IEEE Communications Society Distinguished Lecture

October 8-10, 2007

Next Generation Wireless Broadband

Benny Bing
Georgia Institute of Technology
http://users.ece.gatech.edu/~benny
bennybing@ieee.org

Outline

Overview of Broadband Wireless Access

- Next wireless revolution, after cellphones (1990s) and Wi-Fi (2000s)
  - Vital element in enabling next-generation quadruple play (i.e., voice, video, data, and *mobility*) services
  - Mobile entertainment may be a key application for the future: success of ipod, iphone
- Viewed by many carriers and cable operators as a "disruptive" technology and rightly so
  - Broadcast nature offers ubiquity for both fixed and mobile users
  - Instant access possible since no CPE or set-top device may be required
- Unlike wired access (copper, coax, fiber), large portion of deployment costs incurred only when a customer signs up for service
  - Avoids underutilizing access infrastructure
  - Service and network operators can increase number of subscribers by exploiting areas not currently served or served by competitors
  - Ease of deployment may also lead to increased competition among multiple wireless operators - will ultimately drive costs down and benefit consumers

Overview of Broadband Wireless Access

- Many countries are poised to exploit new wireless access technologies
  - Multiple standards: Wi-Fi, Wi-Max, LTE, DVB-H
- Many municipalities now believe that water, sewage systems, roads and wireless broadband are part of a city's essential infrastructure
  - City governments in over 300 U.S. cities and over 30 countries plan to finance the deployment of Wi-Fi mesh networks
  - Overall aim is to provide ubiquitous Internet access and enhanced public services (e.g., utility, emergency response, security, education)
- What are the right wireless access technologies that maximize ROI and tackle today's ever-changing consumer demands?
  - How should these networks be designed and deployed with minimum overheads?
  - How do you provide different tiers of service cost-effectively?

IEEE 802 Standards

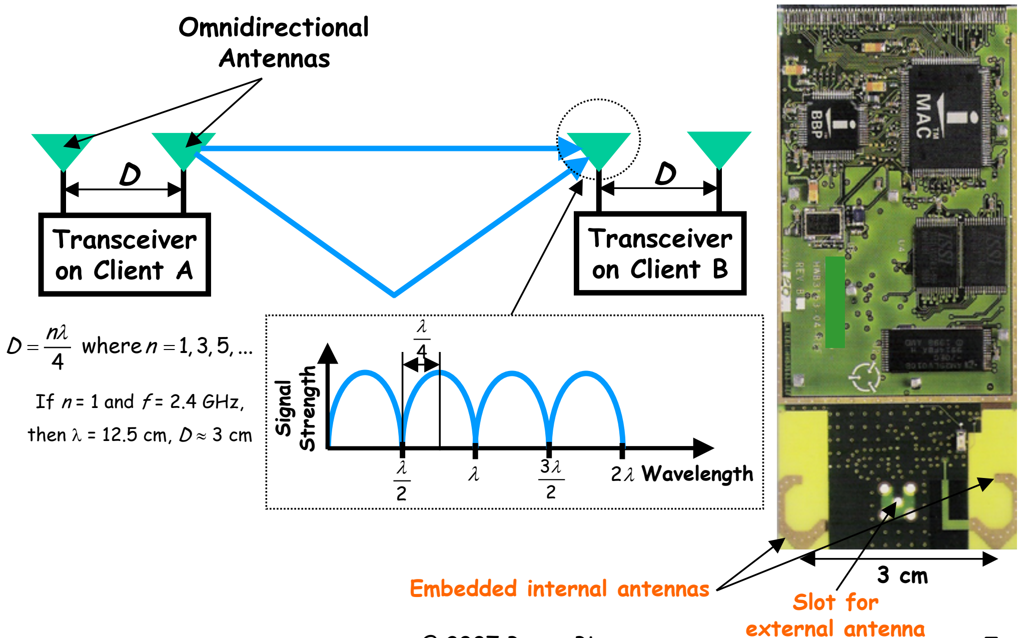
- **Increasingly dominated by wireless standards**
  - Many standards (e.g., 802.11, 802.16, 802.20, 802.22) allow broadband wireless access

Network		802.1 Overview, Architecture, Management, Internetworking						
Data Link	LLC Sublayer		802.2 Logical Link Control					
	MAC Sublayer		CSMA /CD	*Wireless Local Area Networks*	*Wireless Personal Area Networks*	*Broadband Wireless Access*	*Mobile Broadband Wireless Access*	*Wireless Regional Area Networks*
Physical			802.3	*802.11*	*802.15*	*802.16*	*802.20*	*802.22*

