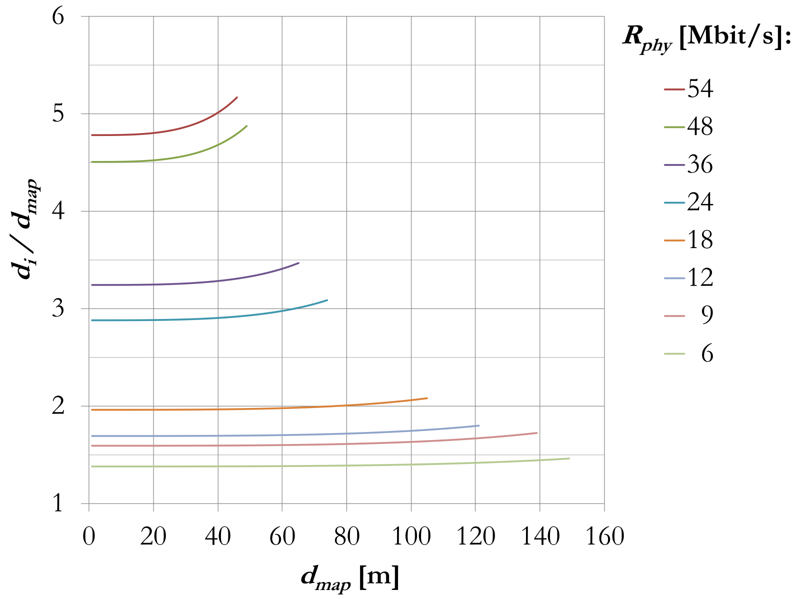


Figure 6.6 – Interference ratio, for the reference scenario.

Table 6.2 – Interference ratio and communication range, for $P_{tx} = 20$ dBm.

R_{phy} [Mbit/s]	d_i/d_{map}		d_{max} [m]	
	$\gamma = 3.3$	$\gamma = 4$	$\gamma = 3.3$	$\gamma = 4$
6	1.4	1.3	92	42
9	1.6	1.5	85	39
12	1.7	1.5	74	35
18	2.0	1.7	65	31
24	2.9	2.4	46	23
36	3.2	2.6	40	21
48	4.5	3.5	30	17
54	4.8	3.6	28	16

The fact that d_i decreases with R_{phy} is explored by the proposed strategies. In the RA and TPC mechanisms, for non-gateway nodes, R_{phy} is minimised to a value that still satisfies the capacity needs of the link. Besides an energy efficient solution, it reduces d_i, enabling in the CA mechanism to reuse the channel within shorter distances.

Although the interference ratios presented in Table 6.2 are widely used in studies, they are based on the assumption that both the transmitter and interferer use the same P_{tx}, an unrealistic situation when TPC mechanisms are used for the optimisation of links. The estimation of a maximum bound for the range within which a node may interfere, only dependent on P_{tx}, is an important parameter for the proposed mechanisms. Values for the maximum supported interference, $P_{rxi\,max}$, defined in (4.11) considering that the received power level is $P_{rx\,min}$, are presented in Figure 6.7. For the $P_{rx\,min}$ and ρ_{min} values presented in Table 5.3, it can be confirmed that $P_{rxi\,max}$ is approximately invariant with R_{phy}, being on average equal to -95 dBm, with a standard deviation of 0.6 dB. The maximum range within which a node may interfere, $d_{i\,max}$, defined in (4.12), depends only on P_{tx}. It is plotted in Figure 6.8, together with the communication ranges, for the various R_{phy} rates and P_{tx} levels.

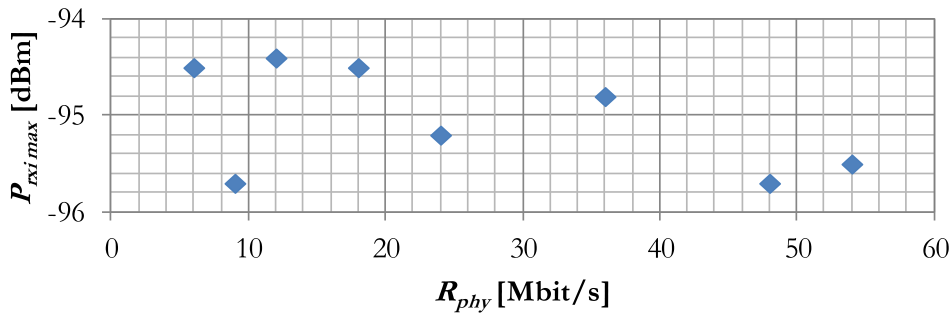


Figure 6.7 – Maximum supported interference.

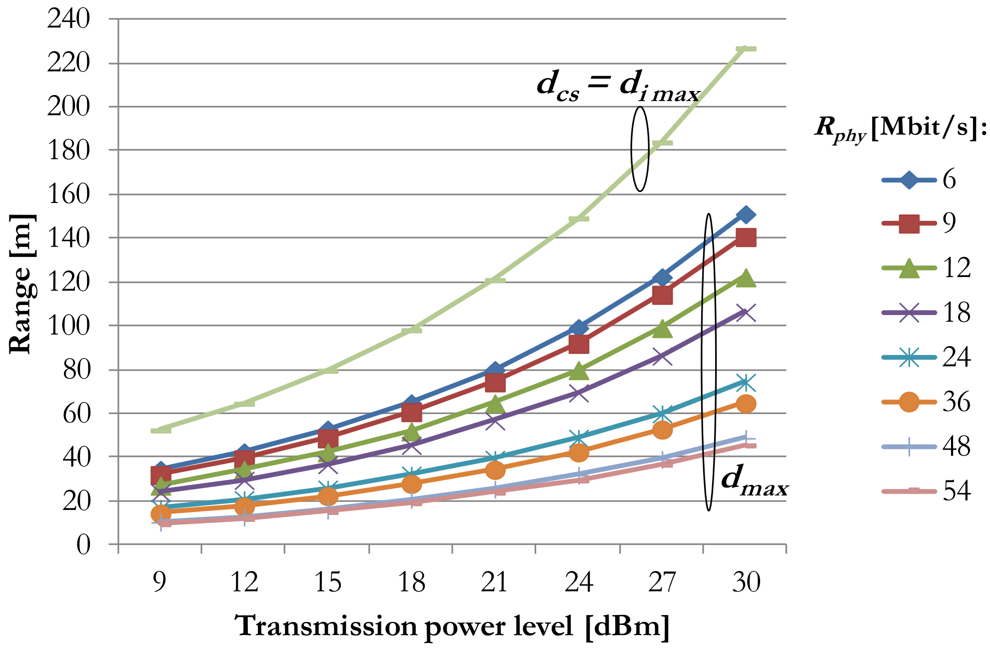


Figure 6.8 – Outdoor communication and maximum interference ranges.

The fact that $d_{i\,max}$ depends only on P_{tx} is explored by the proposed CA mechanism, as the configured P_{tx} enables to identify the maximum interference range within which transmissions using the same channel interfere. The carrier sensing power threshold is configured to

$P_{cs} = P_{rxi\,max}$ = -95 dBm, as suggested in Section 4.2.2. This is a beneficial configuration, as it prevents to interfere in neighbouring nodes. It results in $d_{cs} = d_{i\,max}$, as plotted in Figure 6.8.

In this section it is shown how communication and interference ranges vary with R_{phy}, P_{tx} and the propagation environment, and how multi-hop communication may be advantageous to increase the performance. These dependencies are intensely explored by the proposed strategies.

6.1.2 Throughput and Delay Bounds

Analytical bounds for application-layer throughput and delay for the IEEE 802.11a communication standard, used for mesh communication in the proposed scenarios, are presented next. IEEE 802.11a specifies several operating R_{phy} rates. Still, for the transmission of a data packet, several layers of the stack (IP, MAC and PHY) introduce protocol overheads (headers, inter-frame spaces, backoff time). In this sense, the time used for transmission of a data-packet represents a fraction of the total needed time, expressed by the bandwidth utilisation efficiency, η_{phy}. This overhead is discussed in more detail in Appendix E.

For a given R_{phy}, the protocol overhead determines a maximum application-layer throughput, R_{app}, associated with η_{phy}. From the equations presented in Section 4.2.1 and Appendix E, the curves for R_{app} and η_{phy} are depicted in Figure 6.9 and Figure 6.10, for different UDP/IP packet sizes and physical data rates.

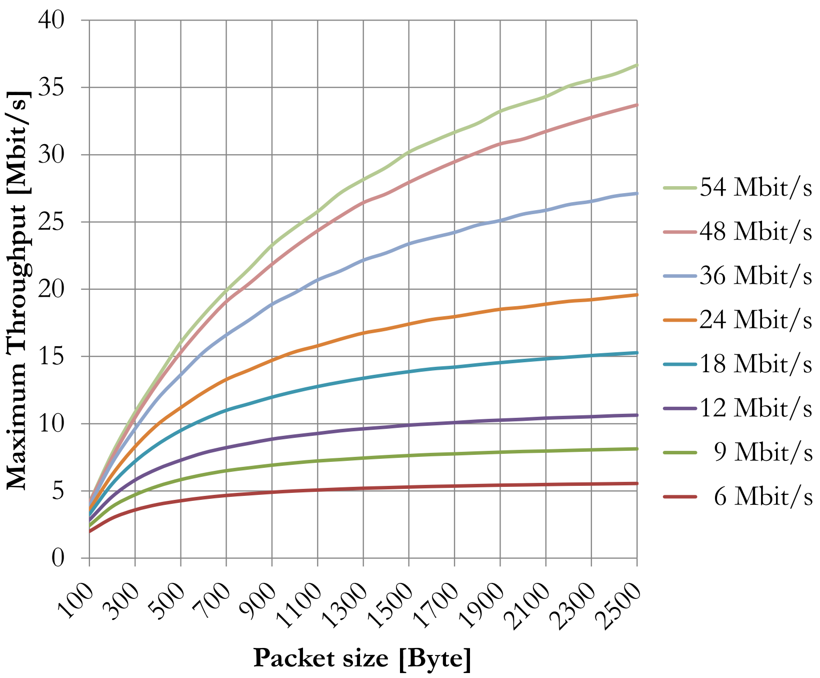


Figure 6.9 – Maximum theoretical application-layer throughput for 802.11a.

In particular, R_{app} values for $K_{packet} = 1\ 472$ bytes packets are presented in Table 6.3. This theoretical maximum throughput is at the application-layer. Considering the UDP/IP headers, this packet size corresponds to 1 500 UDP packets, the maximum size of Ethernet packets. For $R_{phy} = 54$ Mbit/s, analytical results give $R_{app} = 29.9$ Mbit/s, while at the MAC layer (where IP and UDP headers are not an overhead) the maximum payload is 30.5 Mbit/s. Comparing with the achieved simulation results presented in Section F.1, the deviation from theoretical results is below 3 %, assessing the correct implementation of the multi-radio nodes in OPNET.

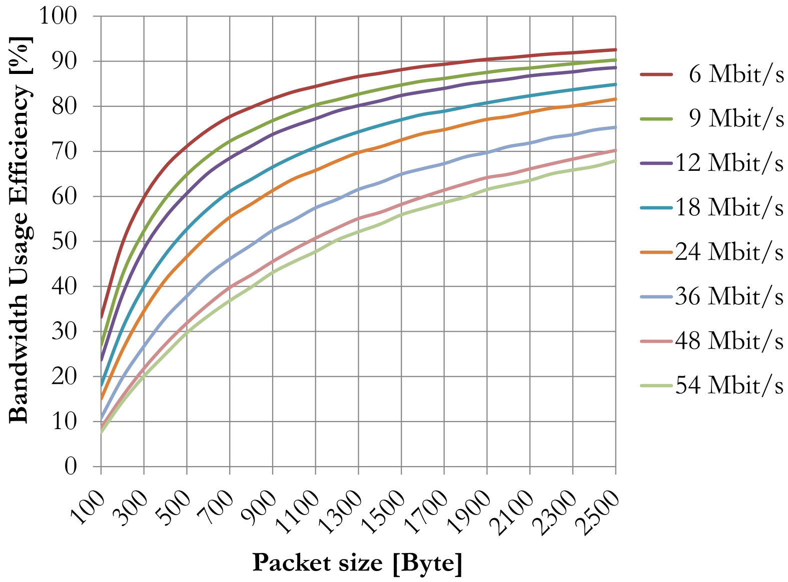


Figure 6.10 – Bandwidth efficiency for 802.11a.

Table 6.3 – Maximum theoretical application-layer throughput for various data-rates.

R_{phy} [Mbit/s]	R_{app} [Mbit/s]
6	5.3
9	7.6
12	9.8
18	13.7
24	17.3
36	23.2
48	27.9
54	29.9

This protocol overhead has also impact on the minimum application-layer packet delay per hop, τ_{app}, as discussed in Appendix E. Figure 6.11 plots the dependency of τ_{app} with K_{packet} and

R_{phy}. As expected, for a given R_{phy} rate, delay increases with K_{packet}, while for a given K_{packet} size, delay decreases with the increase of R_{phy} (e.g., 0.3 and 2.2 ms for 54 and 6 Mbit/s).

It can be concluded that achievable throughput and end-to-end delay are bounded by protocol overheads. The proposed strategy uses the knowledge of these overheads to estimate the needed R_{phy} rates to support the traffic flows it must forward.

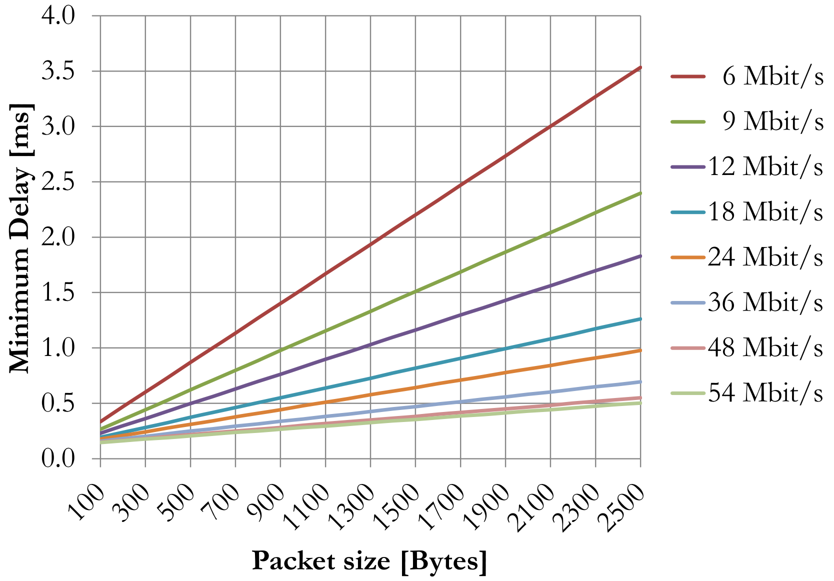


Figure 6.11 – Minimum theoretical application-layer delay for 802.11a, for increasing packet sizes.

6.1.3 Considerations on Radio Resource Management in WMNs

A preliminary discussion on key aspects related to management of radio resources in WMNs is presented next. In multi-hop WMNs, one of the key challenges is the simultaneous communication of multiple node-pairs through a shared wireless medium. If each pair of nodes uses a different channel to communicate, then transmissions may occur simultaneously. If, within the interference range of a node-pair, another node-pair is using the same channel, then the access to the channel must be shared. On the other hand, if a channel is only reused outside the interference range, the two node-pairs might communicate simultaneously using the same channel. Thus, having multiple channels and an adequate mechanism to optimise their allocation enables simultaneous communication between nodes within a WMN.

For the communication between two pairs of nodes using a given channel, multiple R_{phy} rates are available. High R_{phy} are desirable, as they enable a higher link capacity. Nevertheless, this has two disadvantages: smaller communication range and larger interference one. Considering the existence of a set of orthogonal channels, an intelligent management of the R_{phy} rates is desirable to avoid collisions and contention, and guarantee that R_{fair} is achievable for all MAPs.

On the one hand, communication ranges are conditioned by multiple factors, as discussed in Section 6.1.1. The higher the R_{phy} rate is, the smaller the communication range. Also, the existence of maximum levels for the transmitted power, of minimum levels for the received power (associated to the receivers sensitivity), and of minimum SINR thresholds for the correct decoding of packets, as well as the propagation environment, limit the communication ranges.

On the other hand, interference ranges are also influenced by multiple factors, as discussed in 6.1.1. Higher physical data-rates result in larger interference ranges. As an example, consider the hexagonal deployment of MAPs where $d_{map} = 40$ m. Assume that all MAPs use the same channel, R_{phy} and P_{tx}. An R_{phy} of 12 Mbit/s results in an interference range $d_i = 1.7 \cdot d_{map}$. Considering a carrier sensing range equal to the interference range, this means that when a given node transmits, the 6 neighbouring nodes cannot transmit, resulting in a maximum fairly achievable throughput of $R_{thr} = 1.6$ Mbit/s. For an R_{phy} of 54 Mbit/s, $d_i = 4.8 \cdot d_{map}$. In this second situation, 5 rings of nodes are affected, meaning that 60 nodes cannot transmit when this node is transmitting. This means that nodes may transmit in average 1/60 of the time, for $R_{phy} = 54$ Mbit/s corresponding to a maximum achievable throughput of $R_{thr} = 0.5$ Mbit/s.

As a first conclusion, high data rates are not used by every single node, but only for a restricted number of nodes for which it is of high benefit. To identify the nodes that use higher physical data rate, a key specificity of WMNs is explored, its fat-tree traffic flow characteristic, illustrated in Figure 2.6. As traffic flows are mostly exchanged between a gateway and MAPs, high traffic load is expected near each gateway, becoming a traffic bottleneck. On the other hand, the farther from the gateway the lower the load between nodes is – a natural ramification effect of traffic flows. As a first heuristic, R_{phy} is adapted to the expected load within the various links of the WMN network. The maximum possible R_{phy} is used by the gateway to communicate with its neighbours. The maximum load of each gateway neighbour is inversely proportional to the total number of neighbours of the gateway. In this sense, R_{phy} can be lower, as traffic ramifies. Subsequent rationale can be applied for farther nodes. This is an energy efficient usage of resources as, for a given communication range, the lower R_{phy} is, the lower P_{tx} might be. Also, this is an efficient usage of resources in terms of spectrum; as R_{phy} reduces to the periphery, d_i decreases also, as shown in Table 6.2, enabling to reuse a channel without interference within a shorter distance.

This optimisation of R_{phy} rates and P_{tx} levels is tightly related with the number of available orthogonal channels. The set of available channels can be categorised according to the used rate, having associated a d_i. In the selection of a channel, the algorithm takes into account the "hierarchies" of channels, expressed by the associated d_i. For example, the gateway will use two channels at the maximum $R_{phy} =$ 54 Mbit/s, one for each radio, which will not be reused within 5 hops from the receiving nodes. This guarantees the maximum performance of the WMN in its bottleneck. The consecutive rings use lower R_{phy} rates, having a shorter channel reuse distance (d_i), being taken into consideration in the selection and reutilisation of channels. Thus, for the channel selection, channels are weighted by the associated R_{phy} rate. The total number of available channels is a critical parameter, since it will determine, within an interference area, the number of simultaneous transmissions that may occur. If this parameter is well configured (number of nodes within an interference area similar to the number of available channels) the capacity of the network can be maximised. Cellular concepts of clustering and channel allocation are thus applied here. In this sense, channels are divided in hierarchies.

The configuration of radio resources in WMNs has been discussed in this section. Some heuristics used in the design of the proposed RRM strategies have been evaluated from a practical view point, evidencing their potentialities.

6.2 WMN Structured Reference Scenario

6.2.1 FERA Analysis

An analysis of the optimisation procedures of FERA strategy is presented next, applied to the MAPs of the reference WMN scenario, presented in Section 5.3.1. Paths of traffic flows were pre-computed by a routing protocol, in Figure 6.12 the links through which traffic flows being represented. It can be seen that traffic ramifies, e.g., link $l_{0,1}$ is crossed by three traffic flows, from M_1, M_{18} and M_7, while link link $l_{1,7}$ is only crossed by M_7's flow.

For the inter-node distance, $d_{map} =$ 40 m, (4.17) and (4.18) indicate that $R_{phy}\left(M_{0,r=1,2}\right) =$ 54 Mbit/s is achievable for $P_{tx}\left(M_{0,r=1,2}\right) =$ 30 dBm. This is confirmed from Figure 6.8, where the communication range d_{max}(54 Mbit/s, 30 dBm) = 46 m > d_{map}. Each

MPP radio has a capacity of $R_{app}(\mathrm{M}_{0,r=1,2}) = 29.0$ Mbit/s that must be fairly shared among the MAPs it forwards aggregated traffic flows. From Figure 6.12, it can be seen that each gateway radio has $N_{flw}(M_{0,r=1,2}) = 9$ flows. With this configuration and using (4.19), the two gateway radios, $M_{0,1}$ and $M_{0,2}$, may guarantee a max-min fair capacity of $R_{fair}(M_{0,r=1,2}) = 3.2$ Mbit/s to each of the 18 MAPs, M_i, i = 1, … 18. M_0 has no limitation in terms of aggregated traffic of end-users it covers, as it has direct access to the Internet.

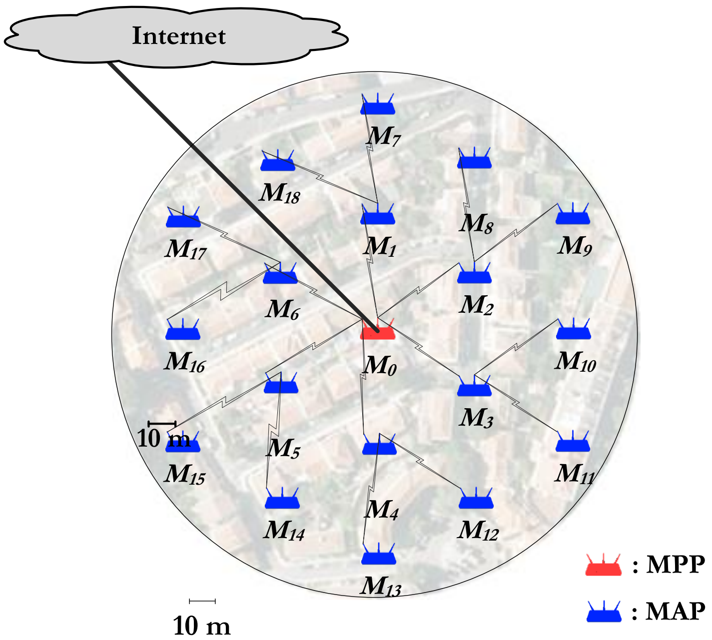


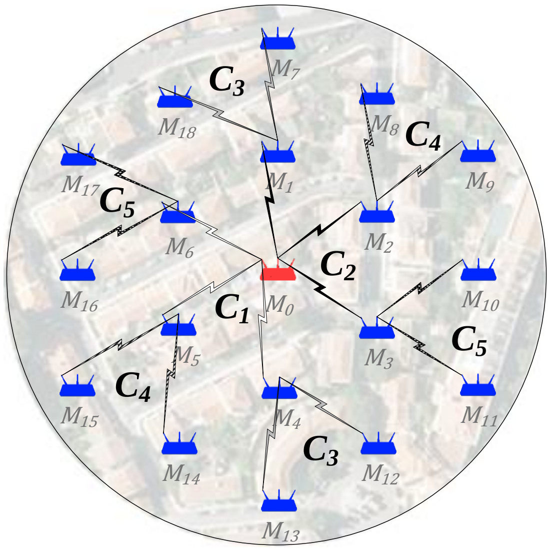
Figure 6.12 – Reference scenario with pre-computed paths for MAPs' traffic flows.

In this scenario, each gateway radio communicates with 3 neighbours, each having 2 children, Figure 6.12. Thus, to guarantee R_{fair} to all MAPs, each radio $M_{i,2}$, i = 1, … 6, needs to support the two R_{fair} flows of its children (e.g., $M_{2,2}$ has to support M_8 and M_9 flows), needing a capacity of at least 6.4 Mbit/s. From (4.20), $R_{phy}(M_{i=1..6,2}) = 9$ Mbit/s. This is confirmed by Table 6.3, as for $R_{phy} = 9$ Mbit/s the maximum achievable throughput $R_{app} = 7.6$ Mbit/s > 6.4 Mbit/s. From (4.18), $P_{tx}(M_{i=1..6,2}) = 12$ dBm is sufficient to guarantee communication within $d_{map} = 40$ m at 9 Mbit/s. This result is confirmed in Figure 6.8, where d_{max}(9 Mbit/s, 12 dBm) = 40 m. The resulting configuration is presented in Figure 6.13 (b).

Once R_{phy} and P_{tx} are optimised, the assignment of channels consists of the evaluation, for each radio, of the less used channel within the interference neighbourhood, as described in Section 4.3.3. The channel assignment is represented in Figure 6.13 (a). $\mathcal{L}_{0,r1}$ and $\mathcal{L}_{0,r2}$ choose each a different channel for its links, C_1 and C_2. For the remaining links, channels are reused: C_3 by $\mathcal{L}_{1,r2}$ and $\mathcal{L}_{4,r2}$, C_3 by $\mathcal{L}_{2,r2}$ and $\mathcal{L}_{5,r2}$, and C_4 by $\mathcal{L}_{3,r2}$ and $\mathcal{L}_{6,r2}$. In fact, for nodes using similar P_{tx}, from (4.10), d_i(9 Mbit/s) = 64 m for d_{map} = 40 m. As the shortest distance between nodes of these sets is 80 m (e.g., between M_1 and M_4, for $\mathcal{L}_{1,r2}$ and $\mathcal{L}_{4,r2}$), no interference is guaranteed among these links. In this sense, 5 channels guarantee max-min fair operation of the WMN.

Links	R_{phy} [Mbit/s]	P_{tx} [dBm]
$\mathcal{L}_{0,r1}, \mathcal{L}_{0,r2}$	54	30
$\mathcal{L}_{i,r2}$, with $i = 1 \dots 6$	9	12

(a) Links' configured rate and power.



(b) Links' channel assignment.

Figure 6.13 – FERA' optimised radio resources for the hexagonal WMN reference scenario.

As an example, the channel assignment to $M_{1,2}$'s links, $\mathcal{L}_{1,r2}$, is analysed. The channel utilisation of each radio of WMN's nodes is given in Table 6.4, for the channels on which radios are active. M_1's interference neighbourhood, $\mathcal{X}_1 = \{M_{0,1}, M_{0,2}, M_{m=2\dots6,1}, M_{2,2}, M_{6,2}, M_{7,1}, M_{8,1}, M_{18,1}\}$, is represented in Figure 6.14. These are the nodes' radios that, due to the used P_{tx}, may interfere with $\mathcal{L}_{1,r2}$ links. In fact, $M_{2,2}, M_{6,2}, M_{7,1}, M_{8,1}$ and $M_{18,1}$ transmit at P_{tx} = 12 dBm, and may interfere as their distance to M_1 is below d_i = 64 m, Figure 6.14. Radios $M_{0,1}, M_{0,2}$ and $M_{m=2\dots6,1}$ use P_{tx} = 30 dBm, and may also interfere with M_1 if using the same channel.

Table 6.4 – Radios' channel utilisation.

Radio	N_{flw}	N_{hop}	$U(M_{m,r}, C_c)$ if active in C_c
$M_{0,r=1,2}$	18	0	18.00
$M_{m=1\dots6,1}$	3	1	1.50
$M_{m=1\dots6,2}$	2	1	1.50
$M_{m=7\dots18,1}$	1	2	0.25
$M_{m=7\dots18,2}$	0	2	0.00

The resulting channel utilisation within $\mathcal{X}_1$ for each channel C_c of $\mathcal{C}$, $\mathcal{U}(\mathcal{X}_1, C_c)$, is presented in Table 6.5. As estimated from (4.25), it can be seen that the less used channel is C_3, being the selected one, as depicted in Figure 6.13 (a).

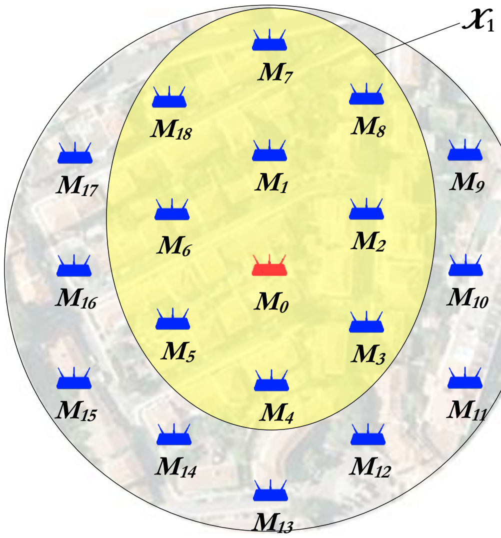


Figure 6.14 – M_1's interference neighbourhood, $\mathcal{X}_1$.

