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Analysis of Channel Models for Wireless Sensor Networks

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Abstract

This thesis addresses the formulation and application of a multi-obstacle channel model for simulation of Wireless Sensor Networks, based on the Geometrically Based Single Bounced Channel Model, which was implemented into a simulator and proposed by GROW at IST-TUL in Lisbon.

The model relies on the assumption that the transmitted signal is divided into many multipath components, where each one is reflected from an obstruction and arrives directly to the receiver, the total received signal being the sum of all components. The second assumption of this model is that components arrive to the receiver in clusters.

A literature survey of wireless sensor networks was performed. There are many real applications of such networks, two of them being chosen. The work focuses on the forest and house scenarios. A multi-obstacle channel model was developed for these scenarios.

The multi-obstacle channel model for the forest assumes that each tree in the scattering region of transmitter and receiver attenuates the signal. The number of trees and their attenuation is given in a statistical way with specific distributions.

The house scenario is defined for a common family house, where each wall is considered as an obstacle. The signal reflects from many objects in the house, like furniture or even people and is attenuated by the walls. Each object influencing the signal is described also in a statistical way.

Many simulations were performed on the influence of the obstructions densities, their parameters and distances of the terminals, on the performance parameters of the channel model. The achieved results and the conclusions are shown in the end of this dissertation.

Keywords

Wireless Sensor Networks, Multi-obstacle Channel model, Geometrically Based Single Bounce.

Streszczenie

Praca ta definiuje wielo-przeszkodowy model propagacyjny, który mógłby być zastosowany w symulacjach Bezprzewodowych Sieci Czujników. Zadanie to zostało wykonane implementując ten model do Jedno-Odbiciowego Geometrycznego Modelu Kanału Radiowego, który został zaimplementowany w symulatorze zaproponowanym przez GROW na IST w Lizbonie.

Wspomniany model kanału jest oparty na założeniu, że transmitowany sygnał dzieli się na wiele składowych, z których każda odbita od jednej przeszkody dochodzi bezpośrednio do odbiornika, gdzie całkowity sygnał jest sumą wszystkich składowych. Drugim założeniem modelu jest fakt, że w rzeczywistości takie składowe dochodzą do odbiornika w paczkach.

W celu zaimplementowanie sieci czujników do programu symulatora, sieci te zostały dokładnie przestudiowane. Kilka rzeczywistych zastosowań takich sieci zostało rozważonych i następnie zostały wybrane dwie z nich. Praca ta skupia się na zastosowaniu sieci czujników w lasach i domach. Wielo-przeszkodowy model został przygotowany dla tych właśnie aplikacji.

Model ten w przypadku lasu zakłada, że każde drzewo w regionie zainteresowania wpływa na sygnał tłumiąc go. Liczba drzew wpływających na sygnał i ich tłumienie charakteryzuje się losowymi właściwościami ze specyficznym statystycznym rozkładem.

Zastosowanie sieci w domu zostało przygotowane dla zwykłego jednorodzinnego domu, w którym każda ściana jest traktowana jako tłumiąca przeszkoda w modelu. Sygnał odbija się od wielu obiektów w domu takich jak meble, ludzie itd. i następnie jest tłumiony przez ściany. Każdy obiekt wpływający na sygnał także charakteryzuje się statystycznymi właściwościami.

W pracy tej zostały przeprowadzone symulacje wpływu gęstości przeszkód, ich parametrów i odległości pomiędzy urządzeniami na parametry kanału definiowane przez jedno-odbiciowy model kanału. Otrzymane wyniki i wnioski zostały przedstawione na końcu tej pracy.

Słowa kluczowe

Bezprzewodowe Sieci Czujników, Wielo-Przeszkodowy Model Propagacyjny, Jedno-Odbiciowy Model Geometryczny Kanału

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List of Abbreviations

AoA	Angle of Arrival
AoD	Angle of Departure
BS	Base Station
CIR	Channel Impulse Response
COST	European Cooperation in the field of Scientific and Technical Research
DL	Down-Link
DoA	Direction of Arrival
DoD	Direction of Departure
FDD	Frequency Division Duplexing
GBSB	Geometrically Based Single Bounce
GPS	Global Positioning System
GROW	Group for Research on Wireless
IEEE	Institute of Electrical and Electronic Engineers
IST	Instituto Superior Tecnico
LoS	Line of Sight
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MT	Mobile Terminal
MWM	Multi-wall empirical narrow-band model
NLoS	Non Line of Sight
PDF	Probability Density Function
PDP	Power Delay Profile
RF	Radio Frequency
RMS	Root Mean Square
Rx	Receiver
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SVD	Singular Value Decomposition

TDD	Time Division Duplexing
ToA	Time of Arrival
TUL	Technical University of Lisbon
Tx	Transmitter
UL	Up-Link
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

List of Symbols

$\lvert\Gamma\rvert$	Magnitude of the reflection coefficient
Γ	Reflection coefficient
η	Capacity of radio channel
λ	Wavelength
ν	Velocity of the MT or the BS
ϱ	Average signal to noise ratio in Rx antenna
Σ	Diagonal matrix of H values
σ_x	RMS delay spread
τ	Time of arrival
τ_i	Delay of the i^{th} component
τ_{max}	Observation time window
φ_0	Angle of Departure from BS
Φ_{sc}	Phase of the reflection coefficient
Φ_{Rx}	Reflector phase shift
$\Phi_{Rx,i}$	Phase of the i^{th} component
B_c	Coherence bandwidth
c	Speed of light
d	Distance between antennas
d_0	Direct distance between BS and MT
d_1	Distance between transmitter and scatterer
d_2	Distance between scatterer and receiver
d_t	Distance between transmitter and tree trunk
E_{rx}	Signal Amplitude
f	Frequency
f_m	Maximum Doppler shift frequency
G_{Rx}	Radiation pattern of Rx antenna
G_{Tx}	Radiation pattern of Tx antenna
h	Channel Impulse Response
$\boldsymbol{H}$	Complex Channel Impulse Response matrix

h_{eff}	Effective length of antenna
h_k	Channel Impulse Response amplitude
I	Number of wall types
$\boldsymbol{I_n}$	Diagonal identity matrix
k	Number of independent radio channels
k_{wi}	Number of penetrated walls of type i
L	Number of multipath components
L_{FS}	Free space loss between transmitter and receiver
L_p	Channel path loss
L_{wi}	Loss of wall type i
$\boldsymbol{N}$	Additive noise vector
P_k	CIR power
P_{Rx}	Received power
P_{Tx}	Transmitted power
$P_{x,\varphi}$	Probability density function
$\boldsymbol{R}$	Correlation matrix
R_A	Feed point impedance of the antenna
R_{max}	MT area radius
S/N	Signal to noise ratio
Tc	Coherence bandwidth
$\boldsymbol{U}$	Unitary matrix
$\boldsymbol{X}$	Transmitted symbols vector
$\boldsymbol{Y}$	Received symbols vector

List of Programmes

Matlab	MathWorks
VS .NET	Microsoft Visual Studio .NET 2003 Professional
Microsoft Word	Microsoft Corporation
Microsoft Excel	Microsoft Corporation
FastSum	FastSum Integrity Control v1.3

Chapter 1

Introduction

This chapter gives a brief overview of this dissertation, being an introduction to the aspects that are considered in this work. The layout of the whole document is presented as well.

Nowadays, in the century of telecommunications, when the transmission of information is a key to expand civilisation, wireless links popularity is increasing very rapidly. The existence of mobile cellular phones, computers connected to the Internet, intelligent buildings and machines, is the best proof that information has a very important value. The evolution of the civilisation would have never happened without exchanging information.

The progress of technology and the big pressure put on the miniaturisation of any electronics and the increase of efficiency of any radio devices enables the production of sensors interfering into nature in order to control and monitor a given covered area. Sensor devices popularity is increasing very rapidly. Such equipments can substitute people in many difficult and dangerous applications, and can increase the efficiency of such applications, being less prone to failure than a human being. A smart wireless sensor could be a small device equipped with sensors, memory, processing and wireless communication units. The size of sensors can range from millimetres (then they are called motes) to a metre. The increase of energy consumption is observed in such devices, thus, in this case power management becomes very important. The decrease of energy consumption is the one of the goals of current research. Sensors are deployed statistically or deterministically, depending on the type of application. The group of sensors works as an ad hoc network, which is defined by IEEE as Wireless Sensor Networks (WSNs). Such networks are needed more and more often in various live applications, and a lot of researchers are engaged in projects focused on them. Some examples of sensors are depicted on Figure 1.1.

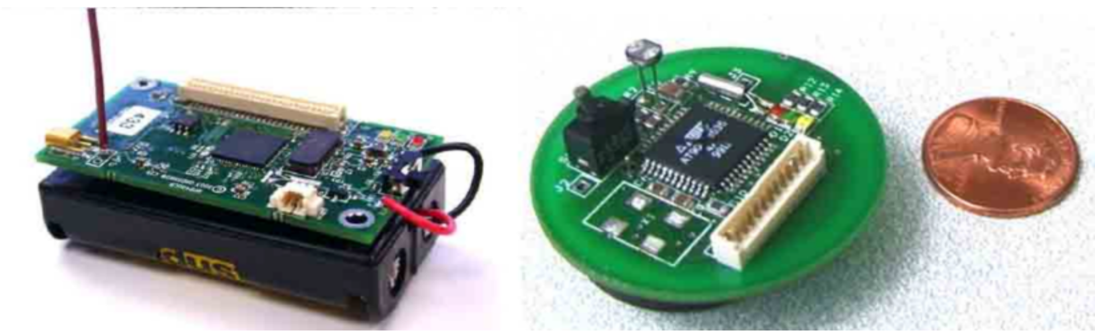


Figure 1.1. Examples of wireless sensors [Xbow06].

WSNs use radio waves as a communication medium, so, because of the complex rules of wave propagation, they are very environment dependent. It is very important to choose a suitable channel model and make the corresponding simulations in order to design the network with the best performance. The environment of the radio waves propagation is usually filled with many obstacles, which strongly influences the signal. The aim of this work is to simulate sensor networks in some scenarios considering the influence of the obstructions in the propagation. The Geometrically Based Single Bounce Model [LiRa99] has been chosen as a channel model. This model assumes that the transmitted signal reflects from the many obstructions, multipath components arriving in clusters to the receiver. The influence of many obstacles is considered by reflections and attenuation during wave propagation, signal attenuation being estimated by the Multi Obstacle Model (MOM), which was developed in this thesis, in order to enable a better characterisation of wireless sensor networks. MOM considers the attenuation of the obstacles that are in signal propagation path, the position and number of obstructions being considered as statistical values, which gives flexibility to the model. The MOM was implemented in the simulator proposed by the Group for Research On Wireless (GROW) from IST-TUL [Koko05] [Zuba05].

Many simulations were performed, and parameters were defined for two types of sensor applications: forest and house.

The first considered scenario is the forest, because of the big danger of fires in dry forests, it being very important to have a good protection and the possibility of fast reaction, thus, Wireless Sensor Networks are very useful in such a case. There are a lot of projects focused on fire protection, like [DoSi05] and [Fire05]. The main idea is that sensors are uniformly deployed in a given covered area, and monitor some phenomena, like temperature, pressure or humidity and is shown on Figure 1.2. Such a scenario becomes interesting by considering trees as obstructions, which was the reason for choosing it. The density of the trees is a key parameter in this case, simulations considering various densities and types of the trees.

The second scenario of interest is a house, since intelligent buildings (smart homes) are becoming very popular nowadays. The idea of such houses is to make live better and easier for example for elderly or physically handicapped people. Definition of the smart house is that such a house allows remote control of particular activities, for example turning on the light when somebody is entering the room or turning on heaters when temperature is too low. The case of monitoring human activity and behaviour in particular inside a house is addressed in a dissertation [OgTo00] and shown on Figure 1.3. There are already devices sensing the existence of human (infrared), temperature, humidity, pressure and light.

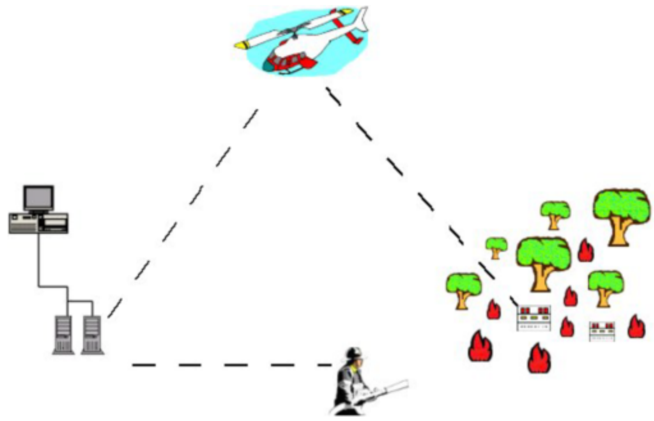


Figure 1.2. The forest scenario usage idea [DoSi05].

The house scenario is also very interesting because of the walls, which strongly influence the signal. Each wall is treated as an attenuating obstruction in MOM.

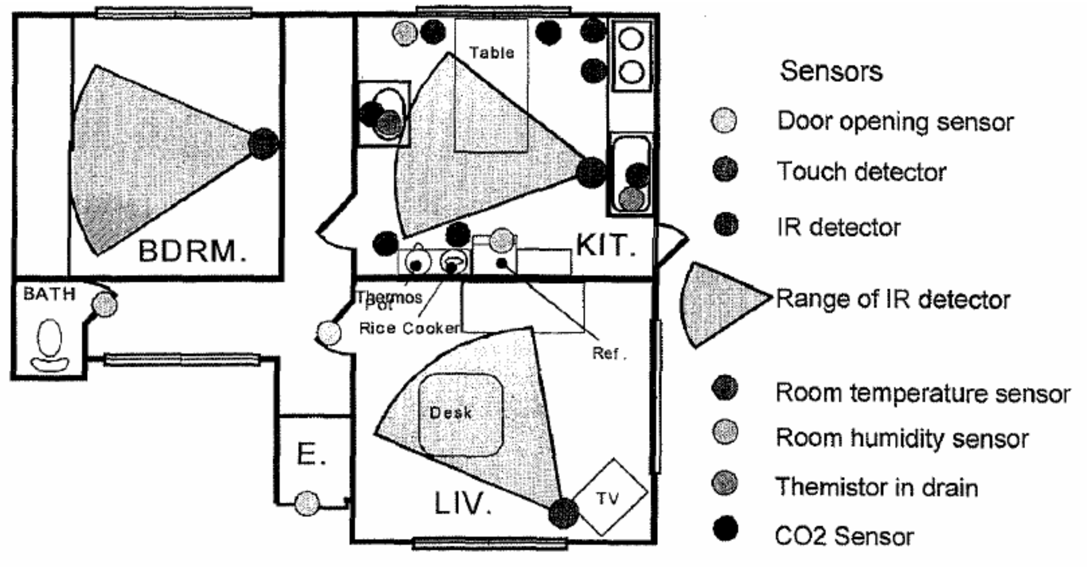


Figure 1.3. Idea of the house scenario. [OgTo00]

This dissertation is divided into six chapters. Chapter 2 contains the basic aspects of Wireless Sensor Networks and some of their real applications, and gives a description of the main issues connected with sensor networks. The second part presents some scenarios and real solutions of implementation of such networks.

Chapter 3 gives the description of some models used in simulations. The first section presents basic aspects of channel modelling and addresses in detail the Geometrically Based Single Bounce Channel Model, showing all assumptions and approaches of the model, and presenting performance parameters. The second part of the chapter contains basic aspects of path loss models. The main considerations of the Multi Obstacle Model are developed, as well as the methods of its implementation into Wireless Sensor Networks for forests and houses. This is the main theoretical part of this work.

Chapter 4 contains the description of the simulator, where all mentioned models are implemented. This chapter is divided into few sections describing the main behaviour of the simulator, input and output parameters, and the changes that have been made in comparison to the previous version. This chapter also gives a short description about the range estimation calculations.

Chapter 5 begins from with a description of the forest and house scenarios. This description presents all parameters of the scenarios, their parameters and possible behaviour. The accuracy of the used assumptions and approaches has a big influence on the final results, which are depicted and analysed in the second part of the chapter.

Chapter 6 contains the conclusions of the thesis, and some ideas for future work.

This dissertation contains also a few annexes, where some less important graphs are drawn.

Chapter 2

Basic Concepts

This chapter provides an overview of the Wireless Sensor Networks and their scenarios.

2.1 Wireless Sensor Networks

Wireless Sensor Networks are part of ad hoc networks, the latter being described in the first subsection, while the second gives basic information about sensor networks.

2.1.1 Ad Hoc networks

The ability of adapting and work without complicated and expensive infrastructure is a fundamental feature of wireless communication systems. Ad hoc networks let their mobile users communicate without a permanent cable infrastructure, which is a goal of the networks demand. Previously, ad hoc networks were used only in military communication systems or disasters regions. Nowadays, technologies like Bluetooth and WLANs, which are commercialised ad hoc networks, allow mass market users to use that type of networks. The rapidly growing usage of devices like notebooks, laptops, palmtops (PDAs) or mobile phones confirms this fact. Wireless ad hoc networks have represented a very attractive object of research and experiments for the last few years, but there are still a lot of unsolved problems.

Nowadays, when the diversity of electronic devices is so popular, we can observe a big necessity for ubiquitous networks, which can connect all standards and make the communication between different devices possible [WeJo02]. The features of such a network should be as follows:

- heterogeneous network – network should enable communication between heterogeneous devices, which means that communication algorithms and protocols should be standardised;
- mobility – such a network must allow users to change position during the connection with different velocities;
- dispersed network – the network scenario is changing in time, due to the motion of terminals, weather conditions, etc.. Additionally, the covered area can be very big, so propagation environment can be very diverse, which means that networks should be

resistant to various propagation conditions;

- scalability – this feature is very important, because the number of terminals can change rapidly, so the increase of the number of users cannot decrease the capacity of the network;
- good power management – distances between devices can be different and can change, so there must be the possibility for multi-hop communications, in which case good protocol stacks must be implemented.

This type of networks is already implemented in a few applications. Internet working on many various devices like phones, PDAs or PCs working in WLAN or Bluetooth are examples of ubiquitous networks. Another example can be Wireless Sensor Networks, which consist of many devices (including computers) working together.

These networks have a lot of advantages. The most important one is the absence of any management devices with complicated usage. The second advantage is the easiness to join the network without any problems, because all communication issues are made automatically. A big size of such networks gives access to a big base of data. The management of the network is simple and it is possible from each node and each place in the covered area.

The disadvantage of ubiquitous ad hoc networks is power management. This is a very important issue, because each device working in the network needs power, and in the case of mobility terminals are limited to the power sources to recharge the battery. Another problem of these type of networks is the complexity of algorithms for network management and communication, which increase the need for better processing units.

2.1.2 Sensor Networks

The description of any network should begin with the description of the devices that compose it. Wireless Sensor Networks are a specific part of ad hoc networks, consisting of many smart sensors. Each sensor is equipped with specialised sensing units (thermal, pressure, acoustic, motion, etc.), processing unit, memory, wireless transceiver with antenna and power supply. The size of such a device can range from millimetres (motes) to one metre, or sometimes more. The size usually depends on the environment and the type of sensing phenomenon.

Sensor devices are usually deployed in places where the battery change is impossible. This fact is the reason why each part of the sensor should consume the least power. Most part of the power is consumed during transmission and reception of the signal. Sensors can work in a various modes:

- Transmission – transmitting the signal.
- Reception – receiving the signal.
- Idle – ready to receive but not doing so.
- Sleep – significant parts of the transceiver are switched off.

The main function of such networks is transmitting the sensed information from each device in order to reach a global view of the monitored region and enabling specific actions in an appropriate way. The type of communication between nodes strongly depends on the environment, so the devices can use various media:

- Radio frequencies – this is most popular medium, used in most cases.
- Optical frequencies – this medium consumes much less energy in communication than radio frequencies, but it requires Line of Sight, which is usually impossible.
- Ultrasound – this medium allows communication in environments where electromagnetic and optical waves do not propagate (e.g. water).

Wireless Sensor Networks consist of many small devices scattered in a sensor field as shown in Figure 2.1. Each sensor collects data and sends it to the sink node, which sends it to the end user. The communication between the sink and the end user can be done via internet or satellite. However, communication between nodes in the sensor field and the sink is based on multi-hop transmission and, because of the environment variability, on infrastructureless communication.

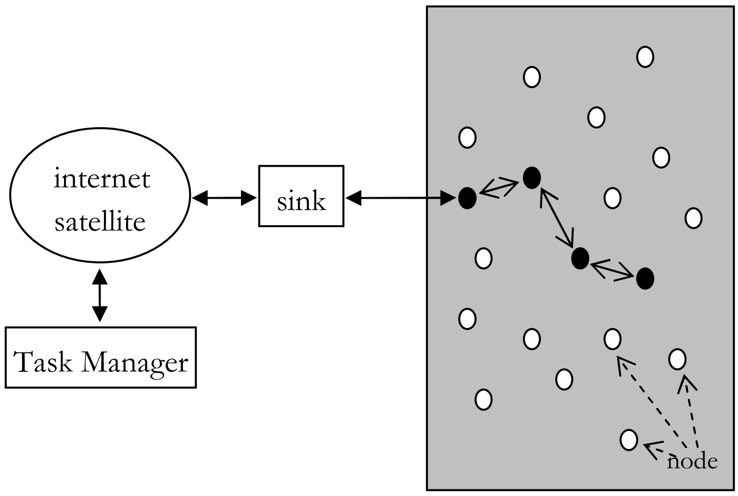


Figure 2.1. Sensor field with scattered nodes.

The size of such network environment may be small (e.g. a car) or very big (e.g. a forest). Wireless Sensor Networks usually work in specific applications, so communication algorithms depended on them. Moreover, their common features are:

- homogenous network – usually, WSNs consist of equal devices, with the same sensed information and communication standards, especially when the used devices are of the same company. A situation when a new model of the device is added to the network is an exception, but each new standard must cooperate with the former one;

- nodes mobility – nodes in such networks can be statically mounted and rarely change their positions or can change their position with various velocities. This is the reason for the usage of specialised routing protocols and power management;

- variable network size – WSNs could be implemented in both very small environments and large ones. The covered area can change rapidly, as well as the number of devices;

- relatively dispersed – because of this feature, communication used between nodes must be multi-hop and routing protocols must be more intelligent in order to increase the capacity of the network.

In connection with these features, there are a lot of factors that should be considered when designing such a network. Because of the big WSNs environment variety, it is difficult to have a unique approach when designing them [AkSa02]. The following main factors must be taken under careful consideration:

1. Fault tolerance – some applications could be extreme, for example in the bottom of the ocean or in a burning forest. In such situations, destruction of nodes is possible, and it should not cause any problems for the communication between other properly working nodes.

2. Scalability – this is a very important factor, because the number of nodes and the working area in sensor networks can change very rapidly. Adding new nodes to such a network is possible at any time, so it cannot cause any problems.

3. Power consumption – WSNs usually consist of devices equipped with batteries. Changing them is very often unfeasible, so power consumption in such sensors is very important. A long working time is required, because it allows us to gather more sensing information of the phenomena.