Table 6.5 – Channel utilisation within $\mathcal{X}_1$.

C_c	$\mathcal{U}(\mathcal{X}_1, C_c)$
C_1	22.50
C_2	22.50
C_3	1.50
C_4	3.25
C_5	3.00

To conclude, in this section, the various steps of FERA to optimise R_{phy}, P_{tx} and channels are analysed, for the reference scenario. With the resulting configuration, the network may guarantee a max-min fair share of capacity among all MAPs. Its performance is evaluated in the next sections.

6.2.2 Evaluation through Simulation

FERA's optimisation procedure is evaluated next through simulation. As the simulation starts and nodes are plugged in, *Hello* messages are periodically broadcasted on all channels, thanks to the hybrid policy. *Hello* messages contain information on nodes' resources (node ID, location, stable-channel, used P_{tx} for *Hello*, etc.). This guaranteed connectivity supports any route discovery protocol, which will establish the paths for traffic flows, Figure 6.12. Once data packets start to be exchanged between nodes, crossed MAPs extract information from these packets, identifying the number of traffic flows/aggregating MAPs that pass through a given node. This collected information allows each node M_m to compute some important parameters and KPIs ($N_{flw}(M_{m,r})$, $\mathcal{L}_{m,r}$, $N_{links}(M_{m,r})$, $N_{flw}(l_{m,n})$, $\mathcal{M}_{m,r}$, $N_{hop}(M_m)$, $L_p(l_i)$, $U(M_m, C_c)$). These parameters may change with time (although in the present scenario they do not), the optimisation process being periodically triggered. Analysing the overhead introduced by FERA's KPIs monitoring and sharing procedure, each MAP broadcasts one 1 500 bytes *Hello* packet per second. For an achieved throughput of 3.2 Mbit/s, it represents an overhead of less than 0.5 %.

With a $T_{Hello} = 1$ s, after 5 seconds of simulation, sufficient information on the neighbourhood enables to start optimising nodes' resources. M_0 runs the TPC and RA mechanisms, computing R_{phy} and P_{tx} for each radio of M_0. The optimised resources are broadcasted with a *Hello* to M_0's neighbours, which optimise their resources subsequently as described previously. Once this first optimisation cycle is achieved (4 s for the reference scenario), the CA procedure is started. Each node runs its CA autonomously, the entire network needing 5 s to converge in an optimised assignment of channels. After this total transitory period of 9 s, the configuration of radio resources of all MAPs becomes similar to the theoretical one presented in Figure 6.13, the network guaranteeing max-min fair share of capacity to all MAPs if $R_{load} \leq R_{fair}$ thanks to the flow-control mechanism. Considering a mix of Up- and Down-Link (UL and DL) aggregated traffics, or only UL, results in similar performance results. During simulation, the dynamic radio stays on a channel a maximum of 150 ms, after which it changes to the next non-empty channel-queue. In case remaining channel-queues are empty, it does not switch channel. Once the allocation of stable-channels has been optimised, nodes do only need to switch channel for the broadcast of *Hello* packets, resulting in sporadic extra-delay due to channel switching.

Network performance is evaluated for various offered load values. For each MAP, one flow of packets is injected in the WMN through M_0. The load is increased by decreasing the inter-arrival time of generated packets. To guarantee fairness among MAPs, the flow-control mechanism guarantees that the injected load in the WMN is below the max-min fair capacity, $R_{load} \leq R_{fair}$. If, for any MAP, $R_{load} > R_{fair}$, packets are dropped, forcing $R_{thr} = R_{fair}$, and guaranteeing max-min fair share of capacity among all MAPs. Sources may react, reducing their load.

Without this proposed flow-control mechanism, when $R_{load} > R_{fair}$, unfairness increases drastically as is evaluated next. In Figure 6.15, the average aggregated throughput, R_{thr}, and corresponding standard deviation, $\sigma_{R_{thr}}$, is depicted, for increasing load per MAP, when the flow-control mechanism is not active. It can be confirmed that up to $R_{load} = R_{fair} =$ 3.2 Mbit/s is achieved $R_{thr} = R_{load}$ with a low standard deviation, $\sigma_{R_{thr}} <$ 40 kbit/s. The allocation of resources is max-min fair, with $f_{max-min} = 1$. This is confirmed from simulation by the inexistence of dropped packets and an average packet delay $\tau_{packet} <$ 6 ms for all MAPs. For $R_{load} > R_{fair}$, a fair share of resources is not anymore guaranteed, certain nodes performing better than others that suffer from starvation. For example, for $R_{load} =$ 4 Mbit/s, an average throughput of $R_{thr} =$ 3.2 Mbit/s is measured, with a large standard deviation, $\sigma_{thr} =$ 1.4 Mbit/s, high packet loss of $\delta_{packet} =$ 20%, and low max-min fairness, $f_{max-min} = 0.83$.

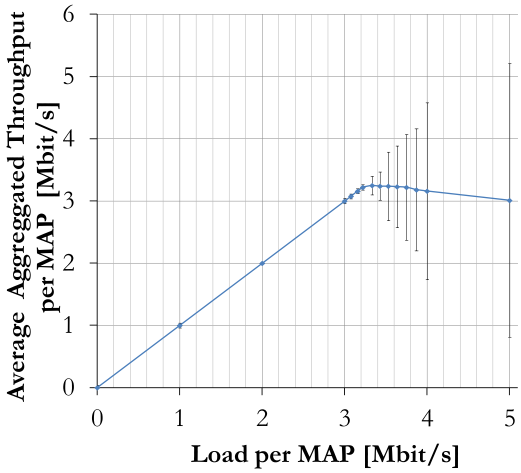


Figure 6.15 – Evolution of the average aggregated throughput for increasing load per MAP.

The evolution of the packet delay is evaluated next, again with the flow-contention mechanism deactivated and considering packet-queues (see Figure 4.6) of infinite size, $K_{packet} = \infty$. In fact, if link-layer packet queues are of finite size, when the load exceeds the capacity of the network results in dropped packets due to due to queue overflow. Still, the percentage of packets dropped depends on the size of the queue, a configurable parameter. For this reason, to make the analysis independent of this, an infinite queue size is considered in simulation, avoiding packet drops due to buffer-overflow, the measurable effect being the evolution of E2E packet delay, τ_{packet}. The evolution of τ_{packet} with simulation time is depicted in Figure 6.16. For $R_{load} \leq R_{fair} =$ 3.2 Mbit/s, τ_{packet} remains stable and low, below 2.5 ms. For R_{phy} of 54 and 9 Mbit/s, τ_{app} is respectively 0.4 and 1.5 ms. This means that packets travelling 1 and 2 hops, from the MPP, have theoretical minimum theoretical τ_{packet} of 0.4 and 1.9 ms respectively, evidencing that overhead introduced by FERA is very low.

For $R_{load} > R_{fair}$, τ_{packet} grows with time for certain nodes, evidencing that packet forwarding of intermediary MAPs has reached capacity limitations, increasing exponentially the buffered packets on the intermediate MAPs. These would result in packet losses if finite channel packet queues would be implemented in nodes.

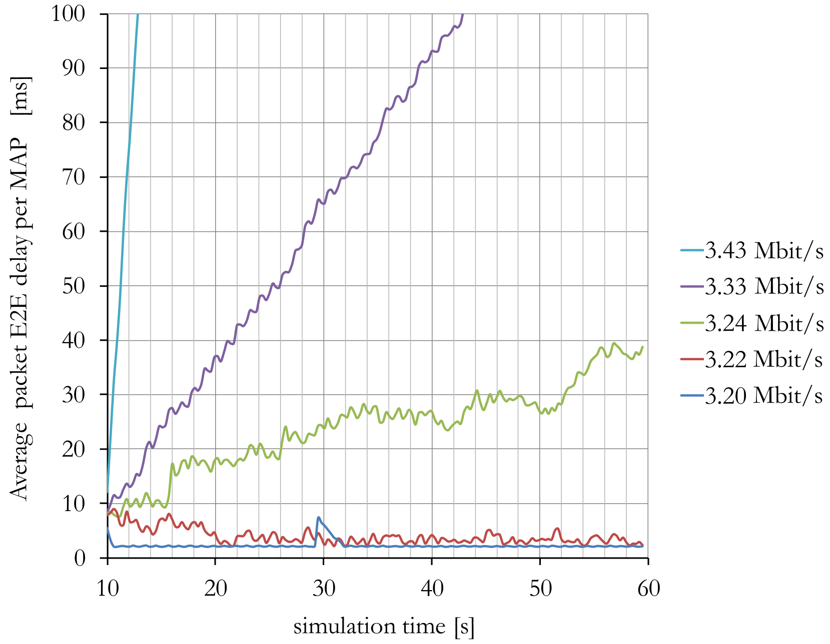


Figure 6.16 – Evolution of the average packet E2E delay, for increasing load per MAP.

To conclude, in this section the performance of FERA's optimisation procedure is analysed through simulation. Each MAP self-optimises its radio resources in such a way that all achieve a max-min fair share of capacity, guaranteed by the flow control. This means that the classical problems of multi-hop communication are overcome with FERA (hidden and exposed nodes problems, associated interference and contention, throughput decrease with number of hops).

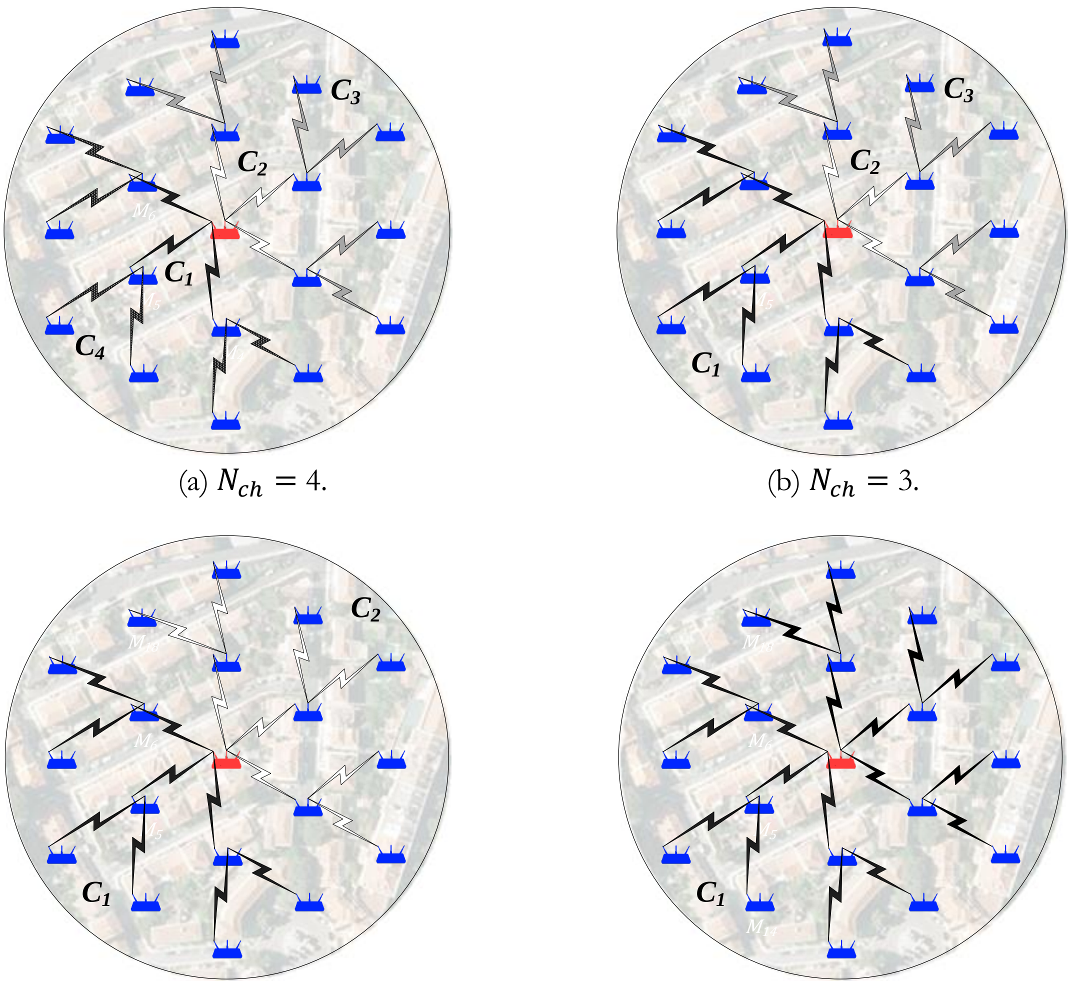
6.2.3 Variation of the Number of Channels

In a WMN, multiple wireless links are simultaneously forwarding traffic. If an unlimited number of channels would be available, each link would use a different channel and neither interference nor contention would exist, every MAP achieving R_{fair}, related with the maximum capacity of the system in use. Nevertheless, in reality, a limited number of channels is available. Their efficient management passes by using different channels within links that may interfere or content, or by allocating sufficient capacity to a channel so that all links sharing it are able to forward the needed traffic.

A comparison of FERA's performance for different number of available channels, N_{ch}, is presented hereafter. Optimised R_{phy} and P_{tx} values for the various WMN's radios are presented in Table 6.6, the resulting channel assignment being plotted in Figure 6.17. Simulation performance results are shown in Figure 6.18 and associated efficiency metrics in Table 6.7. To evaluate the throughput degradation for $R_{load} > R_{fair}$, simulations were performed without the flow-contention mechanism.

Table 6.6 – R_{phy} and P_{tx} optimised by FERA, for various number of available channels.

	$\mathcal{L}_{0,r1}$, $\mathcal{L}_{0,r2}$		$\mathcal{L}_{i,r2}$, with $i = 1 \dots 3$		$\mathcal{L}_{i,r2}$, with $i = 4 \dots 6$	
N_{ch}	R_{phy} [Mbit/s]	P_{tx} [dBm]	R_{phy} [Mbit/s]	P_{tx} [dBm]	R_{phy} [Mbit/s]	P_{tx} [dBm]
≥ 5	54	30	9	12	9	12
4	54	30	36	24	36	24
3	54	30	36	24	54	30
2	54	30	54	30	54	30
1	54	30	54	30	54	30



(a) $N_{ch} = 4$.

(b) $N_{ch} = 3$.

(c) $N_{ch} = 2$.

(d) $N_{ch} = 1$.

Figure 6.17 – FERA's channel assignment, for various numbers of available channels.

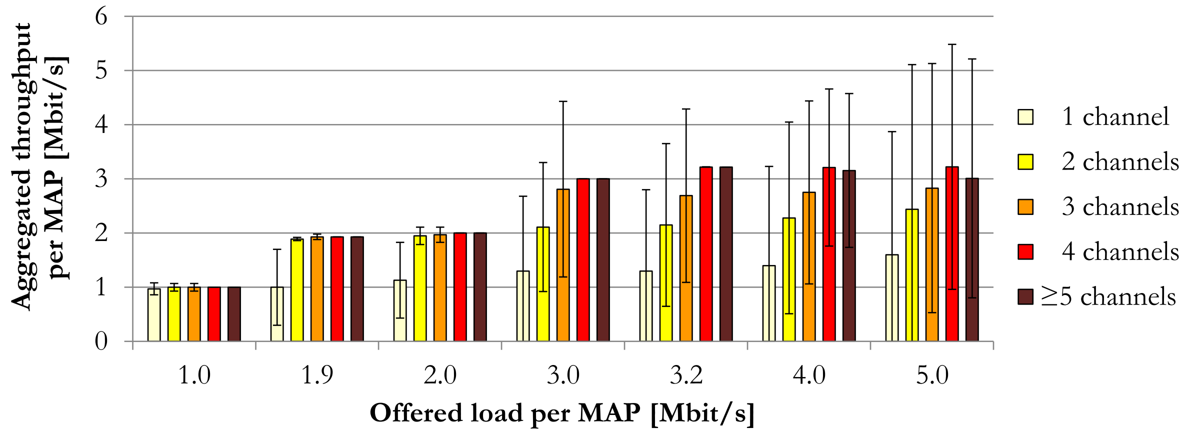


Figure 6.18 – Aggregated throughput per MAP for different offered traffic loads, for various number of available channels.

Table 6.7 – Performance of FERA for various number of available channels, for $R_{load} = R_{fair}$.

N_{ch}	R_{wmn} [Mbit/s]	R_{fair} [Mbit/s]	$f_{max-min}$	$\eta_{capacity}$ [%]	η_{energy} [Mbit/J]	$\eta_{spectrum}$ [bit/s/Hz]
1	17.4	1.0	1.0	53.7	17.5	0.87
2	34.7	1.9	1.0	52.8	17.5	0.87
3	46.4	1.9 (for $\mathcal{M}_{0,r1}$) 3.2 (for $\mathcal{M}_{0,r2}$)	1.0	49.4	20.6	0.77
4	58.0	3.2	1.0	42.9	23.2	0.72
5	58.0	3.2	1.0	59.6	27.7	0.58
6	58.0	3.2	1.0	59.6	27.7	0.48
7	58.0	3.2	1.0	59.6	27.7	0.41
8	58.0	3.2	1.0	59.6	27.7	0.36

With $N_{ch} = 5$ channels, FERA guarantees to each MAP a max-min fair throughput of $R_{fair} = 3.2$ Mbit/s, Figure 6.18, with $f_{max-min} = 1$. When load increases beyond R_{fair}, a fair share of capacity among MAPs is not guaranteed anymore. In fact, for $R_{load} = 4$ Mbit/s, a throughput of $R_{thr} = 3.2$ Mbit/s is achieved with $\sigma_{R_{thr}} = 1.7$ Mbit/s. This large standard deviation evidences that some nodes are favoured, achieving $R_{thr} > R_{fair}$, while others are disfavoured, with $R_{thr} < R_{fair}$, fairness decreasing to $f_{max-min} = 0.83$. When the WMN operates at $R_{load} = R_{fair}$, FERA's selection of data-rates for the different links results in a WMN capacity usage efficiency of $\eta_{capacity} = 59.6$ %, Table 6.7. Channels C_1 and C_2, used in $\mathcal{L}_{0,r1}$ and

$\mathcal{L}_{0,r2}$ links, operate at $R_{phy} = 54$ Mbit/s, a rate with a low bandwidth usage efficiency, $\eta_{phy}(54$ Mbit/s$) = 53.7\%$. Although inefficient due to large overheads, $R_{phy} = 54$ Mbit/s enables the highest throughputs. It offers a capacity of 29 Mbit/s that is 100% exploited by FERA, as the 9 flows of $R_{thr} = 3.2$ Mbit/s forwarded on each of these channels result in the same 29.0 Mbit/s. For the case of channels C_3 to C_5, operating each at $R_{phy} = 9$ Mbit/s and offering a capacity of 7.7 Mbit/s, each uses 84% of the available capacity. Other characteristics are expressed by the energy and bandwidth efficiency metrics, $\eta_{energy} = 27.7$ Mbit/J and $\eta_{spectrum} = 0.58$ bit/s/Hz, evaluated through comparison with results for other N_{ch}.

With $N_{ch} = 4$ channels, $\mathcal{L}_{0,r1}$ and $\mathcal{L}_{0,r2}$ links are optimised similarly to $N_{ch} = 5$, with $R_{phy} = 54$ Mbit/s, $P_{tx} = 30$ dBm, and C_1 and C_2. Using the standard TPC & RA & CA mechanisms to configure the resources of these links ($R_{phy} = 9$ Mbit/s; $P_{tx} = 12$ dBm) would result in interference situations between links. Observing the resulting CA depicted in Figure 6.19, the distance between the M_2, M_4 and M_6 using C_3 is 69 m. When two of them are transmitting and one is receiving, the resulting SINR is ρ=6.4 < ρ_{min}(9 Mbit/s), resulting in interference. This is why FERA must use the capacity sharing mechanism described in Section 4.3.4 for links $\mathcal{L}_{i=1\ldots6,r\,2}$. The resulting configuration is $R_{phy} = 36$ Mbit/s, $P_{tx} = 24$ dBm, assigning C_3 to $\mathcal{L}_{m=1\ldots3,r2}$ and C_4 to $\mathcal{L}_{m=4\ldots6,r2}$, as illustrated in Figure 6.17 (a). With this rate, there is enough capacity to be shared among the 6 links of each channel and guarantee $R_{fair} = 3.2$ Mbit/s to every MAP, as $R_{app}(36$ Mbit/s$) = 22.6$ Mbit/s > 6·3.2 Mbit/s = 19.3 Mbit/s. This is confirmed by simulation results Figure 6.18, where R_{fair} is guaranteed without loss of packets and a delay $\tau_{packet} < 6$ ms for all MAPs. Also, for $R_{load} \leq R_{fair}$, max-min fair conditions are guaranteed, as $f_{max-min} = 1$.

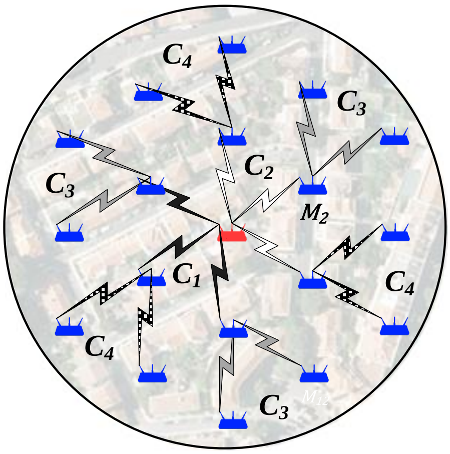


Figure 6.19 – Inefficient channel assignment for $N_{ch} = 4$ using the classical TPC & RA & CA.

A max-min fair capacity of 3.2 Mbit/s is guaranteed to every MAP using 4 or 5 channels. Still, the WMN capacity usage efficiency, $\eta_{capacity}$, is higher for 5 than for 4 channels, with $\eta_{capacity}$ of 59.6 % and 42.9 % respectively, Table 6.7. In fact, although for N_{ch} = 5 and 4 the available capacity in $\mathcal{M}_{2hop}$ links is used similarly (84 % for $R_{phy} = 9$ Mbit/s and 85 % for $R_{phy} = 36$ Mbit/s), the bandwidth usage efficiency is higher for $R_{phy} = 9$ Mbit/s ($\eta_{phy} = 85.2$ % vs. 62.9 %), resulting in a higher $\eta_{capacity}$.

In terms of energy efficiency, using N_{ch} = 5 channels is more efficient than 4, with η_{energy} of 27.7 and 23.2 bit/J respectively. For both cases, $\mathcal{L}_{o,r1}$ and $\mathcal{L}_{o,r2}$ may have, each, an active link transmitting at $P_{tx} = 30$ dBm. For N_{ch} = 5, the six sets of links $\mathcal{L}_{i,r2\ \ i=1\ldots6}$ may have, each, an active link transmitting at $P_{tx} = 12$ dBm. For N_{ch} = 4, links $\mathcal{L}_{i,r2\ \ i=1\ldots3}$ share channel C_3 and $\mathcal{L}_{i,r2\ \ i=4\ldots6}$ share C_4; only one link per channel may be active, transmitting at $P_{tx} = 24$ dBm. Although R_{wmn} is similar for N_{ch} = 5 and 4, these differences of P_{tx} levels justify the differences.

Regarding spectrum efficiency, N_{ch} = 5 is less efficient than 4. Both perform similarly in terms of R_{wmn}, but using one less channel resulting more spectrum efficient, with $\eta_{spectrum}$ of 0.72 and 0.58 bit/s/Hz, respectively.

With $N_{ch} = 3$ channels, one single channel is used in branch $\mathcal{M}_{0,r1}$, while two are used in branch $\mathcal{M}_{0,r2}$, as depicted in Figure 6.17 (b). In fact, FERA uses the capacity sharing mechanism (described in Section 4.3.4) for $\mathcal{M}_{0,r1}$, where all its links must share channel C_1 to forward 15 flows. Operating at R_{phy} = 54 Mbit/s, (4.26) results in $R_{fair}(M_{0,r1})$ = 29.0/15 = 1.9 Mbit/s for MAPs of branch $\mathcal{M}_{0,r1}$. For $\mathcal{M}_{0,r2}$, one gets $R_{fair}(M_{0,r2}) = 3.2$ Mbit/s. A max-min fair share of capacity is guaranteed, $f_{max-min} = 1$, if $R_{load} \leq R_{fair}$ (dependent on the branch), as presented in Table 6.7. For a common R_{load}, a max-min fair share of capacity is guaranteed up to 1.9 Mbit/s, beyond which losses and unfairness increase drastically for nodes of $\mathcal{M}_{0,r1}$ branch, as depicted in Figure 6.18.

For $N_{ch} = 3$ channels, $\eta_{capacity}$ = 49.4 %. Curiously, this result is higher than for 4 channels. In fact, for $N_{ch} =$ 4 channels, each channel operating at R_{phy} = 36 Mbit/s is forwarding 6 flows of 3.22 Mbit/s, resulting in a total of 19.3 Mbit/s. Still, R_{app}(36 Mbit/s) = 22.6 Mbit/s, existing 3.3 Mbit/s of unused capacity. With $N_{ch} = 3$, for the $\mathcal{M}_{0,r1}$ branch using a single channel at R_{phy} = 36 Mbit/s, the available capacity R_{app}(54 Mbit/s) = 29.0 Mbit/s is totally used by the 15 forwarded flows of 1.9 Mbit/s. As this branch is more efficient, and the other one equals the branches of $N_{ch} = 4$, $\eta_{capacity}$ is higher for $N_{ch} = 3$.

In terms of energy efficiency, using N_{ch} = 3 channels is less efficient, with η_{energy} = 20.6 Mbit/J, as higher P_{tx} levels are used, and R_{wmn} decreases. Contrarily, $\eta_{spectrum}$ increases, when compared with N_{ch} = 4, as all links of branch $\mathcal{M}_{0,r1}$ operate with a single channel.

For $N_{ch} =$ 2 channels, $\mathcal{M}_{0,r1}$ and $\mathcal{M}_{0,r2}$ branches use each a single channel, as depicted in Figure 6.17 (c), achieving a max-min fair allocation of resources to every MAP for R_{fair} = 1.9 Mbit/s. $\eta_{capacity}$ increases, compared to $N_{ch} =$ 3, approaching the η_{phy} = 53.7 % upper bound. In fact, the links are almost fully charged, as each branch operating at R_{phy} = 54 Mbit/s forwards 15 flows of 1.9 Mbit/s, representing 98% of available capacity.

For $N_{ch} =$ 1, a single channel is used for all links, as depicted in Figure 6.17 (d). Each MAP only uses one mesh-radio, results being similar to the case of single-mesh-radio WMNs. To avoid interference and guarantee fairness, the available capacity (29 Mbit/s) must be equally shared among the 30 flows to be forwarded within the various links with same channel. This corresponds to $R_{fair} =$ 1.0 Mbit/s. The $\eta_{capacity}$ equals the η_{phy}(54 Mbit/s) upper bound. In fact, the available capacity is used 100% by the 30 flows of 1 Mbit/s (0.9967 Mbit/s, to be more precisely), being only limited by the protocol overhead, expressed by η_{phy}.

In terms of energy efficiency, both for $N_{ch} =$ 1 and 2, the maximum power level P_{tx} = 30 dBm is used by every radio, a very inefficient configuration. Changing from $N_{ch} =$ 2 to 1, both R_{wmn} and the number of active links transmitting at 30 dBm reduce to half, resulting in similar η_{energy} =17.5 Mbit/J. Similarly for spectrum usage, as both R_{wmn} and N_{ch} reduce to half of the values, $\eta_{spectrum}$ values are equal to 0.87 bit/s/Hz. These two cases correspond to the best usage of spectrum.

Evaluating the overall results considering various numbers of available channels, it is shown that with 4 channels, FERA explores the maximum capacity of the system and fairly shares it by all MAPs. In terms of efficiency, using 4 channels is more spectrum efficient than using 5, while using 5 channels is more capacity and energy efficient than using 4. If FERA would use more than 5 channels, the only metric that would vary is $\eta_{spectrum}$, that would degrade gradually, as more channels are being used to achieve the same throughput. Also, more than 8 channels is not possible to use simultaneously in the reference scenario, as there are only 8 parent-radios, each using only one channel for bidirectional communication with its children.

In this section it is shown that, independently of the number of channels, FERA leads to an optimisation of MAPs' resources and guarantees a max-min fair share of capacity to all nodes due to the flow-control mechanism. Classical multi-hop communication problems (hidden and exposed nodes) are overcome, as nodes achieve the max-min fair capacity they have been assigned to without contention or interference. To be noted that this is achieved for a contention-based CSMA/CA access mechanism, confirming the results presented in [JiPs12], [BrMo09] that show close to optimal performance of CSMA/CA access mechanism when radios use adaptive bit rate mechanisms..

6.2.4 Comparison of FERA with other Strategies

FERA's performance is compared with HMCP [KyVa06], LACA [RaGC04] and MesTiC [SGDL07] strategies, described in Appendix C.1. LACA and MesTiC are centralised strategies that need 3 mesh-radios, the third mesh-radio being exclusively used to implement the control plane for optimisation of the resources. HMCP and FERA implement this control plane with the hybrid channel management policy, only needing 2 radios. Simulation results are presented in Figure 6.20. HMCP only optimises the selection of channels, not optimising R_{phy} nor P_{tx}. It only manages to guarantee max-min fair capacity for R_{phy} up to 18 Mbit/s, achieving R_{thr}= 0.8 Mbit/s. This result is due to the fact that it only weights the number of neighbours using the same stable-channel, not weighting the traffic specificities of WMN as done by FERA in (4.22), essential for a well performing WMN.

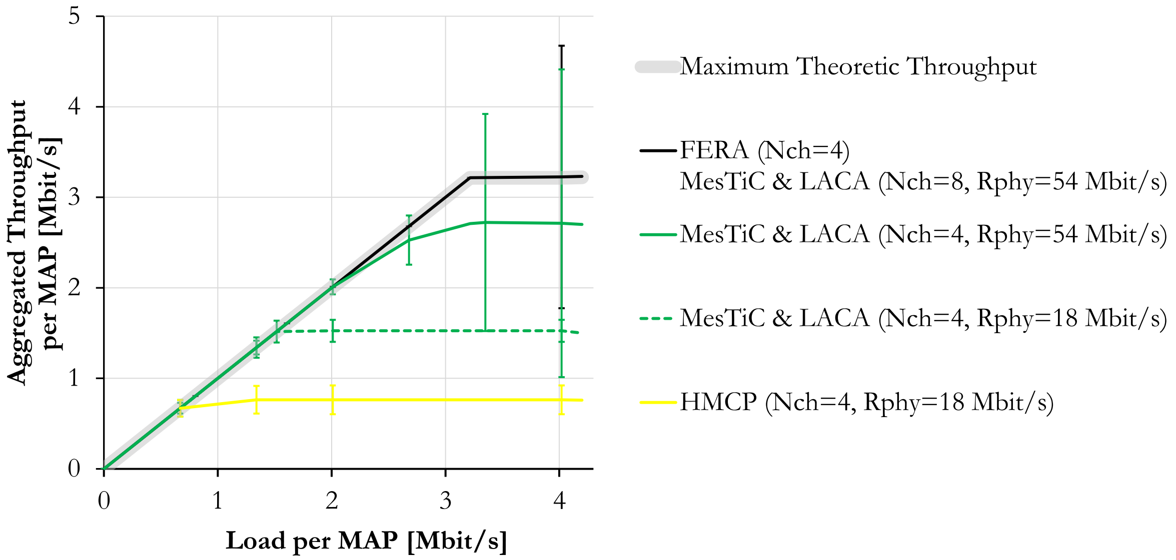


Figure 6.20 – Comparison of FERA with HMCP, LACA and MesTiC strategies, the first two using 2 radios, and the last two using 3 radios.

LACA and MesTiC are load aware strategies, but do not optimise R_{phy} and P_{tx} (common optimum levels are considered for all MAPs) by exploring the fat-tree characteristic of WMNs. This has a strong impact on the achieved performance of these strategies, as depicted in Figure 6.20, presenting lower throughputs than FERA.

With $R_{phy} = 54$ Mbit/s, LACA and MesTiC manage to guarantee max-min fair share of resources up to $R_{load} = 2$ Mbit/s, achieving $R_{thr} = 2$ Mbit/s with $\sigma_{R_{thr}} = 83$ kbit/s. The reason for this low throughput is the resulting channel assignment, as depicted in Figure 6.19, where co-channel links interfere as all have 5 hops of interference range. If each MAP's load is 2 Mbit/s, there is still available unused capacity per link to "correct" problems of collision and contention of packets.

Only by using $N_{ch} = 8$ channels, with one channel per $\mathcal{L}_{i,r2}$, i = 1… 6, LACA and MesTiC achieve similar results as FERA with $N_{ch} = 4$ channels, guaranteeing R_{thr}= 3.2 Mbit/s to every MAP. In fact, with this configuration no channel is reused by any parent-radio, eliminating the possibility of existence of interference.

As a concluding remark, it is shown that FERA guarantees a fair share of resources with only 4 channels, performing better than when using other strategies, such as LACA, MesTiC or HMCP. Other strategies only achieve results similar to FERA if they use the double of the number of channels. The importance of the proposed TPC and RA mechanisms is evident to achieve a high performing and energy efficient configuration of a WMN.

6.3 Structured WMN Deployments Variations

6.3.1 Reference Scenario Area

In this section, the performance of various WMN hexagonal deployments, described in Section 5.3.2, is evaluated, to cover the reference scenario area of $r_{wmn} = 100$ m radius.

As a motivation to use WMNs, the performance of a single AP in providing connectivity to indoor ($\gamma = 4$) and outdoor ($\gamma = 3.3$) end-users is evaluated, results being presented in Table 6.8. IEEE 802.11b/g has stronger limitations in maximum power levels, compared with IEEE 802.11a (20 vs. 30 dBm for outdoor and 20 and 23 dBm for indoor). Still, for similar power levels, IEEE 802.11a operates at higher frequencies (5.5 vs. 2.4 GHz), suffering more from attenuation. Considering indoor end-users and maximum allowe power levels, from Table 6.8 it can be seen that, for 802.11g/b, a lower $P_{tx\,max}$ is compensated by the lower used frequency, achieving better results than 802.11a (18 vs. 38 % of covered area). Still, this is largely insufficient. In the covered area, for IEEE 802.11a, a capacity of 5.3 Mbit/s is available per radio, while for IEEE 802.11b/g it is only 0.9 Mbit/s. This shows that a single AP does not manage to serve adequately the reference scenario, evidencing the importance of WMNs. In fact, for the same scenario, in Section 6.2 was shown that a WMN with 18 MAPs around an MPP gateway is able to offer to indoor users a total throughput of $R_{WMN} = 58$ Mbit/s.

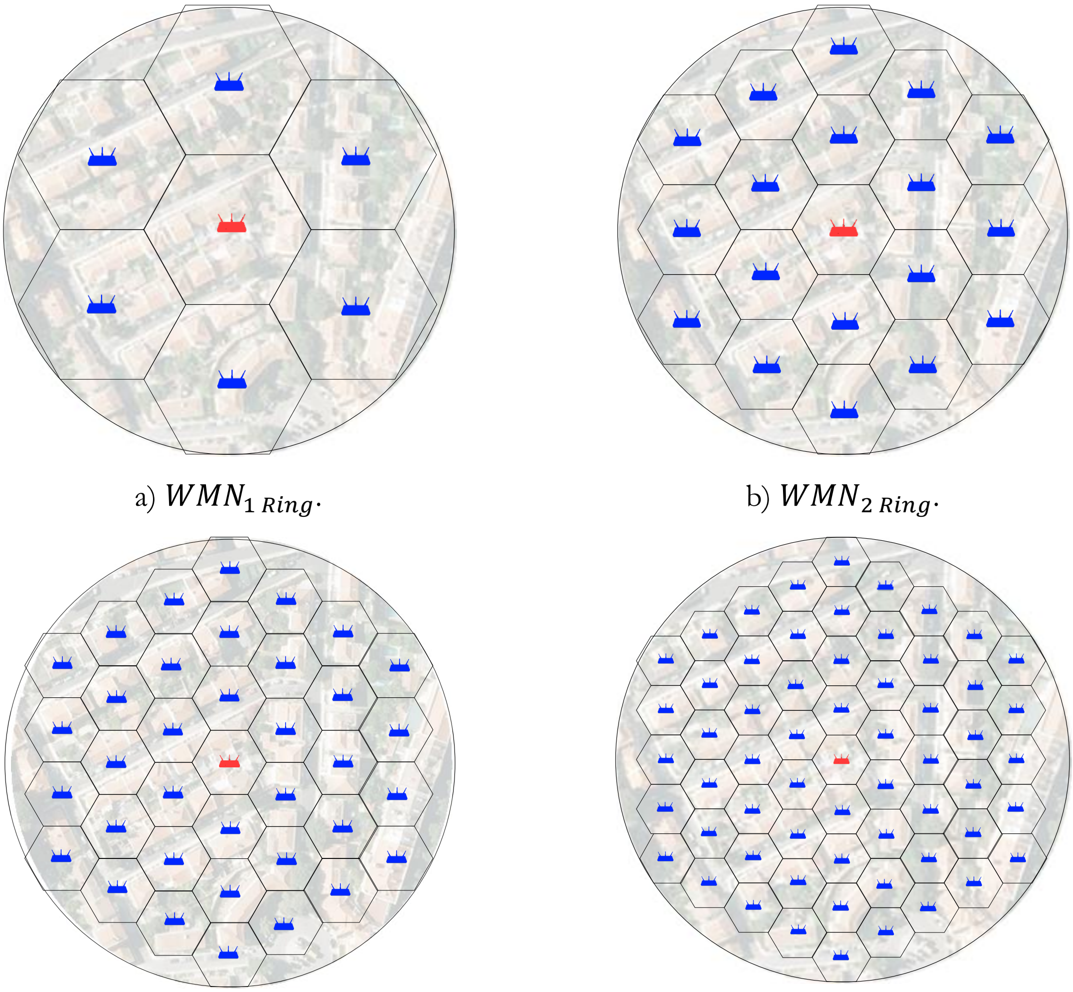
Table 6.8 – Performance of a RAN AP, for a scenario of 100 m radius.

Standard	End-user location	P_{tx} [dBm]	r_{ap} [m]	Coverage [%]	R_{phy} [Mbit/s]	R_{thr} [Mbit/s]
IEEE 802.11b/g	Indoor	20	63	38	1	0.9
	Outdoor	20	100	100	12	9.8
IEEE 802.11a	Indoor	23	42	18	6	5.3
	Outdoor	30	105	100	18	13.7

In IEEE 802.11a, the maximum achievable throughput is $R_{app} = 29.0$ Mbit/s, for $R_{phy} = 54$ Mbit/s. This rate is possible for $d_{map} < 46$ m, determining $R_{wmn} = 57.0$ Mbit/s. This maximum value is related to a system limitation, and not to the WMN or FERA. As it will be shown, FERA explores the system's capacity and extends the coverage range as much as possible.

The performance of several WMN deployments for a $r_{wmn} = 100$ m scenario is evaluated, when FERA is used. $WMN_{x\,Ring}$ hexagonal topologies of $x = 1$, 2, 3 and 4 rings, depicted in Figure 6.21, are evaluated in terms of achievable R_{wmn}.

Results in terms of throughput, fairness and capacity efficiency are presented in Table 6.9. For $WMN_{1\,Ring}$, $R_{wmn} = 34.2$ Mbit/s, only 60% of the maximum possible with IEEE 802.11a. In fact, as $d_{map} = 67$ m, the maximum possible rate is R_{phy} of 24 Mbit/s, from , Table 6.1. With a $WMN_{2\,Ring}$ deployment, d_{map} decreases to 40 m, enabling $R_{phy} = 54$ Mbit/s, the maximum throughput of IEEE 802.11a radios, resulting in $R_{wmn} = 57.0$ Mbit/s. Deployments with more than 2 rings will enable a similar throughput, limited by the gateway maximum capacity (fully explored already with 2 rings).



a) $WMN_{1\ Ring}$. b) $WMN_{2\ Ring}$.

c) $WMN_{3\ Ring}$. d) $WMN_{4\ Ring}$.

Figure 6.21 – WMN deployments for the reference scenario of r_{wmn} = 100 m radius.

Table 6.9 – Performance of WMN deployments.

	R_{wmn} [Mbit/s]	R_{fair} [Mbit/s]	$f_{max-min}$	$\eta_{capacity}$ [%]
$WMN_{1\ Ring}$	34.2	5.7	1.0	71.3
$WMN_{2\ Ring}$	58.0	3.2	1.0	59.6
$WMN_{3\ Ring}$	58.0	1.6	1.0	53.3
$WMN_{4\ Ring}$	58.0	1.0	1.0	48.3

Figure 6.22 shows, for the 4 deployments, the configured R_{phy} rates of the $\mathcal{M}_{xhop}$ radios links. Comparing M_0's and remaining nodes' R_{phy} rates, a strong decrease is observed, due to the high number of flows each M_0's radio has to forward, compared to the 1-hop neighbours, due to

traffic ramification. This enables to drastically reduce the assigned rate. In particular, for $\mathcal{M}_{3hop}$ and farther MAPs, R_{phy} is 6 Mbit/s, the minimum 802.11a rate. In this sense, the first two rings congregate the WMN's links of high throughput, the remaining being of low throughput. Curiously, $\mathcal{M}_{2hop}$ links of $WMN_{2\ Ring}$ use $R_{phy} = 9$ Mbit/s, while $\mathcal{M}_{2hop}$ links of $WMN_{3\ Ring}$ use $R_{phy} = 12$ Mbit/s., Figure 6.22. This rate increase is due to the fact that, for $WMN_{2\ Ring}$, each MAP of the 1st ring must forward 6.4 Mbit/s (2 flows of 3.2 Mbit/s) to the 2nd one, while for $WMN_{3\ Ring}$ this value is higher, 9.7 Mbit/s (6 flows of 1.6 Mbit/s), requiring a higher R_{phy}.

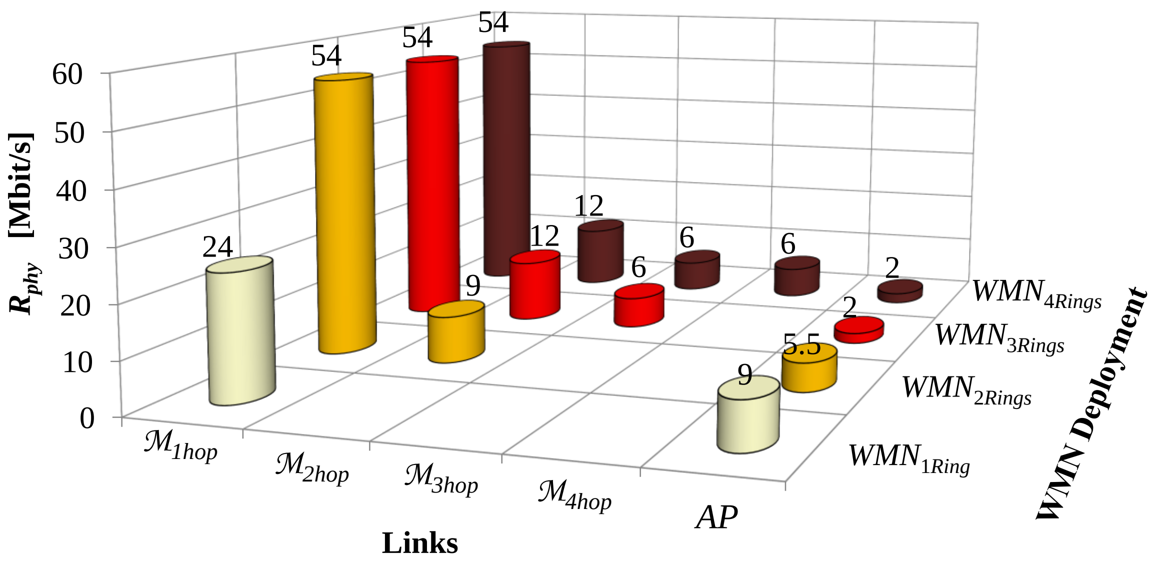


Figure 6.22 – R_{phy} rates used in various links, for several deployments.

With WMN_{2Rings}, the maximum WMN throughput is reached, $R_{wmn} = 58$ Mbit/s, guaranteeing $R_{fair} = 3.2$ Mbit/s to every MAP. For the corresponding 802.11b/g based RAN radio interface, R_{phy} and P_{tx} are adjusted to support R_{fair} within the r_{ap} range. An $R_{phy} = 5.5$ Mbit/s of $R_{app} = 3.9$ Mbit/s is sufficient to explore the available WMN capacity. For the corresponding AP hotspots of $r_{ap} = 20$ m coverage radius, this rate is achievable with $P_{tx} = 5$ dBm. By increasing the deployment size to 3 and 4 rings results in the further reduction of r_{ap} to 14 and 11 m, respectively. The associated increase of MAPs results in a diminution of R_{fair}, Table 6.9, as the total capacity is split among a larger number of MAPs. This influences the needed RAN's physical rates, where $R_{phy} = 2$ Mbit/s is sufficient for both topologies, supported by a lower P_{tx} level of -1 dBm.

From the results presented in Table 6.9, it can be seen that FERA guarantees to all MAPs an R_{fair} capacity, supported by the RAN (in terms of due coverage range, r_{ap}, and supported throughput), evidencing that the network is max-min fair in the share of resources, with $f_{max-min} = 1$, as long as $R_{load} \leq R_{fair}$. The flow-control mechanism guarantees that this condition is respected, dropping packets if flows' throughput is above R_{fair}. As the number of rings increases, the smaller R_{fair} is, as the total capacity R_{wmn} is distributed among more MAPs.

Regarding the used P_{tx} levels, an energy-efficient control of power is essential in the RBN to save energy and increase performance (by the reduction of contention and collisions). Its TPC mechanism configures efficiently the power levels of MAPs' RBN and RAN radios. The P_{tx} levels used in the various links of each deployment are indicated in Figure 6.23.

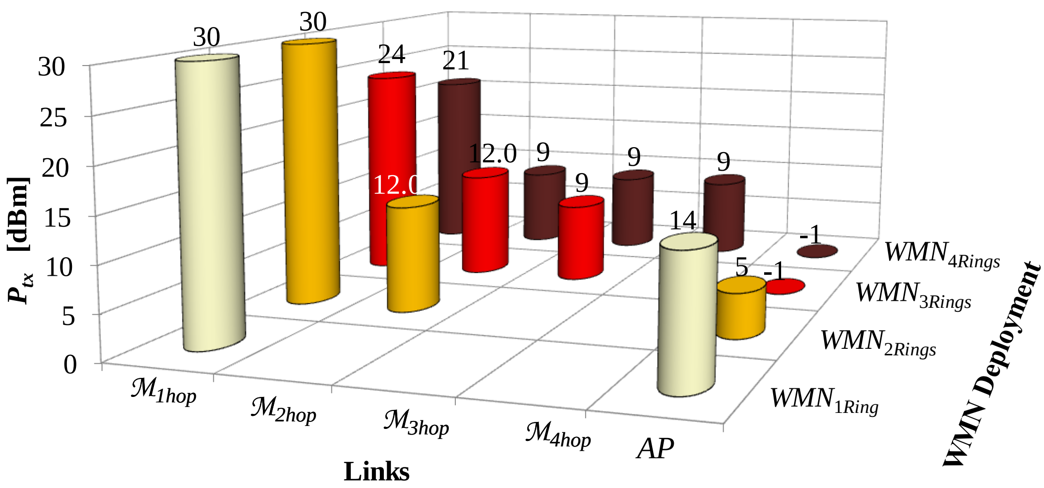


Figure 6.23 – P_{tx} levels used in various links, for several deployments.

As expected, P_{tx} reduces as the farther links are from the gateway node, M_o, Figure 6.23. In fact, as traffic ramifies in WMNs, farther links carry less traffic, being configured to lower R_{phy}, as shown in Figure 6.22. Subsequently, for links of the same length, lower P_{tx} levels can be used. On the other hand, deployments using more rings have lower d_{map} distances, Table 5.5, being able to operate with lower P_{tx} levels, Figure 6.23. For example, from 2 to 4 rings' deployments (where $\mathcal{M}_{1hop}$ links use $R_{phy} = 54$ Mbit/s) P_{tx} decreases, as d_{map} decreases (deployments get more dense). Maximum and minimum P_{tx} levels also influence the achievable results. For the case of WMN_{1ring} with $d_{map} = 67$ m, as P_{tx} cannot be higher than 30 dBm, the maximum supported rate is $R_{phy} = 24$ Mbit/s, confirmed in Table 6.1. On the other hand, in the WMN_{4ring} deployment with $d_{map} = 22$ m, $\mathcal{M}_{3hop}$ and $\mathcal{M}_{4hop}$ links operate at $R_{phy} = 12$ and

6 Mbit/s. With $P_{tx} = 6$ and 3 dBm, these rates would guarantee $d_{max} = 23$ m. Still, as for IEEE 802.11a the minimum P_{tx} level is 9 dBm, Table 5.2, these lower values cannot be used.

Energy efficiency results are presented in Table 6.10. In terms of transmitted power, the less efficient deployment is WMN_{1ring}, and the most efficient one is WMN_{4ring}. For WMN_{1ring}, only two links operating at 30 dBm can be simultaneously active; as $R_{wmn} = 34.2$ Mbit/s, this results in $\eta_{energy} = 17.1$ Mbit/J (half of 34.2). Deployments WMN_{2ring} to WMN_{4ring} achieve $R_{wmn} = 58.0$ Mbit/s; as the transmitted power by mesh-radios decreases, see Figure 6.23, the resulting efficiency increases, as presented inTable 6.10. This metric evaluates the transmitted power, not considering the baseline power consumption of a MAP for operation, $P_{oper} = 15$ W (41.8 dBm), much larger than the power consumed for transmission, bounded to 30 dBm per radio. In this sense, if one evaluates the total energy consumed, $\eta_{total\ energy}$, the number of MAPs used in a deployment will dictate the efficiency metric, and opposite results are concluded, WMN_{1ring} being the most efficient deployment, and WMN_{4ring} the least one, Table 6.10.

Table 6.10 – Energy-efficiency of WMN deployments.

	R_{wmn} [Mbit/s]	N_{map}	d_{map} [m]	η_{energy} [Mbit/J]	$\eta_{total\ energy}$ [Mbit/J]
$WMN_{1\ Ring}$	34.2	7	67	34.2	0.32
$WMN_{2\ Ring}$	58.0	19	40	27.7	0.20
$WMN_{3\ Ring}$	58.0	37	29	83.7	0.10
$WMN_{4\ Ring}$	58.0	61	22	99.1	0.06

Regarding operating channels, the adopted hybrid channel management policy ensures communication between nodes since the moment they are switched on. Regularly, each MAP optimises the used channels with the proposed CA algorithm, combined with RA and TPC results. Simulation results show that, for 1, 2, 3 and 4 rings topologies, using the proposed CA algorithm with $N_{ch} = 2$, 4, 8 and 10 channels, respectively, guarantees no interference (collision of packets) nor contention problems, and guarantees R_{fair} to every MAP. It can be seen that deployments with more rings/MAPs require more channels, $\eta_{spectrum}$ decreasing proportionally.

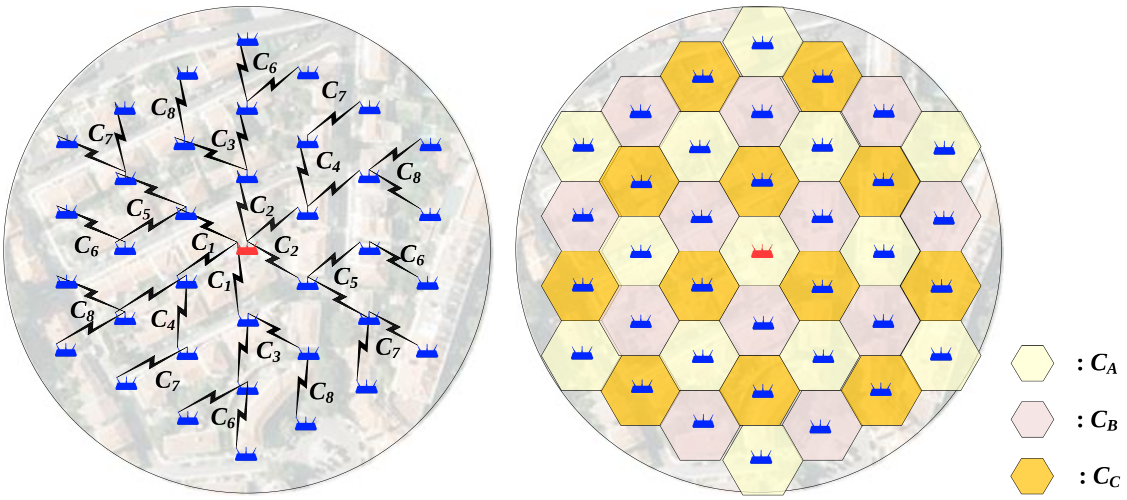
As an example, CA simulation results for $WMN_{3\ Rings}$ mesh-radios are depicted in Figure 6.24.a). In $\mathcal{M}_{1hop}$ links, channels C_1 and C_2 are used for links $\mathcal{L}_{0,r1}$ and $\mathcal{L}_{0,r2}$, respectively, with

$R_{phy} = 54$ Mbit/s. To guarantee no interference, these channels should not be reused by nodes within $d_i = 139$ m. For $\mathcal{M}_{2\,hop}$ links, channels C_3, C_4 and C_5 are assigned, with $R_{phy} = 12$ Mbit/s. As $d_i = 49$ m, each of these channels is reused, Figure 6.24.a), as the nearest co-channel nodes distance is 58 m. For $\mathcal{M}_{3\,hop}$ links, channels C_6, C_7 and C_8 are assigned, with $R_{phy} = 6$ Mbit/s. As $d_i = 41$ m, each of these channels is reused 4 times. Even having 3 MAPs transmitting and 1 receiving, it will not be interfered.

Table 6.11 – Spectrum efficiency of WMN deployments.

	R_{wmn} [Mbit/s]	N_{ch}	$\eta_{spectrum}$ [bit/s/Hz]
$WMN_{1\,Ring}$	34.2	2	0.9
$WMN_{2\,Ring}$	58.0	4	0.7
$WMN_{3\,Ring}$	58.0	8	0.4
$WMN_{4\,Ring}$	58.0	10	0.3

Next, the channel assignment to RAN's radios is evaluated. The IEEE 802.11b/g R_{phy} rates that support the MAPs R_{fair} guaranteed capacity per MAP for 1, 2 and both 3 and 4 rings topologies are 9, 5.5 and 2 Mbit/s, respectively, Figure 6.22. The associated interference ranges are 1.5, 1.3 and 1.2 hops. In this sense, the 3 available 802.11b/g channels are sufficient to guarantee no interference, when allocated as depicted in Figure 6.24.b).



a) RBN channel assignment. b) RAN channel assignment.

Figure 6.24 – Channel assignment for WMN_{3Rings} deployment.

In this section, hexagonal deployments of various numbers of rings are evaluated for the reference scenario. FERA explores the maximum system capacity and achieves the maximum throughput with two rings of MAPs. If the density of MAPs increases (3 or 4 rings), there is no added value in terms of performance, decreasing efficiency in terms of spectrum and total energy, fairness being guaranteed on any deployment.

6.3.2 Enlarged Scenario Area

The performance of WMN deployments for circular scenarios of increasing radius, r_{wmn}, is evaluated below. With a single gateway in the middle, throughput is bounded by the maximum capacity of the gateway, when the two 802.11a radios operate at R_{phy} = 54 Mbit/s, resulting in a R_{wmn} of 58 Mbit/s. Simulation results are presented in Figure 6.25. The more rings a scenario has, the nearer MAPs get, enabling higher R_{phy} rates that result in an increase of the achievable R_{wmn}. It can be seen, from Figure 6.25, that R_{wmn} = 58 Mbit/s is reached for scenarios of 50, 100, 150 and 200 m radius with respectively 1, 2, 3 and 4 rings.

Certain deployments do not reach this maximum capacity. For example, with r_{wmn} = 200 m and WMN_{2Ring}, MAPs are distant d_{map} = 80 m from each other, the maximum supported rate being R_{phy} = 18 Mbit/s, only enabling R_{wmn} = 27.5 Mbit/s. In extreme cases, certain deployments are not able to provide end-user connectivity to the entire area due to RBN or RAN communication range limitations. For r_{wmn} = 300 m and WMN_{1Ring}, no IEEE 802.11a rate and power combination enables communication within d_{map} = 200 m. On the other hand, for r_{wmn} = 200 m and WMN_{1Ring}, although d_{map} = 133 m is supported by R_{phy} = 9 Mbit/s, enabling an R_{wmn} = 15.3 Mbit/s, the associated r_{ap} = 67 m RAN coverage area is not supported by any IEEE 802.1b/g rate and power, for providing indoor end-users coverage. In other cases, RANs are able to cover the associated coverage area, but not achieving to offer R_{fair} as the WMN guarantees. For example, for r_{wmn} = 150 m and WMN_{1Ring}, d_{map} = 100 m is supported by R_{phy} = 18 Mbit/s enabling an R_{wmn} = 27.5 Mbit/s, with an R_{fair} = 4.6 Mbit/s. Still, the associated r_{ap} = 50 m coverage area is only achieved with R_{phy} = 2 Mbit/s, reducing R_{wmn} to 10.2 Mbit/s. These are system limitations, not related to the proposed FERA strategy.

It can be concluded that the performance of WMNs is limited by the system's characteristics, and not by the WMN intrinsic characteristics of the multi-hop environment and flow of traffic, which can be overcome by the proposed RRM strategy. WMNs with FERA explore the maximum system capacity and extend the coverage as much as possible.