4. Network topology – this factor should be taken under consideration, because in different environments different topologies are required to fulfil the communication scheme in the best way. This factor also specifies a routing scheme and used protocols.

5. Transmission media – most common media of transmission in WSNs are the radio, infrared and optic waves. Infrared and Bluetooth are the best known schemes, but this issue is still open for research.

6. Hardware constraints – small wireless sensor devices can be built from different parts, depending on the sensing phenomena and the environment. They can be, for example, equipped with solar batteries, GPS receivers or special antennas.

7. Production costs – all factors mentioned above depend on the price. The goal of an engineer is to design a network with the lowest cost.

The description of the network should be presented using the layer model. Protocols used in such networks are arranged in the stack shown in Figure 2.2. This model is very flexible for WSNs, especially when a designer takes power, mobility and task management planes under consideration. These planes are important in choosing the best protocols in each layer of the model.

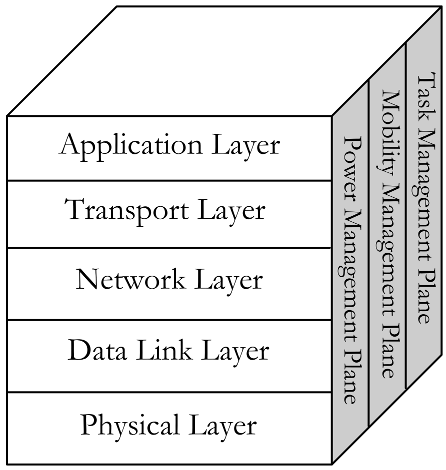


Figure 2.2. WSNs protocol stack [AkSa02]

Beginning with the lower *Physical Layer*, the transmission scheme is very variable and strongly dependent on the environment (ocean, building, air, mine, forest, etc.), so the physical link can be different for each WSN. This layer specifies the modulation scheme, strategies to overcome propagation effects and hardware design. The *Data Link Layer* provides the Medium Access Control (MAC) protocols that are important for an efficient communication. This layer has two goals: to create the best network infrastructure (with thousands of nodes), and to provide a fair share of communication resources among nodes. The *Network Layer* is very important for the efficiency of communication. There are many nodes in WSNs and multi-hop communication is required, so the routing protocols should consist of all features listed in the previous page. These protocols and algorithms are specified in this layer. The next layer is the *Transport Layer,* and its main objective is to encapsulate sensing data and to communicate with other networks, like Internet, phones, etc.. The *Application Layer* protocols strongly depend on the sensing phenomena. This layer specifies the sensing scheme and transport algorithms to collect and send data to the end user through the sink [AkSa02].

When analysing sensor networks, it is important to consider some topologies. Sensor nodes usually are deployed in the sensor field randomly, so the information about the position is not known in the beginning. The topology of the network can be:

- star – each node sends the data only to one node directly; this topology is not complicated, but consumes much power during transmission;
- extended star – nodes transmit data to the specified node in the region of work, and this one forwards it to the sink;

- mesh – the information is transmitted to the sink node via multi-hop communication using the shortest path; this topology is most efficient, but requires smart routing algorithms, being more complex;

This dissertation focuses on the physical layer of the network and considers only the issues connected with radio propagation; a more detailed description is available in [AkSa02]. However, some aspects from the higher layers are considered.

2.2 Scenarios

Wireless Sensor Networks have many and various networks, thus, it is impossible to describe them in general. There are big differences among particular applications. Devices used in networks are different, by considering their sensing phenomena, therefore, communication methods are strongly dependent on the particular network. Some schedules and algorithms are very useful in some networks, but in others they are useless. Some particular scenarios of WSNs are described in this paragraph.

The main types of WSNs applications can be divided into Event Detection and Random Process Estimation [BVNP05], [Crui06]. The main objective of the former type is to detect an event and send the information to the end user via a sink node, while the objective of the latter is to provide estimation of the sensing phenomenon in the field of interest, using periodically waked up (activated) nodes, which send data to the entity collecting information.

Three separate application areas were identified in [BVNP05] and [Crui06]. They were categorised according to the type of sensor deployment environment: Urban, Rural and Indoor. By following this categorisation there are six different Scenario Types:

- Event Detection in Urban environment (ED-U);
- Event Detection in Rural environment (ED-R);
- Event Detection in Indoor environment (ED-I);
- Random Process Estimation in Urban environment (PE-U);
- Random Process Estimation in Rural environment (PE-R);
- Random Process Estimation in Indoor environment (PE-I);

It is difficult to consider a lot of reference scenarios. In this case, there are a few cases described in this dissertation, Table 2.1. All scenarios were taken from real applications, references being shown in the table.

Table 2.1. Sensing phenomena in considered scenarios.

Sensing information / **Scenario**	*temperature*	*gas*	*snow*	*water level*	*pressure*	*humidity*	*seismic*	*magnetic field*	*chemical*	*biological*	*vehicle*	*animal*	*human*	*GPS*	References
MINE	✓	✓		✓	✓	✓	✓	✓	✓				✓		[Crow06] [Gene06] [Futu06] [ShFu05]
MOUNTAINS	✓		✓			✓	✓					✓		✓	[MMSS05] [Well00]
OCEAN	✓			✓	✓		✓		✓	✓		✓		✓	[Mona97]
FOREST	✓		✓			✓				✓		✓		✓	[Fire05] [DoSi05]
TUNNEL	✓	✓				✓		✓	✓		✓		✓		[Chee05]
PARKING								✓			✓		✓		[Gara06]
BATTLE FIELD		✓						✓	✓	✓			✓	✓	[Batt06]
GROUND	✓		✓		✓	✓	✓			✓		✓		✓	[Rain01] [Gard06]
CITY	✓	✓					✓				✓				[Jenn06]
HIGHWAY	✓	✓	✓								✓	✓	✓	✓	[GrSa06]
HOUSE		✓	✓										✓		[OgTo00]

It is also important to group sensor networks into two types, depending on the size of the equipment and the environment. The first group of networks are micro-sensors, where devices are very small compared to the wavelength used in RF communications. ZigBee [ZigB04] defines three bands of radio transmission. These bands and equivalent wave lengths are presented in Table 2.2. This type of division is important, in order to analyse the propagation models that are dependent on frequency. Small sensors with dimensions of one millimetre are not considered, because they usually use wide band communication systems, thus, scenarios like medical monitoring, micro-cameras or microphones, become uninteresting in this perspective.

Table 2.2. WSNs bands and equivalent wavelengths.

Band [MHz]	**Wavelength** [cm]
[868, 868.6]	~35
[902,928]	~33
[2400, 2483.6]	~12

Focus is put on macro-sensor networks, where the device size can by much bigger than the communication wavelength. Some popular sensing phenomena were chosen. The considered scenarios and their sensing information are presented in Table 2.1. The idea of each scenario is to sense particular data in a special environment. Sensed data is sent by multi-hop communication to the sink node, and then presented to the end user.

As it was mentioned earlier, there are big differences between WSNs working in different environments and applications. It is important to consider the parameters describing them, which enable the discussion about scenarios. Table 2.3 presents some parameters and their values for each scenario presented on Table 2.3.

Table 2.3. Parameters of considered scenarios

Parameter / **Scenario**	*Distances between nodes [m]*	*Maximum size of covered area [km²]*	*Max. Number of nodes*	*Type of network*		*type*	*Line of Sight possibility*
				event	*monitoring*		
MINE	[2,50]	1	15		✓	ED-I,PE-I	
MOUNTAINS	[10,300]	5	50	✓	✓	ED-R	
OCEAN	[300,1000]	10	15		✓	PE-R	✓
FOREST	[10,200]	1	15	✓	✓	ED-R	
TUNNEL	[10,200]	1	10	✓	✓	ED-I	✓
PARKING	[5,50]	0.4	200	✓		ED-I	✓
BATTLE FIELD	[10,500]	0.5	10	✓	✓	ED-R,PE-R	
GROUND	[1,50]	0.002	30		✓	PE-R	✓
CITY	[10,400]	0.02	20		✓	ED-U,PE-U	✓
HIGHWAY	[100,2000]	5	20		✓	PE-R	✓
HOUSE	[1,20]	0.0005	20	✓		ED-I,PE-I	

The mine application of sensor networks is related mainly to the sensing of the methane gas, which is a big danger of explosion. Such network must be reliable, because human life depends on it. The radio communication environment is very complicated and varied, so it is difficult to simulate it efficiently. The design of such network should rely on measurements.

The main objective of the mountains scenario is to detect the threat of avalanche, measuring the snow level, temperature and humidity. It is important to react quickly in such case. The propagation environment is usually filled by trees, rocks and mountains. The accuracy of simulation of such scenario depends on the accuracy of the environment definition.

The ocean scenario is used to monitor the behaviour of the ocean. Sensors are usually deployed under water level and sense the information. Communication between them can be done in two ways: first, using the water medium and ultrasounds, and second periodically going to the ocean surface and communicating using radio waves. The second solution is quite simple, because the environment is usually empty and only free space attenuation should be considered.

The forest application is very important to save the wild forest from fires. Sensors deployed there sense the fire danger straight from the source and send the information for fast reaction. The environment is filled with many obstructions, like trees, which are usually the same in all covered area. Each obstruction can be defined depending on the forest type. This scenario of sensor network will be considered in this work in detail.

The tunnel scenario is defined for car tunnels, in order to detect for example the exceed of the limit of the gases, leading to a stronger ventilation. Such scenario environment simulation should consider the reflections from tunnel walls and crossing cars.

The parking application is usually used in huge hypermarket parking to detect empty car places and inform the drivers where to find them. Another objective can be protection against car theft. The propagation area is influenced by many obstructions, like the cars, pillars and people.

The battlefield scenario can be very diverse. The main idea is to detect the occurrence of chemical or biological weapons and inform soldiers about it. The propagation area can range from the desert to the jungle, so simulations must be made for the particular case.

Wireless Sensor Networks are very useful for example in gardens or glasshouses. The ground scenario defines such application to monitor the temperature, humidity and chemical composition of the ground, in order to provide good farming and floriculture. Radio wave propagation is strongly influenced by the light vegetation and can be simulated treating the environment as a constant block with specified electromagnetic coefficients.

Sensor networks can be used in building intelligent cities, which can manage humans, cars, etc.. Such scenario is filled with many obstructions, with a big influence of buildings. Propagation can be simulated by considering many reflections and free space attenuation between them.

The highway scenario is defined to provide more efficient and safer car transport. Such networks can sense the information about the road state and traffic, which can be useful information for drivers. In such a case, sensor devices are deployed in long distances along the highway. Free space loss without any obstructions should be considered during simulations.

Intelligent houses and smart building in general are a place for Wireless Sensor Networks. Such application provides a lot of solutions to improve human well being. A lot of sensing information can cause many reactions to help people and to decrease any unnecessary resources. Such scenario is filled by many walls, which strongly influence radio waves. This scenario is considered in this work in detail.

Chapter 3

Models

This chapter gives a description of the propagation channel models used in the simulator.

3.1 Channel Models

This section describes some issues about channel models and shows general aspects of the modelling, focusing on the Geometrically Based Single Bounce Model.

3.1.1 Models

Increasing capacity of any wireless network working in constant bandwidth is limited by signal interferences. In such case, smart antennas techniques, and therefore adaptive algorithms, become very important; however, the performance of such techniques is strongly dependent on the environment. This approach requires a good channel modelling, which allows the increase of communication efficiency in applications where the mentioned techniques are used. Additionally, assessment and comparison of the performance parameters of different adaptive algorithms require such channel models.

Initial channel models were related only to path loss and delay parameters, not being enough for the new generation of wideband systems. Spatial information becomes very important, so channel models should consider such information.

Radio channels can be described by the following parameters [Kosi04]:

- Mean Excess Delay – this is the first moment of the power delay profile (PDP) of the environment, being given by:

$$\bar{\tau}_{[s]} = \frac{\sum_k h_k^2 \tau_k}{\sum_k h_k^2} = \frac{\sum_k P_k \tau_k}{\sum_k P_k}, \tag{3.1}$$

- RMS Delay Spread – this is the square root of the second central moment of the PDP, being given by:

$$\sigma_{\tau[s]} = \sqrt{\overline{\tau^2} - \left(\bar{\tau}\right)^2}, \tag{3.2}$$

where:

$$\overline{\tau^2}[s^2] = \frac{\sum_k h_k^2 \tau_k^2}{\sum_k h_k^2} = \frac{\sum_k P_k \tau_k^2}{\sum_k P_k}, \tag{3.3}$$

- $h_{k[s]}$: Channel Impulse Response (CIR) amplitude at instant τ_k
- $P_{k[W]}$: CIR power at instant τ_k

The radio channel can be also described by using the coherence bandwidth and the coherence time. The coherence property of these attributes means that all spectral components pass the channel with the same gain and with linear phase shift; in other words, the radio channel is flat. The coherence bandwidth is inversely proportional to the RMS delay spread; assuming the the frequency correlation between amplitudes of frequency components is above 0.9, the coherence bandwidth can be approximated by:

$$B_{C[Hz]} = \frac{1}{50\sigma_\tau}, \tag{3.4}$$

The coherence bandwidth is significantly narrower than the frequency spacing in typical radio channels; in such situations, up- (UL) and down-links (DL) should be considered separately. However, WSNs are ad hoc networks and work in the same bandwidth in both directions, so there is no division into UL and DL.

In mobile communications, where the channel nature is varying because of transmitter and receiver motions, the coherence bandwidth is not enough to describe it, and the coherence time should be taken into consideration as well. This parameter specifies the duration over which the CIR is essentially invariant, and it can be defined as:

$$T_{C[s]} = \frac{1}{f_m}, \tag{3.5}$$

where:

- $f_{m[Hz]}$: a maximum Doppler shift Frequency:
- $f_m = \frac{v}{\lambda}$, (3.6)

- $v_{[m/s]}$: velocity of the MT or the BS
- $\lambda_{[m]}$: wavelength

In case the correlation is assumed above 0.5, the coherence time has the following form:

$$T_{C[Hz]} = \frac{9}{16\pi f_m}, \tag{3.7}$$

It is possible to use the same model for both transmission ways, because in most cases, especially when the velocity of the terminals is low, the coherence time is longer than the time interval in TDD.

Wideband Directional Channel Model is a group of models, which take all these factors into consideration. There are two main types of wideband channel models: statistical and deterministic. Statistical models assume that signals arrive at the receiver with a specific statistical distribution, the assumption making such models flexible for various environments. Deterministic models assume that received signals depend only on the geometrical properties of environment, so their accuracy is strongly dependent of environment reproduction accuracy. The best way for channel modelling is to mix both statistical and deterministic approaches.

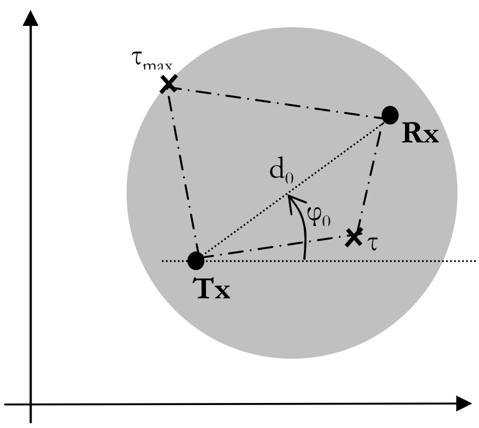
Mixed channel models assume that signals arrive to the receiver in clusters from particular directions, which dependent on the position of scattering objects in propagation path between transmitter and receiver. The second assumption is that scattering object positions can change statistically, and that scattering properties have a particular statistical distribution dependent on the considered environment. These assumptions allow such models to calculate path loss, delay and directions of arrival (DoA) and departure (DoD). These models also distinguish UL and DL in propagation between devices.

Clusters of scatterers, which are usually correlated with particular obstructions in environment, are deployed with characteristic statistical distribution. Each scatterer reflects the signal with a complex coefficient, their phase and magnitude being also statistical. The number of scatterers per cluster is provided by a Poisson distribution, and their positions creating the shape of cluster have a Gaussian distribution. Parameters defining all mentioned assumptions depend on the modelled environment.

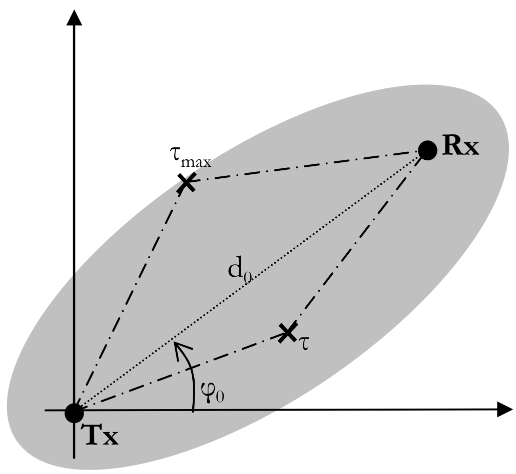
The positions of the clusters are assumed to be bounded by geographical dimensions of the considered scenario. Their behaviour is defined in a different way in every channel model. In mobile systems, the positions of clusters depend on the base station position. However, according to ad hoc Wireless Sensor Networks, clusters dependency should be on the positions of each pair of communicating devices. This assumption allows calculating multipath signal variations, and additionally allows taking Doppler's effect in each scattered path into account.

Given the knowledge of the positions of the scatterers, the calculation of parameters like Angle of Arrival and Angle of Departure becomes easy, based on trigonometric relations. In such a case, antenna radiation patterns can be superimposed, allowing the calculation of the effective received signal for a particular antenna configuration.

In WSNs, two types of channel scenarios can be considered: pico- and micro-cells. Both scenarios assume that obstructions are in the vicinity of transmitting and receiving antenna and between them. The pico-cell scenario defines that the clusters of scatterers and communication devices are deployed inside a circle, while the macro-cell scenario defines the region of influence as an ellipse, in which clusters are deployed and radio devices are in foci of it, Figure 3.1.



a) pico-cell



b) micro-cell

Figure 3.1. Parameters definition for channel scenarios.

The examples of some narrow- and wideband spatial models, providing the mentioned information about the channel, are listed below [ErCa98]:

- Lee's Model – this model is based on the assumption that all scatterers are deployed in a circle around the receiving antenna, and that signals cannot arrive to the receiver directly, line of sight (LoS) not being possible;

- Discrete Uniform Model (DUM) – this model assumes that scatterers are deployed on a beam width line in the path from transmitter to receiver, LoS not being possible as well;
- Gaussian Wide Sense Stationary Uncorrelated Scattering Model (GWSSUS) – this model is a wideband, assuming that clusters of scatterers are deployed around the receiver with a Gaussian distribution;
- Uniform Sectored Distribution Model (USD) – this model is also a wideband one and assumes that clusters are deployed uniformly around the receiver, but bounded by the beam width and distance range;
- Geometrically Based Single Bounce Channel Model – this is a wideband model, which assumes that clusters are deployed in the vicinity of the transmitter and the receiver, being described in detail in this chapter.

3.1.2 Geometrically Based Single Bounce Model

An overview of the spatial channel models is presented in the previous subsection. The GBSB model [LiRa99] is described in detail in what follows. This model is used to calculate power-delay-angle profiles, power delay profiles, time-angle statistics, characteristics of Direction of Arrival, and fading envelopes. The GBSB model is appropriate for systems where scatterers are distributed around transmitters and receivers, including pico- and micro-cells, so it suits WSNs.

The GBSB model assumes that the propagation environment is composed of scatterers, which are distributed statistically. Each scatterer is a source of one multipath component. A signal radiated from the transmitter goes through the position of the corresponding scatterer, being picked up at the receiver, Figure 2.1.

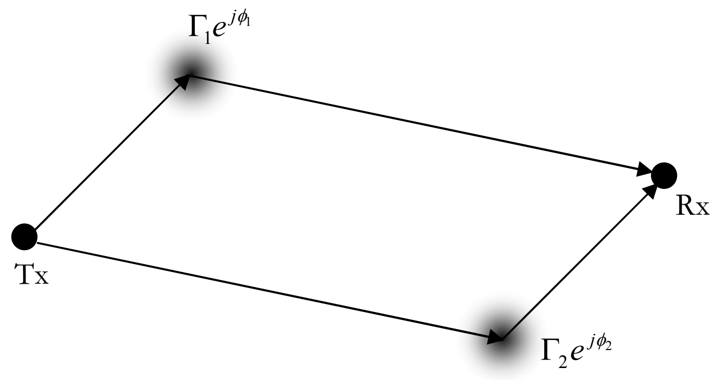


Figure 3.2. Scatterers in GBSB model.

Each scatterer is described by random complex coefficients, which determine the influence on the multipath component. NLoS signals always bounce from one scatterer and arrive to the receiving antenna, so rays bounced from many scatterers are not taken into consideration. The magnitude and the phase of each reflection are random,

$$\Gamma = |\Gamma| e^{j\Phi_{sc}}, \quad (3.8)$$

where:

- $|\Gamma|$: the magnitude of the reflection coefficient with a range in [0;1]
- $\Phi_{sc[rad]}$: the phase of the reflection coefficient with a range in [0;2π]

The component changes its magnitude and phase after bouncing from the scatterer. The magnitude of the multipath is multiplied by the magnitude of the corresponding scatterer, and the phase of the scatterer added to the phase of the multipath component.

The model assumes that scatterers are grouped into clusters. The area of the cluster consists of dense deployed reflectors. The time of arrival (ToA) of the multipath component depends on the location and shape of clusters. The number of clusters is approximated by looking at the number of groups of multipath. The distribution of clusters is characteristic of each considered scenario.

The GBSB model assumes that both the receiver (Rx) and the transmitter (Tx) are in the same plane, which is parallel to the ground. Another assumption is that all scatterers are also located in this plane, therefore, all multipath components also belong to this plane.

When both the Rx and Tx antennas are omni-directional, a complex envelope model for the multipath CIR is given by:

$$h(t) = \sum_{i=0}^{L-1} E_{Rx,i}\delta(t+\tau_i) = \sum_{i=0}^{L-1} \left|E_{Rx,i}\right| e^{j\Phi_{Rx,i}}\delta(t+\tau_i), \tag{3.9}$$

where:

- $E_{Rx,i}$: amplitude of the i^{th} component
- $\Phi_{Rx,i}$: phase of the i^{th} component
- τ_i: delay of the i^{th} component
- L: number of components

In case that all scatterers are deployed in an elliptical form, the probability density function (PDF) is given by:

$$p_{\tau,\varphi}(\tau,\varphi) = \begin{cases} \dfrac{(d_0^2-\tau^2c^2)(d_0^2c+\tau^2c^3-2\tau c^2 d_0\cos(\varphi-\varphi_0))}{\pi\tau_{\max}c\sqrt{\tau_{\max}^2c^2-d_0^2}\,(d_0\cos(\varphi-\varphi_0)-\tau c)^3}, & \dfrac{d_0}{c}<\tau<\tau_{\max} \\ 0 & ,\text{elsewhere} \end{cases}, \tag{3.10}$$

where:

- τ_{max}: observation time window
- d_0, φ_0: geometry parameters defined on Figure 3.3
- c: speed of light

To derive the joint density function for the AoA and ToA, in the case of the circular deployment of scatterers, it is necessary to take advantage of the Jacobian Transformation, which makes it possible to achieve the PDF in an easy way. The resulting PDF is

$$p_{\tau,\varphi}(\tau,\varphi) = \frac{(d_0^2-\tau^2c^2)(d_0^2c+\tau^2c^3-2\tau c^2 d_0\cos(\varphi-\varphi_0))}{4\pi R_{\max}(d_0\cos(\varphi-\varphi_0)-\tau c)^3}, \tag{3.11}$$

where:

- R_{max}, φ_0: geometry parameter

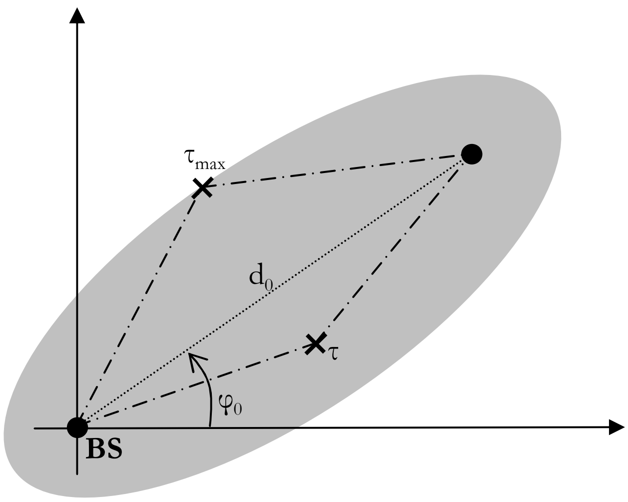


Figure 3.3. Geometry for GBSBEM.