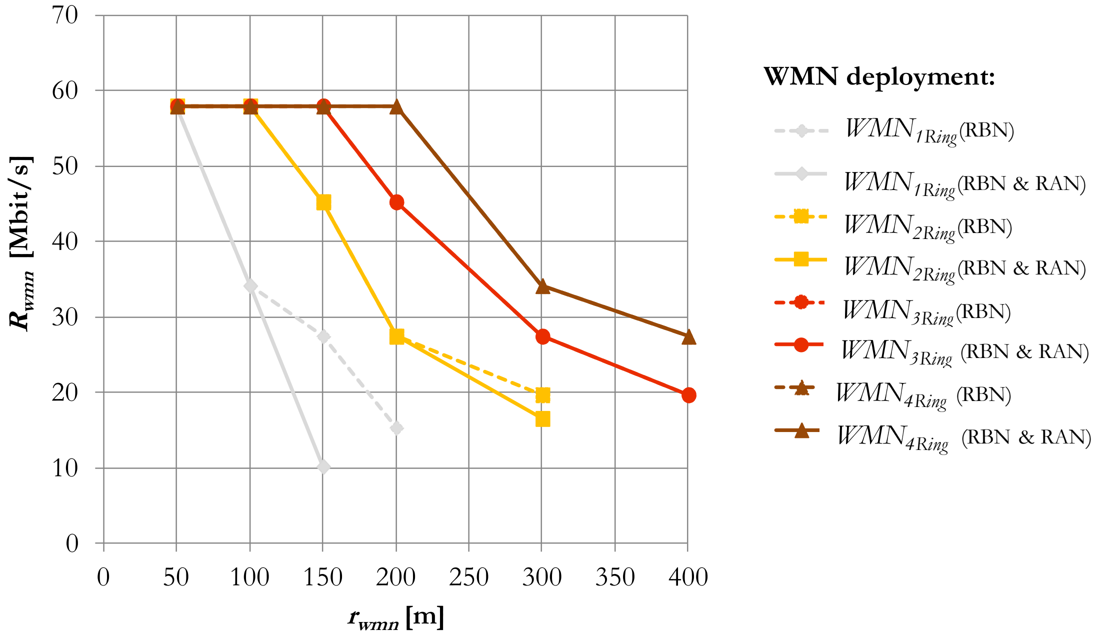


Figure 6.25 – Performance of different deployments for increasing scenario radius.

6.4 Random WMN Deployment Scenario

The spontaneous WMN scenario of randomly deployed MAPs with three MPP gateways, presented in Section 5.3.3, is evaluated, to evidence the capabilities of FERA in challenging conditions. Optimal routes are pre-determined for the various aggregated traffic flows. MAPs optimise autonomously their radio resources with FERA for the links with traffic, simulation results being depicted in Figure 6.26. As an example, links $l_{0,1}$ and $l_{0,2}$, with corresponding radios $M_{0,r1}$, $M_{1,r1}$ and $M_{2,r1}$ use the same configuration of resources: $R_{phy} = 54$ Mbit/s, $P_{tx} = 27$ dBm and C_9. Resources are dimensioned to achieve FERA's estimated MAPs' max-min fair capacity. Each set of MAPs connecting via a given MPP radio has assigned a common R_{fair} value, identified in Figure 6.27. For example, M_1, M_2 and M_3 use MPP's radio $M_{0,r1}$ to access the Internet, and have assigned an $R_{fair} = 9.7$ Mbit/s. To be noted that in this figure are not represented MPP nodes ($M_0, M_9, M_{12},$ and M_{21}), as their performance does not depend on the WMN (RAN traffic is directly offloaded via the gateway).

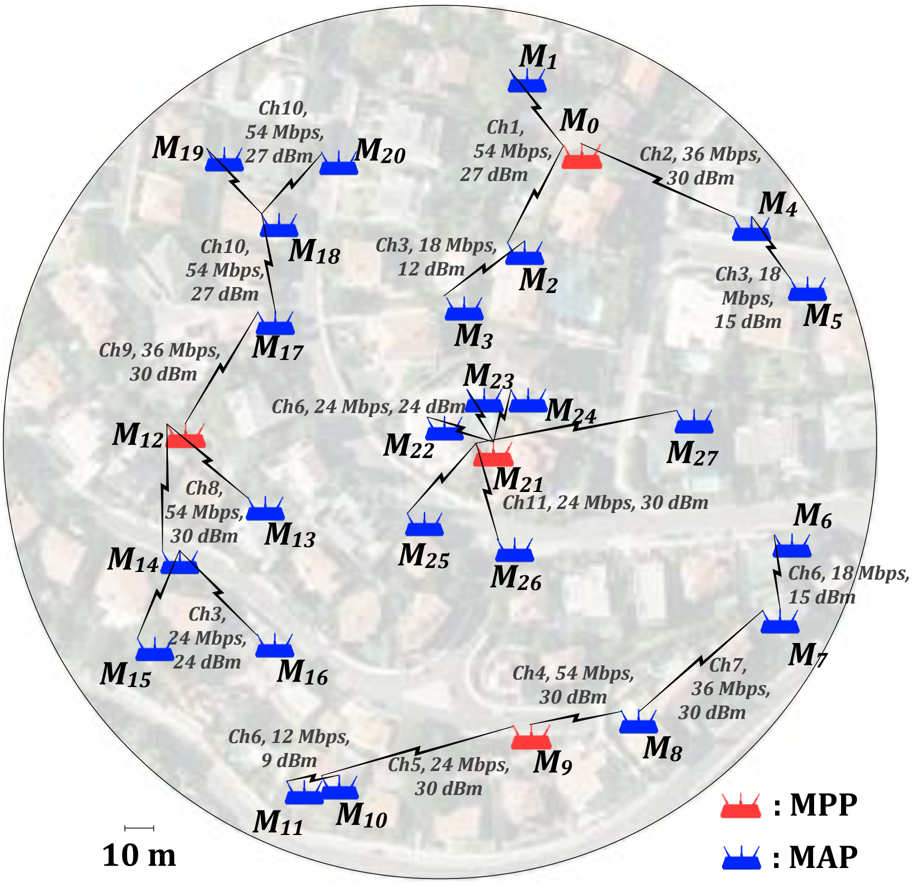


Figure 6.26 – Spontaneous WMN with traffic flows' links, with FERA's optimised resources.

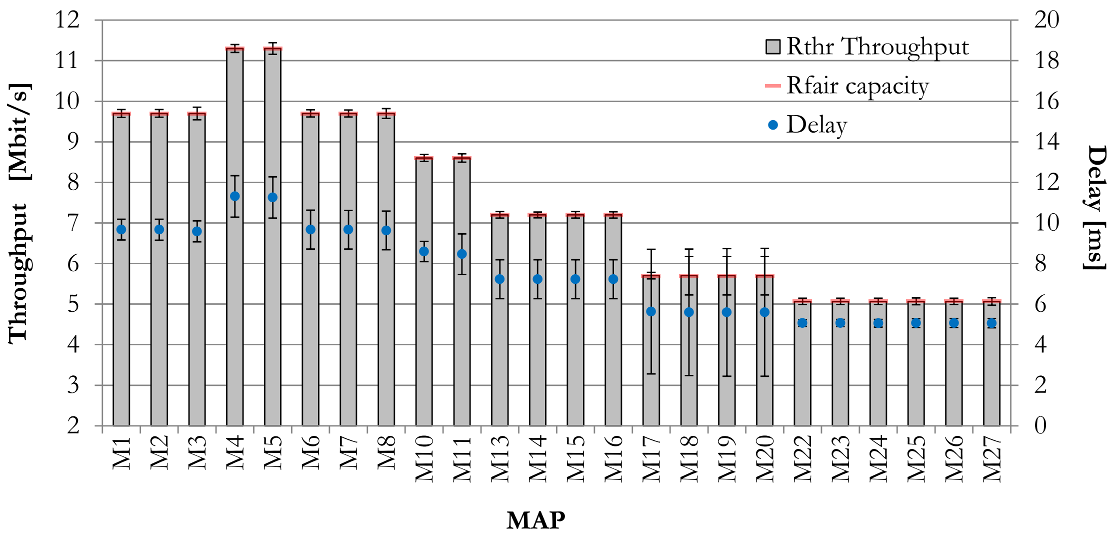


Figure 6.27 – Achieved throughput and delay for an offered load of R_{fair}.

The performance of the WMN in terms of achieved throughput R_{thr} for an offered load $R_{load} = R_{fair}$ is depicted in Figure 6.27. Results confirm that FERA configures efficiently resources, as the network is max-min fair in the allocation of resources to every MAP, with

$f_{max-min} = 1$. In fact, all MAPs achieve a throughput $R_{thr} = R_{fair}$, with a low standard deviation, $\delta_{packet} \approx 0\%$ and $\tau_{packet} < 12$ ms, even for MAPs several hops away from MPP. This is a low delay, compared with the 150 ms maximum delay allowed for one-way delay for voice [ITUT03]. This confirms that the multi-radio WMN with FERA overcomes the main limitation of classical single-radio WMNs, where throughput and delay per MAP strongly decrease with the number of hops from the gateway.

An analysis of some configurations of FERA is presented next. The distance between communicating MAPs dictates the maximum achievable rate. For example, node M_9 using the maximum power, P_{tx} =30 dBm, enables to operate at $R_{phy} =$ 54 Mbit/s in link $l_{8,9}$ of 36 m length, while in link $l_{9,10}$ of 69 m length, the maximum supported rate is $R_{phy} =$ 24 Mbit/s. This impacts directly in the available capacity for the corresponding branches, where $R_{fair}(\mathcal{M}_{9,r1})$ = 8.6 Mbit/s, while $R_{fair}(\mathcal{M}_{9,r2})$ = 9.7 Mbit/s, even if the later one serves one more MAP. This evidences how the propagation conditions between MAPs influence the achievable performance.

On the other hand, for certain communication ranges and bit rates, a lower power level is sufficient to guarantee communication. For example, for link $l_{6,7}$ to operate at $R_{phy} =$ 18 Mbit/s a $P_{tx} =$ 15 dBm is sufficient. This energy efficient minimisation of P_{tx} has beneficial effects in the reduction of interference, besides being energy saving.

The overall inexistence of interference is confirmed by the simulation results, where all simultaneous links achieve the expected throughput without suffering from collisions. FERA is efficient in the allocation of resources, reducing transmitted power as much as possible and enabling the efficient reuse of channels in many links, as it can be seen in Figure 6.26. For example, FERA reuses channel C_3 without interference in links $l_{2,3}$, $l_{4,5}$, $l_{14,15}$ and $l_{14,16}$. In fact, considering that M_2 is receiving from M_3 with M_4 simultaneously transmitting, ρ =12 dB > ρ_{min}(18 Mbit/s) = 9.6 dB. The same occurs inversely, when M_4 is receiving from M_5 and M_2 transmits, resulting in ρ =17 dB > ρ_{min}(18 Mbit/s). These results are only possible due to the efficient minimisation of rate and power. In fact, if a higher bit rate would be used, e.g., 54 Mbit/s, $l_{2,3}$ and $l_{4,5}$ would interfere.

FERA's capacity sharing mechanism is applied in links $l_{17,18}$, $l_{18,19}$ and $l_{18,20}$, where channel C_{10} is shared, Figure 6.26. Five flows of $R_{fair} =$ 5.7 Mbit/s have to be forwarded using the same channel (3 flows on $l_{17,18}$ and 1 on $l_{18,19}$ and $l_{18,20}$); to achieve this, the throughput of the channel must be above 28.5 Mbit/s, possible with the configured $R_{phy} = 54$ Mbit/s. Observing the simulation results in Figure 6.27, with this mechanism all MAPs achieve $R_{thr} =$ 5.7 Mbit/s, although with larger standard deviation, due to the existence of 4 nodes competing for the same channel, a relative burstiness existing when the channel is catched, vs. some periods where they have to wait for getting the channel. The capacity reduction mechanism of FERA is applied for $\mathcal{M}_{21,r2}$ (M_{22}, M_{23} and M_{24}). In fact, when $M_{21,r2}$ optimises its resources, no channel is available to operate at $R_{phy} = 54$ Mbit/s without interference. Thus, channel C_6 is re-used with a reduced $R_{phy} = 24$ Mbit/s and $P_{tx} = 24$ dBm, Figure 6.26, a configuration that guarantees no interference with the other links operating with this channel ($l_{6,7}$ and $l_{10,11}$). The available capacity is fully used by $\mathcal{M}_{21,r2}$, achieving $R_{thr} = R_{fair} =$ 5.1 Mbit/s. Curiously, the performance is similar for $\mathcal{M}_{21,r1}$ (M_{25}, M_{26} and M_{27}), which also uses $R_{phy} = 24$ Mbit/s, but due to propagation conditions, as $l_{21,27}$, of 67 m length, does not support higher rates.

Another interesting aspect is the impact of using multiple hops to reach MAPs. M_{10} and M_{11} are respectively 69 and 81 m distant from M_9, both reachable from M_9 in a single hop if $R_{phy} = 18$ Mbit/s and $P_{tx} = 30$ dBm are used. Nevertheless, trying to reach both MAPs from M_9 would only result in a $R_{fair} = 6.9$ Mbit/s for each. The proposed strategy configures M_9 to reach only M_{10}, establishing an extra hop from M_{10} to reach M_{11}. With this approach, $R_{phy} = 24$ Mbit/s can be used for $l(M_9, M_{10})$, rising R_{fair} to 8.6 Mbit/s. This is possible due to the fact that MAPs have two radios, able to operate simultaneously in 2 channels, not introducing extra delay nor share of capacity when relaying packets. In classical single-radio multi-hop scenarios this would not be advantageous, as the same radio would be used for both links, decreasing performance by half.

The strategy does a fair optimisation of radio resources to each MAP, determining a max-min fair capacity to each MAP, R_{fair}, that guarantees fairness. Each MPP's radio has associated a different R_{fair}, dependent on the number of associated MAPs and topological conditions, but guaranteed equally to this sub-set of MAPs. These values match with the simulation results of maximum achievable throughput per MAP that still guarantees fairness conditions to all MAP. The flow-control mechanism guarantees fairness, preventing some MAPs to be favoured for the price of others being disfavoured. Increasing the traffic load beyond R_{fair} results in unfairness conditions, where the throughput for certain MAPs decreases.

As an example, the performance of MAPs M_{13}, M_{14}, M_{15} and M_{16} is considered for analysis. These MAPs use MPP $M_{12,r1}$ as gateway. FERA configures R_{fair} = 7.2 Mbit/s for each MAP. To evaluate the evolution of the throughput per MAP with increasing load, the flow-control mechanism is deactivated. Simulation results of the achieved throughput per MAP are depicted in Figure 6.28. Up to 7.2 Mbit/s, the three MAPs aggregate fairly the offered load. Nevertheless, when the offered load is increased beyond 7.2 Mbit/s (equally to every MAP), fairness decreases, augmenting the contrast between favoured MAPs (achieving a throughput above R_{fair}) and disfavored ones (achieving a throughput below R_{fair}). For example, for an offered load of R_{load} =8 Mbit/s, M_{16} is dissatisfied, as its throughput is reduced to R_{thr} =5 Mbit/s, below the assigned R_{fair}, while M_{13}, M_{14} and M_{15} are favoured, achieving a R_{thr} =8 Mbit/s, above the assigned R_{fair}. These unfair situations augment for higher R_{load} values. For R_{load} = 12 Mbit/s, M_{13} and M_{14} are favoured, achieving a R_{thr} =12 Mbit/s, while, M_{15} achieves only 5 Mbit/s and M_{16} 0 Mbit/s. MAPs nearer the MPP are in natural advantage. It can be seen in Figure 6.28 that the fairness metric, $f_{max-min}$, correctly identifies situations of unfairness. In fact, $f_{max-min}$ = 1 for $R_{load} \leq R_{fair}$. On the other hand, higher load values ($R_{load} > R_{fair}$) result in a decrease of fairness ($f_{max-min}$ < 1), where some flows are favoured and others are dissatisfied.

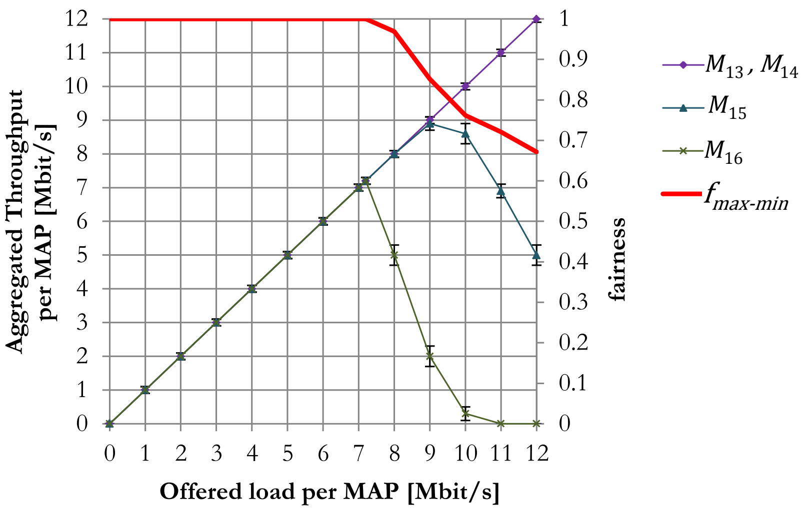


Figure 6.28 – Variation of throughput and fairness with the offered load per MAP.

For MAPs of the same branch (associated to the same MPP) with different offered loads, fairness is guaranteed as long as the sum of the MAP's R_{load} is below the capacity of the MPP. For example, if M_{13} has R_{load} = 12 Mbit/s (above R_{fair}) and M_{14}, M_{15} and M_{16} an

R_{load} = 5.6 Mbit/s (below R_{fair}), all MAPs would manage to fairly aggregate their offered load, as the total load (28.8 Mbit/s) is below M_{12}'s capacity (29.0 Mbit/s).

As a concluding remark, in this section with more challenging scenario, it is shown how FERA fully exploits the heterogeneous traffic and propagation characteristics of each link in a scenario with random deployment of MAPs and multiple MPPs gateways, using all its mechanisms to guarantee a max-min fair capacity to every MAP. The resulting network is 100% fair, without packet loss and delay below 12 ms, supporting real time services.

6.5 Opportunistic Connectivity Service

For evaluation of the proposed Opportunistic Wireless Resource Allocation OConS Service (OWROS), presented in Section 4.4, the residential neighbourhood scenario described in Section 5.3.4 is used. First the WMN performance without OWROS and without the flash crowd is evaluated. The pre-computed paths are depicted in Figure 6.29. WMRs' resources of the spontaneous network are self-optimised by FERA, represented in Figure 6.29 for each mesh link, identifying also the WMCs covered by each WMR.

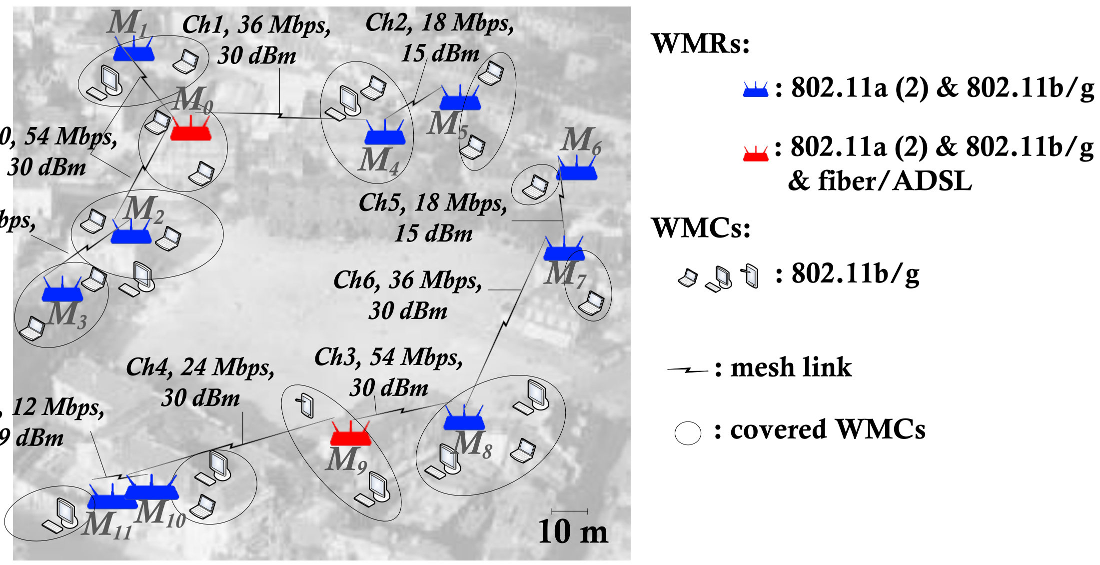


Figure 6.29 – Optimised radio-resources by FERA for each mesh traffic flow link, and identification of covered WMCs.

The theoretically estimated max-min fair aggregated throughput, R_{fair}, together with the simulation results for the aggregated throughput, R_{thr}, for $R_{load} = R_{fair}$ and for the packet delay, τ_{packet}, are represented in Figure 6.30. FERA manages to guarantee to every WMR its maximum capacity, with low delays. It can be offered by the RAN to WMCs by using $R_{phy} = 18$ Mbit/s in the 802.11g radio. MPP gateways naturally achieve the maximum aggregated throughput (for $R_{phy} = 54$ Mbit/s), as they are directly connected to the gateway.

Next, the case of a sudden flash crowd of end-users, without using OWROS, is analysed. With a range up to 86 m for IEEE 802.11g at 18 Mbit/s, every WMC of the crowd is within communication range of at least one WMR. Still, the limited number of orthogonal channels to be used by all WMRs (only 3 orthogonal IEEE 802.11g), and the associated interference range (twice the communication range), do not allow all WMRs to use simultaneously the dimensioned capacity, R_{fair}, as nodes would interfere. To reduce interference ranges, lower power levels have to be used, reducing also the coverage range of each WMR. In conclusion, a large number of WMCs of the flash crow will remain uncovered by the WMN, as represented in Figure 6.31.

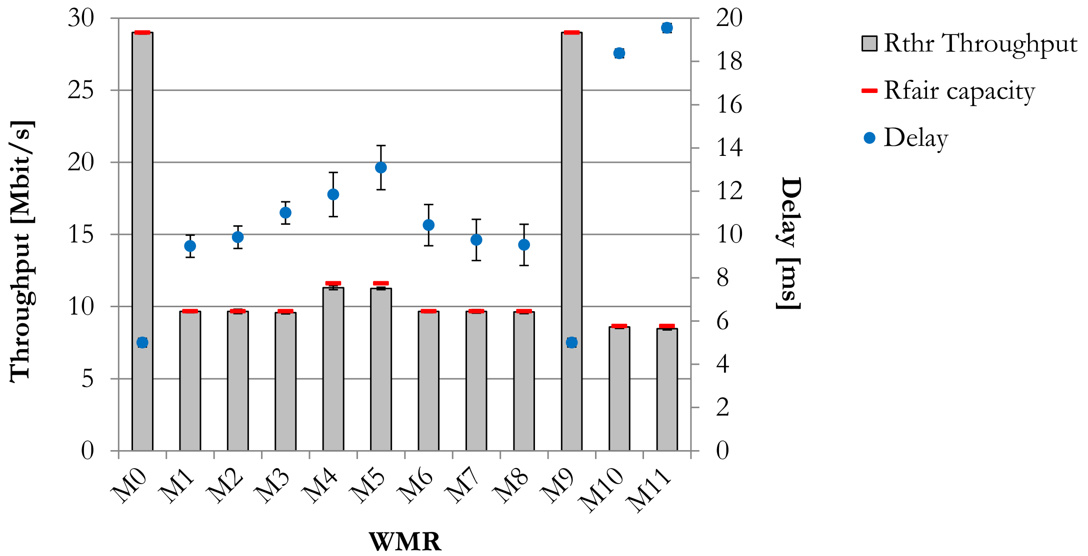


Figure 6.30 – Performance of the WMRs for the community-based scenario.

The performance of the community-based scenario is now evaluated when OWROS is offered to WMCs willing to join the community-based WMN. In this case, besides WMRs, some WMCs opportunistically assume network functionalities suggested by OWROS, becoming SuperWMCs, as shown in Figure 4.12. SuperWMCs capabilities are explored by the service in the most advantageous way, as illustrated in Figure 6.32. Many provide access and forwarding network functionalities, enabling to provide coverage to all WMCs and increase the offered capacity. Others share within the WMN their wireless LTE connectivity to the fixed Internet, providing extra gateways that increase the overall available capacity in the WMN.

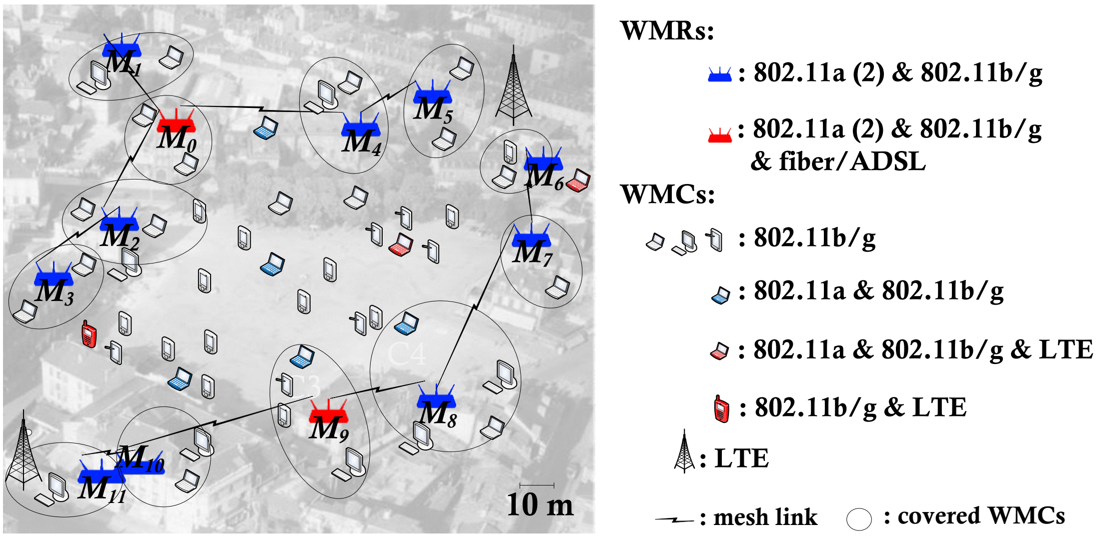


Figure 6.31 – Classical WMN with a flash crowd of end-users, evidencing it is unable to provide coverage to all flash crowd WMCs.

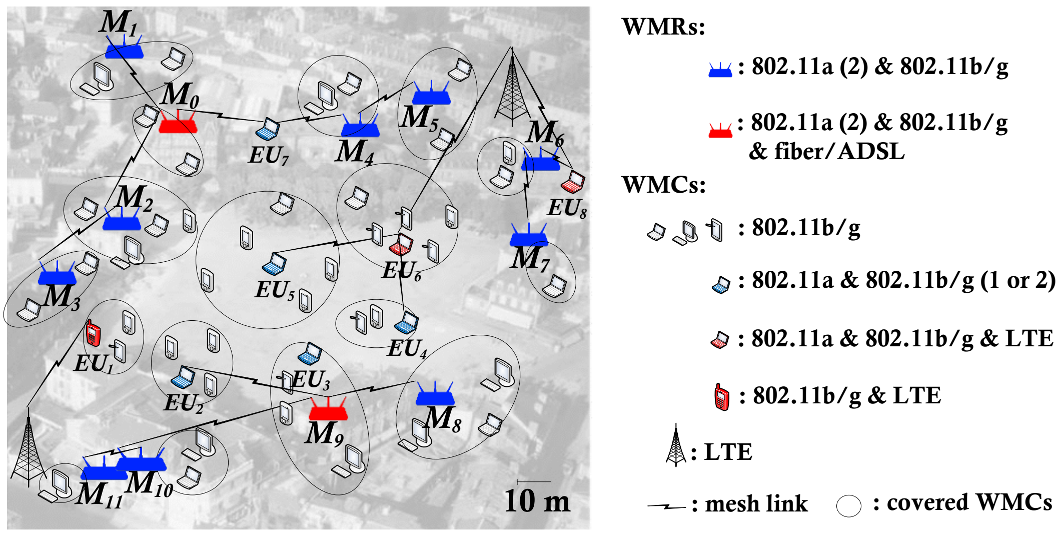


Figure 6.32 – Community-based WMN with a flash crowd, where the proposed OWROS service enables some WMCs to become SuperWMCs, guaranteeing coverage to all WMCs.

An analysis of various improvements brought by SuperWMCs is presented next. WMC EU_1 has both an LTE and an 802.11g interface. After accepting an invitation to join the community, it is upgraded with OConS-related software, and starts the orchestration process described in Figure 4.12. It receives the conditions of the network, and the available OWROS mechanisms. Based on its capabilities, SOP validates the two mechanisms it can assume: gateway and access provisioning, with the 802.11g and LTE interfaces, respectively, accepting to become a SuperWMC and launch OWROS, starting to provide Internet access to end-users over the 802.11g interface. For the case of EU_2, as it has both 802.11g and 802.11a interfaces, the SOP suggests to launch access and forwarding mechanisms, providing access to end-users via its 802.11g, while the 802.11a forwards traffic to R9. For EU_3, SOP does not suggest to become SuperWMC, as it is not necessary for the network. For EU_6, SOP launches OWROS, using its LTE connection as a gateway to the Internet, its 802.11g to provide access to uncovered end-users, and its 802.11a interface to forward traffic to EU_5 and EU_4. EU_7 is equipped with two 802.11a radios, and will launch FERA's forwarding mechanism to forward the traffic between M_0 and M_4, reducing the hop distance, thus, enabling to use a higher bit rate and increase the overall throughput. Finally, SOP will suggest EU_8 to use its LTE interface as gateway and is 802.11a one as forwarder, EU_8 provides a faster access to the Internet to M_6 and M_7.

The simulation results for the WMN with the improvements brought by OWROS are depicted in Figure 6.33. It can be seen that the offered R_{fair} capacity has increased for many WMRs, as more gateways to the Internet are available and the ranges between many forwarders is shorter, due to the SuperWMCs. SuperWMCs also provide coverage extension to many WMCs that originally were not covered.

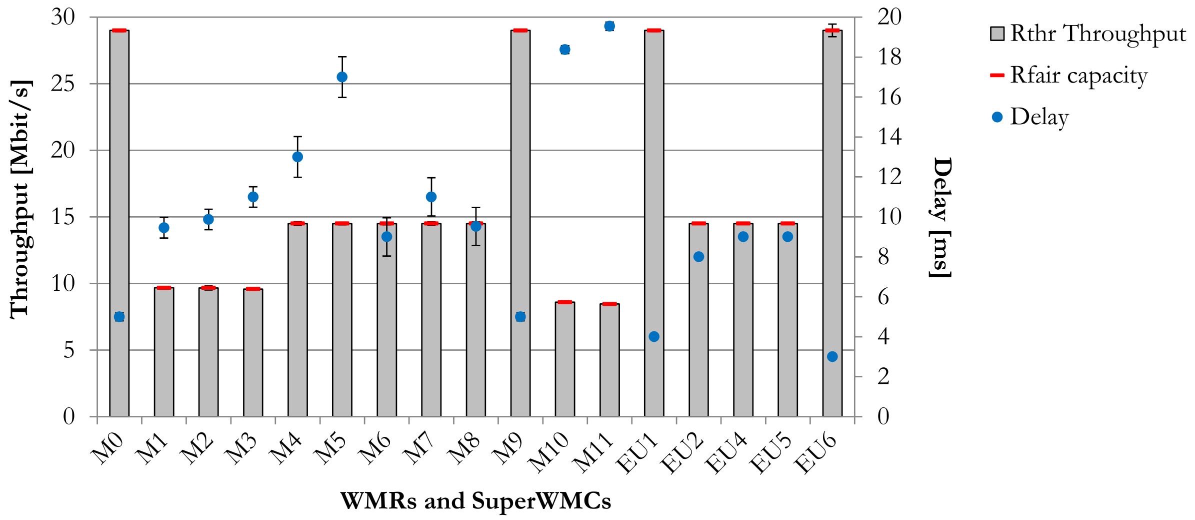


Figure 6.33 – Performance of the aggregating nodes (WMRs and SuperWMCs) of the opportunistic WMN, when the OConS service assigns networking tasks to many WMCs.

For the flash-crowd scenario, OWROS enhances the throughput of WMCs. With OWROS, WMCs have better connectivity conditions than without OWROS, Figure 6.34, almost doubling the average throughput per WMCs, from 3.5 to 6.1 Mbit/s. In fact, in a classical WMN, an increase of the number of WMCs means that the same available capacity has to be shared among more end-users.

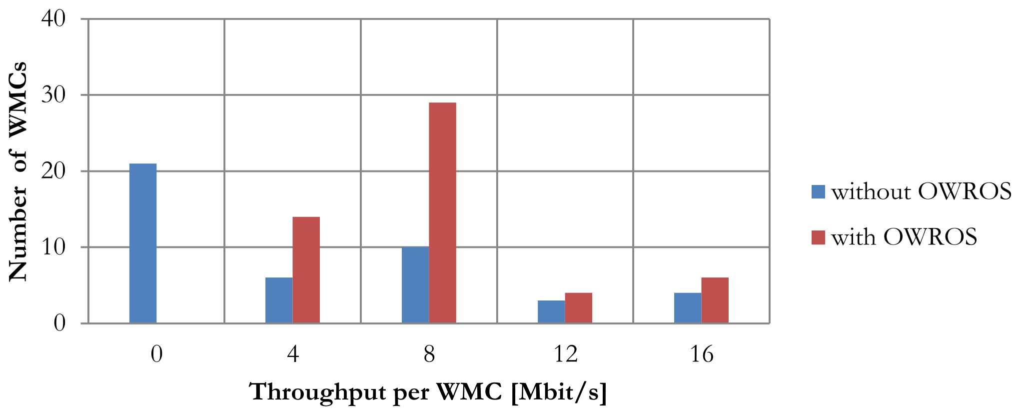


Figure 6.34 – WMCs' performance without and with OWROS.

It is concluded that the presence of a flash crowd in a community-based WMN scenario can be beneficial in the improvement of coverage, capacity, and connectivity, when the proposed OConS service is offered by the community to joining members. Several WMCs become SuperWMCs, providing access, forwarding or gateway functionalities in the WMN. R_{fair} increases for many WMRs, as more gateways are available, and ranges between many forwarders are shorter, thanks to the SuperWMCs. SuperWMCs also provide coverage extension to many WMCs that originally were not covered. OWROS enhances the average throughput per WMC from 3.5 to 6.1 Mbit/s. In fact, in a classical WMN, an increase of the number of WMCs means that the same available capacity has to be shared among more end-users. Using OWROS, an increase of WMCs may opportunistically bring benefits in terms of connectivity, coverage and capacity to the overall WMN and existing WMCs.

Chapter 7

Conclusions

Chapter 7 presents the main conclusions of the thesis. Section 7.1 presents a summary of the thesis. Section 7.2 presents the main findings and results. Section 7.3 provides some considerations about future work.

Key concepts: conclusion; summary; novelty; major results; future work.

7.1 Summary

This thesis is organised in 8 chapters. Chapter 1 presents a brief history of wireless mesh networks, a challenging evolutionary path of wireless communications that extends the use of the wireless medium from access towards backhaul networks. It also presents the motivation and main objectives of the thesis, together with the identification of the claimed novelties and contributions, as well as the research path and strategy plan.

In Chapter 2, basic concepts of WMNs are presented as well as an overview of its main characteristics is presented. Then, scenarios and applications where wireless mesh technology is likely to provide a more versatile or affordable solution than other wired or wireless technologies are highlighted. Critical design factors and performance issues from different domains of WMNs are presented. Advances and research challenges are then identified, related to the MAC layer, as well as to multi-radio and multi-channel strategies. An overview of existing solutions for channel assignment, transmission power control and rate adaptation mechanism is then presented. Finally, the key self-organisation principle on which the management of WMNs is based and the challenging community-centric concept, where the WMN paradigm seems the most appropriate solution to enable the spontaneous formation of such networks.

Chapter 3 presents novel frameworks for management of WMNs. First, a novel organisational framework for the opportunistic management of flexible and spontaneous WMNs is proposed, where an opportunistic resource manager suggests specific functionalities and/or tasks that nodes are free to accept or not. Then, a novel functional open connectivity services architecture (OConS) is proposed, enabling the flexible and modular description of connectivity resources and mechanisms, and the orchestration of both legacy and enhanced connectivity mechanisms, which can be dynamically adapted, integrated and orchestrated into OConS Services offered to the network.

Chapter 4 proposes strategies for the management of WMNs radio resources. First, design choices are setup, identifying the assumptions made. Then, a set of models that support the proposed strategy are presented. First, characteristics of WMNs are modelled. Secondly, radio propagation aspects useful for the proposed strategies are presented. A multi-radio node model is presented, with a radio agnostic abstraction-layer on top of the Data-Link layer, a virtual MAC supporting multiple radio interfaces (MAC & PHY), to higher layers (IP) representing the abstraction of a single one. It enables the transparent management of multiple radios, where RRM strategies can be implemented. A hybrid channel management policy is then presented, guaranteeing connectivity with any neighbouring node. After these models, the novel FERA strategy is presented, for the self-organised management of tightly interdependent radio resources such as channels, data-rates and transmission power levels of multi-radio nodes' WMNs. It is composed of several mechanisms that enable rate adaptation, transmitted power control, channel assignment and flow control. OWROS is another proposed strategy, an opportunistic WMN resources allocation OConS service, which can opportunistically orchestrate adequate mechanisms in a node according to its capabilities. Mechanisms may by "legacy" client access or Internet gateway provisioning mechanisms, as well as the novel mesh forwarding FERA.

Chapter 5 describes the implementation in the OPNET Modeler simulation platform of the multi-radio mesh node and of the proposed strategy. Then, input configuration parameters and output evaluation metrics are identified. Finally, a set of scenarios is defined for performance evaluation, ranging from structured hexagonal deployments with a single gateway, to randomly deployed scenarios with multiple gateways and a flash crowd of end-users with heterogeneous terminals.

In Chapter 6, performance results are presented for the FERA strategy and the OWROS service, proposed in Chapter 4, for the scenarios defined in Chapter 5. Performance is evaluated using the evaluation metrics presented in Chapter 4. In a preliminary discussion, coverage, throughput and delay bounds are identified, as well as general considerations on the proposed FERA strategy. Secondly, an evaluation of FERA for the reference scenario is done, presenting results of an analytical evaluation, which are then compared with simulation ones. The impact of the variation of number of channels is studied in detail, and a comparison of FERA with other strategies is presented. As a third evaluation step, the performance of FERA for different scenarios is compared, varying the number of mesh nodes and size of the scenario. As a fourth analysis, a random WMN deployment scenario is evaluated, a larger scenario with more mesh nodes and several gateways to the Internet. Finally, as fifth step, the performance of the novel opportunistic connectivity service is evaluated for a random residential neighbourhood scenario with a flash crowd of users equipped with heterogeneous terminals.

Finally, the current chapter presents novelties and main findings, also providing some considerations about future work.

7.2 Main Findings

This thesis claims novelties within two fields of the management of WMNs. On the one hand, novel frameworks for the management of WMNs are proposed, and on the other, strategies integrating multiple mechanisms are proposed for the management of radio resources of multi-radio mesh nodes. It is shown that the combination of these two result in high performing, efficient, fair and opportunistic WMNs.

An organisational framework for the flexible and opportunistic formation and maintenance of spontaneous and networks WMNs is proposed, relying on the concept of self-organisation and collaboration. The main idea is that the network takes advantage of the specific resources and characteristics of heterogeneous nodes in an opportunistic fashion. In our vision, any wireless node (routers and clients) can perform any network functionality, if they can and if they wish. These nodes collaborate in a network in which they self-organise and share duties by taking tasks according to their capabilities, all having one common objective: make the network working as efficient as possible. By introducing this flexibility, spontaneous networks are likely to respond better to the expected services.

The above framework needs an architecture and communication protocol to support such exchange information, as well as to implement network functionalities in nodes. An Open Connectivity Service (OConS) architecture is proposed, flexible and modular in the description of connectivity resources and mechanisms, based on the identification of functional entities and their interfaces. It enables the orchestration of both legacy and enhanced connectivity mechanisms, which can be dynamically adapted and orchestrated into OConS Services offered to the network.

A novel multi-radio node model is also proposed with a virtual MAC, a radio agnostic abstraction-layer supporting multiple radio interfaces (MAC & PHY), to higher layers (IP) representing the abstraction of a single one. It enables the transparent management of multiple radios, where radio resource management strategies can be implemented, without needing to introduce changes to the system in use. A hybrid channel management policy is considered, flexibly guaranteeing connectivity with any neighbouring node.

This thesis also claims two strategies for the management of WMNs radio resources: a novel Fair and Efficient Resource Allocation strategy (FERA) and an Opportunistic WMN Resources allocation OConS Service (OWROS). FERA is designed for efficient and fair mesh forwarding in multi-radio WMNs. It combines multiple mechanisms that efficiently optimise radio resources (rate, power and channel) to guarantee max-min fair capacity to every node. FERA is composed of a rate adaptation and power control mechanism, sensitive to the fat-tree traffic specificities of WMNs, using the highest bit rates at MAP gateways and using, for the ramified links, the minimum ones that satisfy their capacity needs. This enables to efficiently reduce the transmitted power and interference, advantageous for channel reutilisation. FERA also integrates a load and interference aware channel assignment mechanism, allowing the simultaneous operation of all links without interference. When this is not achievable, two auxiliary mechanisms of capacity sharing and capacity reduction can be sub-sequentially used, reducing the capacity of certain MAPs to guarantee fairness to all nodes. FERA's gateway flow-control mechanism guarantees that all MAPs respect the allocated capacity, guaranteeing that every MAP is able to operate at its max-min fair capacity. Several network and usage evaluation metrics are defined and used to evaluate the performance, namely throughput, delay, max-min fairness, capacity usage efficiency, energy efficiency and spectrum efficiency.

Due to the novel organisational framework and novel OConS architecture, this thesis also proposes OWROS, which exploits network conditions and node capabilities to improve connectivity. Appropriate connectivity mechanisms, such as "legacy" client access or Internet gateway provisioning mechanisms, as well as the novel mesh forwarding FERA strategy, may be orchestrated by OWROS in nodes. In a community-based neighbourhood WMN scenario of randomly deployed mesh nodes, where a flash crowd of end-users equipped with heterogeneous terminals appears, this service improves the network performance, increasing overall coverage, connectivity and capacity.

Besides the innovative perspective presented previously, major results related to specific achievements obtained throughout this work, which are summarised in the following paragraphs.

The problem of flexibility in WMNs for spontaneous community-based networks was addressed. One supports the argument that the traditional two-tiered architecture is too rigid to adapt to the heterogeneous nature of community nodes. In order to solve this problem, one proposes a new architectural framework that completely separates the functional plane from the physical one. The operation of the network is planned in such a way that benefits from the opportunistic possibilities of the nodes, instead of static role assignment. This is achieved through the concept of super wireless mesh clients, which are nodes whose characteristics (mobility, computational capacity, memory availability, etc.) are sufficient for the client to perform tasks usually accomplished only by mesh routers (thus, increasing the availability of the infrastructure). One shows through an example, the advantages of using our proposal.

An alternative approach has been presented to handle connectivity in the Future Internet, based on Open Connectivity Services. One claims that the proposed architecture serves the two sought goals: first, it has the required degree of novelty, openness and innovation so as to appropriately cope with the challenges of the new services and applications. On the other hand, it is flexible enough so as to integrate and orchestrate the already existing solutions, as well as those that are not yet available. In this sense, OConS ensures a smooth migration strategy and the required flexibility to incorporate new mechanisms as they become available. One has illustrated how the architecture can be used to effectively address some of the most relevant application scenarios of the Future Internet, namely Cloud Networking and Network of Information. Besides, OConS is able to integrate mechanisms that are usually considered on a completely orthogonal manner; by combining them, one argues that the joint operation would lead to better performances, in contrast with the sub-optimal (or even contradictory) operations of today's communications. The heart of the OConS operation is the orchestration mechanisms that operate at different connectivity levels: link, network and flow. They instantiate, on a dynamic manner, the mechanisms that are best suited to handle the particular requirements of the applications and services requested by the users. The OConS architecture is based on three functional entities, corresponding to the basic phases of any connectivity process: information gathering, decision taking and decision enforcement. This common way of representing all the involved mechanisms allows their easy orchestration and integration.

The FERA strategy was implemented in OPNET, its performance being compared with analytical results. The analysis of results shows that this strategy exploits 100% of the system capacity, guarantees a maximum fair throughput per node, and uses efficiently capacity, spectrum and energy. FERA's autonomous configuration of resources on each MAP and the resulting performance are evaluated through simulation for two different scenarios and using IEEE 802.11a, a classical hexagonal deployment and a random one.

For the classical hexagonal deployment of 19 MAPs with a single MPP gateway at the centre in a circular scenario of 100 m radius, 40 m of each other, and 5 available orthogonal channels, is shown that FERA's resources assignment guarantees to every MAP a max-min fair capacity of 3.2 Mbit/s (dictated by the system and propagation environment characteristics), being 100% max-min fair, without packet loss and a packet delay below 6 ms. The network's efficiency in the usage of available capacity is 69% (upper bounded by system MAC/PHY overheads that limit throughput), minimises efficiently the use of transmitted power, with $\eta_{energy} = 26.5$ Mbit/J, and efficiently uses spectrum, with $\eta_{spectrum} = 0.58$ bit/s/Hz. It is shown that even if more than 5 channels are available, FERA efficiently configures its resources with only 5. For a lower number of channels down to 1, it is shown how FERA optimises resources always managing to guarantee a max-min fair capacity to every MAP, even if low. FERA outperforms existing solutions, such as HMCP, MesTIC and LACA.

Scenarios of various sizes were evaluated, between 50 and 400 m, with hexagonal deployments of 1 to 4 rings of MAPs. It is concluded that the performance of WMNs is limited by the system's characteristics, and not by the WMN intrinsic characteristics of the multi-hop environment and flow of traffic, which can be overcome by the proposed RRM strategy. It is proven in the present study that, independently of the system in use, WMNs with the proposed RRM mechanism enable to explore the maximum system capacity and extend the coverage as desired. Several system improvements (Multiple-Input Multiple-Output (MIMO), higher modulations and receiver sensitivities of novel standards), which result in higher system physical data-rates and communication ranges, will enable higher WMN performance levels reached using the proposed FERA strategy.

For a more challenging scenario of 400 m radius, with 28 MAPs randomly distributed and 4 MPPs gateways, it is shown how FERA fully exploits the heterogeneous traffic and propagation characteristics of each link, using all its mechanisms to guarantee a max-min fair capacity to every MAP, ranging between 5 and 11.2 Mbit/s. It is 100% fair, without packet loss and delay below 12 ms, supporting real time services.

Spontaneous community-based WMNs networks, of random deployment and distributed management, present many connectivity and coverage challenges. When a flash crowd of end-users with heterogeneous devices intends to access such a network, these limitations are evidenced even more. It is shown through simulation how this OConS service, when offered by the community-based WMN, can be orchestrated in nodes willing to join the community WMN by cooperating. OWROS is able to orchestrate, in nodes with adequate capabilities, networking functionalities, such as end-users access provisioning, Internet gateway connectivity, and mesh forwarding connectivity. It is shown how the presence of an end-users flash crowd in a community-based WMN scenario can be beneficial in the improvement of coverage, capacity, and connectivity, when the proposed OConS service is offered by the community to joining members. Due to OWROS, several of these WMCs may become SuperWMCs, providing access, forwarding or gateway functionalities in the WMN. R_{fair} increases for many WMRs, as more gateways are available and ranges between many forwarders are shorter, thanks to the SuperWMCs. SuperWMCs also provide coverage extension to many WMCs that originally were not covered.

OWROS enhances the average throughput per WMC from 3.5 to 6.1 Mbit/s. In fact, in a classical WMN, an increase of the number of WMCs means that the same available capacity has to be shared among more end-users. Using OWROS, an increase of WMCs may opportunistically bring benefits in terms of connectivity, coverage and capacity to the overall WMN and existing WMCs.

As a final conclusion, it is shown that the combination of the two innovations claimed in this thesis – novel frameworks and novel strategies for the management of multi-radio WMNs – transparently enable to fully explore and equally share the capacity of the communication systems in use. The combination of these innovations provide the means to achieve high performing, efficient, fair and opportunistic WMNs of both structured and randomly deployed nodes, with single or multiple Internet gateways

7.3 Future Work

Naturally, this work can be continued by exploring several other topics related to the management of WMNs. Examples of these topics are proposed below.

The integration of several system improvements (MIMO, higher modulations and receiver sensitivities) will be of interest, as it will result in higher system physical data-rates and ranges, enabling higher WMN performance levels. In particular, the integration of channel aggregation capabilities in FERA (suggested in many standards, such as IEEE 802.11ac or LTE) enables higher bit rates and throughputs, increasing the overall available capacity that can be fairly distributed among nodes. This is of special interest for gateway nodes, which are typical traffic bottlenecks, enabling higher throughputs. Nodes some hops away from gateways will not use such mechanism, as the forwarded throughput decreases due to natural traffic ramification, the bit rates available with a single channel being sufficient to support the capacity needs.

The integration of other mechanisms in OWROS is also be of interest, such as multipath routing, network coding, or mechanisms related to delay tolerant networks. In particular, a multi-path routing protocol could be implemented and its performance compared to single-path routing protocols, when using FERA. On the other hand, the optimisation of traffic flows' paths could also be integrated in the FERA strategy, which could also influence the nodes through which traffic flows, providing a more refined optimisation of available communication resources.

Together with the optimisation of RBN resources, the optimisation of RANs' radio resources (channel, bit rate and transmission power) can also be studied, integrated and evaluated, to see the E2E impact of FERA in the performance of typical services used by end-users. In particular, the usage of specific service mixes can be evaluated, with an asymmetric mix of up- and downlink traffics.

Specific application scenarios could be studied, to evaluate the performance of the foreseen services they should provide. Other deployments can be analysed. In particular, grid ones, used in many metropolitan areas, could be evaluated. Realistic propagation conditions of a specific geographical area could also be considered, to evaluate the performance of FERA.

The performance of legacy IEEE 802.11a mesh nodes with FERA strategy can also be compared with an implementation of multi-radio nodes with IEEE 802.11s mesh standard. On the other hand, the proposed FERA strategy can be used to propose enhancements to the IEEE 802.11s standard.

The network energy efficiency topic can be further explored. Analysis of the offered traffic variations during the day may be used by new mechanisms that turn off certain mesh nodes. In fact, when offered traffic is low, less traffic needs to be forwarded, and lower bit rates that enable larger communication distances may be used.

The implementation of FERA and OWROS in a testbed, like the KAUMesh multi-radio/multi-channel wireless mesh one [KAUM13], would be a second step for the validation of the performance of these strategies.

Another future and relevant research activity that can be further extended is considering mesh-radios with more than two radios for mesh forwarding, to be evaluated and compared with the selected approach of two radios for mesh and one for access. As current mobile terminals are equipped with heterogeneous interfaces, the combined use of different communication standards for mesh connectivity is of special interest (e.g., WLAN, WIMAX and LTE), enabled by an extension of the OWROS opportunistic service.

Appendix A

Overview of WMN Standards

Appendix A presents an overview of existing WMN standards for Wireless Personal, Local Metropolitan and Wide Area Networks.

A.1 Wireless Personal Area Network Mesh

WPANs are short range wireless networks (typically 10 m) for interconnecting wireless devices within a personal operating space, allowing them to communicate and interoperate with each another. WPANs are short-range, low power, low cost and small networks. The IEEE 802.15 working group has currently several standards designed for different purposes, such as Bluetooth [IEEE07c], High Rate (HR) and Low Rate (LR) WPANs (WiMedia [IEEE03a] and Zigbee [IEEE03b]). The IEEE 802.15.5 group [IEEE06] specifies an architectural framework for interoperable, stable, and scalable wireless mesh topologies for WPAN devices. IEEE 802.15.5 defines PHY and MAC layers modifications and enhancements to IEEE 802.15.3/3b [IEEE03a], [IEEE05] and IEEE 802.15.4 [IEEE03b] standards to support mesh networking. A mesh WPAN network employs full mesh topology or partial mesh topologies: in the full mesh topology, each node is connected directly to each of the others; in the partial one, some nodes are connected to all the others, while others are only connected to those nodes with which they exchange most of the data. IEEE 802.15.5 developed a 2 hierarchy levels approach, where several Piconet Coordinators (PNCs) interconnect to form a mesh network, Figure A.1 [IEEE06]. The proposal is based on the so-called meshed tree approach. In a Mesh WPAN, instead of one PNC, several PNCs are allowed to participate. Therefore, the single instance that coordinates the channel access (the PNC) is replaced by a homogenous set of Mesh-PNCs (MPNCs), which will negotiate the occupancy of the channel between them. As seen in Figure A.1, data can be transmitted between devices belonging to one PN, between devices and their MPNC, between MPNCs, or between devices and MPNCs/devices of another PN (if the devices possess a light-weight mesh layer enabling the addressing of devices in other piconets). While the first two items describe intra-PN communication, the last two describe inter-PN communication.

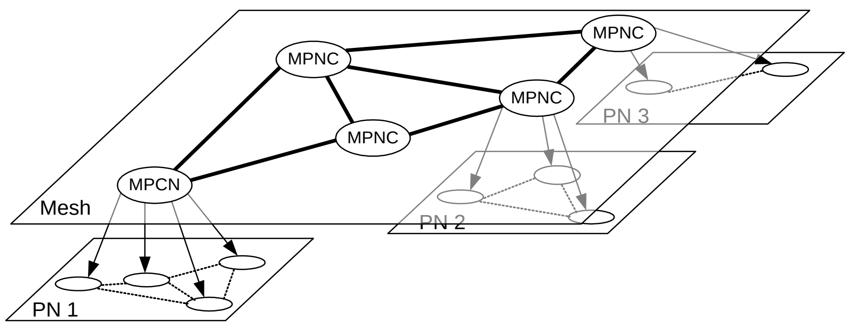


Figure A.1 – Two level hierarchy of the mesh architecture (extracted from [IEEE06]).

PNCs must coordinate access of devices in their WPAN to the wireless medium. It is the PNC's responsibility to mute their associated devices during specific intervals, to let neighbouring PNC and devices communicate interference-free [WaMB06]. For intra-PN traffic, the MPNC has to reserve the needed time during the superframe, and assign it to the participating devices of his PN. In contrast, inter-PN traffic requires a negotiation of the channel occupancy for every link that is needed for this traffic. A special channel time management negotiation protocol is defined for inter-PNC traffic, which is also coined mesh traffic. The superframe is partitioned into equal-length Medium Access Slots (MAS) used for addressing medium reservations between MPNCs. MAS are reserved using a three-way handshake between transmitting and receiving MPNCs: a reservation request frame is transmitted or included into the beacon, indicating the MAS slots to be reserved; reservation reply is sent announcing the reservation to its neighbouring; the transmitting MPNC announces the successful conclusion of the negotiation to its neighbours by including a reservation IE into its beacon. Only after the first transmission of the IE are MASs reserved.

From the viewpoint of each MPNC, parts of the superframe can be reserved for the following purposes:

- Transmission and reception of beacons (own beacon transmission, beacon reception from neighbouring MPNCs, beacon transmission for distant MPNCs that cannot be reserved for other transmissions due to interference);
- Data frames exchange (in the own PN or in neighbouring PNs, inter-PN traffic that originating or ending at the MPNC or at neighbouring MPNCs, outside those reservations, MPNCs may send frames using a contention-based access method without prior reservations).

Beacons are used to mutually signal the intended channel usage. The beacon transmitted by every MPNC serves multiple crucial functions in the PN and the mesh network. Inside the PN, it is used to announce the presence of the PN, synchronise all devices and inform them about reserved superframe time for data transmissions. For the mesh network, the beacon is equally important, used to announce the presence of the MPNC, introduce the timing of the MPNC to the distributed synchronisation algorithm, negotiate and announce fixed reservations and disseminate information about neighbour's reservations. Therefore, each MPNC has to listen to the beacons transmitted by its neighbouring MPNCs and respect any indication of a beacon transmission (relayed by the neighbours) by deferring from accessing the medium during this time. Beacons shall be transmitted using the most robust PHY mode available and with the maximum transmission power.

For HR-WPAN, IEEE 802.15.5 specifies a specific mesh routing. When a device wants to send a packet to a destination outside its PN, it will always forward the packet to its MPNC, via inter-PAN communication. The source MPNC will deliver the packet to the destination MPNC by using one of the available remote routing methods (proactive route establishment, tree routing, centralised routing, location-based routing and distributed routing). If the destination is a device, the destination MPNC will forward the packet to the device via intra-PAN communication. When a source MPNC finds that the destination MPNC is one of its neighbours, it will forward the packet to the destination MPNC directly (local routing). If the destination MPNC is not its direct neighbour, it may check whether one of its neighbour MPNCs can reach the destination MPNC. If the destination MPNC can be reached through a neighbour MPNC, the source MPNC may forward the packet to this neighbour MPNC. For LR-WPAN, IEEE 802.15.5 also specifies a particular mesh routing procedure. Logic addresses are bound to the network topology, and routing can be carried out without going through route discovery. The address assignment is broken down into two stages: association and address assigning. During association stage, beginning from the root, nodes gradually join the network and a tree is formed.