The validity area for the BS and the MT cases are, respectively:

$$\frac{d_0^2 - 2d_0\tau c\cos(\varphi-\varphi_0)+\tau^2c^2}{\tau c - d_0\cos(\varphi-\varphi_0)} \le 2R_{\max} \wedge \tau > \frac{d_0}{c}, \tag{3.12}$$

and

$$\frac{d_0^2 - \tau^2c^2}{d_0\cos(\varphi-\varphi_0)-\tau c} \le 2R_{\max} \wedge \tau > \frac{d_0}{c}, \tag{3.13}$$

In other cases, the PDF is equal to zero.

The presented model is based on geometrical assumptions, so all output parameters are calculated in a geometrical way. All variables, which are needed to obtain the parameters, are presented in Figure 3.4.

The AoA (φ) and AoD (θ) are obtained from d_0, d_1 and d_2 using the cosine formula. Distances d_0, d_1 and d_2 are taken into account during the calculation of the received power level. The signal transmitted is attenuated by the propagation environment in the way to and from scatterer and multiplied by the magnitude of the reflection coefficient. The GBSB model does not specify the attenuation in the channel, so concerning sensor networks working in various conditions, it is important to consider different propagation models. Propagation models, which can be considered in sensor networks, are described in the next section.

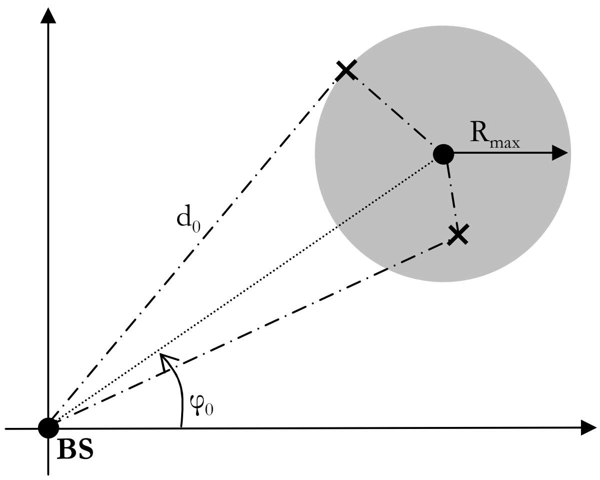


Figure 3.4. Geometry for GBSBEM

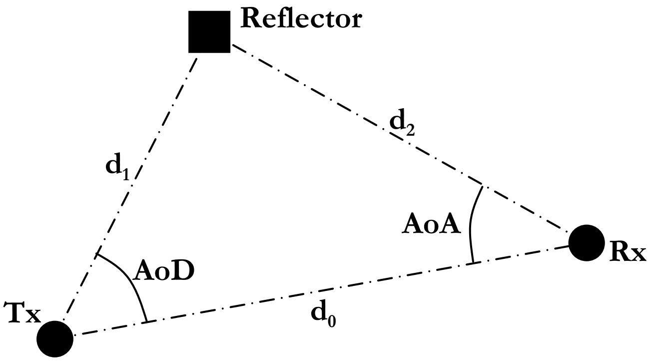


Figure 3.5. Definition of some output parameters.

The attenuation in the channel and the reflection by scatterers must be taken into consideration to calculate the amplitude of a multipath component. The amplitude of the electric field at the Rx is defined by:

$$E_{Rx[V]} = \sqrt{\frac{P_{Tx} \cdot G_{Tx}(\theta_1) \cdot G_{Rx}(\theta_2)}{(d_1 + d_2)^2 \cdot L}} \cdot \Gamma \,, \tag{3.14}$$

and in the in case of the LoS component:

$$E_{Rx[V]} = \sqrt{\frac{P_{Tx} \cdot G_{Tx}(\theta_1) \cdot G_{Rx}(\theta_2)}{d_0^{\ 2} \cdot L}}, \qquad (3.15)$$

where:

- $P_{Tx[W]}$: the power of the Tx
- Γ: the reflection coefficient of the reflector
- G_{Tx}: radiation pattern of Tx antenna
- G_{Rx}: radiation pattern of Rx antenna
- L: attenuation of the radio channel

The phase is another parameter obtained from the simulation. The phase is related to the distance covered by the corresponding multipath component and complex reflection coefficient. The signal propagating from the Tx to the Rx covers the distance, which may not be equal to an integer multiple of the wavelength. In case the signal reflects from a scatterer, an additional phase shift Φ_{sc} exists. An equation for the phase shift has the form:

$$\Phi_{Rx[°]} = mod360\left(\left(\frac{d_1}{\lambda} - \left|\frac{d_1}{\lambda}\right| + \frac{d_2}{\lambda} - \left|\frac{d_2}{\lambda}\right|\right) \cdot 360 - \Phi_{sc}\right), \qquad (3.16)$$

and in the case of LoS component:

$$\Phi_{Rx[°]} = \left(\frac{d_0}{\lambda} - \left|\frac{d_0}{\lambda}\right|\right) \cdot 360, \qquad (3.17)$$

where:

- *mod360(…)*: operation of modulo 360
- $\Phi_{SC[°]}$: the reflector phase shift

The ToA describes the time delay component, which is connected only to the distance of propagation:

$$\tau_{[s]} = \frac{d_1}{c} + \frac{d_2}{c}, \qquad (3.18)$$

and for the LoS component:

$$\tau_{[s]} = \frac{d_0}{c}, \tag{3.19}$$

3.2 Path loss models

3.2.1 Basic Aspects

The analysis of channel models and of the rules of radio wave propagation is very important to make any simulation of wireless radio based systems. One of the main parameters of the channel is path loss. Referring to the GBSB model and WSNs, various possibilities of attenuation must be taken into consideration. Propagation models can be grouped into three types [COST99]:

- empirical (statistical) models
- deterministic models
- mixed (based on empirical and deterministic information) models

When modelling the channel attenuation, it is necessary to consider the behaviour of electromagnetic waves propagation. There are three main mechanisms of wave behaviour, which should be considered:

- reflection – it takes place when the dimension of obstruction is much larger than the signal wavelength;
- diffraction – it is the phenomenon that relys on the direction change of the signal when it hits an obstruction with a size similar to the wavelength;
- scattering – appears when the obstruction is smaller than the wavelength and has an irregular shape;

Given the basic propagation mechanisms relevance, the channel attenuation can be calculated by using developed propagation models. The knowledge of the attenuation and radio devices parameters allows one to calculate the received power level, from the following equation [Kosi04]:

$$P_{Rx[\text{dBm}]} = P_{Tx[\text{dBm}]} + G_{Tx[\text{dB}]} + G_{Rx[\text{dB}]} - L_{p[\text{dB}]}, \tag{3.20}$$

where:

- P_{Rx} – received power
- P_{Tx} – transmitted power
- G_{Tx} – transmitting antenna gain
- G_{Rx} – receiving antenna gain
- L_p – channel path loss

The channel path loss should be calculated with the appropriate propagation model for the particular scenario of the network. Some propagation models are described in the next subsection.

3.2.2 Models

Path loss estimation in WSNs is not an easy task. Sensor networks can work in various environments, so, the designing process requires an accurate choice of the propagation model. The accuracy of such network simulations is strongly related to the accuracy of the model. A few models, which can be used in WSNs simulations, are described below.

A large part of sensor networks applications work with simple and rather homogeneous environments. Usually, in such environments, the propagation medium is air. It is possible to assume that for frequencies up to 5 MHz, the air channel is constant; for upper frequencies, the propagation behaviour can be influenced by some factors, like humidity or ionisation level. Sensor Networks specified by ZigBee [ZigB04] work with lower frequencies, so air propagation can be characterised by free space loss. Scenarios of networks working in the city, parking, car, etc., can be considered with such a model.

Free space is appropriate for the whole range of distances, loss being calculated from [Kosi04]:

$$L_{FS[\mathrm{dB}]} = 36.6 + 20\log\left(d_{[km]}\right) + 20\log\left(f_{[MHz]}\right), \qquad (3.21)$$

where:

- d – distance between antennas
- f – frequency

When considering environments where radio waves cannot travel only through free space and always penetrates another medium, it is not possible to assume the free space loss model. In such a situation, attenuation depends on the type of medium and its parameters. The propagation environment can be diverse and consist of many obstructions, with different penetration parameters. Propagation models consider such complexity in two ways. The first way is to treat the environment as a big homogeneous block, with always the same penetration parameters, which are the average of the all parameters of obstructions founded in considered area; then, the path loss is continuously dependent only on the distance of penetration of such a "block". An interesting example of such assumption is the attenuation model in a forest or orchard; the attenuation in vegetation regions consisting of trees and plants can be accurately estimated by the following equation [ITUR00], which is an addition to the free space loss:

$$L_{[\mathrm{dB}]} \cong 0.2 f_{[\mathrm{MHz}]}^{\;0.3} d_{[\mathrm{m}]}^{\;0.6}, \qquad (3.22)$$

The second way of propagation estimation in non free space environments is by considering each penetrated obstruction in the signal path. The total attenuation of the signal in a particular path is calculated as the sum of free space loss and the attenuation of each penetrated object. This type of model allows dividing the attenuation into steps, which depend on the number of obstructions. Each obstruction can be characterised by different parameters and cause different attenuation. Furthermore, such models allow treating the scenario in a statistical way, where the number of obstructions and their parameters can change with a particular distribution. Propagation loss estimation in this way can be called a multi-obstacle model.

The number of obstructions in the multi-obstacle model is integer, and depends on the propagation environment. The range of amount of obstructions can be from zero to infinite. The zero case means that the path loss is equal to the free space. In WSNs, it is important that in fact such devices are mounted on bigger objects, which can be treated as obstructions in radio propagation (e.g. wall or tree). This fact implies the division of the minimum number of obstructions in one, if the transmission is through the obstruction, and zero in the opposite case. If the radio device antenna is in the close vicinity of the obstruction surface, then it means that the probability that the signal will go through such obstruction or not, is 0.5.

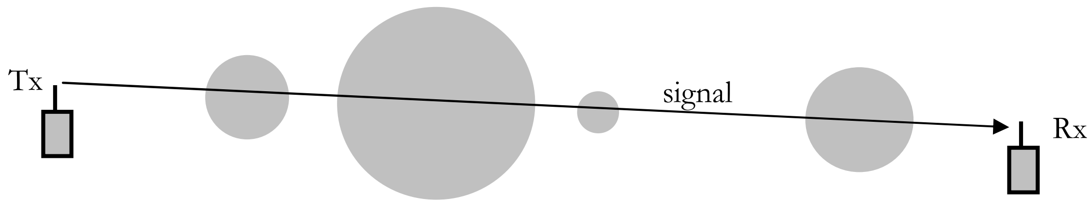


Figure 3.6. Example of the Multi Obstacle Model work.

The Multi Obstacle Model (MOM) for the house scenario is described in [COST99]. This indoor propagation model treats all walls in the house as obstructions, which are penetrated by the signal and cause attenuation. The attenuation of the wall can be different, depending on the different thickness of it and on the type of material. The considered value of attenuation of each wall is related to the average wall thickness of the family houses built from bricks. The Multi Wall Model (MWM) assumes that the signal goes only in a horizontal plane and does not penetrate floors. The whole communication is inside the house, so, outside walls, which are thicker, are not considered as well.

The path loss of this model is given by:

$$L_{[\mathrm{dB}]} = L_{FS[\mathrm{dB}]} + \sum_{i=1}^{I} k_{wi} L_{wi[\mathrm{dB}]} \,, \tag{3.23}$$

where:

- L_{FS} – free space loss between transmitter and receiver
- k_{wi} – number of penetrated walls of type i
- L_{wi} – loss of wall type i
- I – number of wall types

The MW model defines two types of walls (I = 2): light wall (<10cm) and heavy wall (>10cm). The loss of each wall type has been measured empirically, being L_{w1}=3.4 dB and L_{w2}=6.9 dB. The signal frequency does not influence the attenuation, its influence is considered in free space loss.

The MO model can be used for propagation estimations in other scenarios, as well. The forest scenario can be modelled with it too. The simulation of this scenario using an obstacle model should give values of attenuation closer to the results achieved from simulations using ITU-R [ITUR00] model. The MO model simply assumes that each tree can be an obstruction penetrated by the signal and causes the attenuation. The maximum attenuation of particular tree depends on the type of forest, ranging from 2 to 15 dB. The minimum value can be considered in the kind of orchards (e.g. apple or pear) where the tree radius is around 10 cm. The biggest attenuation can be achieved with really thick trees (e.g. Amazon rainforest), where the radius can achieve 1 m. The method of calculating the total path loss for this model is similar to the multi wall model. The only one difference is in the values of a particular obstacle loss and in the number of their types. In general, the MO model allows using the continuous number of loss types by obstructions, and their values can have a statistical distribution. These parameters are defined considering particular cases of scenarios.

In connection to the GBSB model, it is important to consider some issues associated to the inclusion of the MO model into it. The main principle of GBSB model is that the received signal is a sum of all multipath components arriving at the receiving antenna. This model gives information about power level and delay spread of the signal. In a dense forest, where every tree can reflect the signal, the number of multipath components can be very high. In such situation, delay spread and received power can reach big values, which would be not correct. In fact, each component is strongly attenuated by trees in dense forest, so a lot of components arrive with small amplitude. The solution for this consideration is that during calculation of delay spread and total signal, components with amplitude lower than the receiver sensitivity should not be taken into calculation. Figure 3.7 a shows theoretical example of received components, with marked average sensitivity of common WSN receivers. Coloured in red components are not taken into calculation of delay spread and power. In this case delay spread will be 3 μs instead of 5 μs.

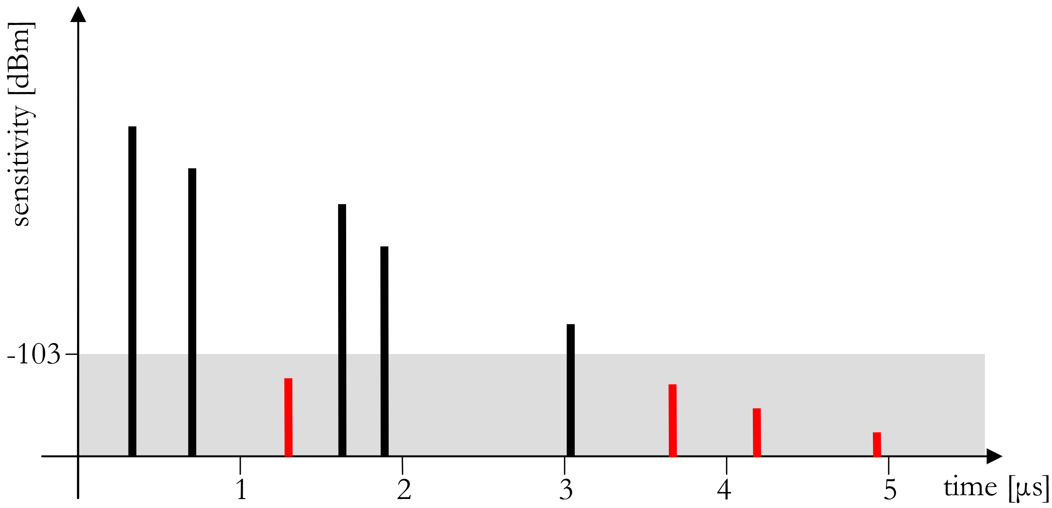


Figure 3.7. Theoretical received multipath components.

trunk radius, it is possible to calculate the range of the beam crossing the tree using a formula for the maximum angle (counting from the direct line connecting the centre of the tree):

$$\alpha_{max} = \arcsin\left(\frac{R_{[m]}}{d_{[m]} + R_{[m]}}\right), \tag{3.24}$$

where:

- R – tree radius (which can be approached by a mean value with a given standard deviation and a particular distribution)
- d_t – distance from transmitter to the tree trunk border

The loss of the ray crossing the tree depends on chord length, through which the ray goes. This length depends on the angle of the ray from direct line connecting the transmitter and the centre of the tree. The curve showing the attenuation of the tree depending on the distance, tree radius and angle is given by:

$$\mathrm{L}_{tree} = 2(d_{[m]} + 0.5 \cdot L_{\max[dB]})\cos\alpha - 2d_{[m]}, \tag{3.25}$$

where:

- L_{max} – maximum attenuation of particular tree
- α – angle in range [-α, α]

This considered case is depicted in Figure 3.8. A more detailed description is given in Annex 2.

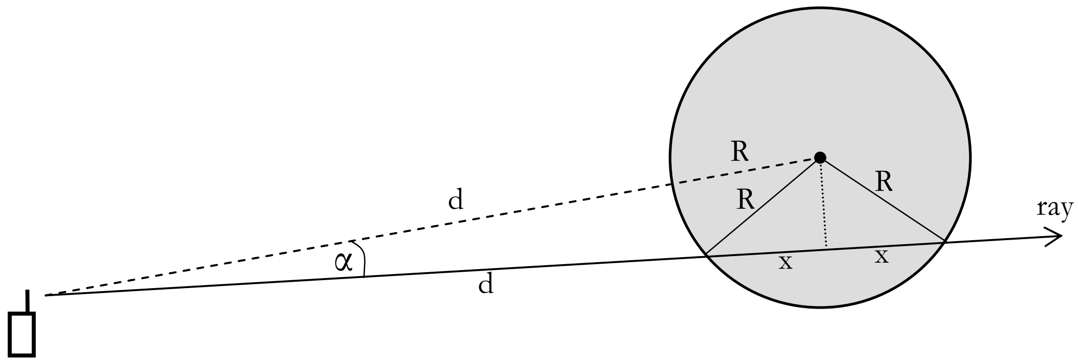


Figure 3.8. Tree crossing schema.

The Multi Obstacle model is really flexible, and can be used on the various types of propagation environments. The accuracy of such model is strongly related to the accurate choice of obstacles number and attenuation.

Chapter 4

Simulator

This chapter gives a description of the simulator and of the assumptions taken in it.

4.1 Brief Description

The structure of the radio channel simulator has been decomposed into three blocks, Figure 4.1. This decomposition shows in a simple way the steps in which all simulations are made.

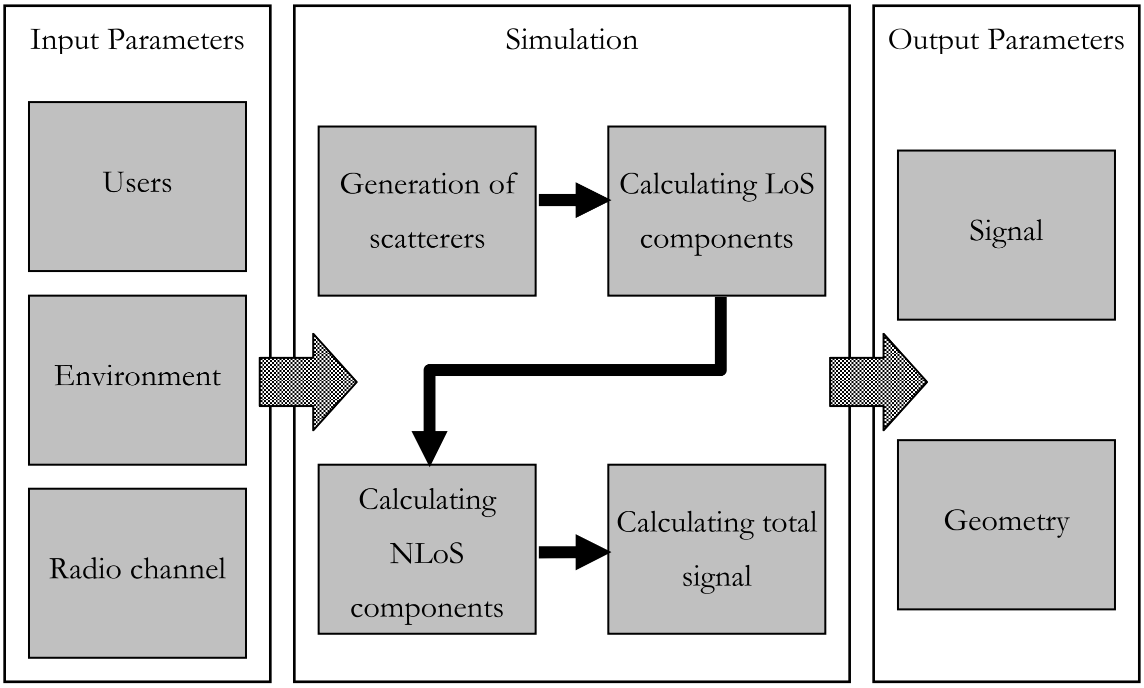


Figure 4.1. General structure of the simulator.

The *Input parameters* block represents the input parameters, which determine the simulator mode and specify scenarios and other data. The *Simulation* block represents the main tasks of the program. Last, the *Output parameters* block represents output parameters calculated by the program in the previous block. A more detailed description is available in [Koko05], [Zuba05].

The structure presented in Figure 4.1 shows only the calculation between a pair of transmitting and receiving antennas and represents only a common SISO system. The first step of calculation is the computation of the positions of the clusters and scatterers in the region. Clusters are deployed uniformly in the region, in a circle or ellipse shapes, depending on the pico-, micro- or macro-cell cases. Each object is deployed in a 2-D plane. The positions of the scatterers in the cluster are defined by spherical coordinates, where the radius is determined by a Gaussian distribution with mean value 0. Each scatterer belongs only to the one cluster. The angle is defined by a uniform distribution in [0, 2π]. The number of scatterers per cluster is not deterministic, having a Poisson distribution around the average value given by the user. This approach enables a large variety in the sequence of the simulations.

The second step of simulation is the calculation of LoS component. The initial approach was to calculate the distance between transmitter and receiver and then the channel propagation loss with the free space model. This approach is not correct with WSNs, working with already mentioned environments, and various models of path loss calculation between Tx and Rx were included. The new version of the simulator allows choosing among the free space, multi wall or multi tree path loss models. The parameters defining the attenuation calculations are specified by the user.