Many applications for Mesh WPANs have been identified [ZaHH04], such as cable replacement in multimedia home networks and interconnecting PCs and peripherals, mobility oriented interconnection among handheld devices (mobile phone, photo camera, cordless headset, PDA), temporarily & rapidly set-up of mesh network between, e.g., laptops and projectors in a meeting room, indoor location based services for, e.g., museums, exhibitions and shopping malls. Although a lot of research efforts have been put into this area, there is still a big gap between theoretical work and industry realisation [Zhan12]. Mesh WPANs face several challenges. Concerning MAC, efficient spatial frequency reuse, hidden and exposed nodes, interference, QoS support and mobility are open issues [MLee06]. Path selection (routing) is also critical, with respect to self organising, redundant links, loop prevention and broadcast data issues. A mesh WPAN MAC should be able to differentiate devices according to their capabilities and functionalities (e.g., power sensible or connected device, mesh or non-mesh enabled) and assign functions according to their capabilities (e.g., packet forwarding). An optional distributed channel time allocation method is proposed, which achieves both fair resource allocation and admission control [Rhee07].

A.2 Wireless Local Area Network Mesh

IEEE 802.11 refers to a family of IEEE standards for WLANs [IEEE07b]. It describes the functions and services required by an IEEE 802.11 compliant device to operate within infrastructure and independent (ad-hoc) networks. WLANs are organised in terms of layering of protocols that cooperate to provide all the basic functions of a LAN. The IEEE 802.11s amendment defines the operation as a mesh network of a WLAN Wireless Distribution System (WDS) using the IEEE 802.11 MAC/PHY layers that support both broadcast/multicast and unicast delivery over self-configuring multi-hop topologies [IEEE11].

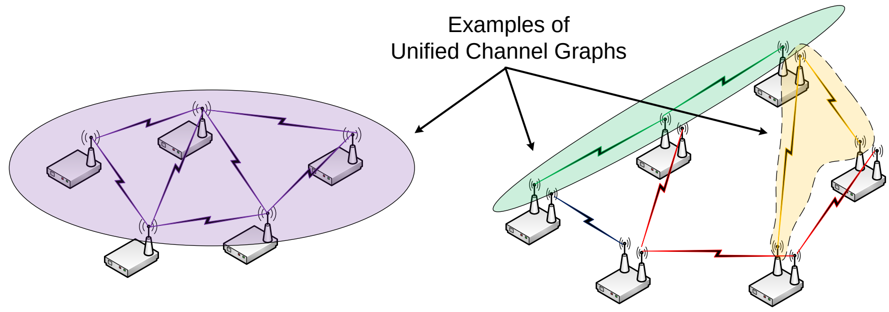
The original IEEE 802.11 standard provides a four-address frame format for exchanging data packets between stations for the purpose of creating a WDS, but does not define how to configure or use it. This amendment defines this missing functionality by providing a mechanism to produce a Mesh in an auto-configuring manner. An IEEE 802.11 Mesh is a collection of MPs interconnected with IEEE 802.11 wireless links that enable automatic topology learning and dynamic path configuration. A Mesh may support zero or more MPPs entry points. IEEE 802.11s benefits from multi-hopping in multiple ways: multi-hop within backbone infrastructure (MAP-MAP-MPP), multi-hop to backbone infrastructure (MP-MPP), and multi-hop among client devices (MP-MP-MP). With respect to non-Mesh Stations (STAs) relationship with the Basic Service Set (BSS) and Extended Service Set (ESS), a Mesh is functionally equivalent to a wired ESS. On the other hand, many uses are found for Mesh capabilities in non-AP stations. For example, something like a station operating as a simple 802.11 frame radio relay can be implemented as a Mesh station, and there is no reason to burden such a station with AP functionality. Another example would be a portal between a WLAN mesh and a wired 802 network. There is no need for such a portal to be an AP.

IEEE 802.11s enables the interoperable formation and operation of a WMN, but it is extensible to allow for alternative path selection metrics and/or protocols based on application requirements. It is intended that the architecture defined by the amendment will allow a WMN to interface with higher layers and to connect with other networks using higher layer protocols. The amendment allows the use of one or more IEEE 802.11 radios on each station.

Optional features provide the MAC with the necessary functionalities to segregate BSS and mesh traffic, to prioritise mesh backhaul over local BSS frames, and to make use of one or more frequency channels with one or more transceivers. An overview of the features of interest for the present work is given. MPs discover candidate neighbours through passive (beacons) or active scanning (using mesh probe requests), where management frames with mesh-specific Information Elements (IEs) are exchanged. IEEE 802.11 MAC frame formats are extended in order to support ESS mesh services. The MAC frame header is appended with a mesh forwarding field that includes a Time To Live (TTL) field (for use in multi-hop forwarding to avoid possibility of infinite loops) and a mesh End-to-End (E2E) sequence number (for use in controlled broadcast flooding and other services). Request and clear to Switch (RTX and CTX, respectively) control frames are proposed, for backhaul channel change operations. Exchange of management frames will be supported between neighbouring nodes, exchanging IEs such as Mesh ID (name of the mesh), Mesh capability (summary of supported protocols and metrics, as well as channel coalescence mode and channel precedence indicators), Neighbour list, Peer request and response, and Active profile announcement.

A Mesh WLAN topology supports single and multi-channel meshes, Figure A.2. Each MP may have one or more radio interfaces, and may utilise one or more channels for communication between MPs. The channel may change during the lifetime of the mesh network according to Dynamic Frequency Selection (DFS) requirements, as well as different topology and application requirements. A set of MP radio interfaces interconnected to each other by a common channel are referred to as Unified Channel Graph (UCG). The same device may belong to several UCGs, Figure A.2. Each UCG shares a channel precedence value given by the channel precedence indicator, used to join disjoint graphs and support channel switching for DFS.

A simple channel unification protocol is defined. A MP performs passive or active scanning to discover neighbouring MPs. If it is unable to detect any neighbouring MPs, it adopts a mesh ID and selects a channel for operation, as well as an initial channel precedence value. If a disjoint mesh is discovered, the channel indicated by the peer that has the highest channel precedence indicator is selected as unification channel. A channel cluster switch protocol is also presented. An MP that determines the need to switch the channel of its cluster first chooses a channel cluster switch wait time. It sets a local timer with this wait time, and then sends a channel cluster switch announcement frame to each peer MP that has an active association in the UCG. This announcement frame contains the value of the new candidate channel, its associated precedence indicator, and the channel switch wait time. All MPs that receive this frame set a local timer for switching to the announced channel and forward this announcement frame to other MPs associated to the UCG.



a) Simple mode with a common channel. b) Advanced mode with several channels.

Figure A.2 – Examples of radio backhaul mesh network topologies and unified channel graphs.

An MP must be able to establish at least one link with a peer MP, and may be able to establish many such links simultaneously, as shown in Figure A.2. It is possible that there are more candidate peer MPs than the device is capable of being associated to simultaneously. In this case, the MP must select links based on some measure of signal quality. An MP continues to look for received beacons on any of the UCGs it is operating on. If a beacon is received from an unknown neighbouring MP, but with a matching mesh ID, the MP will attempt to create a link to the neighbouring MP.

Providing QoS in WMNs, a multi-hop contention-based network, represents a big challenge. Two areas focus on ensuring QoS in a WLAN mesh network: backhaul and access traffic separation, with backhaul traffic prioritisation and backhaul congestion control. Separation of backhaul and access traffic, in a single device, can have a profound impact on QoS. Backhaul traffic travels farther than any local BSS one, hence, prioritising backhaul traffic over local BSS makes sense for reducing the latency of the former. Traffic prioritisation may have different implications from the view point of fairness, and prioritisation policies may depend on the scenario and business model in use. Employing multiple radios to separate BSS traffic and mesh forwarding traffic is essential, as discussed in detail in Section 2.4.

Multi-hop data forwarding is not addressed in any extension of 802.11 MAC. Each MP contends for the channel independently, without any regard for what is happening in the up- or downstream nodes. Local congestion is defined as the condition when an intermediate MP receives more packets than it can transmit in a predefined time window, the result being that the local buffer gets filled up quickly, and packets may have to be dropped by the buffer. The situation is exacerbated by the presence of hidden and exposed nodes on the same channel, causing extensive back-off and retransmissions, as discussed in Section 2.3.

One of the recommendations is to use transport layer QoS in order to achieve QoS over a multi-hop path. Nevertheless, most multimedia QoS dependent applications use the User Datagram Protocol (UDP) transport, which does not have any form of congestion control of QoS provisioning. On the other hand, TCP congestion control does not work well across a multi-hop wireless network, largely due to its susceptibility to high packet loss, cf. Section 2.3.

Mesh networks have heterogeneous link capacities along the path of a flow, traffic being aggregated in multi-hop flows sharing intermediate links. Nevertheless, nodes transmit blindly as many packets as possible, regardless of how many reach the destination, resulting in throughput degradation and performance inefficiency. A hop-by-hop congestion control mechanism is proposed for each MP, and it includes three basics elements: local congestion monitoring, congestion control signalling and local rate control. The basic idea is that each MP will actively monitor its channel utilisation condition so that it can detect local congestion when it happens. If congestion is detected, previous-hop neighbours and/or neighbourhood are notified. Three new mesh action frames are defined for this purpose: congestion control request and response (unicast), and neighbourhood congestion announcement (broadcast). By receiving congestion control request from a downstream MP, upstream neighbours employ local rate control to help relieve the congestion being experienced downstream, and upon receiving neighbourhood congestion announcement from a neighbour MP, the neighbours employ local rate control to help relieve the congestion being experienced in the neighbourhood. Rate control may be on per-AC basis, e.g., data traffic rate may be adjusted without affecting voice traffic. One example is that MAPs adjust BSS Enhanced Distributed Channel Access (EDCA) parameters (e.g., augmenting CWmin in BSS) to alleviate congestion due to associated STAs.

EDCA is the mandatory MAC mechanism for 802.11s, being compatible with legacy devices. This results in an easy to implement mesh network, providing reasonable efficiency in simple Mesh deployments. The handling of WDS and BSS traffic in a device is treated as implementation choice. Besides the Intra-mesh congestion control mechanism previously described, two other optional 802.11s MAC enhancements are suggested:

- Common Channel Framework (CCF), a multi-channel operation mechanism.
- Mesh Deterministic Access (MDA), a reservation-based deterministic mechanism.

CCF [BeTa06] was adopted by IEEE 802.11s as an optional feature that enables single and multi-channel MAC operation for devices with single and multiple radios. MDA is an access method that works as a Wireless Medium (WM) reservation mechanism that enables the prediction of future channel usage. Using IEs in management frames such as beacons, transmitter and receiver MPs negotiate on a MDA Transmission Opportunity (MDAOP). A MDAOP has predefined start and duration times, which allows deferring transmissions from two hops neighbouring MPs not involved in the MDAOP, storing in their local Network Allocation Vector (NAV) start and duration information on direct and indirect MDAOP negotiations. To use MDA, MPs involved in the MDAOP need to be synchronised, in order to know exactly when MDAOP periods start. At the beginning of an MDAOP, the owner has the right to access the WM using a set of EDCA parameters (AIFSN, CWmin and CWmax) providing higher priority of access. After transmission, any remaining MDAOP time is announced as given over. Nodes that defer during a known MDAOP set NAV to the end of the MDAOP, shortening it if announced.

The MDA method works as a collision prevention mechanism, allowing reservation of resources in the time domain. Nevertheless, better spatial frequency reuse, than with the current IEEE 802.11, is not achieved. Neighbours inside the interference range are deferred of using the frequency channel. Also some MPs that might be outside the interference range might be deferred of transmission.

Mesh path selection services consist of baseline management messages for neighbouring discovery, local link-state measurement and maintenance, an identification of an active path selection protocol. Each WMN uses a single method to determine paths through the mesh, although a single device may be capable of supporting several methods. A default mandatory protocol and metric for all implementations is specified to ensure baseline interoperability between devices of different vendors. The proposed mesh routing framework is based on a layer-2 MAC routing protocol, applicable for small to medium unmanaged mesh networks up to 32 nodes. For larger meshes, it must be augmented with 802 LANs and/or IP layer routing. IEEE 802.11s specifies as mandatory the HWMP routing protocol, using an airtime link metric [IEEE11], based on a cost function for establishment of radio-aware paths. A local link-state discovery procedure is followed to build the neighbouring table with the used bit rate and the packet error rate fields. Each MP calculates the cost for each ML. The airtime cost reflects the amount of channel resources consumed by transmitting the frame over a particular link. It is approximate and designed for each of implementation and interoperability.

A.3 Wireless Metropolitan Area Network Mesh

The IEEE 802.16 WMAN working group, also known as Worldwide Interoperability for Microwave Access (WiMAX), has defined a broadband wireless radio standard for local and metropolitan area networks. There are several subtypes of the standard that are currently active, under development or outdated. Typically for an 802 standard, the PHY and MAC layer are defined. The original 802.16 standard [IEEE01], so called Fixed Wireless Access (FWA), was designed for fixed point-to-multipoint line-of-sight broadband wireless transmission. With the 802.16-2004 revision [IEEE04], also referred to as "fixed WiMAX", it was extended to mandatory fixed non-LoS Point to Multipoint (PMP) and an optional mesh (MSH) mode. PMP is defined for all different air-interfaces, while MSH is only supported by OFDM, in unlicensed bands. In the PMP configuration, traffic only occurs between the Base Station (BS) and Subscriber Stations (SSs). Scheduling is exclusively coordinated by a central BS; SSs cannot communicate directly with each other. In contrast, in the MSH mode traffic can be routed through other so called Mesh SSs (MSSs), foreseeing an infrastructure-based centralised scheduling with Mesh BS (MBS), as well as a distributed scheduling between SSs without any infrastructure.

The access of the channel in the 802.16 mesh mode is TDMA based. The TDMA frame consists of multiple slots and is divided into a control- and a data-subframe [ZhLH07]. The control-subframe, divided into transmission opportunities, is used for the transmission of management messages. It has two primary functionalities; one is creation and maintenance of cohesion between different MSSs; the other is coordinated scheduling of data transferring among MSSs. The data frame, composed of minislots, is used for transmission of MAC Protocol Data Units (MPDUs) from different users. An MPDU consists of a generic MAC header, a mesh sub-header and optional data. Instead of the control-subframe, a network-subframe is periodically included in the frame, which provides a basic level of communication between nodes, e.g., for synchronisation, initial network entry and exchange of neighbourhood lists. Key procedures within network and scheduling control subframes are shortly described next [AhIl08]:

- In the network subframes, Mesh Network Configuration (MSH-NCFG) and entry (MSH-NENT) messages are transmitted for creation and maintenance of the network configuration. A scheduling tree rooted at the mesh BS is established for the routing path between each SS and the mesh BS. Active nodes within the mesh network periodically advertise MSH-NCFG messages with the network configuration. A new node that wishes to join the network scans for active networks by listening to these messages.
- Mesh Centralised Schedule (MSH-CSCH) and Mesh Distributed Schedule (MSH-DSCH) messages are exchanged in the scheduling control subframe to assign the data minislots to different stations. Centralised scheduling is mainly used to transfer data between the mesh BS and SSs, while distributed scheduling targets data delivery between any two

stations (BS or SS) in the same WiMAX mesh network.

The stations with which a node has direct links (one hop away) are called neighbours, forming a neighbourhood. An extended neighbourhood contains, additionally, all the neighbours of the neighbourhood.

The mesh mode allows centralised as well as distributed scheduling. The centralised scheduling requires a mesh BS that coordinates the data transmission. The Mesh BS shall gather resource requests, in the form of MSH-CSCH Request messages, from all the MSSs within a certain hop range. It shall determine the amount of granted resources for each link in the network in both down- and uplink, and communicates these grants, with the MSH-CSCH Grant message, to all the MSSs within the hop range. Grant messages do not contain the actual schedule. Each node computes its actual up- and downlink transmission times by using a predetermined algorithm that divides the frame proportionally. To disseminate the Mesh SS topology, routing and scheduling tree configuration information to all participant Mesh SS within the mesh network, the mesh centralised scheduling configuration message is broadcasted by the Mesh BS and then re-broadcasted by all intermediate nodes.

With distributed scheduling, nodes schedule time slots independently. This can be done in a coordinated and uncoordinated way. In coordinated distributed scheduling, all the nodes including the MBS coordinate their transmissions in their two-hop neighbourhood and broadcast their schedules (available resources, requests and grants) to all their neighbours in the control-subframe. In uncoordinated scheduling, the schedule may also be established by direct uncoordinated requests and grants between two nodes send in the data-subframe. Both distributed scheduling modes comprise a three way handshake which can be overheard by every neighbouring node of both communication partners so that collision during data transmission due to the hidden node phenomenon can be avoided.

The benefit of the coordinated scheduling is that the distributed and reliable allocation of transmission opportunities in the control-subframe avoids collisions during the three-way-handshake. Every node is ready to receive if a neighbour transmits its scheduling messages in the control subframe. Therefore, every node is aware of a planned transmission and can respect it. This is not always the case for transmissions of scheduling messages with uncoordinated distributed scheduling in the data subframe. Because minislots in the data subframe can be multiple used if receivers are out of radio range, some neighbours might not receive all the messages of the three-way-handshake, therefore collisions can occur.

The disadvantage of the coordinated scheduling is the low frequency of transmission opportunities in the control subframe, which is also independent of the traffic load, while uncoordinated distributed one allows a faster and therefore real-time allocation of transmission slots. The number of transmission opportunities in the data subframe, which are in fact already reserved minislots, is much higher, and it can be also adapted to the traffic load.

Performance of centralised and distributed scheduling approaches is evaluated in [ReLo04]. In a multi-hop scenario, centralised scheduling outperforms the distributed one. In particular, the efficiency gap increases slightly with the number of hops. Several proposals of centralised [SDMH06], [XiJW07] and distributed [CMZW05] scheduling algorithms are available in the literature.

As an enhancement towards mobile communication, the IEEE 802.16j Mobile Multi-hop Relay (MMR) Sub Group [WaMB06] addresses multi-hop relaying in the licensed band only. The development of relaying is divided into three phases: in the first phase fixed, an infrastructure relay is introduced (fixed relay stations), then in the second phase, a mobile infrastructure relay is added (nomadic relay stations), and finally in the last one, a client based relay is added.

The mesh mode was not supported until now by the industry. In particular, it is not compatible with 802.11e, OFDMA based, possibly being one of the drawbacks. The 802.16j approach will simply enable multi-hop communication for WiMAX. The main motivation is coverage extension and throughput enhancement. IEEE 802.16j will be compatible with .16e, resulting in an 802.16e capable relay network. The IEEE 802.16j implements a star topology based on relays, centrally controlled by a BS. These relays will functionally serve as an aggregating point on behalf of the BS for traffic collection from and distribution to the multiple MSs associated to them, and thus naturally incorporate a notion of ”traffic aggregation” [TaTW07]. This is different from a mesh topology, where nodes have multiple connections to neighbouring ones. Although multi-hop, 802.16j cannot be addressed as a mesh solution, such as the mesh mode of IEEE 802.16-2004.

Several research challenges are under study in WiMAX mesh. There is no QoS mechanism for the mesh mode guaranteeing QoS over multiple hops [ZhLH07]. Interference is also an issue, since the IEEE 802.16 mesh mode depends on an assumption that there is no interference more than two hops away. This is unrealistic in high dense networks, where interference may propagate several hops away. Scalability is also an issue for the IEEE 802.16e mesh mode. The use of multi-radio and multi-channel systems is a potential approach, in which routing and dynamic channel allocation scheme becomes the important components to achieve higher capacity and throughput. The PMP mode cannot be combined with the MSH mode, since both modes have different message types and are defined for different air interfaces, not existing means against mutual interference. In [NIDM07], the way mesh trees are built is discussed. Long links are split into multiple shorter ones that support higher data rates, the use of multiple-channels and frequency spatial reuse being a challenge. Most current research works on centralised scheduling for WiMAX mesh networks are based on a unidirectional concurrent scheme, i.e., transmissions of up- and downlinks are considered separately. In [XiJW07], the interference model of IEEE 802.16 TDMA mesh networks is analysed, and a bidirectional concurrent transmission model is proposed. Recently, important research has been conducted addressing load awareness [FeXi08] and fairness [WaJi12].

A.4 Wireless Wide Area Network Mesh

Wireless Wide Area Networks (WWANs) refer to cellular networks offered regionally, nationwide, or even globally, provided by a wireless service provider. The evolution of WWANs is lead by the 3rd Generation Partnership Program (3GPP) [3GPP08a], which produced global technical specifications for the 3G Universal Terrestrial Radio Access Network (UTRAN). New releases have been issued, implementing new physical features. Release 99 implemented the UMTS, release 5 the High Speed Downlink Packet Access (HSDPA) Release 6 the High Speed Uplink Packet Access (HSUPA), and release 8 the LTE or Evolved UTRAN (E-UTRAN) [3GPP08b], defines a new high-speed radio access method for mobile communications systems, conceived as the next step on a clearly-charted roadmap to 4G mobile systems [UMTS08].

WMNs can become an added value in the provision of flexible solutions for the backhaul of WWANs such as LTE. The interconnection of eNBs represents a big challenge, for the throughputs that are expected. The wireless meshed topology might bring advantages in terms of robustness, share of resources and load balancing. The wireless interconnection of BSs through FWA is since long a reality, being a first step towards mesh topologies. The LTE architecture gives higher autonomy to eNBs, where management of radio resources is controlled locally, instead of 3G's centrally controlled architecture. The adoption of wireless mesh topologies can be foreseen in the interconnection of eNBs, to take advantage of the flexibility, robustness and cost-effectiveness of deployment for these topologies [Taip12]. As an example, the deployment of meshed pico-cells can bring strong benefits. Also, new deployments can benefit from the cost-effectiveness of mesh not needing expensive fixed infrastructures; the combination of this flexible topology with directional antennas can bring many advantages. Under the umbrella of Fixed-Mobile Convergence solutions, femto-cells [3GPP08c] is a solution that allows an operator to rout an indoor mobile cellular connection over fixed broadband access network (e.g., digital subscriber line) instead of sending it to an outdoor cellular BS. This is a much cheaper approach than using the cellular infrastructure to provide indoor coverage. The use of femto-cells can be efficiently and flexibly extended using the wireless mesh topology, providing locally indoor cellular coverage with several femtocells connected by a WMN. An example of this is the all-wireless network of femtocells [CTTC13]. Being an indoor solution, isolated from the outdoor environment, spectrum can be allocated in an opportunistic way, by choosing channels not sensed as busy within the indoor area. This possibility of dynamic spectrum management by evolved meshed nodes has the advantage of not needing fixed infrastructures to interconnect all femto-cells; it only needs to have one or a couple of femto-cells to be connected to a fixed broadband access network in order to provide wireless connectivity to all nodes spread within the indoor area of deployment of mesh femtocells.

Appendix B

Characterisation of WMN Application Scenarios

Appendix B characterises various scenarios where WMNs are likely to provide a more versatile or affordable solution than other wired or wireless technologies.

Table B.1 – Characterisation of scenarios of application of WMNs.

WMN Scenario	Environment	Network	Usage	Advantages	Challenges
Neighbourhood Community	• Mixed indoor-outdoor mesh propagation • Coverage area: residential neighbourhood • Size: 50 × 50 m^2	• Random deployment • 5-10 MAPs & 1 MPP • 2-3 neighbours/MAP	Residential	• Sharing expensive (monthly subscription) and under-used (10% of capacity) high-capacity (e.g., 100 Mbit/s) Internet Gateway(s) • Large percentage of areas in between houses covered with wireless services • Easy sharing of information within the community, providing distributed file storage and access, video streaming • Robustness	• Random deployment • Medium size
Enterprise (companies, airports, hotels, shopping malls, convention centres, sport centres)	• Indoor mesh propagation • Coverage area: office, building or several buildings • Size: 100 × 100 m^2 • (IST campus: 300 × 300 m^2)	• Random deployment • 10-20 MAPs & 2-3 MPPs • 3-4 neighbours/MAP	Professional	• Multiple interconnected MAPs without need of wired cables reduce drastically cost of such networks • Increased robustness and resource utilisation • The network can easily grow as the size of the enterprise expands	• Medium size random deployment • High network demand

Table B.1 – Characterisation of scenarios of application of WMNs.

WMN Scenario	**Environment**	**Network**	**Usage**	**Advantages**	**Challenges**
Municipal/ Metropolitan Area Network	• Outdoor mesh propagation • Size: 5 × 5 km^2	• Designed deployment • 20-50 MAPs & 5-10 MPPs • 3-4 neighbours/MAP	Residential & Professional	• In a metropolitan area, enables higher throughput than cellular systems. • Economical alternative to broadband networking in underdeveloped regions Provides inexpensive, ubiquitous Internet access • Robustness of mesh connectivity, not relying on wired backbone	• Large deployment • Multiple hops. • Network scalability
Spontaneous networking	• outdoor mesh propagation • Size: 100 × 100 m^2	• Random deployment • 5-20 MAPs & 1 MPP • 3-4 neighbours/MAP	Mixed professional (emergency) & public	• Fast deployment of an emergency/disaster WMN network • Fast deployment of a flash crowd network	• Random deployment
Transportation systems	• Indoor mesh propagation • Coverage area: vehicle • Size: 4 × 20 m^2	• 2-10 MAPs & 1 MPP • Chain topology • 2 neighbours/MAP	Mixed	• Mesh network within a vehicle (car, train, bus) with Internet connectivity through high-speed mobile backhaul.	

Table B.1 – Characterisation of scenarios of application of WMNs.

WMN Scenario	Environment	Network	Usage	Advantages	Challenges
Broadband home networking	• Indoor mesh propagation • Coverage area: home • Size: 40 × 40 m^2	• Random deployment • 2-5 MAPs & 1 MPP • 2 neighbours/MAP	Residential & home broadband	• Easy and robust coverage of a home without dead zones (without need of expensive site survey and cabling between APs, etc.) • embedded wireless environment for a large set of new services (sharing and storage)	• Indoor propagation • Random deployment
Automation, Security and surveillance systems	• Indoor mesh propagation • Coverage area: building	• Designed deployment • 5-20 MAPs & 1 MPP • 2-4 neighbours/MAP	Professional	• Easy and cheap deployment of secure and robust seamless network	• Indoor propagation

Appendix C

Overview of Channel Assignment Strategies

Appendix C presents an overview of channel assignment strategies. In Section C.1, a description and discussion of channel assignment strategies for multi-hop communication is presented in Section C.1. A taxonomy is presented in Section C.3.

C.1 Overview

Channel assignment consists in assigning channels to radio interfaces in order to achieve efficient channel utilisation and minimise interference. The use of non-overlapping channels can significantly improve the performance of WMNs. The problem of optimally assigning channels in an arbitrary mesh topology has been proven to be NP-hard, based on its mapping to a graph-colouring problem [RaCh05], thus, channel assignment schemes use predominantly a heuristic approach. The design of CA strategies for multi-channel WMNs has been investigated in several works. An overview of several link layer radio-agnostic CA strategies is presented below. These have the particularity of not being designed for a certain radio-interface (e.g., IEEE 802.11 or IEEE 802.16), exploring particularities of MAC and PHY layers specificities. On the other hand, these radio-agnostic CA strategies are designed on top of MAC specificities of a radio-interface, enabling the heterogeneity of radio-interfaces.

In the **on-Demand Channel Assignment** (**DCA**) [WLTS00] protocol, each node has two interfaces, one fixed in a common control channel, and the other available to transmit data on an agreed channel. Negotiation of channels occurs on the control channel, and data packets are transmitted on the data channel. The sender includes a list of preferred channels. On receiving this information, the receiver decides on a channel and includes the channel information in the answer. Then, data packets are exchanged on the agreed data channel. This protocol does not need synchronisation and can utilise multiple channels with little control message overhead. This is an expensive solution considering that control traffic is much lower than data traffic. When the number of channels is small, one channel dedicated for control messages can be costly. On the other hand, if the number of channels is large, the control channel can become a bottleneck and prevent data channels from being fully utilised.

The **Receiver-Based Channel Selection** (**RBCS**) [JaDa01] has one control channel and several data channels, and selects the channel maximising the SINR at the receiver. It is similar to DCA, assuming nevertheless that nodes can receive packets simultaneously on all channels.

Interleaved CSMA (**ICSMA**) [JaMM03] is a CSMA/CA handshaking process interleaved between two channels. For example, if a sender transmits RTS on channel 1 and if the receiver is willing to accept the request, it sends the corresponding CTS over channel 2. If the sender receives the CTS packet, it begins the transmission of DATA packets over channel 1. Again the receiver, if the data is successfully received, responds with ACK packet over channel 2. This simple mechanism of interleaving carrier sense enhances the throughput achieved by the two-channel WMNs by alleviating the exposed terminal problem. There are two main reasons for this. First, if a node receives RTS on channel 1, and does not receive CTS on channel 2, then it can understand its sender-exposed status. Therefore, if it needs to initiate another session, it uses channel 2 to transmit the RTS and data packets. Secondly, if a node hears only a CTS packet, it realises that it is a receiver-exposed node to the transmission. Therefore, this node can initiate a new transmission on channel 1. Nodes switch between 2 channels on a packet basis.