The NLoS component is calculated by using the same method like in LoS. The idea is that the signal goes first to the scatterer, then reflected with a given coefficient, and then goes directly to the receiver. The attenuation is calculated like with LoS but with a different distance. Moreover, the reflection gives a reduction of the signal power by the magnitude of the reflection coefficient and the phase shift of the angle specified by that coefficient. This approach is possible only with the assumption that there is a guarantee of direct path between transmitter and scatterer and between scatterer and receiver. The algorithm of the NLoS component calculation described above is depicted on Figure 4.2.

The simulator can work in a few modes, leading to different types of averaging of the output parameters, allowing the user to achieve more accurate results. There are 4 modes, defined below:

- 0 – each run of the simulator causes only the changes in the reflection coefficient and positions of all objects remain the same (output parameters from all iterations are saved);
- 1 – works like 0, but all results are averaged and put as one output;

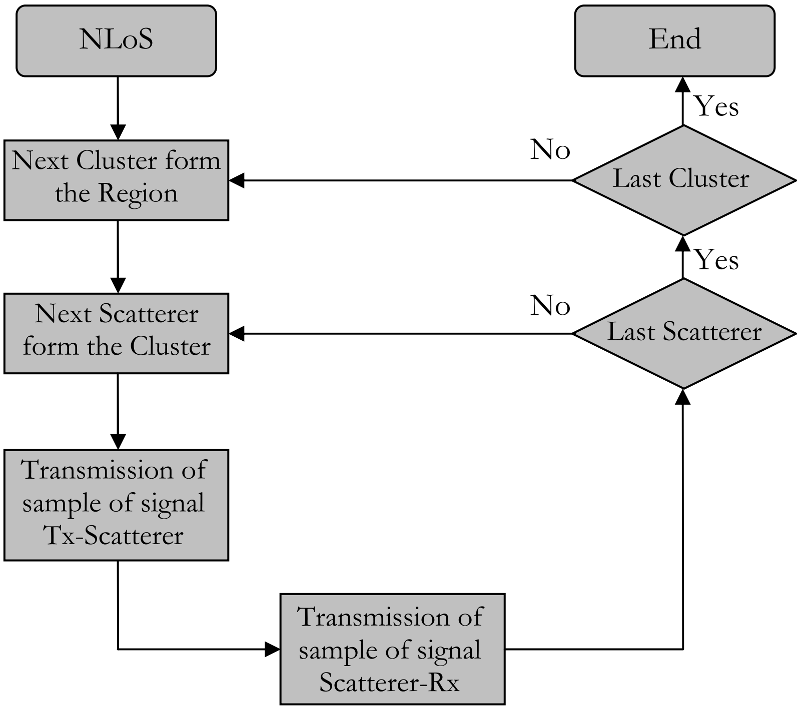


Figure 4.2. Calculation of NLoS component [Koko05].

- 2 – the positions of the scatterers and coefficients are changed for each iteration (output parameters from all iterations are saved);
- 3 – the positions of radio devices remain the same, but the rest is changed every time (output parameters from all iterations are saved).

A detailed description of the simulator is shown in [Zuba05] and [Koko05].

4.2 Models implementation

The scheme of the simulator was described in the previous section. This simulator is a direct implementation of the Geometrically Based Single Bounce (GBSB) channel model. This is a spatial model that gives information about ToA and AoA with reference to the position of the transmitting antenna, distribution of the scatterers and the position of receiving antenna. Trigonometric relations are used to calculate all spatial information. The parameters of the scatterers are random, with specific statistical distributions. Each scatterer generates one multipath bounced component with random magnitude and phase. A scatterer never overshadows another. The delay of each component is random.

Following the previous version of this simulator, which was focused on mobile communication devices, some changes have been made. The simulator has been accommodated to Wireless Sensor Networks. These networks usually work in special, not common, environments. Three environments were considered to be implemented into the simulator: forest, building and free space. Accordingly, the models describing the attenuation of the radio waves have been changed. Normally, in most of the scenarios, the free space path loss is the best model for channel attenuation; the forest attenuation, when each tree is considered as a separate cluster, can be also estimated by free space loss, while house environments give different attenuations, so the specific models have been implemented. The models of this scenario are described in the next section. The parameters required by such models are accounted by the program automatically, and dependent only on the distance between nodes. The number of walls crossing by each ray is calculated randomly, but with conditions defined in input parameters. The number of crossed trees depends on the distance, but one can define its deviation for each specified distance.

Since each sensor is equipped with both transmitter and receiver, and because WSNs are ad-hoc networks, there is no division between UL and DL communications; the previous version of the simulator had such a division, which was removed. Each device works in the same frequency range, so the rules of radio communication are the same for each device and each way of communication.

4.3 Input parameters

Input parameters are divided into three groups, Figure 4.1. The first group consists of parameters describing location and properties of the wireless sensor devices. The next group determines information about scenario and propagation environment. The last one gives information about radio propagation issues.

The *User* group of parameters gives information about all users working in the simulated network, being the same as in the previous version of simulator. These parameters can be divided into two subgroups:

1. Basic radio device parameters:

   - $S_{dev[\mathrm{m,m}]}$ – position of the sensor device in 2-D plane
   - $P_{Tx[W]}$ – transmit power of Tx
   - $N_{Rx[W]}$ – noise level of Rx
   - $S_{Rx[W]}$ – sensitivity of the Rx

2. Antenna array parameters:

   - N_a – number of antennas in array
   - $d_{[m]}$ – spacing between antennas in case of linear array
   - $a_{[m]}$ – radius of the circle in case of circular array
   - $\Phi_{0[rad]}$ – phase shift between consecutive radiators
   - $\Phi_{n[rad]}$ – phase feeding of n^{th} radiators
   - $I_{n[A]}$ – amplitude of feeding of n radiator

The *Environment* group of parameters contains information about the simulated scenario, where devices are deployed. This group of parameters was strongly changed in the current version of the simulator, in order to accommodate WSNs. According to WSNs, there are two types of scenarios, pico- and micro-cells, macro-cells not being considered. This group gives information about scattering objects in the considered environment. The main parameters are:

- $dim_{[m]}$ – dimension of scenario
- $d_{c[1/m2]}$ – cluster density
- n_{sc} – average number of scatterers per cluster

The *Radio channel* group contains parameters describing the radio channel, and it was also strongly changed. This group gives information about frequency and the type of path loss depending on the considered application of the network and all parameters needed to estimate the attenuation of the radio channel. These parameters give information to calculate the path loss of the wave, e.g. number of walls depending on distance. This section allows defining the possible numbers of walls in defined ranges for the house scenario. The program randomly chooses the number of walls using this specification. Referring to the forest scenario, the number of trees treated as attenuating obstructions depends on the forest density, but one can define the deviation of this value for specified ranges, as well.

The simulator still has other input parameters, to achieve more accurate results, but they are not taken into consideration in this dissertation. More details are in [Zuba05] and [Koko05].

4.4 Output parameters

Output parameters are divided into two groups, in Figure 4.1. The group of *Signal* parameters gives a set of information about each signal ray. The number of these parameter sets depends on the number of scatterers and on the LoS possibility. These parameters are:

- Angle of Arrival (AoA)
- Angle of Departure (AoD)
- Amplitude of ray
- Phase of ray
- Time of Arrival (ToA)

The second part of output parameters is the *Geometry* group. This group of parameters contains information about the calculated scenario, like positions of scattering clusters. In order to simulate WSNs, the number of obstacles was taken into consideration, and the attenuation for each ray was also added to this group of parameters. It allows the user to verify the correctness of input parameters and to assess the simulator.

Output parameters can be averaged in a few different ways, which allows achieving better accuracy in simulations. The type of averaging is described in [Koko05] in detail.

More parameters, which give statistical information and are very useful to take conclusions from the simulations, are not calculated in the program. The values of these parameters are calculated outside the simulator in another environment, like Matlab or Excel.

4.5 Assessments

The goal of this dissertation is to analyse the implementation of the Multi Obstacle propagation model into GBSB channel model simulating Wireless Sensor Networks. The simulator of MIMO networks has been taken into consideration [Zuba05], [Koko05]. This simulator has been written in C++ language. The source code has been changed to enable the simulations of WSNs with the MO model. It is important to check if the program works correctly and the output values are the same like in previous version. A very detailed assessment of the simulator has been done in previously mentioned theses. An assessment was done, by comparing the previous and the current version of the program.

The best way to compare two versions is to compare the output files by comparing their MD5 checksums [Fast06]. It is important to compare the output files for each possible work path of the program. Since the program was written to work with multi antenna systems, then a few possibilities of simulations were considered, and some different input files were selected describing various scenarios:

- SISO system for pico-, micro- and macro-cells
- MIMO system for pico-, micro- and macro-cells
- Multi-user SISO system for pico-, micro- and macro-cells

All scenarios were simulated by two versions of the program and checksums calculated for each output file. The checksums were calculated and compared by FastSum Standard Edition program [Fast06]. All comparisons were successful, which means that the output of the new version of the program is reliable.

Before making any simulations for the analysis of results, the assessment of the changes made into the program must be performed as well. Since only the type of attenuation has been changed, then the output level of power in the case of various distances has been assessed. The first test has been made in the house scenario, due to the wall attenuation. Four cases of SISO system were chosen, but with different number of walls, as follows:

- Attenuation with 1 wall in the whole distance
- Attenuation with 2 walls in the whole distance
- Attenuation with 3 walls in the whole distance
- Attenuation in various number of walls, growing with distance

Some simulations were made with these scenarios and path loss was calculated. The results are depicted on Figure 4.3.

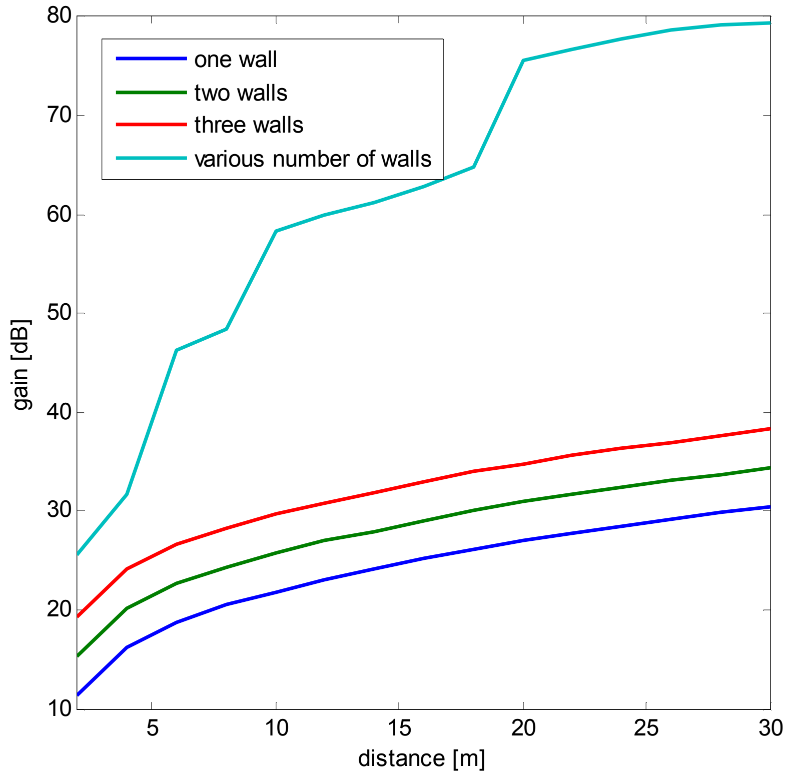


Figure 4.3. Attenuation in house scenario with various numbers of walls.

The shape of the first three curves is exactly the same like in the range estimation calculations, which means that the attenuation model has been correctly implemented into the simulator and any simulation results are reliable. The last curve is different, because the attenuation has a different dependency on distance: a larger number of walls was taken into the path loss calculation in longer distances, so there is a bigger slope of the curve.

The second test was performed with the attenuation in the forest scenario. The description of the trees attenuation is depicted in A. Annex . The same calculations were made with the simulator and plotted with Matlab. The results are exactly the same, which brings to the conclusion that the algorithm was implemented correctly, Figure 4.4.

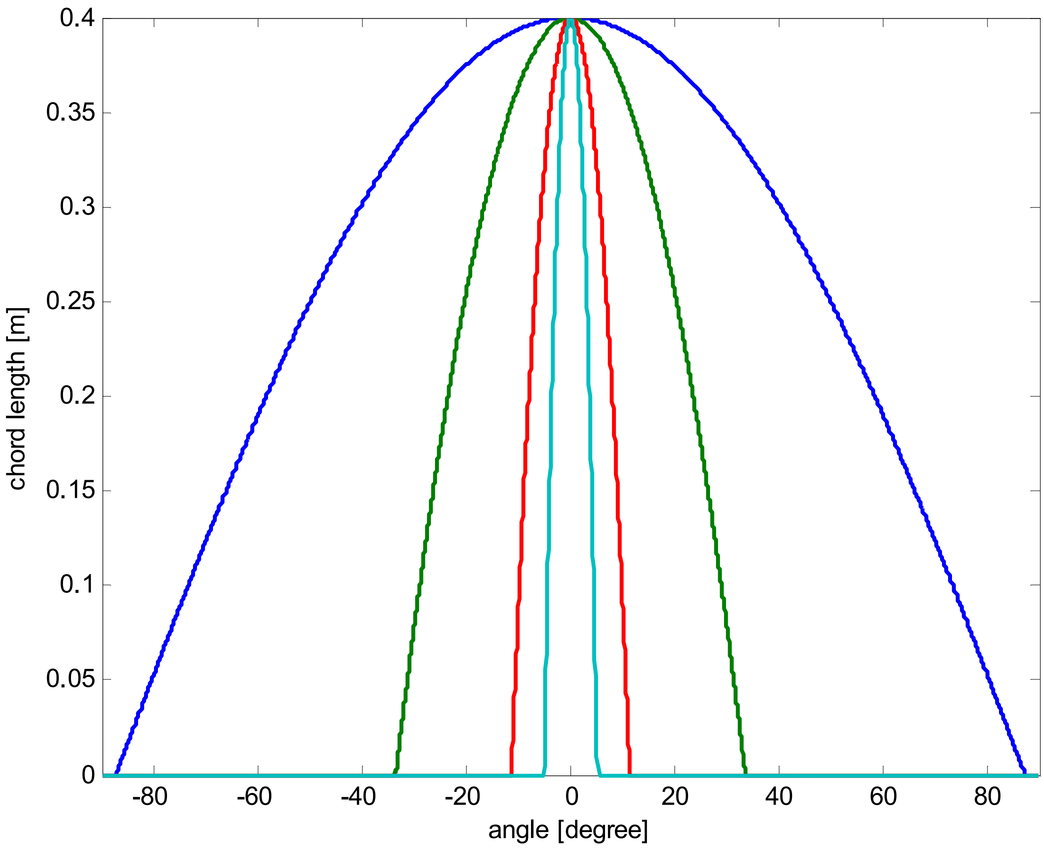


Figure 4.4. Calculated tree attenuations with various distances.

Knowing the attenuation of a particular tree, the attenuation of the channel with various distances should be tested. Such calculation with various maximum tree attenuations has been made. The density of the trees was set to 0.006 trees/m^2, what gives 2 trees per each 30 metres. Figure 4.5 shows the attenuation with various maximum attenuations of the tree. Curves are characterised by two steps, which are the result of the tree attenuation. The step amount depends on the maximum attenuation. The shape of the curve between the steps is similar to the free space attenuation. These approaches allow to consider the implementation as correct.

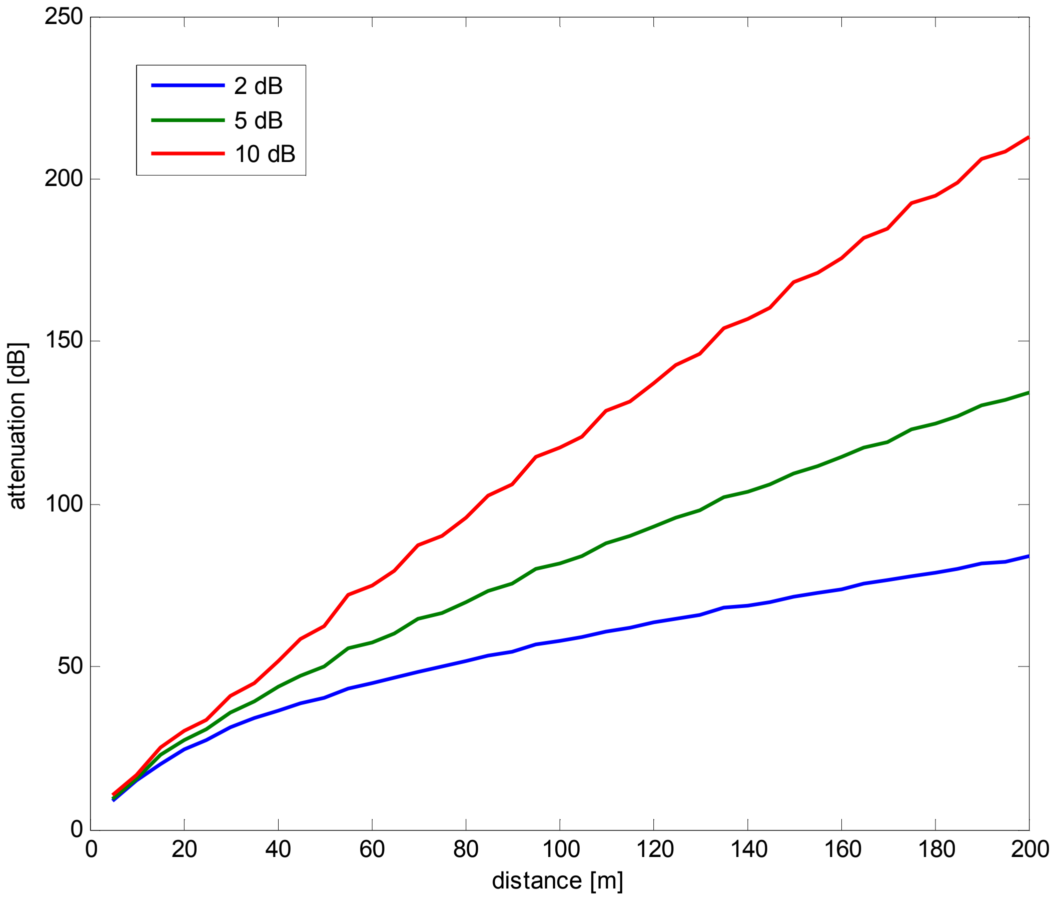


Figure 4.5. Attenuation in forest scenario with various maximum tree attenuations.

4.6 Range estimation calculations

When analysing and estimating real scenarios of a network, it is important to calculate some parameters. The accuracy of the simulation of the scenarios strongly depends on the accuracy of the chosen values. Some values of the parameters can be measured, but if this is not possible, they can be calculated using adequate models.

An important parameter is the range of the radio devices. This value gives information on how dense the nodes can be deployed in the sensor field to make communication possible. A program was written that calculates the range of the radio communication for each environment (forest and house). The program was developed with C# language using Microsoft Visual .NET Studio.

The range estimation models described in the previous chapter were implemented into it. The program calculates the attenuation of the signal using free space, multi-wall model and ITU-R vegetation model. The output of the program is the level of the signal for the distances from 0 to 200 metres with 1 m step. All outputs are saved in a file, which can be opened in Microsoft Excel.

Chapter 5

Analysis of results

This chapter gives a description of the simulated scenarios, their assumptions and the analysis of results.

5.1 Scenarios description

This section contains a detail description of the simulated scenarios. The scenarios were taken from real applications implemented in forests and houses. The assumptions on the parameters of these scenarios regarding simulator and used models are presented in this section.

The simulator allows averaging calculations in any iteration using four modes, as previously mentioned. Simulation parameters were chosen in a way to achieve the most reliable results. The discussion on the influence of the number of iterations and time resolution was done in [Koko05]; accordingly, the number of iterations is 100 and the time resolution is 200 ns. The mode of simulation is set to 3, which means that, for each iteration, the positions of all clusters and their scatterers are generated from the beginning.

5.1.1 The forest scenario

The scenario considered first in simulations is the forest one. Because of the big danger of fires in dry forests, it is very important to have a good protection and the possibility of fast reaction, thus, WSNs become very useful in such a case. There are a lot of projects focused on fires protection, like [DoSi05] and [Fire05]. The simulations performed in this dissertation follow these projects.

The general case of the scenario is depicted in Figure 5.1; this figure shows a particular deployment of nodes and some distances between them. In the normal case, the distances are less than 100 metres, but in case of fire, when some nodes can be burned, the distance to communicate among existing nodes increases. In this case, it is important to simulate both cases, with short and long distances. The shape of the cells is shown in sky colour; the trees deployment is uniform, like the deployment of clusters in the GBSB model; sensor devices are marked by the black and red stars.

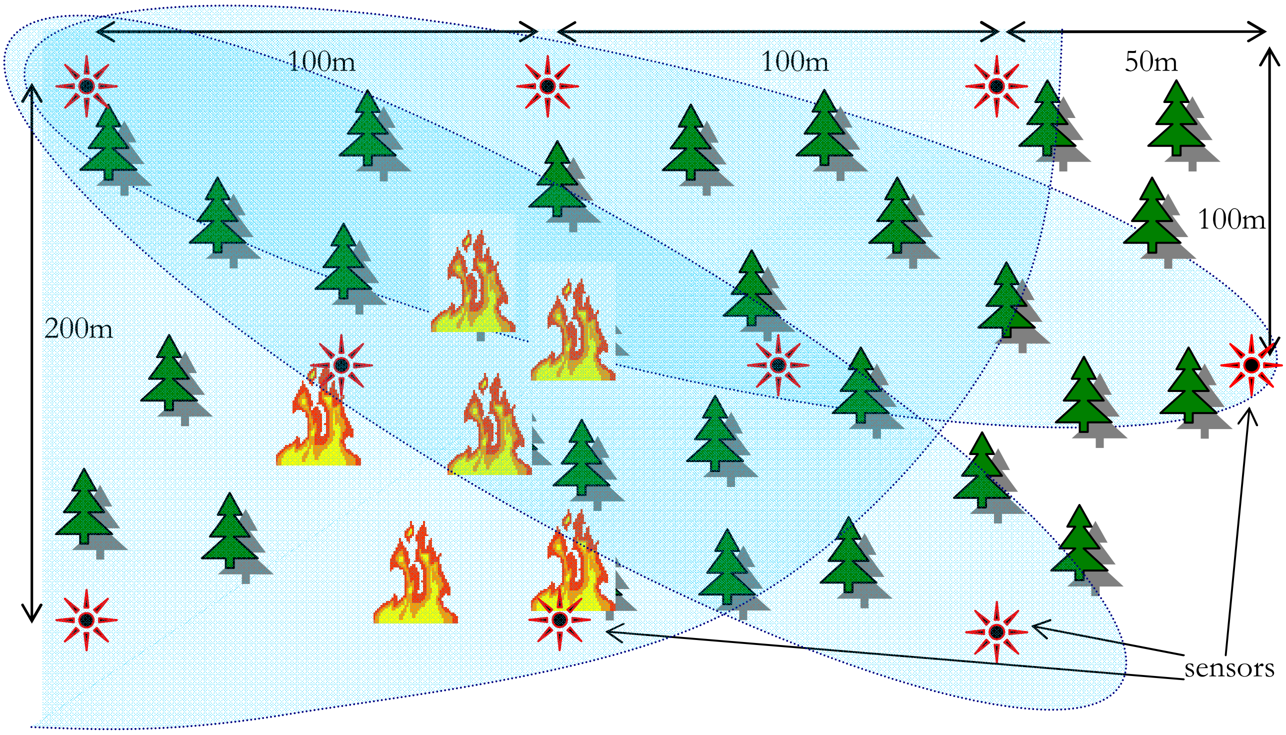


Figure 5.1. Forest scenario of simulated network.

The simulated scenario consists of 9 nodes, deployed deterministically. Each node is equipped with a device sensing temperature, humidity, pressure and position (GPS). All sensing data is sent by multi-hop communication to the sink node. Distances between nodes are varied, ranging between 100 metres (the pico-cell case) and 200 metres (the micro-cell case). Line of Sight in radio communication is impossible because of the various density and random uniform distribution of trees. Each tree in the scenario is a cluster of scatterers, so the type of forest is given by the density of clusters, their radius and average number of scatterers per cluster. Referring to the GBSB channel model, which assumes that each NLoS signal path reflects only from one scatterer and goes directly to the receiver, it can cause unreliable values of the received signal amplitude, which is the sum of amplitudes of all multipath signals, since the attenuation of the signal in the path to scatterer and from scatterer cannot be estimated only by the free space model. The multi obstacle model is chosen, where each penetrated tree can be treated as an attenuating obstruction. It is possible to calculate the number of trees influencing the signal for a NLoS component, from a given forest density, by the following:

$$N_t = \left(d_{1[m]} + d_{2[m]}\right) \cdot \sqrt{\rho_{[\text{trees/m}^2]}}\,, \qquad (5.1)$$

where:

- d_1, d_2: distances from transmitter to scatterer and from scatterer to receiver;
- ϱ: density of trees.

In the case of LoS, the sum of d_1, d_2 should be exchanged by d_0, which is the distance between transmitter and receiver. The attenuation of each obstruction (tree) is set according to the forest type.

The considered scenario can represent two types of forests: an apple orchard and the Amazonian rain forest. These types of vegetation were chosen in order to compare the influence of the GBSB model with the multi obstacle model on output parameters. The density and the thickness of the trees in such a forest is the main difference, lading to different outputs, which allows drawing many conclusions.

The first type of the vegetation is an apple orchard [CyKa05]. These trees' thickness is not large, being around 10 cm, leading to an attenuation of the tree around 5 dB. This type of trees is not big, and does not have a lot of big branches, so each of them can be considered as one cluster, with a maximum of two scatterers and a radius around 0.5 m. The density of clusters in this case varies, and depends of the type and class of the orchard. Possible densities are shown in the Table 5.2 [CyKa05]:

Table 5.1. List of density classes of apple orchards

density classes [trees/ha]						
< 400	[400,799]	[800, 1599]	[1600, 2399]	[2400, 3199]	[3200,3999]	4000 >

The second type of forest is the Amazonian rain forest [Stee03]. This type of forest has a very large density of big trees, with a lot of branches and smaller vegetation. Because of the irregular positions of trees, LoS communication is not possible. The trunks of such trees can reach a thickness around 1 m, what gives a maximum attenuation near 15 dB. Each tree can be considered as one cluster as well, but with 3 or more scatterers. The radius of the cluster can be up to 2 metres, because this is the area of influence on radio wave propagation. The variety of trees density is depicted in Figure 5.2.

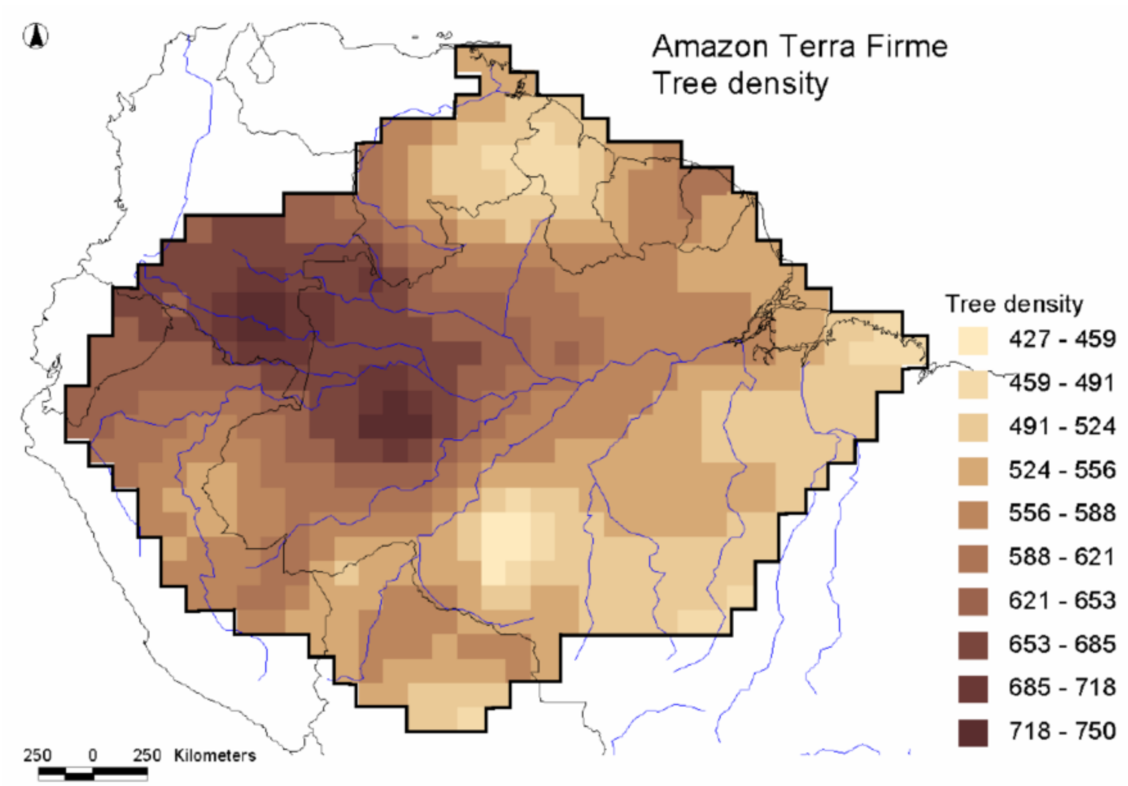


Figure 5.2. Density of the trees in Amazonian rain forest [Stee03]

The forest scenario was simulated with the parameters shown in Table 5.2.

Table 5.2. Parameters of the forest scenario

parameter	Value
the minor axis of the ellipse [m]	dependent of distance
the major axis of the ellipse [m]	dependent of distance
the radius of the circle [m]	dependent of distance
cluster density [1/m^2]	dependent of the forest
average number of scatterers	2 – orchard 3 – Amazon rain forest
cluster radius [m]	0.5 – orchard 2 - Amazon rain forest
carrier frequency [MHz]	920
power of transmitter [dBm]	1
type of the antenna	omni directional
sensitivity of the receiver [dBm]	-112

5.1.2 The house scenario

The second scenario of interest is the house one. Intelligent buildings (smart homes) are becoming very popular nowadays. The idea of such houses is to make life better and easier, for example for elderly people. A definition of the smart house is that such a house allows the remote control of particular activities, for example, turning on the light when somebody is entering the room or turning on heaters when the temperature is too low. The case of monitoring human activity and behaviour in houses is addressed in [OgTo00], where a deployment of devices is done, sensing the existence of human (infrared), temperature, humidity, pressure and light. Following such idea, a similar environment is simulated in this dissertation.

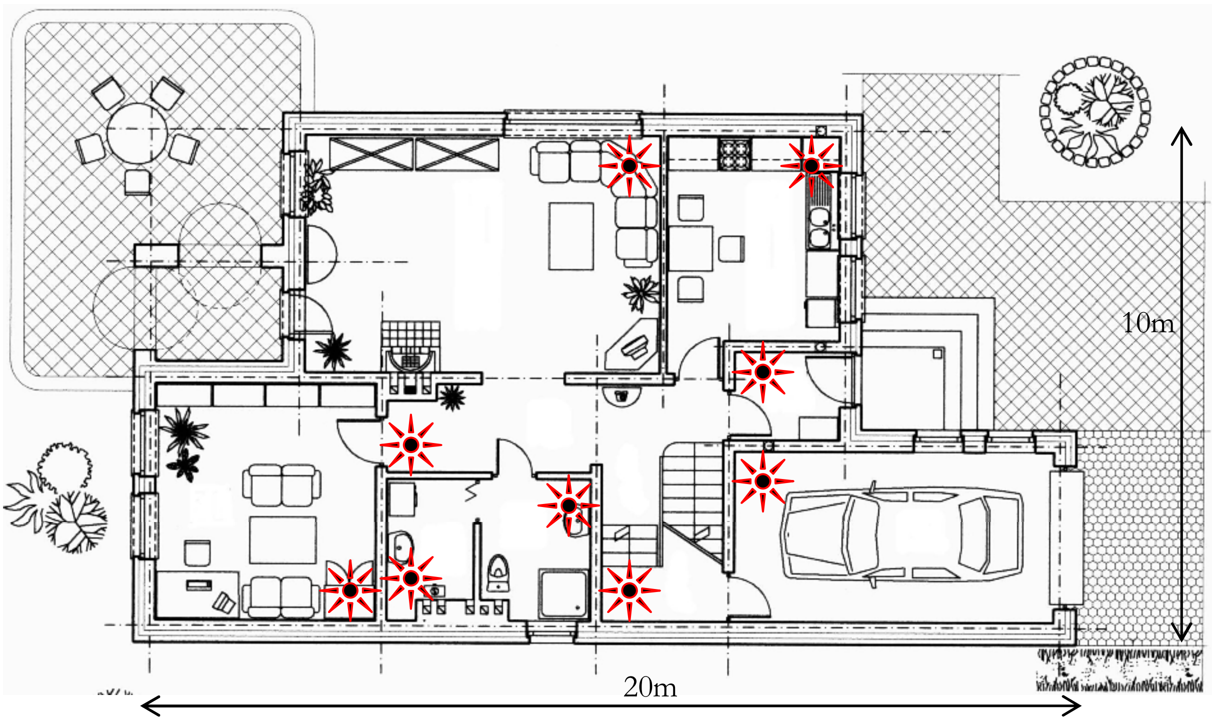


Figure 5.3. House scenario of simulated network.

There are 9 sensors (sensing the same phenomena) implemented on the wall in each room like on Figure 5.3; the house plane is taken from a real house in Poland. The distances between nodes vary between 1 and 20 m, which leads to consider only pico-cells. The covered area is near 120 m^2. The density of clusters depends on the number of furniture items, like tables, flowers, and sofas.

Path loss depends on the number of walls. All sensing devices are mounted on walls and separated by them, which leads to a minimum number of obstructions (walls) as one. There is only one type of walls in the house (30 cm thick) that is considered in the simulator, which attenuation is 3.4 dB [COST99]. The simulation assumes that walls are not sources of reflections and multipath components, but rather their influence is taken into account only in the calculation of path loss with the multi wall model in the path transmitter-scatterer-receiver or only transmitter-receiver. The number of walls between sensors is simulated with the following scheme:

- distance between d_0 m and d_1 m – uniform possibilities of 0, 1, 2 walls
- distance between d_1 m and d_2 m – uniform possibilities of 1, 2, 3 walls
- distance between d_2 m and d_3 m – uniform possibilities of 2, 3, 4 walls
- distance between d_3 m and d_4 m – uniform possibilities of 3, 4, 5 walls
- distance between d_4 m and d_5 m – uniform possibilities of 4, 5, 6 walls

Such values have been changed to achieve conclusions on various numbers of walls. The density of walls can specify the type of the building (e.g. in a family house the size of rooms is much lower than the size of classrooms in a school).

Parameters of such a house scenario are listed in Table 5.3.

Table 5.3. Parameters of the house scenario

parameter	**Value**
the radius of the circle [m]	20
cluster density [1/m^2]	0.06
average number of scatterers	2
cluster radius [m]	1
carrier frequency [MHz]	920
power of transmitter [dBm]	1
type of the antenna	omnidirectional
noise level of the receiver [dBm]	-120

The channel model is simulated only us a pico-cell, because of the small distances between nodes considered in this types of buildings. The presence of walls is considered in path loss estimation. The rest of the obstructions, like furniture, plants, and people, are modelled by the GBSB model as sources of multipath components.

5.2 Range estimation calculations

Wireless Sensor Networks use three ranges of frequencies, defined by ZigBee [ZigB04]. Referring to the relatively small distances between radio devices in the considered scenarios, and the small dispersion of the environment, one can assume that there are minimal differences of path loss between each frequency specified by ZigBee. As a consequence of such assumption, 920 MHz has been used in simulations and this value was never changed.

The power of transmitter is considered as an average transmitting power of common WSN devices shown in Table 5.4. The transmitting antenna is omni directional, so its gain is 2 dBi.

It is important to calculate propagation path loss and estimate possible ranges between nodes in the considered environments, before performing simulations with the GBSB model. The transmitter parameters are required to evaluate the attenuation of the channel. These values are taken from some of the vendors of WSN equipment, Table 5.4.

Table 5.4. Parameters of transmitters.

vendor	frequency [MHz]	modulation format	output power [dBm]	sensivity [dBm]	references
Analog Devices	[431, 478] [862, 956]	GFSK,FSK,ASK,OOK	13	-112	[Anal06]
Atmel	915	FSK,OOK	10	-107	[Atme06]
Ember	2400	O-QPSK	4	-97	[Embe06]
Freescale	2400	O-QPSK	[-27, 4]	-94	[Free06]
Texas Instruments	315, 433, 868, 915	FSK, OOK, MSK	[-30, 10]	-110	[Texa06]
Crossbow Technology	433 [868, 916] [2400, 2483.5]	-	[-20, 10]	–101	[Xbow06]

All WSN devices are equipped with quarter wave antennas, which are omnidirectional in the horizontal plane, its gain being near 2 dBi. In such case, the last parameter – path loss – should be modelled separately for each considered scenario.

According to the data, maximum ranges were calculated with the highest possible power to be transmitted by devices and the maximum sensitivity. Ranges were calculated with a function written in C++ and Microsoft Excel.

The attenuation calculated in each considered scenario is depicted on Figure 5.4. The attenuation of a free space is smaller in comparison to the forest, where there is a strong loss of signal caused by vegetation. The forest attenuation has been estimated by the vegetation model [ITUR00], and for the house, the range estimation was done with the multi wall model, considering one wall in the whole distance.

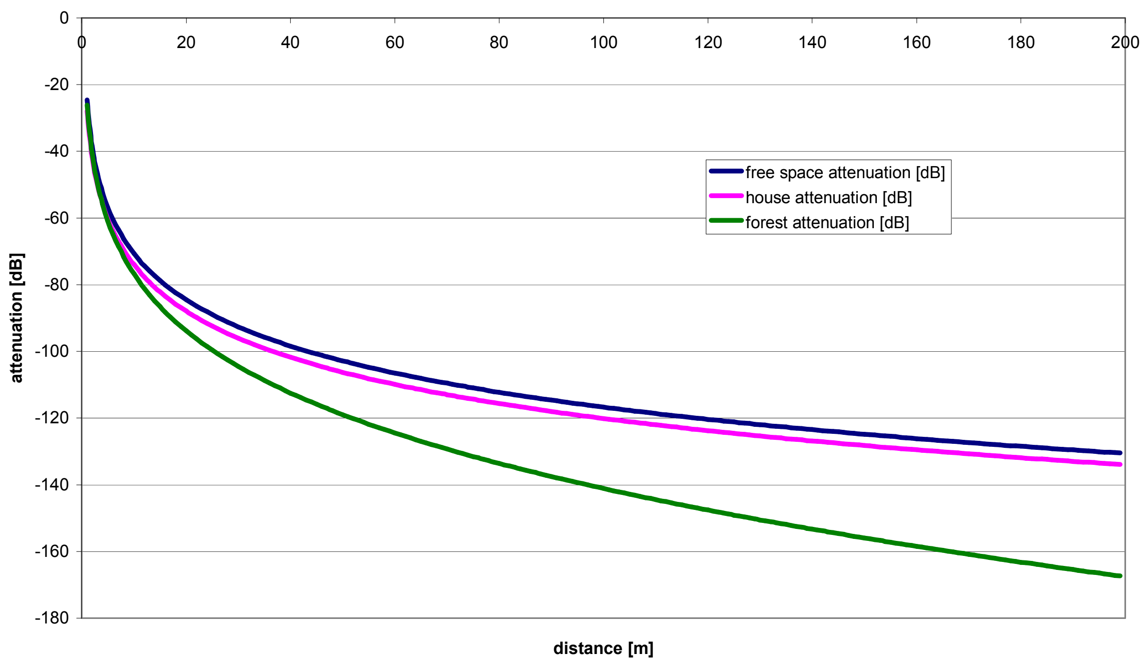


Figure 5.4. Attenuation plots for free space, house and forest.

Ranges are depicted on Table 5.5, calculated with minimum (-30 dBm), average (0 dBm) and maximum (13 dBm) transmit powers, and minimum (-94 dBm), average (-103 dBm) and maximum (-112 dBm) sensitivities. These values are used to simulate each scenario of Wireless Sensor Networks.

Table 5.5. Ranges in considered scenarios with various assumptions.

<table>
<tr><th colspan="3" rowspan="3">scenario</th><th colspan="3">range [m]</th></tr>
<tr><th colspan="3">receiver sensitivity</th></tr>
<tr><th>minimum</th><th>average</th><th>maximum</th></tr>
<tr><td rowspan="9">transmit power</td><td rowspan="3">free space</td><td>minimum</td><td>7</td><td>35</td><td>61</td></tr>
<tr><td>average</td><td>11</td><td>50</td><td>96</td></tr>
<tr><td>maximum</td><td>17</td><td>79</td><td>151</td></tr>
<tr><td rowspan="3">house</td><td>minimum</td><td>6</td><td>27</td><td>61</td></tr>
<tr><td>average</td><td>9</td><td>42</td><td>81</td></tr>
<tr><td>maximum</td><td>15</td><td>67</td><td>127</td></tr>
<tr><td rowspan="3">forest</td><td>minimum</td><td>5</td><td>20</td><td>32</td></tr>
<tr><td>average</td><td>8</td><td>28</td><td>45</td></tr>
<tr><td>maximum</td><td>12</td><td>39</td><td>61</td></tr>
</table>

5.3 Forest

5.3.1 Influence of the density

In order to simulate the influence of the trees density, a few tests were made. Concerning the GBSB model and scenario assumptions, each tree is treated as one separated cluster of scatterers, which number depends on the forest type. The trees density also impacts on the number of obstacles crossed by the signal, which allows one to estimate the attenuation of the path.

When simulating this influence, the rest of the scenario parameters where chosen deterministically. The density's influence was made considering only the Amazon rainforest density ranges. The observed behaviour is the same for the other types of vegetation. Received components were calculated only with a constant distance between transmitter and receiver of 100 m. Each tree radius was set to 0.2 m and the maximum attenuation to 5 dB. Many branches existence was taken into account by the cluster radius of 2 m and an average number of scatterers of 3, which is characteristic of the rainforest. All channel model performance parameters were calculated beginning from 0.015 trees/m^2 to 0.095 trees/m^2 with a step of 0.01 trees/m^2.

The RMS delay spread is the most interesting parameter, being depicted in Figure 5.5.

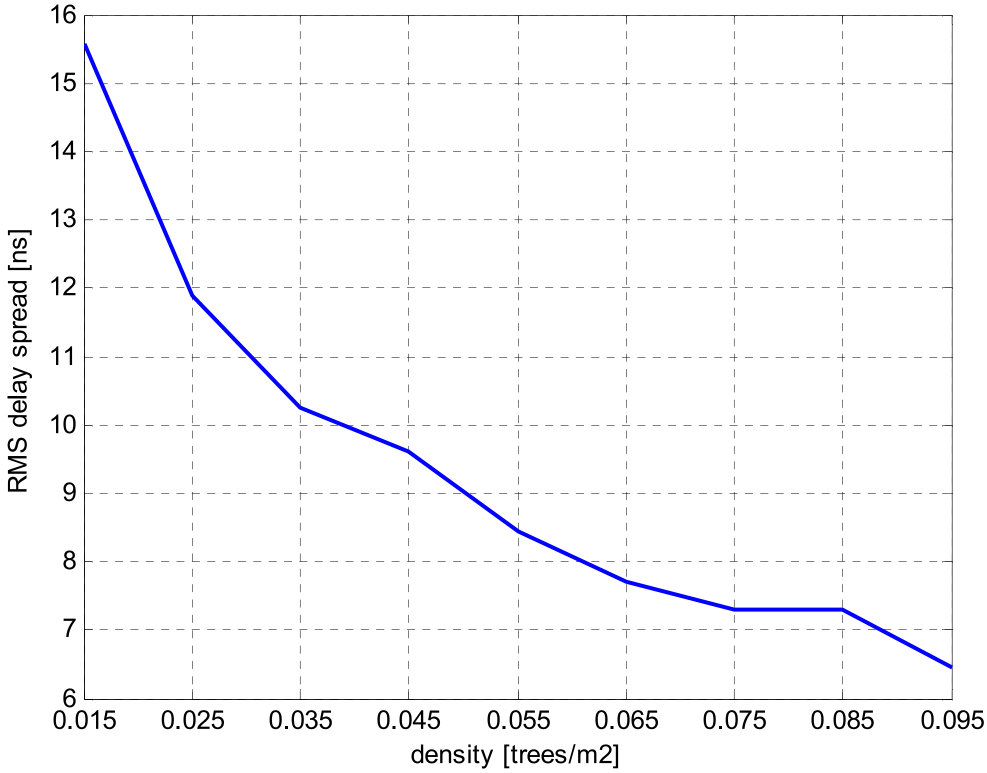


Figure 5.5. RMS delay spread for various densities of the forest.

By increasing the density of trees in the forest, the attenuation of the signal is also increasing because more trees are taken into consideration. This is the reason why some multipath components are more attenuated, and can no longer be received by the receiver, because of the limited sensitivity. This fact causes that the more delayed components, which have the longer propagation path, are not taken into the calculation of the total signal, thus the RMS delay spread is decreasing.

The second interesting parameter is the mean power of the received signal, Figure 5.6. This graph shows the mean received power level for each density, with the standard deviation.