The **Multi-radio Unification Protocol** (**MUP**) [ABPW04] coordinates nodes with multiple radios. The channel assignment is fixed for several seconds. Packets are scheduled on the Network Interface Card (NIC) transceiver and channel that experiences the least contention. MUP is a link protocol, concealing multiple Network Interface Cards (NICs) from layers above it by presenting a single virtual interface. MUP experiences starvation within each channel much like a single-radio / single-channel IEEE 802.11 Distributed Control Function (DCF) system.

In the **Multi-channel MAC** (**MMAC**) protocol [SoVa04], [KyCV06] all nodes meet periodically on a well-known channel to negotiate channels for data transmission. The proposed scheme requires only one transceiver per node, and nodes must be synchronised. Beacons are periodically transmitted. The Announcement Traffic Indication Message (ATIM) time window, placed at the start of each beacon interval, is available for negotiation of channels among nodes that have packets to transmit. Nodes suggest a Preferable Channel List which specifies the channel usage in its neighbourhood. The receiving node selects a channel considering sender's preferable channel list and its own, being the preferred channel being the used by a minimum number of nodes in the vicinity of both sender and receiver nodes. After the ATIM window, nodes switch to their agreed channel and exchange messages on that channel for the rest of the beacon interval. This ensures that the traffic load is distributed across channels. This technique avoids the multi-channel hidden terminal and missing receiver problems. Simulation results show that MMAC performs better or at least comparable to DCA in most cases. As drawbacks of MMAC, nodes cannot exchange data packets during the ATIM window. So it is desirable to change the size of ATIM window dynamically, based on the traffic condition. Global synchronisation in an ad-hoc network with a large number of hops and nodes is also difficult to achieve. The channel switching time may also be large, significantly degrading the performance. Channel selection criterion based in source-destination lowest number of pairs per channel is no always the best. Using pending packets is a metric achieving a better performance. MMAC eliminates hidden-nodes, but generates many exposed ones because using RTS/CTS and ATIM/ATIM-ACK procedures.

Seed-Slotted-Channel Hopping (**SSCH**) [BaCD04] is a single-transceiver, multi-channel protocol. Each node hops between channels using a 13-hop pseudo-random sequence, designed such that any two nodes will overlap in at least one of the 13 hops. Within a channel hop duration a node uses IEEE 802.11 DCF to transmit data or control packets (which advertise its channel hopping schedule) to its neighbours. Each node uses the channel hopping schedules of its neighbours to transmit to them, by tuning the corresponding hops in its own hopping schedule. Slot duration is of 10 ms. Longer slot duration would have further decreased the overhead of channel switching, but would have increased the delay that packets encounter during some forwarding operations. It avoids the control channel bottleneck by distributing both control and data packets to different channels. Furthermore, since every node may decide to change its hopping schedule to transmit to others, the missing receiver problem can be extremely severe. This also requires synchronisation, among nodes. Furthermore, frequent switching interface from one channel to another incurs in delays which may adversely affect performance.

Hyacinth [RaGC04] is a **Centralised Load-Aware Channel Assignment (C-LACA) and routing algorithm** for multi-channel multi-radio WMNs. Traffic profile between aggregation and gateway nodes is assumed to be known; the total expected load on each virtual link is estimated based on the contributions from the different passing traffic flows, given by the concept of link criticality [GoCL04]. Given the set of initial link flows, channels are assigned in the attempt to have the resulting link capacity exceed the link load. Each virtual link is visited then in decreasing order of expected traffic load and assigns the channel with least degree of interference, i.e., the minimum sum of expected load from the virtual links in the interference region that are assigned to the same radio channel. All available channels are evaluated except in the case where a node has all its interfaces already assigned to a channel, being chosen the channel with least degree of interference from the available ones. Once channels are assigned to all links, link capacity of each link is estimated, used as input to a routing algorithm that computes the shortest feasible path for every flow of the given traffic profile. The resulting link flows are used as virtual link loads in a new channel assignment iteration, in the attempt to have the resulting link capacity exceed the link load. This approach achieves a large improvement in the overall goodput up to 8 times with just two radios, when compared to conventional single radio nodes, due to the break of each collision domain into several collision domains operating in different frequencies, being also spatially broken when ingress-egress node pairs originally passing through the collision domain take different paths to route the traffic. Nevertheless, this method may suffer from ripple effect [RaCh05], whereby already assigned links have to be revisited, increasing the time complexity of the scheme.

The **Hyacinth' distributed LACA** (**D-LACA**) [RaCh05] utilise only local topology and local traffic load information to perform channel assignment and route computation. It is a distributed version of LACA channel assignment algorithm that can adapt to traffic loads dynamically, balancing the load on the mesh network to avoid bottleneck links, increasing the network resource utilisation efficiency and maximising the overall network goodput (the number of transported bytes between the traffic aggregation devices and the wired connectivity gateways within a unit time). It presents a multiple spanning tree-based load-balancing routing algorithm that can adapt to traffic load changes as well as network failures automatically. It presents similar performance results than the centralised LACA. The *routing tree construction* starts from the gateway that broadcasts periodically reachability information to its one-hop neighbours using an *Advertise* packet, stating the cost to reach the gateway. This effect is propagated to the nodes down the tree. A new node broadcasts a *Hello* message to its one-hop neighbours. Upon receiving this *Hello* message from a new node, each of its neighbours establishes a reliable connection with the new node and also sends an *Advertise* message to expedite the route discovery for the new node. Three cost metrics are available: rapid converging hop count; gateway residual link capacity of the *uplink* that connects the root gateway of a tree to the wired network; path capacity, approximated by subtracting the aggregate usage of the link's channel within its neighbourhood from the channel's raw capacity which is assumed to be fixed within any collision domain.

Each WMN node is responsible for assigning channels to its down -NICs. Each of the node's up-NICs shares the same channel as its parent DOWN-NIC. The channel assignment of a WMN node's up-NICs is of the responsibility of its parent. To assign channels to a WMN node's down-NICs, it needs to estimate the usage status of all the channels within its interference neighbourhood, exchanging periodically its individual channel usage information as a CHNL USAGE packet with all its (k + 1)-hop neighbours. The aggregate traffic load of a particular channel is estimated by summing up the loads contributed by all the interfering neighbours that happen to use this channel. To account for the MAC-layer overhead such as contention, the *total load of a channel* is a weighted combination of the aggregated traffic load and the number of nodes using the channel. Based on the per-channel total load information, a WMN node determines a set of channels that are least-used in its vicinity. As nodes higher up in the spanning trees need more relay bandwidth, priority of a WMN node is equal to its hop distance from the gateway. When a WMN node performs channel assignment, it restricts its search to those channels that are not used by any of its interfering neighbours with a higher priority. The interface-to-channel mapping is adjusted periodically. As soon as the node finds a relatively less loaded channel after accounting for priority and its own usage of current channel, it moves one of its down-NICs operating on a heavily-loaded channel to use the less-loaded channel.

The division of collision domain across different frequency channels is the key reason for the nonlinear goodput improvement (6-7 times) with respect to the increase in the number of NICs (from 1 to 2). Moreover, the interference among adjacent hops of an individual path and among neighbouring paths is greatly reduced. One potential area of interest is to incorporate future 802.11k measurements in determining the link conditions to use as a link metric. Other degrees of freedom are transmission power control, carrier sense threshold selection, receive sensitivity setting, and choice of transmission data rate. Joint optimisation over these various criteria provides a rich area for future investigations.

The **Connected Low Interference Channel Assignment (CLICA)** [MaDa05] computes the priority for each mesh node and assigns channels based on the connectivity graph and conflict graph. It is a topology control approach for utilising multiple channels in multi-radio wireless mesh networks where the notion of a traffic independent channel assignment scheme is proposed to enable an efficient and flexible topology formation, ease of coordination, and to exploit the static nature of mesh nodes to update the channel assignment on large timescales. However, the algorithm can override the priority of a node to account for the lack of flexibility in terms of channel assignment and to ensure network connectivity. Thus, while this scheme overcomes link revisits, it does not consider traffic patterns in channel assignment for WMNs.

The **Mesh based Traffic and interference aware Channel assignment (MesTiC)** algorithm [SDLC06], [SGDL07] is a fixed, rank-based algorithm for centralised channel assignment, which visits nodes once in the decreasing order of their rank. It has some resemblances with C-LACA, although it is not an iterative approach. Topology connectivity is guaranteed by a common default channel on a separate radio. The rank of each node R is computed on the basis of its link traffic characteristics, distance to the gateway and number of radios on a node. Clearly, the aggregate traffic flowing through a mesh node has an impact on the channel assignment strategy. Each node, selects for each link the least used channel. It is stated to perform better than C-LACA, being a single run approach that avoids ripple effects as in C-LACA.

The **Asynchronous Multichannel Coordination Protocol** (**AMCP**) [ShSK06] is a distributed medium access protocol that requires only a single half-duplex transceiver, not requiring synchronisation. It uses a dedicated control channel on which nodes contend to reserve data channels by exchanging RTS/CTS packets according to 802.11 DCF. Upon successful control packet exchange, both the sender and the receiver switch to the reserved data channel, denoted by *x*, and transmit a data packet. Node A selects a data channel by inspecting its channel table. They may contend for data channel *x* immediately or contend for other data channels after the timers of these channels expire (timer is set to expire after a data transmission duration). In case of collision, they contend for a different channel. This simple waiting scheme of AMCP on the control channel effectively addresses the Multi-channel Hidden Terminal Problem, the information asymmetry and flow in the middle problems, by providing fair channel access opportunities to contending flows. It increases aggregate throughput and addresses the fundamental coordination problems that lead to starvation. The aggregate throughput increases linearly until 7 channels. Existing multi-channel MAC protocols can achieve similar or slightly higher aggregate throughput than AMCP. For example, for 4 channels and under heavy load, DCA also achieves three times the aggregate throughput of 802.11, similar to AMCP. This is because both AMCP and DCA dedicate a separate channel for control traffic. On the other hand, MMAC transmits control and data packets over 4 channels and achieves an additional gain of 20%-30%. However, DCA requires two radio transceivers per node and MMAC requires global synchronisation. AMCP uses a single transceiver and no global synchronisation.

The **Hybrid Multi-Channel Protocol** (**HMCP**) [KyVa05], [KyVa06], [KyCV06] is a link layer protocol to manage the use of multiple interfaces, presenting the abstraction of a single channel to higher layers, allowing existing higher-layer protocols to operate unmodified. Nodes are equipped with at least two wireless network interfaces divided into two groups: one where the interfaces are fixed on specific channels (announced as its receiving channels); another where the interfaces can switch among channels. It guarantees network connectivity even using multiple channels, and allows implementation on existing hardware. Nodes maintain a *ChannelUsageList* containing a count of the number of nodes in its two-hop neighbourhood using each channel as their fixed channel. The node changes its fixed channel to the less used channel. Simulations on a test-bed of 5 bidirectional VoIP calls, with 27 ms delay and packet loss rate below 4%, are supported only for 2 hops. This is due to the 802.11 overhead over small voice packets as well as minimum channel switching time specifications of HMCP.

The **Common Channel Framework** (**CCF**) proposed by [BeTa06] was adopted by IEEE 802.11s as an optional feature enables single and multi-channel MAC operation for devices with single and multiple radios. It has some resemblances with MMAC protocol. It defines two logical channels: a Common Control (CC) channel and multiple Mesh Traffic (MTr) channels. The CC channel is a channel on which all MPs and MAPs operate. MPs with multiple radios may use a separate common channel for each interface. CCF supports channel switching procedure, for negotiation of destination channel for data transmission, Figure C.1.

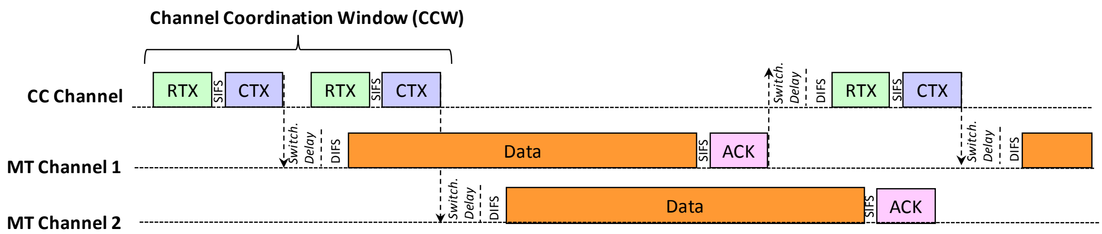


Figure C.1 – Common Channel Framework.

Using a RTX message, the transmitter MP suggests a destination channel. The receiver MP accepts/declines the suggested channel using CTX. After a successful RTX/CTX exchange, both MPs switch to the destination channel and transmit the data, and then switch back to the common UGS channel. Switching is limited to channels with little activity. A Channel Coordination Window (CCW) is defined on the common channel, for MPs with a single transceiver. At the start of CCW, CCF enabled MPs tune to the common channel. This facilitates arbitrary MPs to get connected. Channel Utilisation Vector (U) of each MP is reset. MPs mark the channel as unavailable based on channel information read from RTX/CTX frames. *P* is the period with which CCW is repeated. CCF enabled MPs initiate transmissions that end before *P*. MPs can stay tuned to the CC beyond CCW duration. *P* and CCW are carried in beacons. Groups of MPs may also switch to a negotiated destination channel. To devices that do not implement CCF, the common channel appears as a conventional single channel. In fact, the common channel can be used for data transmission. A MAP with a single radio may use the common channel for WDS as well as BSS traffic. Dynamic channel selection is restricted to MPs that support CCF. This framework is agnostic to the number of physical radios. For single radio devices, both CC and MTr channels share the same physical radio. For devices with multiple radios a radio is dedicated to CC and other carry multiple MTr channels. As demonstrated by simulation results [BeTa06], CCF achieves impressive delay and aggregate throughput performance (which increases linearly with the number of available data channels increases). The control channel is not a bottleneck, even at 6 Mbit/s. CCF offers distributed channel access for backbone meshes with delay properties suitable for VoIP and other QoS-sensitive applications.

The **Interference-Aware Channel Assignment (IACA)** [RABB06] is a dynamic centralised interference-aware algorithm aimed at improving the capacity of the WMN backbone and minimising interference. This algorithm is based on an extension to the conflict graph concept described in [MaDa05], called the Multi-radio Conflict Graph (MCG), where the vertices in the MCG represent edges between mesh radios instead of edges between mesh nodes. To compensate for the drawbacks of a dynamic network topology, the proposed solution assigns one radio on each node to operate on a default common channel throughout the network, the least interfered one. This strategy ensures a common network connectivity graph, provides alternate fallback routes, and avoids flow disruption by traffic redirection over a default channel (when a node's intended transmitter or receiver is incapable of delivering/receiving packets). Channel assignment to remaining radios is rank-based, using for ranking the Breath First Search (BFS) algorithm. With BFS, links in the MCG (without the common channel links) are visited in order of increasing average distance to the gateway (of the two radios that make the link), starting with the links emanating from the gateway. Within the same distance, links are ordered by increasing delay, using the Expected Transmission Time (ETT) metric [DrPZ04]. The channel assignment scheme works also on a rank-based strategy. Each mesh node derives two separate channel rankings. The first ranking is according to increasing number of interfering radios. The second ranking is according to increasing channel utilisation. The mesh node then merges the rankings by taking the average of the individual ranks, resulting in a channel ranking used for selection of the channel for a certain node. Is selected the highest ranked channel that does not conflict with the channel assignments of its neighbours. Are removed then from MCG the links that contain either radio from the assigned link (that has already an assigned channel). The algorithm continues from the farther node of the assigned link.

The **Maxflow-based CA and Routing (MCAR)** algorithm [AvAk08] ensures connectivity and feasibility. The goal is to guarantee that a given set of flow rates is schedulable. This strategy computes the flow rate values based on the maximum throughput of the potential communication graph in the absence of interference, computed as the maximum network flow. The objective of this computation is to identify the relative importance of links in carrying traffic, rather than accurately determine absolute values. The CA algorithm is based on the notion that a set of flow rates is schedulable if the sum of the ratio of the flow rate to the capacity of all the links interfering with the link (total utilisation of the collision domain of the link) is below 1. The goal is to minimise the maximum total utilisation of all links. CA solution is splitted in two stages. First, groups of links are created. Each node is visited and a new group is assigned to each unassociated link, starting from the links with largest flow rate. If the number of groups and radios is the same, the unassociated link is given the group with least maximum group utilisation. In case the links of a node belong to a larger number of groups than the number of available radios, then the two groups with least maximum group utilisation are merged. Secondly, groups are assigned a channel, ranked in descendent order of maximum total utilisation. If there is(are) channel(s) not used by any potentially interfering link, then is assigned to the group the one used by more links (to spare channels). If no channel satisfies this condition, then is chosen the channel with least maximum total utilisation of the collision domain of its links.

The **Flow-based Channel and Rate Assignment** (**FCRA**) algorithm [AvAV09] uses the notions of maximum network flow for computation of link loads and the notion of total utilisation of the collision domain of a link already presented in [AvAk08]. It aims the maximisation of the aggregate throughput. It uses a physical interference model. One radio of every node is assigned a common channel to guarantee connectivity between every node. Links are evaluated in decreasing order of total utilisation of the collision domain. Is chosen for this link the channel whose resulting total utilisation of its collision domain is below the maximum total utilisation of the neighbouring links, which have this link in its collision domain. In case this is not possible, the rate of the link is reduced in order to reduce the collision domain of the link and so reduce its total utilisation (a rate reduction results in higher robustness to interference, reducing the collision domain size). The flow rate between two nodes can be then split over the existing links, since is allowed to have more than one link between the same pair of nodes. The rate adaptation results in a high increase of capacity of the overall network, when compared to well-known algorithms such as LACA.

C.2 Strategies Pros and Cons

In this section, an overview of the above CA strategies is presented in Table C.1, with a summary of the key ideas behind each strategy, its pros and cons, highlighting interesting ideas.

Table C.1 – Summary and evaluation of CA strategies.

CA strategy	Description	Pros	Cons
DCA On-Demand Channel Assignment [WLTS00]	One interface is fixed in a common control channel (used to negotiate channels for data transmission), being the other available to transmit data on an agreed channel.	No multi-channel hidden terminal problem. Uses multiple channels with little control message overhead.	One radio and one channel for control. Suffers from starvation. With a large number of channels, the control channel is fully loaded and cannot distribute data channels.
RBCS Receiver-Based Channel Selection [JaDa01]	One control channel and *n* data channels. For a communication, is selected the channel maximising the SINR at the receiver.	No multi-channel hidden terminal problem.	Need of a dedicated control channel. Suffers from starvation. Assumes that nodes can receive packets simultaneously on all channels.
ICSMA Interleaved Carrier Sense Multiple Access [JaMM03]	Handshaking process interleaved between two channels (packet/channel: RTS/1, CTS/2, Data/1).	No exposed terminal problem (nodes aware of being sender- or receiver-exposed).	Suffers from starvation.
MUP Multi-radio Unification Protocol [ABPW04]	Channel assignment based on channel quality. Packets are scheduled on the NIC with least contention.	Improves the utilisation of the spectrum by coordinated use of multiple NICs.	Suffers from starvation.

Table C.1 – Summary and evaluation of CA strategies.

CA strategy	**Description**	**Pros**	**Cons**
MMAC Multi-channel MAC [SoVa04]	All nodes meet periodically on a known channel to negotiate channels for data transmission.	Avoids the multi-channel hidden terminal and missing receiver problems. Channel selection criterion based in source-destination lowest number of pairs per channel is no always the best. Load is distributed across all available channels. Broadcast supported during ATIM window	Need of a dedicated control channel. Suffers from starvation. Nodes cannot exchange data packets during the ATIM window. Generates exposed nodes because using RTS/CTS and ATIM/ATIM-ACK procedures. Channel switching overhead.
SSCH Seed-Slotted-Channel Hopping [BaCD04]	Each node hops between channels using a 13-hop pseudo-random sequence. Any two nodes will overlap in at least one hop. A node uses the channel hopping schedule of its neighbour to transmit to it.	Avoids the control channel bottleneck.	Suffers from starvation. Missing receiver problem can be extremely severe. To achieve good performance short slot times are needed, requiring fast interface switching.
C-LACA Centralised Load Aware CA [RaGC04]	Ranks nodes according to a link load estimate. Assigns the channel with least degree of interference. Resulting link capacity is estimated, used by the routing algorithm to compute the link load. Iterative CA and routing strategy in the attempt to have the resulting link capacity exceed the link load.	High performance achieved through separation of collision domains in frequency and space. Takes traffic load information into account, giving more capacity to links that need to support higher traffic.	Centralised strategy. Iterative strategy that suffers from CA ripple effects. Relies on prior availability of traffic demand of each node, not always possible.

Table C.1 – Summary and evaluation of CA strategies.

CA strategy	Description	Pros	Cons
D-LACA Distributed LACA [RaCh05]	Uses local topology and local traffic load information. Tree-topology, where nodes connects to parent with least cost. Each node controls down-NICs channels, selecting least used ones, from the not used by higher priority neighbours. Performs child CA load balancing aware.	Distributed CA algorithm inspired in C-LACA. Fat-Tree topology, designed for hierarchical traffic towards gateways. Takes traffic load information into account, giving more capacity to links that need to support higher traffic.	Spanning-tree topology, not enabling multi-path routing. Relies on prior availability of traffic demand of each node, not always possible.
CLICA Connected Low Interference Channel Assignment [MaDa05]	Computes the priority for each mesh node and assigns channels based on the connectivity graph and conflict graph. Traffic independent channel assignment scheme is proposed to enable an efficient and flexible topology formation	Assigns channels based on the connectivity graph and conflict graph. Flexible topology formation, ease of coordination, and to exploit the static nature of mesh nodes	Does not incorporate the role of traffic patterns in CA.
MesTiC Mesh based Traffic and interference aware Channel assignment [SGDL07]	Visits nodes once in the decreasing order of their rank (based on sum of link loads crossing the node, number of hops to gateway and number of radios).Assigns channel with least interference.	Performs better than C-LACA. Takes traffic load information into account, giving more capacity to links that need to support higher traffic. Topology connectivity is guaranteed by a common default channel on a separate radio.	Centralised strategy. Uses common channel in dedicated interface to prevent channel disruption. Relies on prior availability of traffic demand of each node, not always possible.

Table C.1 – Summary and evaluation of CA strategies.

CA strategy	**Description**	**Pros**	**Cons**
AMCP Asynchronous Multichannel Coordination Protocol [ShSK06]	Uses a dedicated control channel on which nodes contend to reserve data channels.	Avoids the multi-channel hidden terminal and starvation problems.	Need of a dedicated control channel.
HMCP Hybrid Multi-Channel Protocol [KyVa06]	Joint multi-channel and a routing solution: link layer protocol to manage the use of multiple interfaces, and a routing protocol that interacts with the link layer protocol to select good routes. Interfaces are divided into two groups: one of interfaces fixed on specific channels (announced as receiving channels); another of switching interfaces (to send data to specific nodes receiving on specific channels). MCR routing metric extends WCETT metric considering path diversity and switching delay.	Designed for networks where typical traffic pattern involves communication between arbitrary pairs of nodes. Guarantees network connectivity. Allows implementation on existing hardware (e.g. IEEE 802.11).	Large overheads (due to channel switching, minimum switching time on a channel, waiting time on queues and *Hello* packets). TCP only performs properly with three interfaces (1 fixed and 2 switchable). Overhead for broadcasts.

Table C.1 – Summary and evaluation of CA strategies.

CA strategy	Description	Pros	Cons
CCF Common Channel Framework [BeTa06]	Single and multi-channel MAC operation for devices with single and multiple radios. It has some resemblances with MMAC protocol, using a channel for control and remaining for data. Periodically, nodes meet on a window to negotiate channels.	Agnostic to the number of physical radios. Good delay and throughput performance. Control channel is said not to be a bottleneck. Enables delay sensitive services (VoIP).	Requires packet based channel switching.
IACA Interference-Aware Channel Assignment [RABB06]	Ranks links using the BFS algorithm in a MCG, visiting them in increasing average distance to the gateway and increasing delay (ETT).For each link, channel ranking results from the average of two ranks: increasing number of radios rank, and increasing channel utilisation. Is selected the highest ranked channel that does not conflict with the channel assignments of its neighbours.	Dedicated radio operating on a common channel guarantees connectivity, provides alternate fallback routes and avoids flow disruption.	Requires that each node performs interference monitoring and delay computation.

Table C.1 – Summary and evaluation of CA strategies.

CA strategy	Description	Pros	Cons
MCAR Maxflow-based CA and Routing [AvAk08]	The goal is to guarantee that a given set of link loads is schedulable. Link load values are computed as the maximum network flow. The notion of total utilisation of the collision domain of a link is introduced, as the sum of the ratio of the flow rate to the capacity of all interfering links.CA is split in two stages: first links are grouped; then channels are associated to groups.	Link rate values estimated. Evaluates the total utilisation of the collision domain.	Centralised strategy.
FCRA Flow-based Channel and Rate Assignment [AvAV09]	Links are evaluated in decreasing order of total utilisation of the collision domain. Is chosen for each link the channel whose resulting total utilisation is below the maximum total utilisation of the neighbouring links, which have this link in its collision domain. In case this is not possible, the rate of the link is reduced in order to reduce the collision domain.	Rate adaptation results in high improvements of performance. Evaluates the notion of total utilisation of neighbours where the link might interfere, trying not to perform worse. Uses physical interference model.	Centralised strategy.

C.3 Taxonomy

A taxonomy enabling the comparison among the above CA strategies is proposed, highlighting key aspects to be considered in these schemes. Several characteristics, used in our taxonomy and distinguishing CA strategies, are discussed below, before describing each strategy individually.

- **Control**: Algorithms can be controlled in two possible ways:
  - Centralised (C), where CA is coordinated by a single centralised entity, which has the knowledge of the entire network.
  - Distributed (D), where CA is done locally on each node.
- **Category**: Three main categories of CA strategies may be identified [KyVa05], depending on the frequency with which the CA scheme is changed:
  - Fixed (Fx) or static CA strategies, which assign each interface to a channel either permanently, or for "long intervals" of time (relative to the interface switching time). Fixing interfaces on a channel has the benefit of simplifying protocol implementation, however, keeping interfaces fixed on different channels may affect network connectivity, arising network partitions. Static assignment strategies are well-suited for use when the interface switching delay is large. In addition, if the number of available interfaces is equal to the number of available channels, interface assignment is trivially a static assignment. Static assignment strategies do not require special coordination among nodes (except perhaps to assign interfaces over long intervals of time) for data communication. With static channel assignment, the network topology is controlled by deciding which nodes can communicate with each other.
  - Dynamic (Dy) assignment strategies, which allow any interface to be assigned to any channel, and interfaces can frequently switch from one channel to another. In this setting, two nodes that need to communicate with each other need a coordination mechanism to ensure they are on a common channel at some point of time (e.g., nodes visit a common "rendezvous" channel periodically). The benefit of dynamic assignment is the ability to switch an interface to any channel, thereby offering the potential to cover many channels with few interfaces. Nevertheless, switching an interface from one channel to another incurs a delay, and frequent switching may adversely affect performance.

  - o Hybrid (Hy) assignment strategies combine static and dynamic assignment strategies by applying a static assignment for some interfaces and a dynamic assignment for others. Hybrid strategies can be further classified based on whether interfaces that apply static assignment use either a common channel approach or a varying one. Hybrid assignment strategies are attractive, as they allow simplified coordination algorithms supported by static assignment, while retaining the flexibility of dynamic assignment.

- **Radio communication channels**. Considering the number of radio communication channels (# radios) per mesh node for mesh functionalities (if the node provides access to end-users, it has an extra radio-channel dedicated to that functionality), these can be single- or multi-radio nodes.
- **Channel switching overhead**. In CA strategies, channel switching may be on a per-packet basis, frequent (e.g., each 10 ms), infrequent (only after several seconds), or even not required. Channel switching involves time overheads that decrease the efficiency of the CA strategy.
- **Synchronisation**. The CA scheme may require, or not, synchronisation among nodes. This is an important feature, essential for some CA strategies that, e.g., rely on meeting on a certain time window for negotiation of channels. If global synchronisation among nodes of a network with a large number of hops and nodes is guaranteed, which is difficult to achieve, an efficient scheduled access to the medium based on TDMA can be drawn. Nevertheless, it is a big challenge to design CA strategies that do not have this requirement and result in a performing network.
- **Connectivity**. A CA strategy must ensure connectivity between neighbouring nodes, which can be done in different ways. Some CA strategies ensure connectivity by a default radio-interface configured to a common control channel, by channel switching, or simply a control channel where nodes meet on a regular basis. Other CA strategies, as shown latter, ensure connectivity by the CA scheme itself.
- **Ripple effect**. Some iterative CA strategies may have ripple effects on the assignment of channels to certain nodes, where already assigned links have to be revisited [RaCh05].
- **Interference model**. CA strategies may base their decisions on simplified propagation and interference models, such as the disk model, or recur to more realistic propagation and interference models where the SINR is considered, the so-called physical interference model [GuKu00].