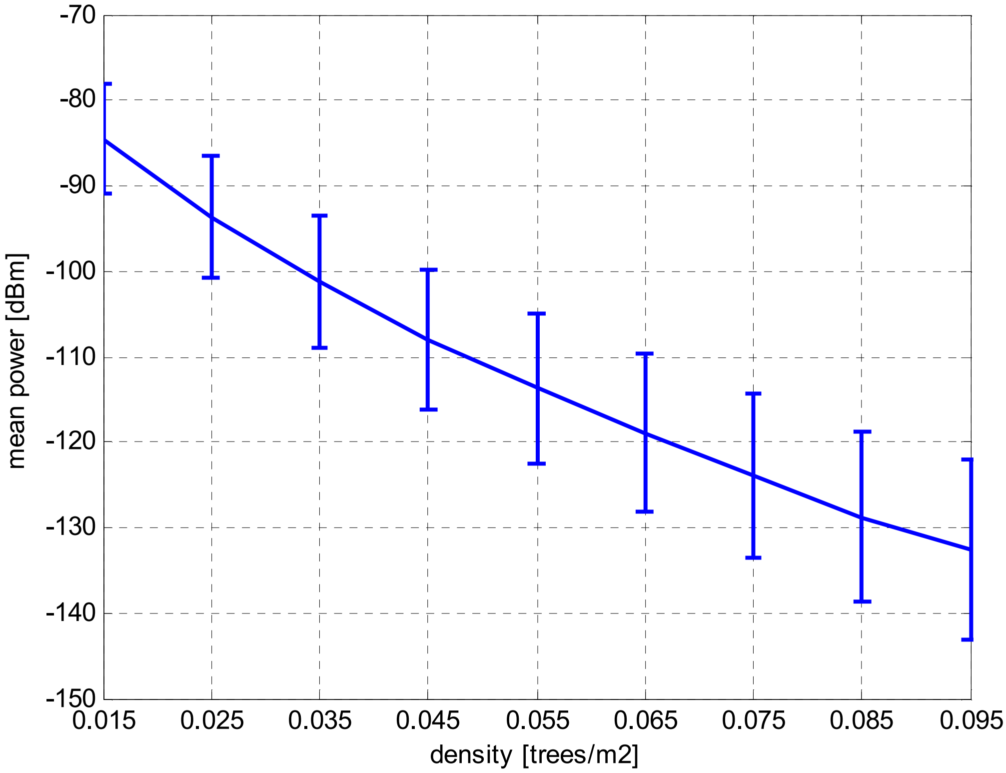


Figure 5.6. Mean received power for various densities of the forest.

Increasing the density causes a stronger attenuation, as previously mentioned, which leads to a decrease in the received power. The transmitted power was set to 10 dBm; in the case that there are no trees attenuating the signal, only the free space loss with 100 m was considered.

The increasing density causes the increase of the number of trees obstructing the signal. The number of trees for each density was also calculated, Figure 5.7. The curve shows that the number of trees is really growing and can cause such effects.

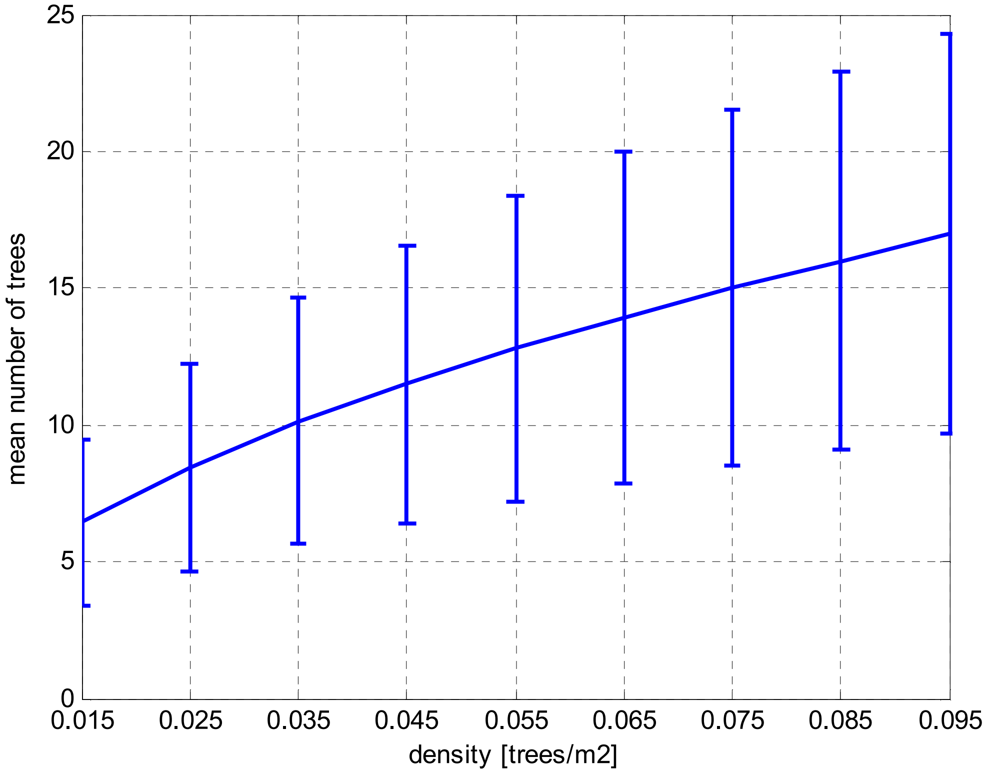


Figure 5.7. The number of trees for various densities of the forest.

5.3.2 Influence of the maximum tree attenuation

Simulations of the forest were made using the multi obstacle propagation model. Each tree can influence the path attenuation and can be an obstruction, which reflects the signal. The density of the forest specifies the number of multipath components and the attenuation, which depends on the number of trees crossed. After knowing the number of trees, one needs to know the maximum attenuation of each tree, which depends on the tree type. The influence of this parameter was tested and the achieved results are shown in this section.

The accompanying parameters of the simulations were considered as follows:

- Tree radius: 0.2 m
- Communication distance: 100 m

- Forest density (clusters): 0.045 trees/m^2 (Figure 5.8)
- Cluster radius: 2 m
- Average number of scatterers per cluster: 3

Figure 5.8 shows the calculated positions of the trees. Each tree is placed inside the circle defining the pico-cell between the transmitter and the receiver, which are marked as blue triangles.

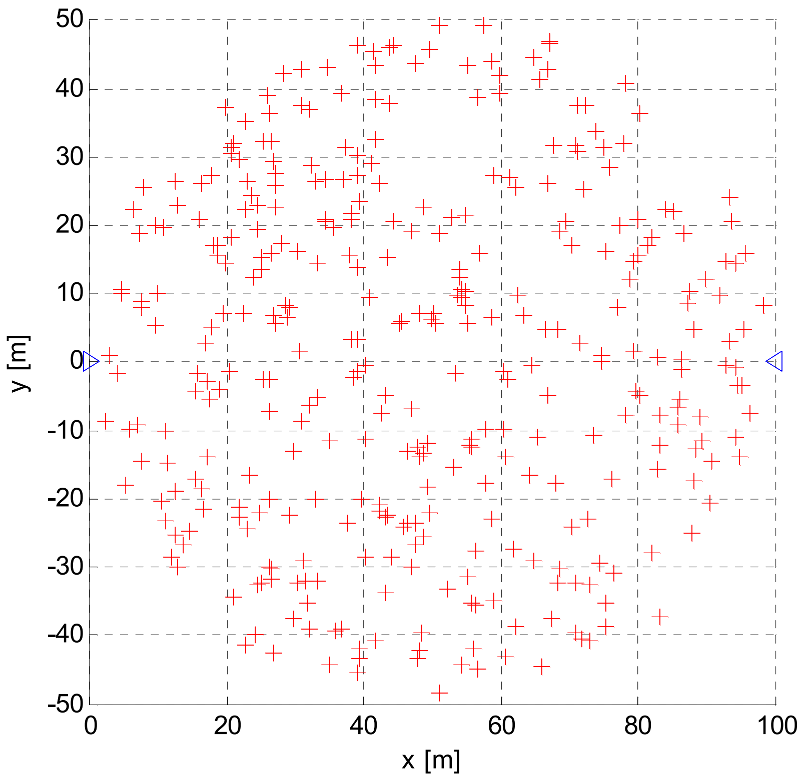


Figure 5.8. Positions of the trees with 0.045 trees/m^2 density.

The calculated RMS delay spread by changing the maximum attenuation of the tree within the range from 2 dB up to 10 dB with 1dB step is depicted in Figure 5.9.

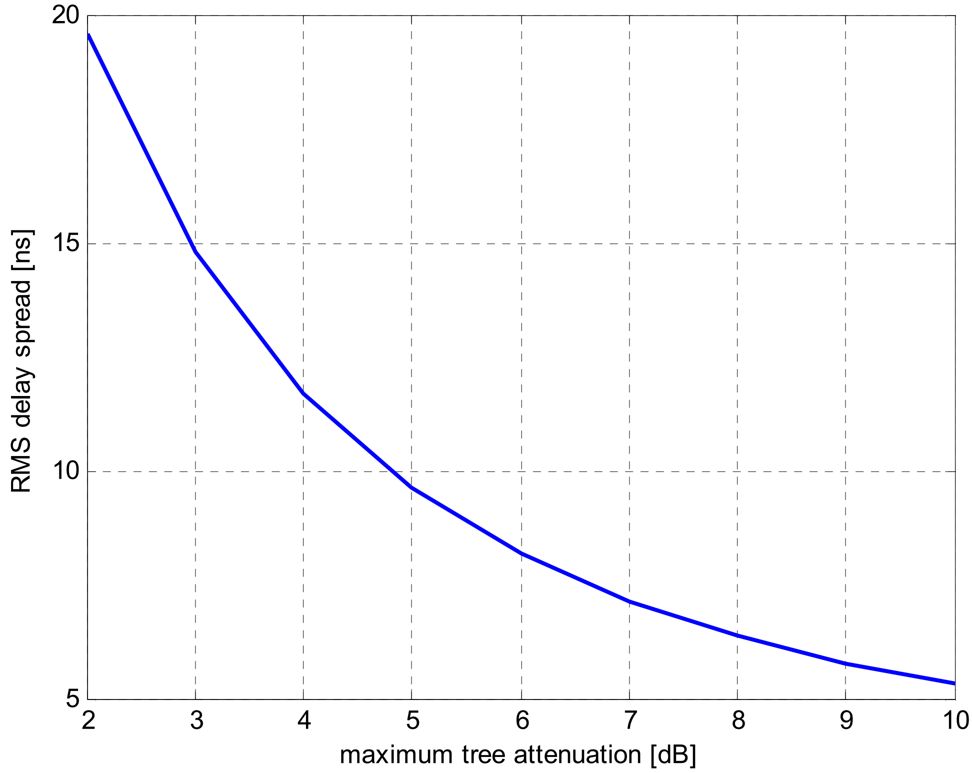


Figure 5.9. RMS delay spread for various maximum tree attenuation.

The curve shows that when the maximum attenuation decreases, more multipath components can be received at the received, hence, its increase implies that the number of components of the level lower than the receiver sensitivity increases.

The same behaviour can be observed for the mean received power level, Figure 5.10. The number of trees does not depend on their attenuation, so they remain the same.

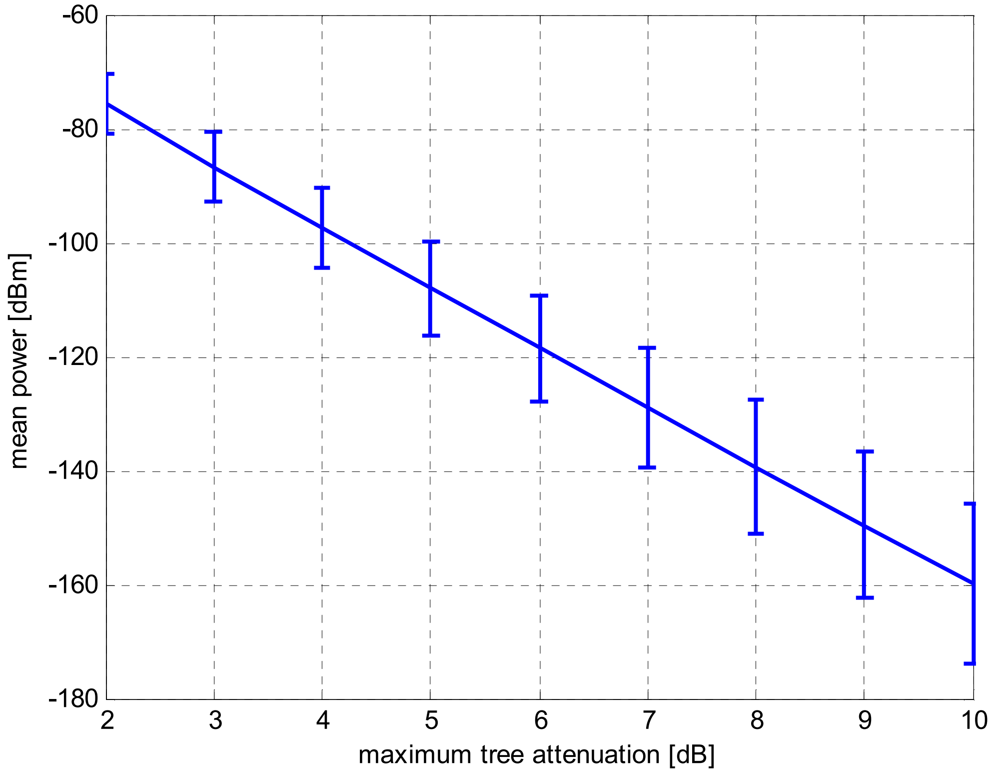


Figure 5.10. Mean power level for various maximum tree attenuations.

5.3.3 Influence of the tree radius

The tree radius is an important parameter, which is considered as well. Each component of the signal crosses the tree, which causes attenuation. The maximum tree attenuation is given for the specified radius. In fact, trees can have various radii, which leads to the various attenuations. This relation is considered as linear. Another fact is that the signal never crosses the tree through its centre. The attenuation is dependent on the crossed chord length, which is calculated uniformly from the angle and the distance from the signal source to the tree (A. Annex). In such situation, the tree radius has a big influence on the attenuation of the particular tree. The behaviour of the RMS delay spread and the received power is analysed in what follows.

The accompanying parameters of the simulations were considered as follows:

- Maximum tree attenuation: 10 dB

- Communication distance: 100 m
- Forest density (clusters): 0.045 trees/m^2 (Figure 5.8)
- Cluster radius: 2 m
- Average number of scatterers per cluster: 3

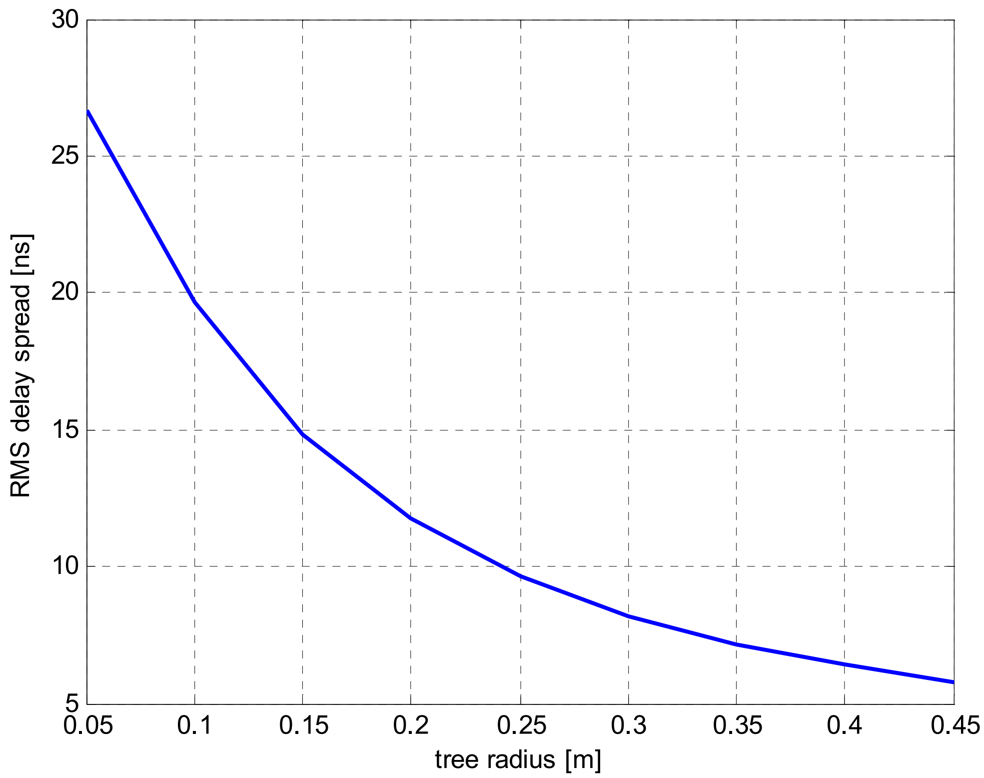


Figure 5.11. RMS delay spread for increasing tree radius.

An increase of the tree radius causes an increase of its attenuation. Such situation, as in previous sections, causes a lower number of received components, which is reason for the RMS delay spread increase. The same situation occurs with the received power, Figure 5.12.

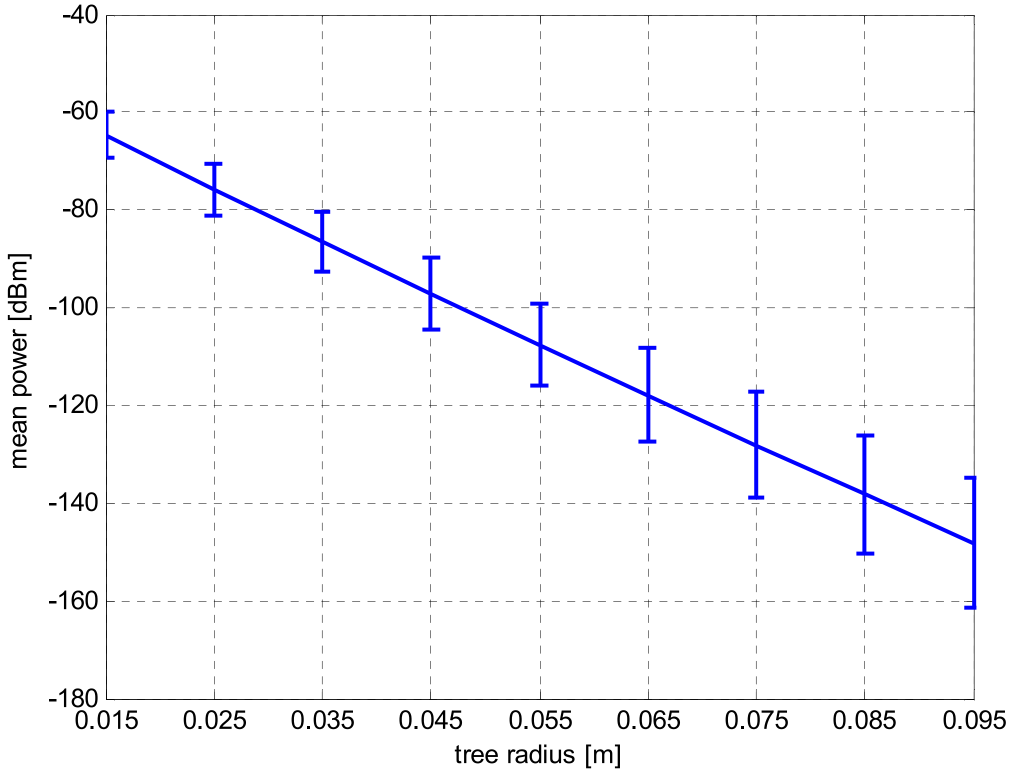


Figure 5.12. Mean power level for various tree radii.

5.3.4 Influence of distance

In order to simulate the influence of the distance on performance parameters, some assumptions had to be made. The received signal is the sum of all multipath components from the region of the influence defined before the simulation. It is obvious that for various distances the dimension of the region changes. In such a case, the pico-cell scenario was chosen, which defines the region as a circle with the centre in the middle of the direct distance and the radius of the half of it Figure 5.13. Such assumption causes more trees to impaction the signal with reflections, which can cause the increase of the received power, but in fact these trees also attenuate each component. Thus, the received power and the delay spread is the result of this joint effect.

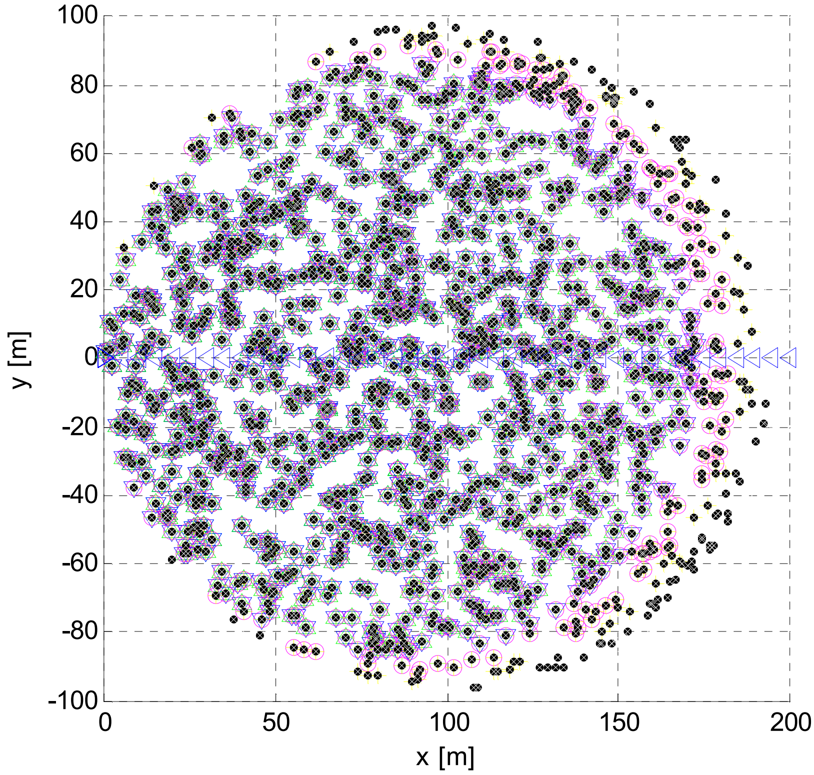


Figure 5.13. Positions of the trees and the terminals within the region.

The simulation parameters of the scenario were set as in previous simulations, with the tree radius of 0.2 m.

The delay spread for each distance is depicted on Figure 5.14. In the distance up to 80 m, the increase of the delay spread is noticeable caused the increasing number of multipath components. In higher distances, there is a larger influence of the trees attenuation, what causes the fluctuation

The influence of the distance on the received power is depicted on Figure 5.15. The shape of the curve is linear because the trees are deployed with a uniform distribution, which gives the linear increase of the number of trees with distance. The curve slope depends on the trees density.

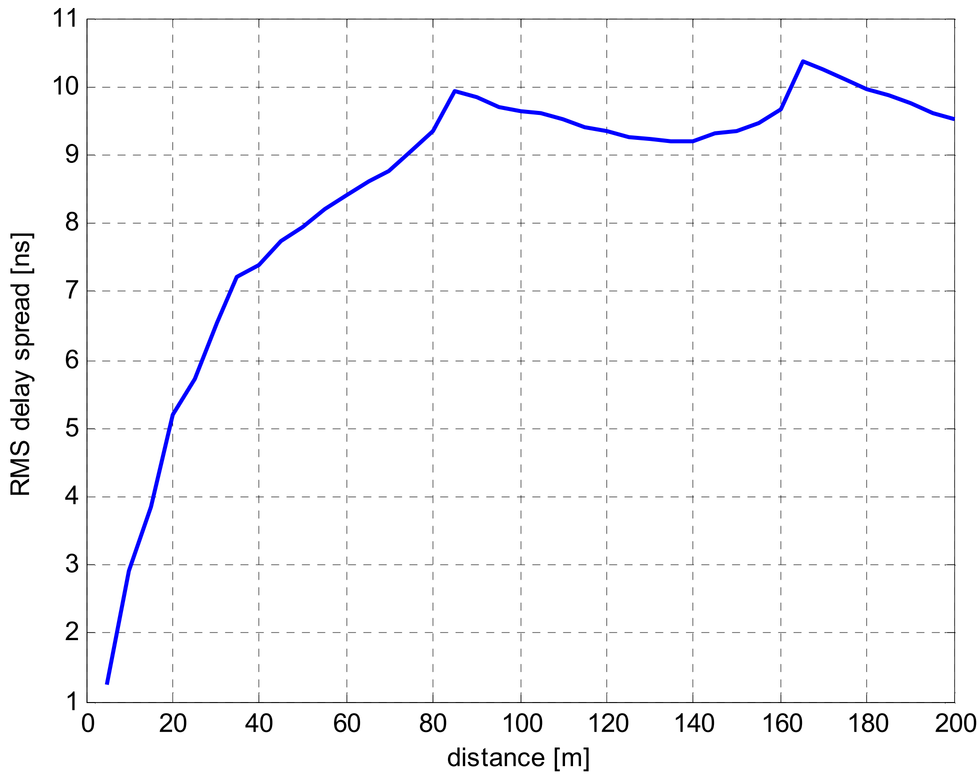


Figure 5.14. RMS delay spread for increasing distance.

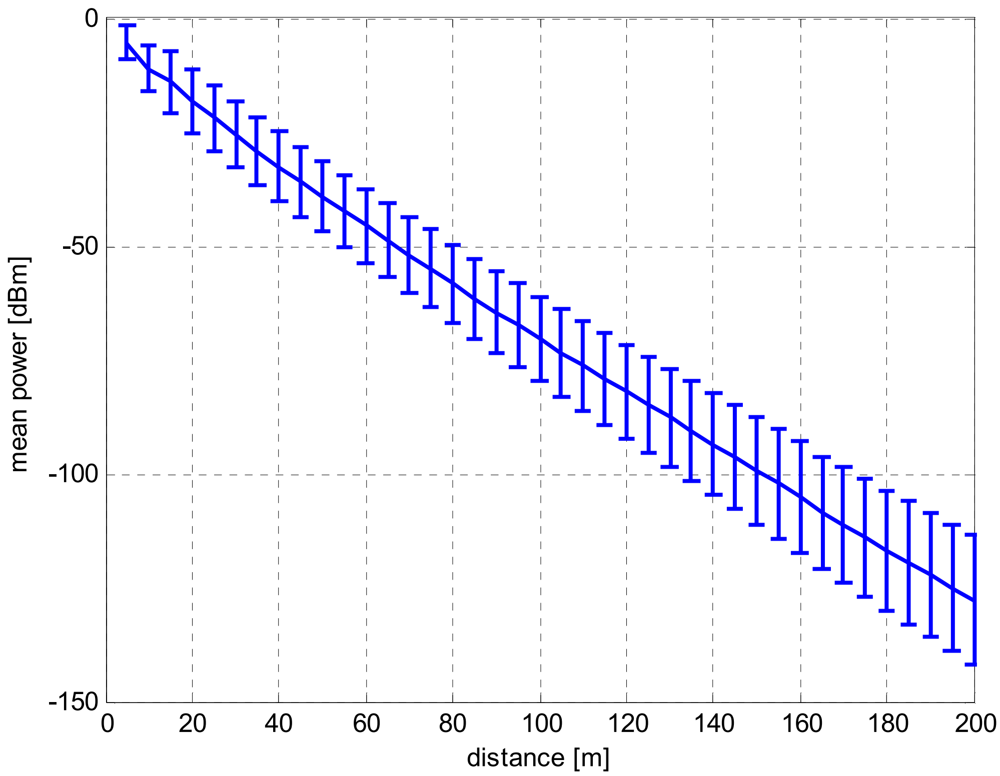


Figure 5.15. Mean power level for increasing distance.

The noticed behaviour in such simulation is caused by the linear increase of the numbed of trees, Figure 5.16.

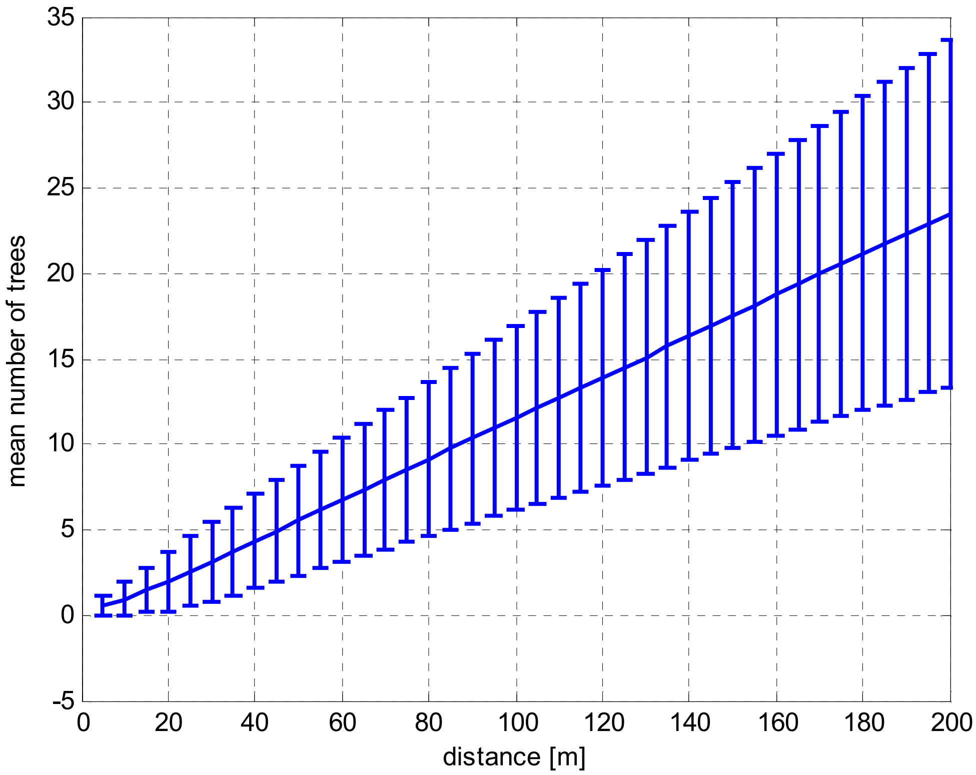


Figure 5.16. The number of trees for increasing distance.

5.4 House

5.4.1 Influence of the walls density

Tests on the walls density has been made to check its influence on the received signal. The number of walls crossed by the signal causes additional attenuation, depending on the type of wall. Such attenuation was set to 3.4 dB, which is typical for the considered type of houses. The simulations have been made with a constant distance between transmitter and receiver, which was set to 20 m, around the maximum possible distance in a house. The density of the clusters of scatterers is also constant, leading to a distribution of clusters like in Figure 5.17. Each cluster is considered as a part of the house, like for example furniture, with a mean radius of 1 m.

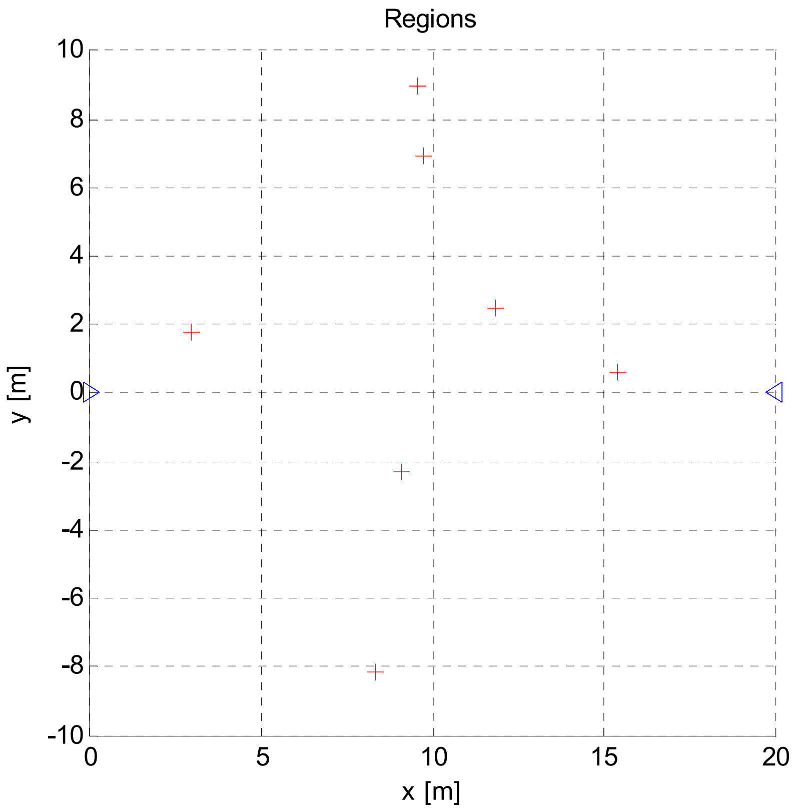


Figure 5.17. Distribution of the cluster in the house scenario.

The range of walls density from 0 to 0.4 walls/m gives a maximum of 8 walls for a 20 m distance. This number of walls does not attenuate the signal as strong as to prevent the reception of each component. In such situation, the RMS delay spread is always the same, being obtained as 6.5 ns.

The higher influence of the walls is observed in the received power. This behaviour is shown in Figure 5.18. This characteristic is linear, because the number of crossed walls increases linearly for a constant change of the density.

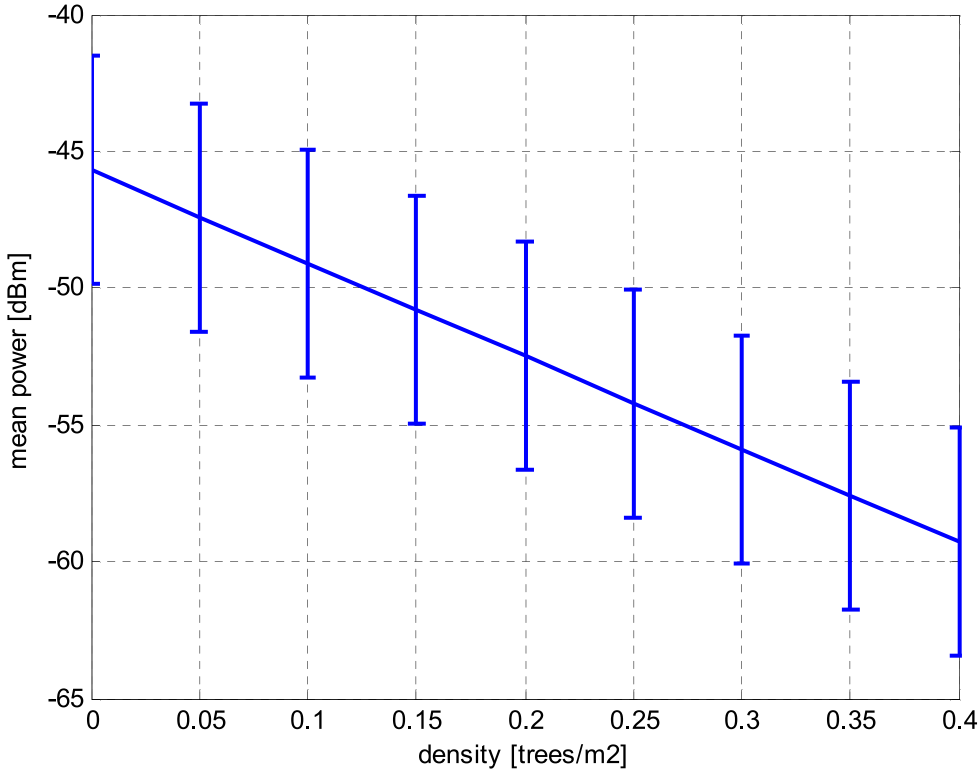


Figure 5.18. Mean power level for increasing density of walls.

The number of walls with a growing density, calculated for the distance of 20 m is shown in Figure 5.19.

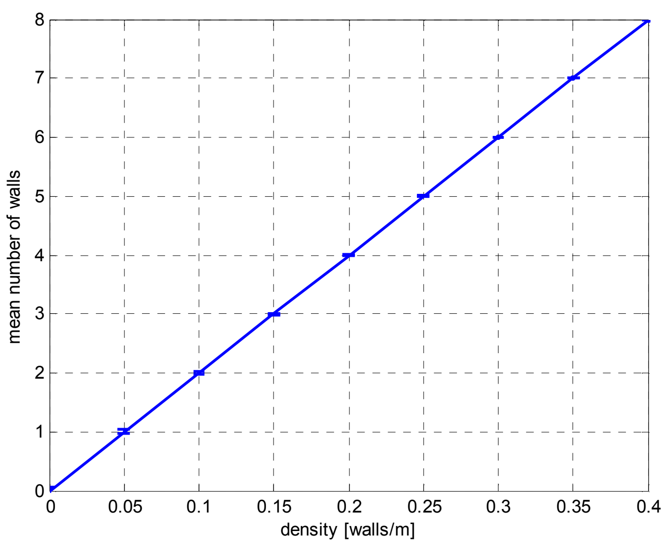


Figure 5.19. The number of walls in 20 m distance for various walls densities.

5.4.2 Influence of the wall attenuation

Wall attenuation is an important parameter of the house scenario. The analysis of its influence was done in conditions similar to the previous section; the only difference is that the density of walls was set constant, as follows:

- for the range [0,3] metres the number of walls can be 0, 1 or 2
- for the range [3,7] metres the number of walls can be 1, 2 or 3
- for the range [7,10] metres the number of walls can be 2, 3 or 4
- for the range [10,15] metres the number of walls can be 3, 4 or 5
- for the range [15,40] metres the number of walls can be 4, 5 or 6

For each range of distances, the number of walls was chosen randomly from the specified values. This specification allows treating the simulations like in a common family house. The results obtained for the delay spread are depicted on Figure 5.20.

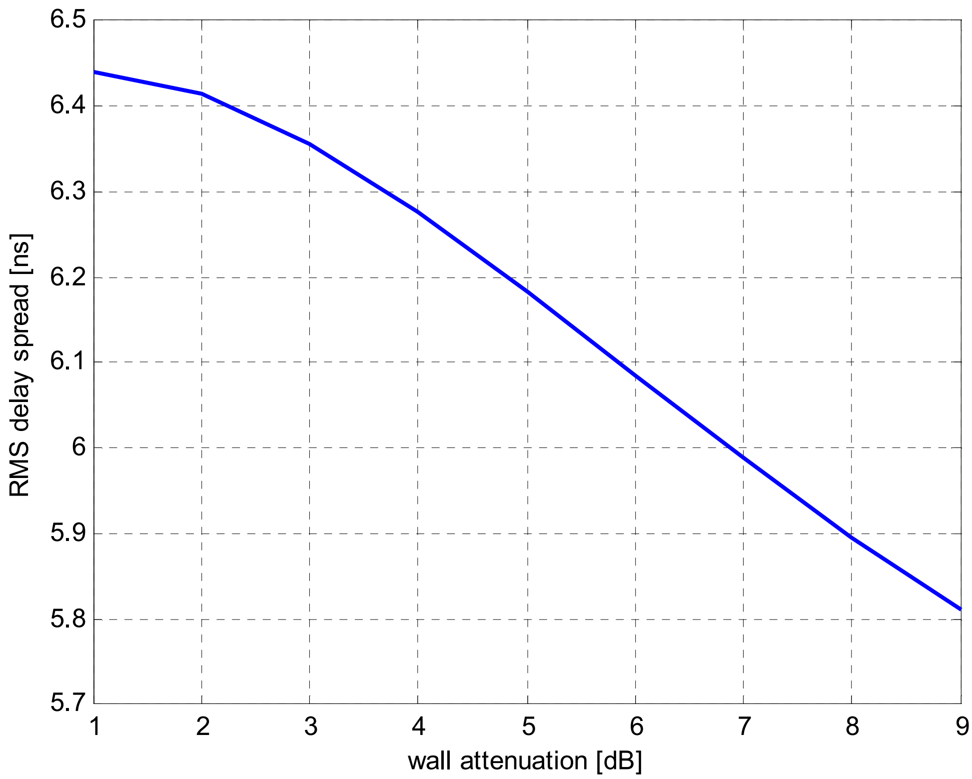


Figure 5.20. RMS delay spread for various wall attenuations.

The number of components is decreasing due to the growing attenuation of the path. This situation is the reason for the delay spread decrease. A similar situation occurs for the power lever, Figure 5.21.

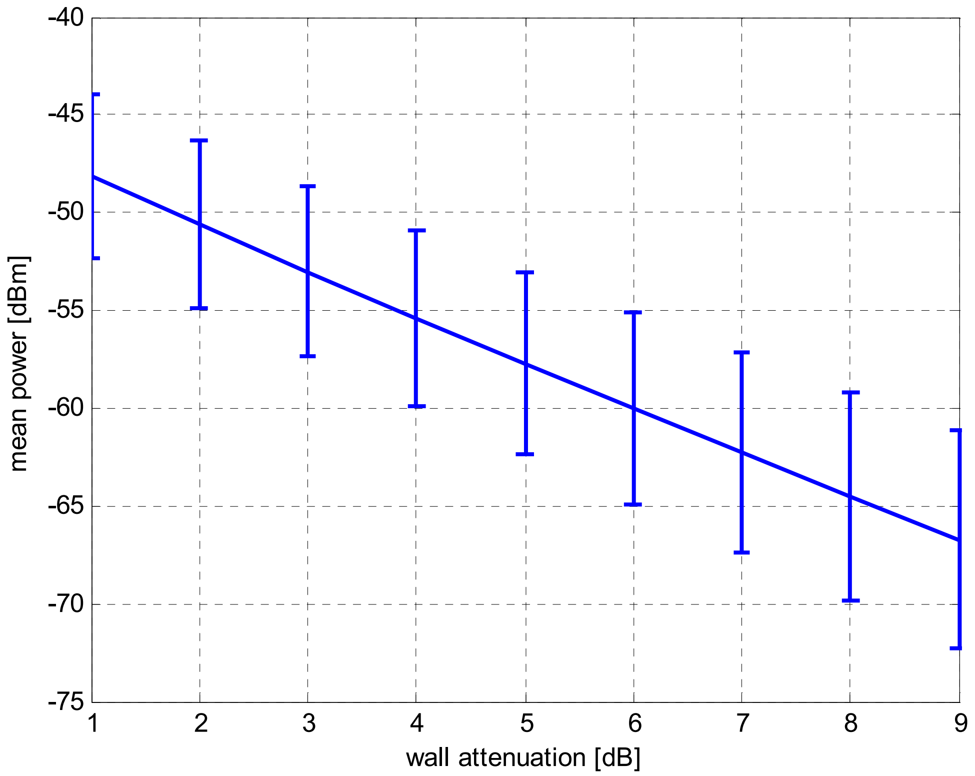


Figure 5.21. Mean power level for increasing density of walls.

The number of walls remains constant and for given distance and density is around 4.

5.4.3 Influence of distance

The analysis of the distance influence was done in the same similar to the forest scenario. The growing distance causes an increase of the influence region. The simulation parameters were set as:

- Wall attenuation: 3.4 dB

- Clusters density: 0.02122
- Cluster radius: 1 m
- Average number of scatterers per cluster: 2

The delay spread behaviour is depicted in Figure 5.22.

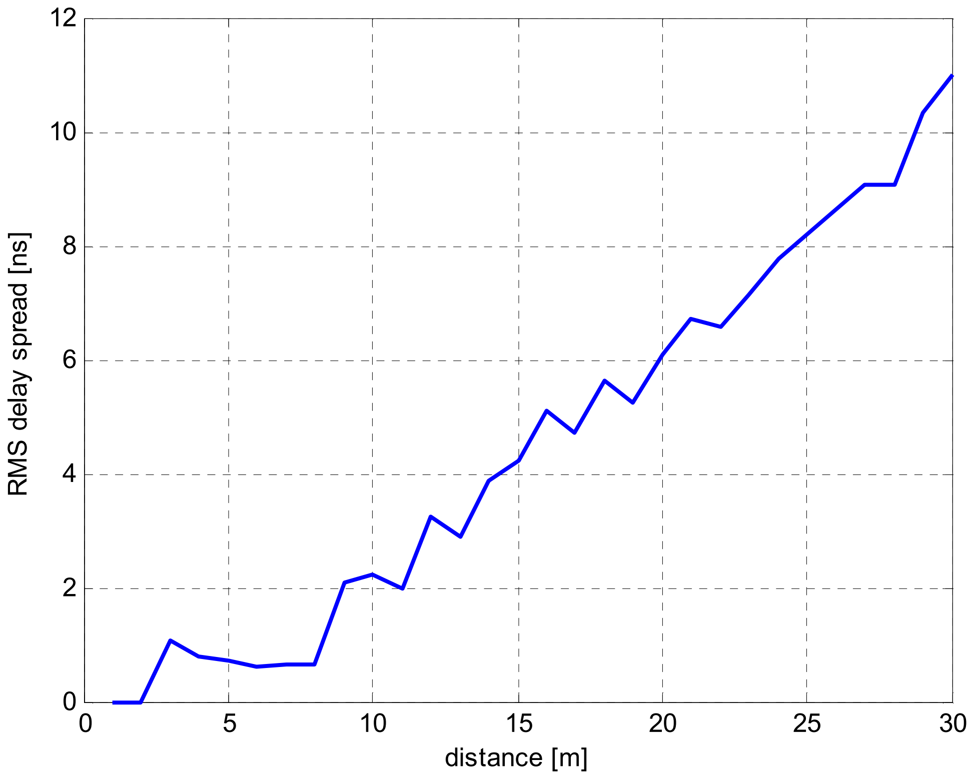


Figure 5.22. RMS delay spread for various distances.

By increasing the distance, the number of multipath components in such situation increases as well. The attenuation of each one is not that large in order to cause the impossibility to receive them. The maximum number of walls with 30 m is 8, which gives a 27.2 dB maximum attenuation. The distance of 30 m is also not that large compared to the free space loss between walls. These facts are the reason of the delay spread increase.

A different situation occurs for the mean received power level. The power for each component decreases with distance. This behaviour is shown in Figure 5.23.