- **Load awareness**. In WMNs, most of the traffic flows between nodes and gateway(s), resulting in a peculiar traffic distribution that presents typical bottlenecks towards the gateway. Some CA strategies neglect this aspect, while others consider it, assuming the knowledge of the link' traffic loads crossing each node, or consider that the CA strategy manages to estimate link loads.
- **Topology control**. In a WMN, CA can be viewed as a topology control problem. Being so, the topology may be fixed or dynamically changing, defined by the CA strategy. In other cases the topology is defined by, e.g., a routing, based on which the CA is performed.

This taxonomy is used in Table C.2 and Figure C.2 to classify and characterise the CA strategies.

Table C.2 – Taxonomy of CA strategies.

CA strategy	Radio-agnostic	Control	Category	# radios	Channel Switching	Synchro-nisation	Connectivity	Ripple effect	Interference model	Load awareness	Topology control
DCA [WLTS00]	Y	D	Hy	2	Yes (per packet)	No	Ensured by default radio	No	N/A	No	Dynamically changing
RBCS [JaDa01]	Y	D	Hy	1	Yes (per packet)	No	Ensured by default channel	No	Physical model	No	Dynamically changing
ICSMA [JaMM03]	N	D	Dy	1	Yes (per packet)	No	Ensured by CA scheme	No	N/A	No	Dynamically changing
MUP [ABPW04]	Y	D	Hy	≥ 2	Infrequent (several seconds)	No	Ensured by CA scheme	No	N/A	No	Dynamically changing
MMAC [SoVa04]	Y	D	Dy	1	Yes (beacon period of 10 ms)	Yes	Ensured by CA scheme	No	N/A	No	Dynamically changing
SSCH [BaCD04]	Y	D	Dy	1	Yes (10 ms slot duration)	Yes	Ensured by CA scheme	No	N/A	No	Dynamically changing
C-LACA [RaGC04]	Y	C	Fx	≥ 2	No	No	Ensured by CA scheme	Yes	Protocol model	Yes	Fixed
D-LACA [RaCh05]	Y	D	Fx	≥ 2	Infrequent	No	Ensured by CA scheme	No	Trace driven	Yes	No.Topolog y is defined by the routing tree

Table C.2 – Taxonomy of CA strategies.

CA strategy	Radio-agnostic	Control	Category	# radios	Channel Switching	Synchro-nisation	Connectivity	Ripple effect	Interference model	Load awareness	Topology control
CLICA [MaDa05]	Y	C	Fx	≥ 2	No	No	Ensured by CA scheme	No	Protocol model	No	CA scheme defines the topology
MesTiC [SGDL07]	Y	C	Fx	≥ 2	No	No	Ensured by default radio	No	Protocol model	Yes	Fixed
AMCP [ShSK06]	Y	D	Dy	1	Yes (per packet)	No	Ensured by CA scheme	No	Protocol model	No	Dynamically changing
HMCP [KyVa06]	Y	D	Hy	≥ 2	Yes (per packet)	No	Ensured by channel switching	No	Protocol model	No	Dynamically changing
CCF [BeTa06]	Y	D	Dy	≥ 1	Yes (per packet)	Yes	Ensured by CA scheme	No	Protocol model	No	Dynamically changing
IACA [RABB06]	Y	C	Fx	≥ 1	Infrequent (10 minutes)	No	Ensured by default radio	No	Trace driven	Yes	Fixed
MCAR [AvAk08]	Y	C	Fx	≥ 1	No	No	Ensured by CA scheme	No	Protocol model	Yes	Fixed
FCRA [AvAV09]	Y	C	Fx	≥ 1	No	No	Ensured by default radio	No	Physical model	Yes	Fixed

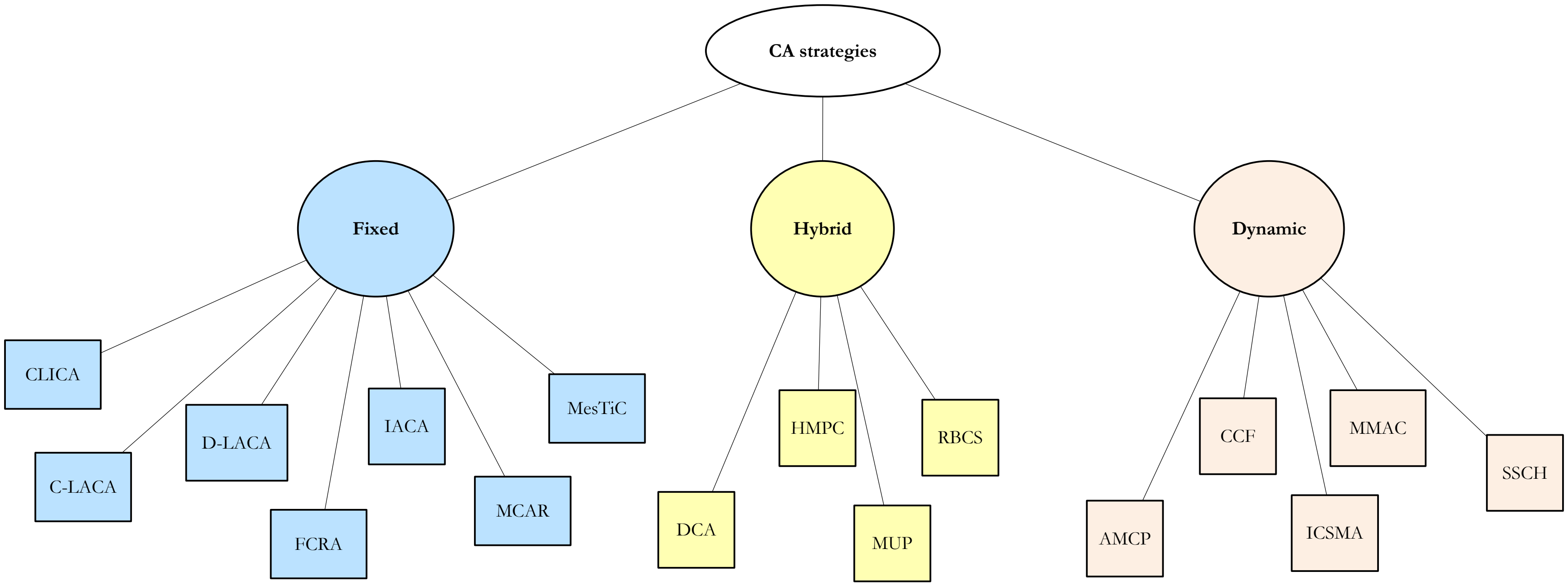


Figure C.2 – Classification of CA strategies with respect to their category (fixed, hybrid or dynamic).

Appendix D

Considerations on Routing for WMNs

Appendix D presents some considerations on routing for WMNs.

The dynamic and self-organising nature of WMNs wireless backhaul raises many challenges to routing. An optimal protocol for WMNs must capture several features [ZhLH07]. It must be fault tolerant to node or link failures. WMNs can ensure robustness against link failures by nature. Correspondingly, routing protocols should also support path reselection subject to link failures. Must be able to deal with load balancing, a key feature of mesh nodes in choosing the most efficient path for data. The conservation of bandwidth is imperative to the success of any wireless network. It is important to reduce the routing overhead, especially the one caused by rebroadcasts. A mesh network is scalable and can handle hundreds or thousands of nodes, needing a routing protocol with such properties. Due to the limited channel capacity, the influence of interference, the large number of users and the emergence of real-time multimedia applications, supporting QoS has become a critical requirement in such networks.

Protocols for this kind of networks can generally be classified into two categories:

- **Proactive routing protocols collect routing information in advance** such that it is available when need arises. Periodic updates may be used to maintain fresh information. Such protocols are suitable for networks in which nodes have a low degree of mobility. Examples include Destination Sequence Distance Vector (DSDV) [PeBh94] and Optimised Link State Routing (OLSR) [ClJa03].
- **Reactive routing protocols look for information only when required**. For example, when a node needs to reach another node, routes are dynamically created as a result. These protocols are very useful for scenarios with high mobility. Examples include Dynamic Source Routing (DSR) [JoMH04] and Ad-hoc On-demand Distance Vector (AODV) [PeBD03].

Several routing protocols specific for WMNs are being proposed, such as the Mesh Routing Strategy (MRS) or the Multi-Radio Link-Quality Source Routing (MR-LQSR) Protocol [ZhLH07].

In particular, a Hybrid Wireless Mesh Protocol (HWMP) routing protocol routing protocol is proposed for IEEE 802.11s [IEEE11], combining on-demand route discovery with efficient proactive routing to a mesh portal, with flexibility to adapt to the requirements of a wide range of scenarios. The protocol would be proactive towards MPs in the neighbourhood, and reactive towards MPs far away [FWKD06]. It supports any path selection metric, having as mandatory the airtime metric described above. On-demand routing in HWMP is based on Radio Metric Ad-hoc On Demand Distance Vector (RM-AODV) routing algorithm, using route request and reply mechanisms to establish routes between two MPs. Being MAC based, all IP and IP-addressing is changer to MAC and MAC addresses. Extensions are defined to identify the best-metric path with arbitrary path metric. Pro-active routing in HWMP is based on tree-based routing. If a root node exists, a distance vector routing tree is built and maintained. This is an efficient routing mechanism for hierarchical networks, avoiding unnecessary flooding during discovery and recovery. Another optional protocol is the Radio Aware Optimised Link State Routing (RA-OLSR).

Packet forwarding in WMNs is not a trivial issue, since several alternative routes to a given destination are available [Bing08]. The routing node must decide the next node to send a packet. Determining the best path to a given destination requires the use of a consistent set of metrics. All nodes must interpret and measure metrics of a given link or path in the same way. Path metrics may take many forms: hop count, path bandwidth, link load, SINR. Each node should keep track of overall cost of network path. Deriving the path cost may not be straightforward. Hop count and bandwidth can be additive, but SINR does not have this property. In general, the metric complexity depends on the resource constraints. If the link throughput exceed the overall traffic demand of the entire network, then the hop count is adequate. Conversely, if the link throughput is limited or variable throughout the network, link parameters will be important, possibly more than hop count.

Depending also on the objectives of optimisation of the network towards the performance of a certain service type, specific metrics might be more appropriate. Short voice packets re time sensitive, so to optimise a network for this service both link reliability (which can be improved by lowering transmission rate) and hop count metrics are important. Conversely, best-effort data traffic is not time sensitive, but data packets may be long, being link bandwidth more important. Packets from time sensitive video traffic may be large, so hop count, link reliability and link bandwidth are all important. For multicast services, OLSR can provide efficient routing.

The Expected Transmission count (ETX) [ZhLH07] routing metric is found to be a suitable routing metric to achieve high throughput, designed to find a path based on (i) the packet delivery ratio of each link, (ii) the asymmetry of the wireless link, and (iii) the minimum number of hops. The ETX routing metric helps an underlying routing protocol to find a path that provides a much better throughput performance.

Appendix E

Protocols Overhead Impact on Throughput and Delay

Appendix E describes the impact on throughput and delay of the overhead introduced by protocols.

In the transmission of packets, overheads are introduced by several layers of the IP stack (IP, MAC and PHY), proportionally magnified as the data rate becomes higher, resulting in throughput upper limits and a delay lower limits presented in the current section.

Considering a CSMA system (e.g., IEEE 802.11a), a transmission cycle consists of DCF Interframe Space (DIFS) deferral, backoff, data transmission, Short InterFrame Space (SIFS) deferral and ACK transmission. In Figure E.1 it can be observed the needed overhead for the transmission of a data packet, considering the introduced IP, UDP/TCP, MAC and PHY headers. Each of these components of delay are exemplified and quantified below for IEEE 802.11a.

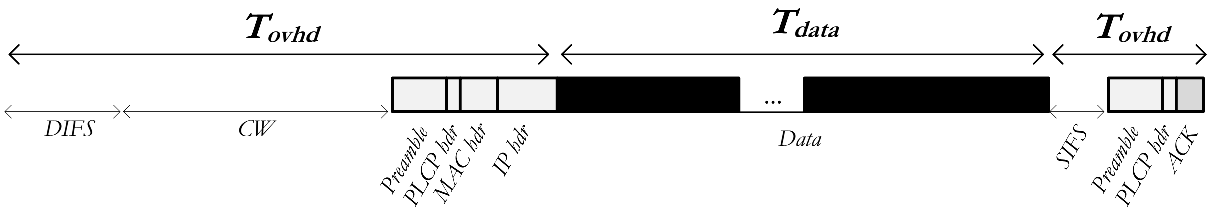
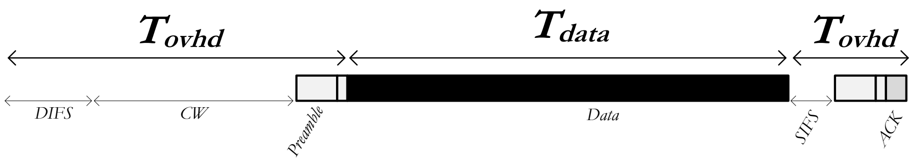
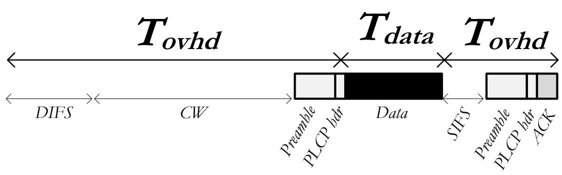


Figure E.1 – Overhead in the transmission of a data packet.

The introduced protocol overhead is approximately similar for all used R_{phy} rates, only varying the time needed to transmit a data packet, dependent on the packet size, K_{packet}, and R_{phy} rate. This dependency is analysed next. For a given R_{phy}, when transmitting a larger data packet, the total percentage of time data is being transmitted is larger (Figure E.2 (a) vs. (b)), being more efficient. On the other hand, for a given data packet size, using a higher R_{phy} the data packet will be sent faster (Figure E.2 (b) vs. (a)), nevertheless being less efficient, as the percentage of time data is being transmitted is smaller.



(a) Long packet or slow transmission bit rate.



(b) Short packet or fast transmission bit rate.

Figure E.2 – Protocol overhead impact on bandwidth usage efficiency.

The duration of DIFS and SIFS deferral – T_{DIFS} and T_{SIFS} – are respectively of 34 μs and 16 μs. The average backoff time, $\overline{CW}$, is given by

$$\overline{CW}_{[\mathrm{s}]} = \frac{CW_{min} \cdot T_{slot\,[\mathrm{s}]}}{2} \quad \text{(E.1)}$$

where:

- CW_{min}: congestion window minimum size, 15 slots.
- T_{slot}: slot duration, 9 μs.

When sending a data packet from the application layer to the lower layers, several headers are introduced. This results in a data transmission delay given by:

$$T_{p\ data\,[\mathrm{s}]} = T_{pmb\,[\mathrm{s}]} + T_{phy\,[\mathrm{s}]} + T_{mac\,[\mathrm{s}]} + T_{ip\,[\mathrm{s}]} + T_{data\,[\mathrm{s}]} \quad \text{(E.2)}$$

where:

- T_{pmb}: transmission time of the physical preamble, 16 μs, during which are transmitted 12 symbols (10 short and 2 long) at 6 Mbit/s.
- T_{phy}: transmission time of the PHY header, 4 μs.
- T_{mac}: transmission time of the MAC header of 34 bytes, K_{mac}, transmitted at R_{phy}.
- T_{ip}: transmission time of the TCP/UDP and IP headers, K_{ip}, transmitted at R_{phy}.The IP and TCP headers have 20 bytes while the UDP header has 8 bytes.
- T_{data}: transmission time of the payload of K_{data} bytes transmitted at physical data rate R_{phy}.

The ACK transmission delay is given by:

$$T_{p\ ack\,[\mathrm{s}]} = T_{pmb\,[\mathrm{s}]} + T_{phy\,[\mathrm{s}]} + T_{ack\,[\mathrm{s}]} \quad \text{(E.3)}$$

where:

- T_{ack}: transmission time of the ACK of 14 bytes, K_{ack}, transmitted at a specific control rate R_{ctrl} (6 Mbit/s for R_{phy} of 6 and 9 Mbit/s, 12 Mbit/s for R_{phy} of 12 and 18 Mbit/s, and 24 Mbit/s for R_{phy} equal or greater than 24 Mbit/s).

Considering the PPDU frame format, and given the transmission time for a symbol, T_{sym}, of 4 ms, the resulting data transmission delay is given by

$$T_{p\ data\ [s]} = T_{pmb\ [s]} + T_{phy\ [s]} + T_{sym\ [s]} \cdot \left\lceil \frac{16 + 8 \cdot K_{ip} + 8 \cdot K_{mac} + 8 \cdot K_{data} + 6}{N_{DBPS}} \right\rceil \tag{E.4}$$

The ACK transmission delay is given by:

$$T_{p\ ack\ [s]} = T_{p\ [s]} + T_{phy\ [s]} + T_{sym\ [s]} \cdot \left\lceil \frac{16 + 8 \cdot K_{ack} + 6}{N_{DBPS}} \right\rceil \tag{E.5}$$

The maximum link throughput, $R_{link\ max}$, considering a propagation delay, T_{prop}, is then given by:

$$R_{link\ max\ [\text{Mbit/s}]} = \frac{8 \cdot K_{data\ [\text{Mbit}]}}{T_{DIFS\ [s]} + \overline{CW}_{[s]} + T_{p\ data\ [s]} + T_{prop\ [s]} + T_{SIFS\ [s]} + T_{p\ ack\ [s]} + T_{prop\ [s]}} \tag{E.6}$$

The minimum link delay, $T_{link\ min}$, is then given by:

$$T_{link\ min\ [s]} = T_{prop\ [s]} + T_{DIFS\ [s]} + \overline{CW}_{[s]} + T_{p\ data\ [s]} \tag{E.7}$$

Appendix F

Implementation Assessment

Appendix F presents the assessment of the implementation of the proposed multi-radio nodes and RRM strategy in OPNET Modeler simulation platform.

F.1 Coverage and Throughput

In this section an assessment of the development and implementation in OPNET Modeler of multi-radio mesh node with the proposed RRM strategy is made. The achieved communication range, d_{max}, and maximum application-layer throughput, R_{app}, are assessed, for the reference scenario conditions, outdoor communication where one node is sending packets of 1 500 byte to another one, with P_{tx} of 30 dBm. Simulation results are presented in Figure F.1.

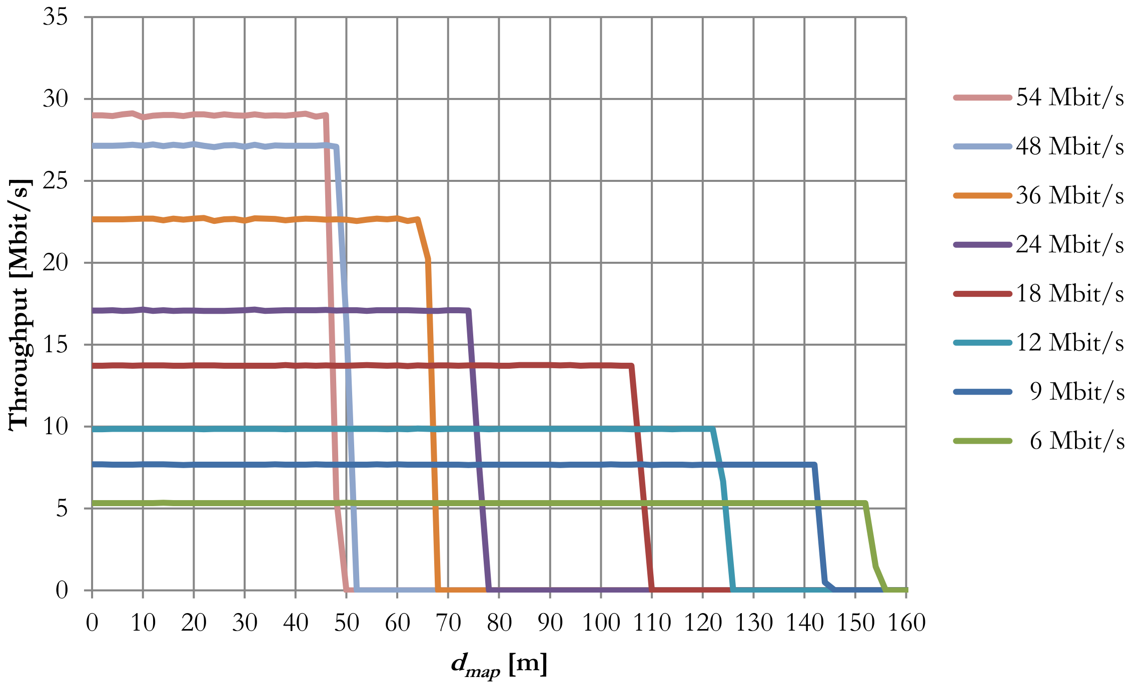


Figure F.1 – Simulated application-layer throughput and communication range.

The simulated maximum achievable throughput for various bit rates, presented in Table F.1, has deviations below 3 % from analytical ones, assessing the correct implementation and performance of the developed multi-radio nodes in OPNET.

The communication range was evaluated in simulation for increasing distances between a node pair, not considering the existence of interferers. A comparison of simulation results with analytical ones, presented in Figure 6.1 for the same propagation conditions and $P_{tx} = 30$ dBm, is presented in Table F.2. Simulation results match theoretical ones with an error, $\Delta_{d_{max}}$, below 2%, assessing the correct implementation and performance of multi-radio nodes in OPNET.

Table F.1 – Comparison between simulated and theoretical maximum throughput.

R_{phy} [Mbit/s]	Simulated		Theoretic	Comparison	
	$\overline{R_{app}}$ [Mbit/s]	$\sigma_{R_{app}}$ [Mbit/s]	R_{app} [Mbit/s]	$\Delta_{R_{app}}$ [Mbit/s]	Δ [%]
6	5.322	0.004	5.250	0.072	1.369
9	7.671	0.007	7.568	0.102	1.353
12	9.842	0.007	9.824	0.018	0.183
18	13.721	0.012	13.738	0.017	0.121
24	17.083	0.022	17.303	0.220	1.269
36	22.643	0.054	23.188	0.544	2.348
48	27.147	0.049	27.938	0.792	2.834
54	28.999	0.057	29.886	0.887	2.970

Table F.2 – Comparison between simulated and analytical maximum communication range.

R_{phy} [Mbit/s]	d_{max} [m]		$\Delta_{d_{max}}$ [%]
	Simulated	Analytical	
6	148	149	0.9
9	138	139	0.9
12	120	121	0.9
18	104	105	1.3
24	74	74	0.4
36	64	65	1.0
48	48	49	1.8
54	46	46	0.9

F.2 Transmission Power Levels Impact

Next, the impact of different transmission power levels among nodes is studied. Consider again the situation of Figure 6.4, where $d_{map} = d(A - B) =$ 40 m. *X* and *Y* are considered interferers. In this case, *X* interferes with the reception at *B* from a transmission of *A*. Different physical data-rates are evaluated for the link *A*-*B*. Within the 8 possible P_{tx} levels, $P_{tx}(A)$ is set to guarantee that $P_{rx}(B) \geq P_{rx\,min}$, as shown in Table F.3. For example, at 54 Mbit/s, $P_{tx}(A)$ must be 30 dBm, while at 12 Mbit/s 15 dBm are sufficient.

Table F.3 – Minimum P_{tx} level that guarantees communication between *A*-*B*.

R_{phy} [Mbit/s]	$P_{tx}(A)$ [dBm]	$P_{rx}(B)$ [dBm]	$P_{rx\,min}$ [dBm]
6	12.0	-88.1	-89.0
9	15.0	-85.1	-88.0
12	15.0	-85.1	-86.0
18	18.0	-82.1	-84.0
24	24.0	-76.1	-79.0
36	24.0	-76.1	-77.0
48	30.0	-70.1	-73.0
54	30.0	-70.1	-72.0

In Figure F.2, $d_I(B)$ is plotted, considering various $P_{tx}(X)$ levels, various $R_{phy}(A-B)$ rates using the corresponding $P_{tx}(A)$ levels identified in Table F.3. The impact in d_i of the variation of $R_{phy}(A-B)$ is smaller than of the variation of $P_{tx}(X)$, when $P_{tx}(A)$ is according to the values shown in Table F.3. The generalised assumption of an interference margin per data-rate, as presented in Table 6.2, does not hold when the transmitted power levels are different between nodes. In this sense, when power control mechanisms are used, the identification of interfering nodes should be ruled differently.

Table F.4 shows the average and standard deviation values of the interference range. The standard deviation is always below 5%, evidencing that it is a reasonable approximation to consider that the interference range is proportional to $P_{tx}(X)$. For a given $P_{tx}(X)$ level, the observed standard deviation is partly due to the discrete levels of $P_{tx}(A)$ used to guarantee received power levels above $P_{rx\,min}$; ρ_{min} also varies with R_{phy}, being more robust to interference for lower rates.

This evidences that, in the determination of the interference range, the transmitter's and interferer's P_{tx} have more impact than R_{phy}. As it can be concluded from the results presented in Table F.4, the interference range can be estimated for neighbouring nodes by the transmitted power level of the interferer, being independent from the used bit rates, when considering that nodes minimise their transmitted power level so that the received power level is approximated to $P_{rx\,min}$.

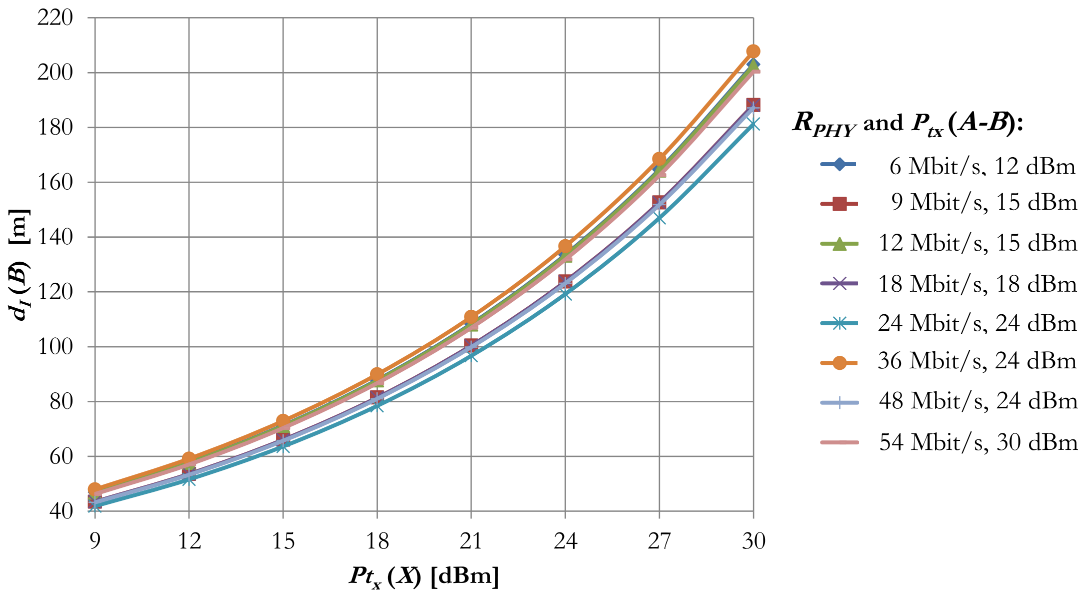


Figure F.2 – Interference range for various $P_{tx}(X)$, considering *A-B* communicating at various rates and associated power levels.

Table F.4 – Interference range at node *B*, for various interferer power levels, considering *A-B* communicating at various rates and minimum required P_{tx} level.

	$R_{phy}(A-B)$ [Mbit/s] , $P_{tx}(A)$ [dBm]								$\overline{d_I}$ [m]	σ_{d_I}[m]
$P_{tx}(X)$ [dBm]	**6, 12**	**9, 15**	**12, 15**	**18, 18**	**24, 24**	**36, 24**	**48, 30**	**54, 30**		
9	47	43	47	43	42	48	43	46	45	2.2
12	58	54	58	54	52	59	53	57	55	2.8
15	71	66	71	66	64	73	66	70	68	3.4
18	88	81	88	81	78	90	81	87	84	4.2
21	108	100	108	100	97	111	100	107	104	5.2
24	134	124	133	124	119	137	123	132	128	6.4
27	165	153	164	153	147	168	152	163	158	7.9
30	203	188	202	188	181	208	187	200	195	9.7

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