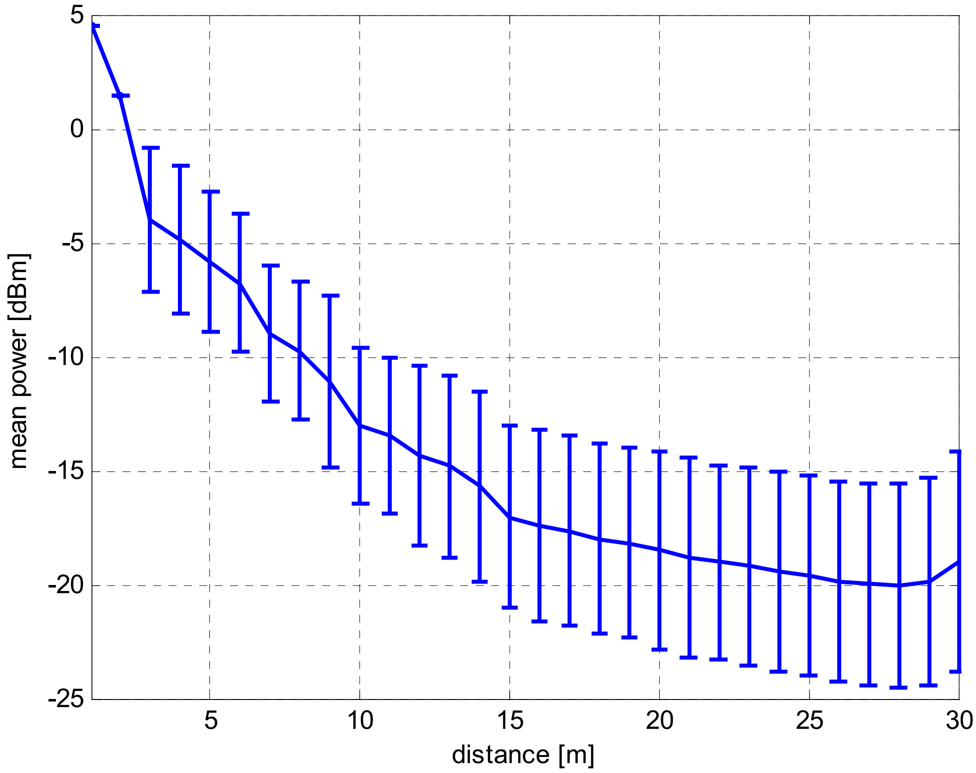


Figure 5.23. Mean power level for increasing distance.

The number of walls for each considered distance is shown in Figure 5.24

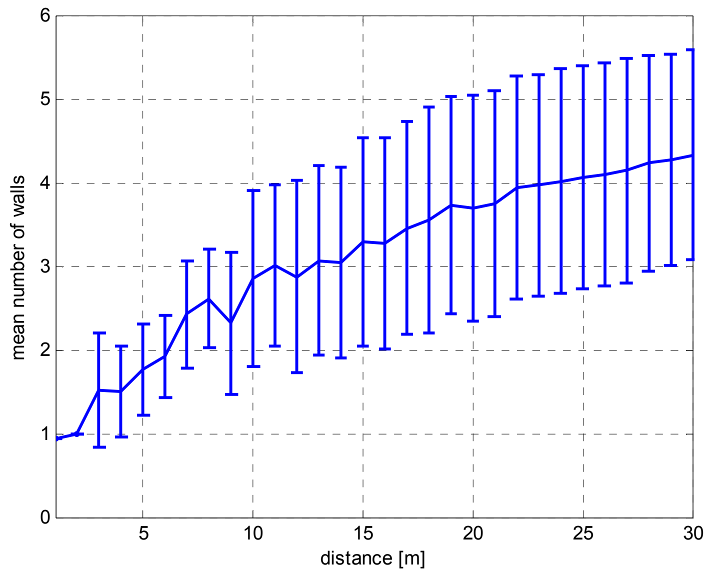


Figure 5.24. The number of walls in various distances.

Chapter 6

Conclusions

This chapter presents final conclusions and possibilities for future work.

The aim of this work was to analyse and then to simulate the channel behaviour in various scenarios of the Wireless Sensor Networks, namely by using the multi-obstacle model.

In order to achieve such objective, a review of Wireless Sensor Networks is presented in Chapter 2. Many aspects of these network features are discussed in this chapter as well. The focus is put on radio communication issues and on various scenarios for sensor networks.

This work mainly focuses on radio channel models. Sensor networks have been simulated with the GBSB channel model, which was implemented in the simulator proposed by GROW, IST-TUL. A review of some models and the main issues connected with them are presented in Chapter 3, where detailed definition of the multi-obstacle model is shown. The Multi-obstacle model for channel attenuation modelling is the novelty of this thesis. In order to enable the analysis of sensor networks, working in complicated environments with many obstructions, the multi-obstacle radio propagation model has been implemented into a simulator program. The whole program has been written in C++, and its description is presented in Chapter 4. This chapter contains also the descriptions of the input and output files required for simulations and the assessments that have been made.

The work has concentrated on two types of Wireless Sensor Networks scenarios: a forest and a house. Considerations about the parameters of these scenarios and some approaches are described in the first section of Chapter 5. Simulations on the influence of obstructions density and attenuation, as well as transmission distance, on the performance parameters of the GBSB model, like power level and delay spread, were done, being described in the second part of Chapter 5.

The purpose of the development of the multi-obstacle model was the fact that the GBSB model assumes that there is always a direct path between each reflecting obstruction and transmitter or receiver. Such approach is accurate for the common scenarios in mobile communications, but it is not adequate for sensor networks. In scenarios like a forest or a house, the direct connection without any obstructions is usually impossible, which is not considered in the GBSB model. This fact is the reason to consider another attenuation in the channel, besides the one of free space.

The influence of the multi-obstacle model is noticeable, considering the results achieved in Chapter 5. Without the additional attenuation of the many obstructions in the communication environment, the number of components received in the receiver would be very high, which would cause that the total received power would very high and that the total delay spread could achieve very high values. This phenomenon is eliminated by using the multi-obstacle model.

The influence of the developed model is noticeable, especially in the analyses of the obstructions density influence. Both house and forest scenario results show that the increase of the obstructions density causes the decrease of the received power. This fact is also confirmed by the number of the considered obstructions for each density, which is also shown in this work. The main behaviour of the RMS delay spread and the mean received power is similar for both house and forest environments. The difference is only in the slope angle of the curves. This fact is caused by the different assumptions for each scenario. Trees in forest are considered as an attenuating obstacles, but reflecting as well. In the house each wall does not reflect the signal, but rather it only attenuates. Such assumptions cause an increase of the multipath components in the forest for an increasing the density. This effect does not occur in the house, which is the reason for the difference between the influences of the obstacles density on the channel performance parameters.

The influence of the distance was also simulated for both scenarios. This analysis has been made by increasing distance and augmenting the region of influence. Such solution causes the increase of the reflecting obstructions and number of components. In such case, the values for delay spread and received power are fluctuating, which is caused by the trade-off between the number of components with the attenuation of each one. Curves do not present a smooth growing, which is caused by the pseudo random processes in the simulator.

The Multi-obstacle model also takes the influence of the threes radius on the attenuation of the particular tree into account. The tree loss is proportional to its drawn chord. The statistical distribution of the drawn attenuation in this way depends on the distance from the signal source to the considered tree. The dependence between the attenuation and the tree radius is linear, with a maximum attenuation for a maximum radius. Increasing the tree radius from a minimum to a maximum decreases the received power and the delay spread, as expected. Such behaviour is obvious, because the increase of the radius causes the increase of the attenuation from the tree.

The multi-obstacle model allows the simulation of radio communication systems in many more environments. The accuracy of the simulations depends on the proper choice of the models' input parameters. The parameters used in this work are taken from real applications of Wireless Sensor Networks. The assessment of the results accuracy can be done by comparing them with the real measured values in the considered environments, which would be a good opportunity for future work.

Analysis of results

The expansion of the program with the multi-obstacle model, which is very flexible and can be controlled by the user, allows simulating various radio systems. This is a good opportunity to simulate the influence the various environments on the MIMO systems and check their efficiency. The simulator is a program written without any user interface, which could be a next step in the evolution of the program.

Annex A

Range estimation graphs

These annex present curves of the received power level for each case of transmitted power and of receiver sensitivity. Gains of transmitting and receiving antennas are included.

In order to simulate a Wireless Sensor Network and design the positions of radio devices, it is important to calculate the possible ranges of the nodes. This information is of key importance when choosing the distances between nodes or their density in the case of statistical deployment. Range estimation has been done by using a simple program written in the C++ language, the output values being obtained by using a Microsoft Excel program.

The program calculates the attenuation for each environment, which influences the transmitted signal. The transmit power is taken from some vendors of sensor devices. The average, minimum and maximum power is taken into consideration. The maximum range is chosen by comparing the attenuated signal power level, increased by antennas gain (2 dBi for each), with the sensitivity of the receiver, considering average, minimum and maximum values, as well.

The considered output power is shown in Table A1.1:

Table A1.1. Considered output power of transmitters.

	minimum	average	maximum
Power [dBm]	-30	0	10

The considered sensitivity is shown in Table A1.2:

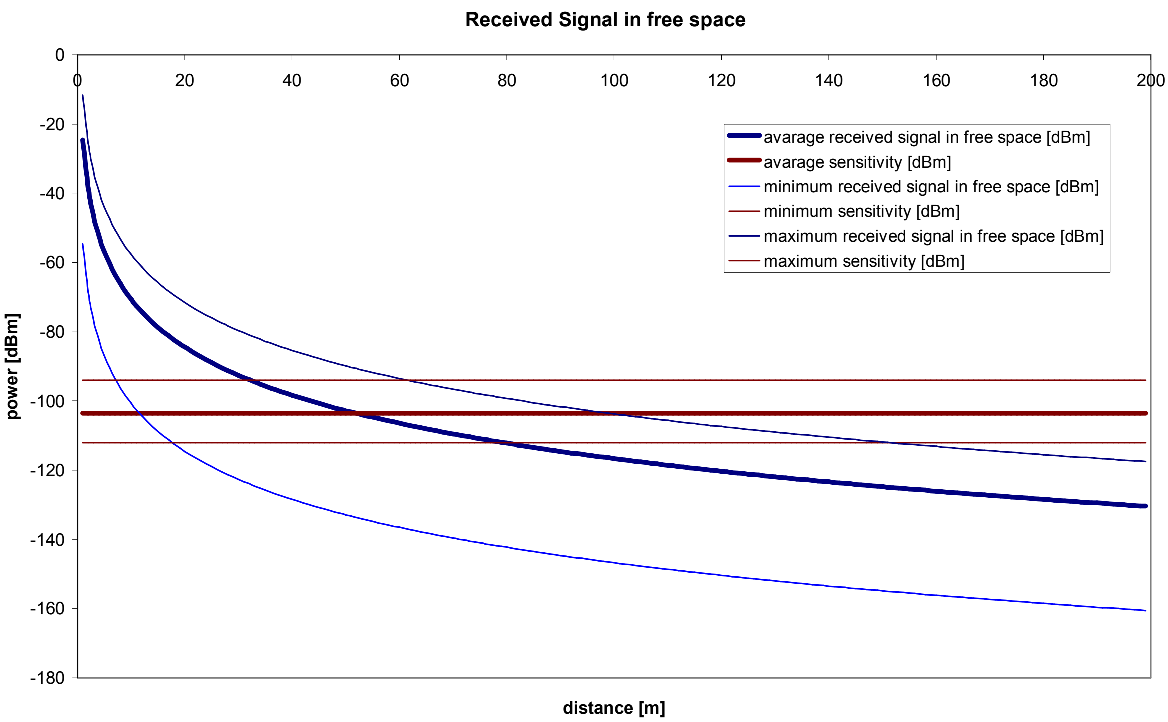
Table A1.2. Considered sensitivity of receivers.

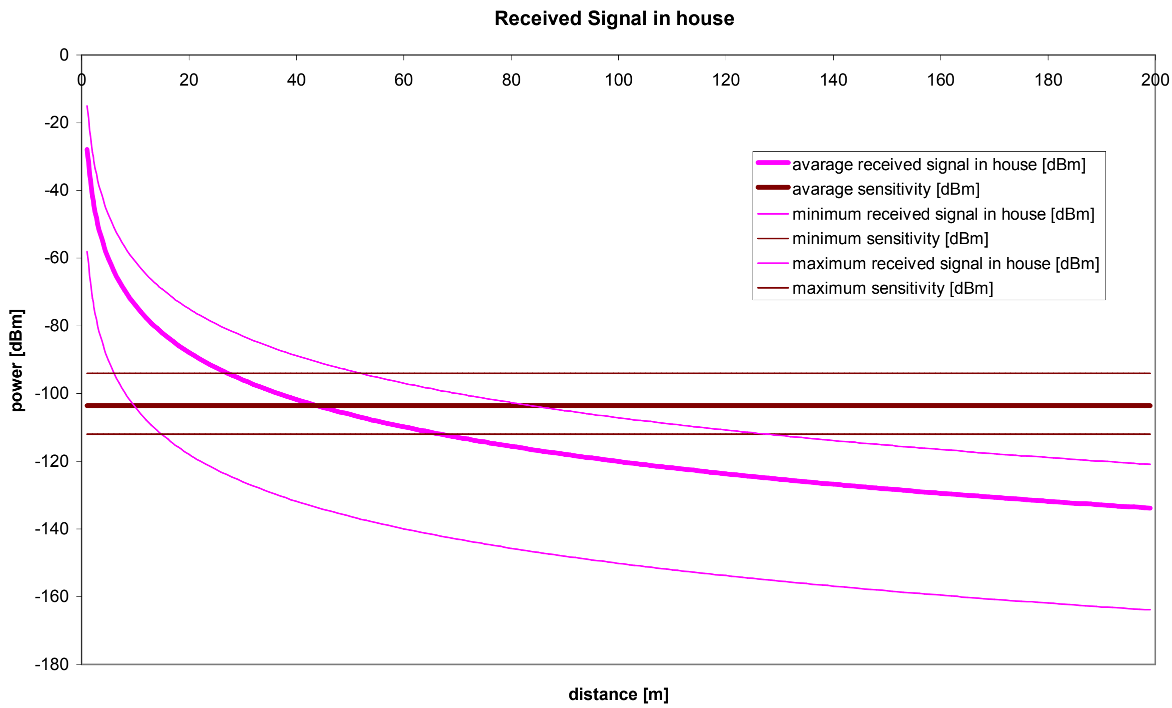
	minimum	average	maximum
Sensitivity [dBm]	-112	-103.5	-94

Range estimation has been done for three types of propagation environments, using three different models: house scenario ranges were calculated with the multi wall model, considering only one wall in the whole distance, with 3.4 dB attenuation; the ITU-R vegetation attenuation model [ITUR00] has been used to calculate for the forest. The results are shown in Table A1.3.

Table A1.3. Ranges in considered scenarios with various assumptions.

scenario			range [m] receiver sensitivity minimum	range [m] receiver sensitivity average	range [m] receiver sensitivity maximum
transmit power	**free space**	minimum	7	35	61
		average	11	50	96
		maximum	17	79	151
	house	minimum	6	27	61
		average	9	42	81
		maximum	15	67	127
	forest	minimum	5	20	32
		average	8	28	45
		maximum	12	39	61





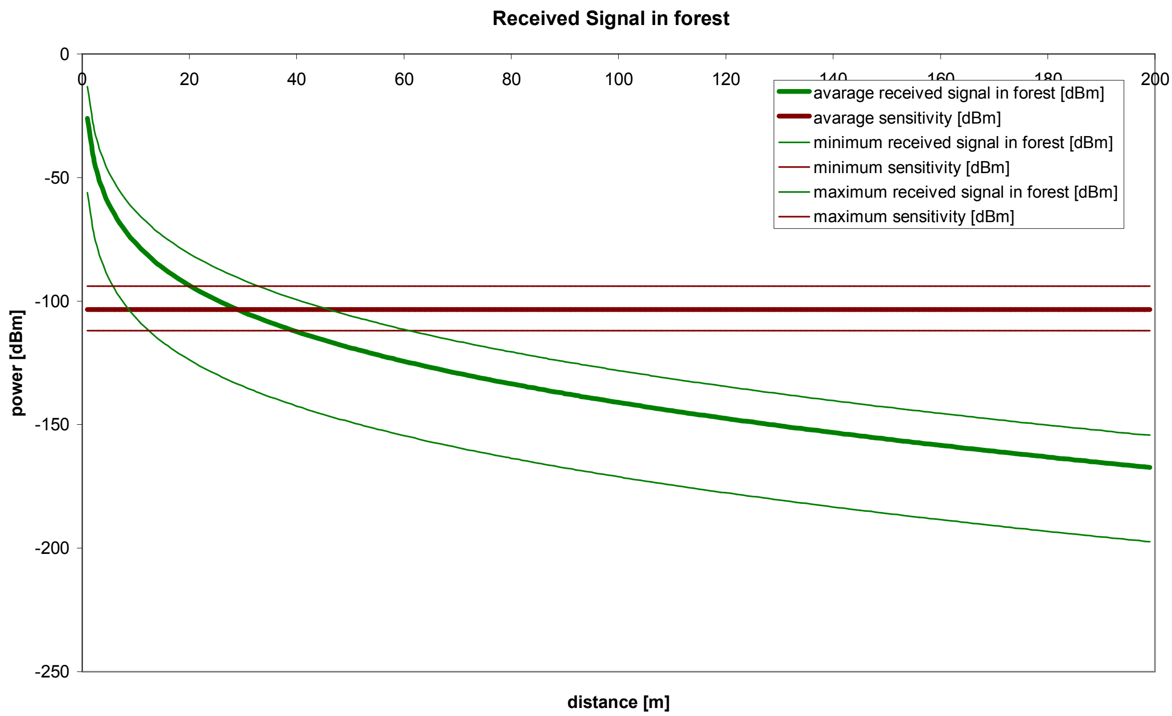


Figure A1.1. Received power and receiving sensitivity levels.

Annex B

Tree crossing length and angle calculations

This annex presents the description of the calculation of the chord length in the circle, knowing the distance of the transmitter and the circle radius.

The calculation of the chord length in the circle with a given radius and distance is based on one main assumption, which is that the distance is much larger than the radius (at least 2 times). The geometry of this calculation is presented in Figure A2.1.

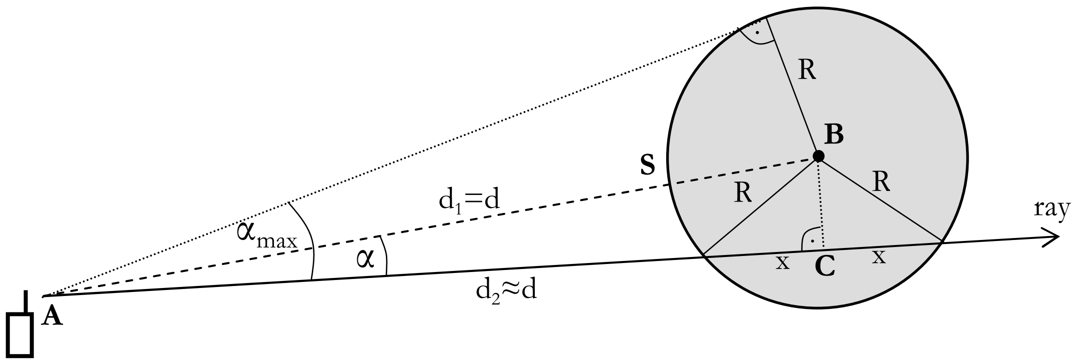


Figure A2.1. Tree chord calculation geometry.

This assumption allows treating distances d_1 and d_2 as being the same, equal to d. This approach makes the calculation easier, and does not have a significant impact on the results. The calculation of the chord, which is given by 2x, leads to the simple trigonometric formula for the ABC triangle:

$$\cos\alpha = \frac{d_{[m]} + x_{[m]}}{d_{[m]} + R_{[m]}}, \tag{B.1}$$

where:

- R – circle radius
- d – distance from point A to S.
- x – half of the chord length
- α - angle

The transformation of this relation gives:

$$2x = 2(d_{[m]} + R_{[m]})\cos\alpha - 2d_{[m]}, \tag{B.2}$$

where $2x$ is required chord length.

The same assumption allows defining the range of the angles, when the considered ray crosses the tree trunk. The angle is calculated relative to the line connecting the transmitter and trunk centre. The transformation of the following formula allows calculating the maximum angle:

$$\sin\alpha_{max} = \frac{R_{[m]}}{d_{[m]} + R_{[m]}}, \tag{B.3}$$

which gives:

$$\alpha_{max} = \arcsin\left(\frac{R_{[m]}}{d_{[m]} + R_{[m]}}\right), \tag{B.4}$$

The function of the chord length with various angles, considering distances from 1 cm, 1 m, 10 m and 50 m, are depicted in Figure A2.2.

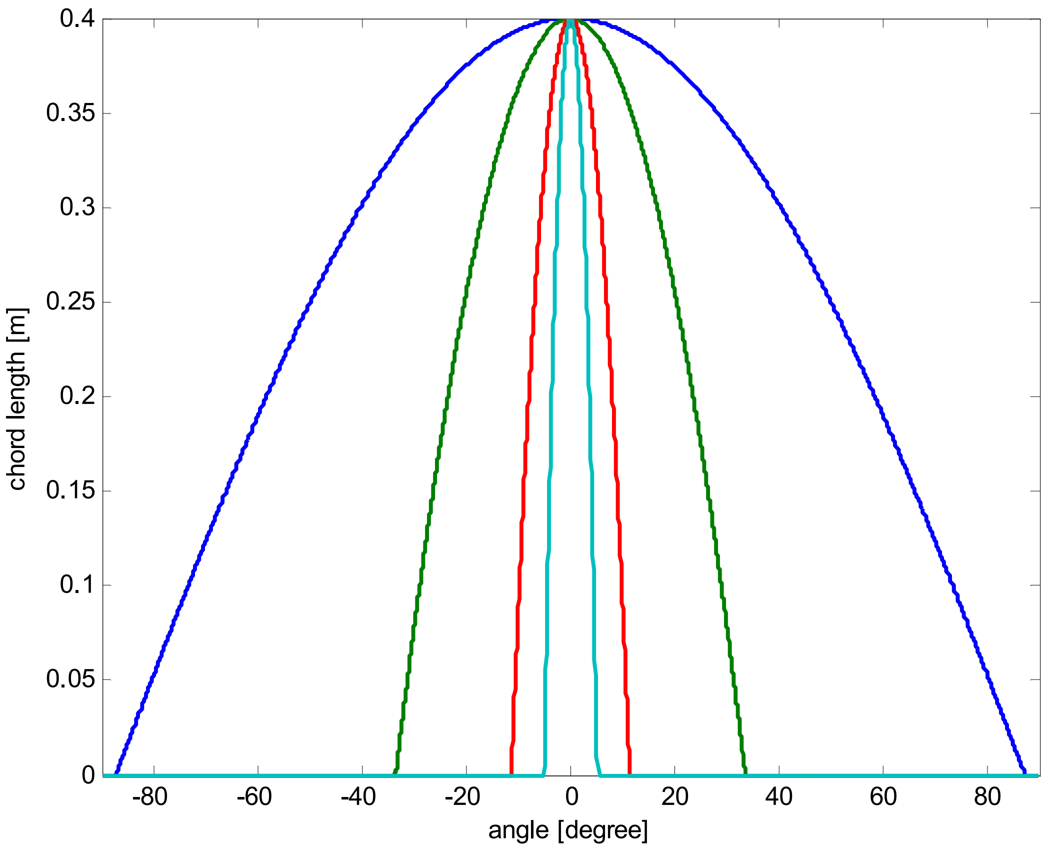


Figure A2.2. Function of chord lengths with various distances.

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