Wi-Fi Technologies Today

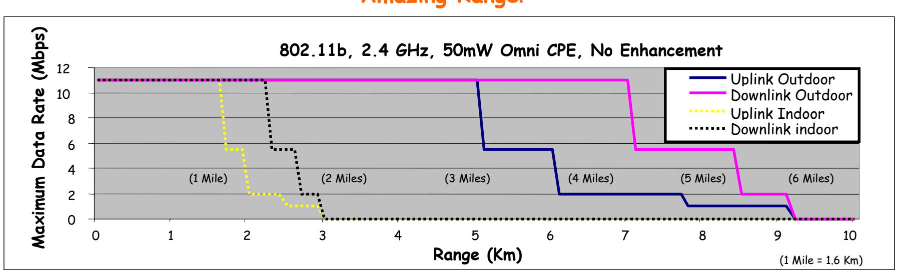
- **Diverse applications in addition to enterprise WLANs**
  - Trains, airplanes, parking/utility meters, sprinklers, RFIDs
  - Dual-mode cellular/Wi-Fi handheld smartphones
  - Nearly 200,000 Wi-Fi hotspots in 136 countries (as of Sept 2007)
- **Data rates climbed from 11 to 54 Mbit/s**
  - Data rates for current 802.11n draft topping 600 Mbit/s
  - May eventually displace wired Ethernet LANs
- **Access points, PC cards, chipsets from different vendors interoperate**
  - End-users can access different networks without switching cards or laptops
  - Wi-Fi enabled laptops can be used virtually anywhere (e.g., from office and public spaces to the home) and in different countries
  - Unified network device management for building large-scale networks, including outdoor mesh networks supporting diverse end-user devices
- **Exciting convergence of wireless communications and computing**
  - Intel embeds Wi-Fi in all microprocessor chips
  - Windows OS can search for 802.11 networks automatically
  - Silicon radio versus silicon chip

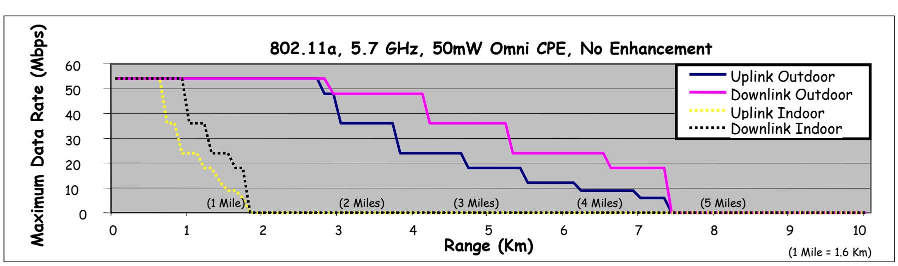
802.11 Antenna Evolution: Switched Diversity



802.11 Antenna Evolution: Phased Antenna Arrays

Amazing Range!





Based on the Vivato[TM] Wi-Fi switch (reproduced with permission from Horwitz International LLC, GA, USA)

802.11 Antenna Evolution: Multiple Input Multiple Output

- Spectrally efficient, just like OFDM
  - MIMO systems have realized impressive efficiencies in the order of 10 bits/s/Hz
  - Compare current Wi-Fi technologies (0.5 bits/s/Hz for 802.11b, 2.7 bits/s/Hz for 802.11a/g)
- Unprecedented levels of individual and aggregate capacities
  - Toshiba and Airgo (Qualcomm) chipset vendors have demonstrated that MIMO can boost current 802.11 data rates to over 100 Mbit/s
  - Netgear's 108 Mbit/s router has three MIMO antennas, offers better range, and is compatible with 802.11b/g
- Recommended for indoor environments
  - Rich multipath reflections from walls and structures (may not always be present in outdoor environments – compare 802.16 standard)

802.11n Data Rates

Modulation and Coding Schemes (MCS) for 1 and 2 spatial streams

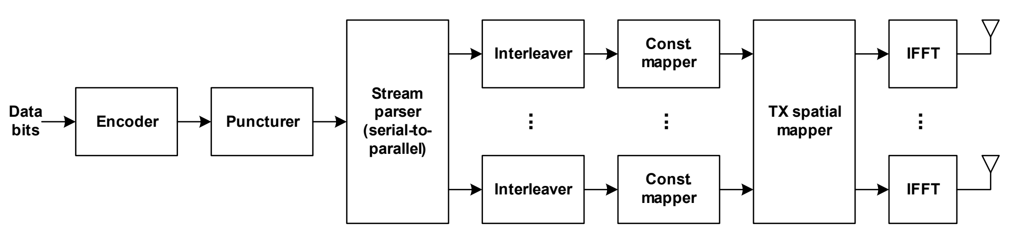
MCS	Code Rate	Modulation	Number of Spatial Streams	Data Rate in 20 MHz, 800 ns GI	Data Rate in 20 MHz, 400 ns GI	Data Rate in 40 MHz, 800 ns GI	Data Rate in 40 MHz, 400 ns GI
0	1/2	BPSK	1	6.5	7.2	13.5	15
1	1/2	QPSK	1	13	14.4	27	30
2	3/4	QPSK	1	19.5	21.7	40.5	45
3	1/2	16-QAM	1	26	28.9	54	60
4	3/4	16-QAM	1	39	43.3	81	90
5	2/3	64-QAM	1	52	57.8	108	120
6	3/4	64-QAM	1	58.5	65	121.5	135
7	5/6	64-QAM	1	65	72.2	135	150
8	1/2	BPSK	2	13	14.4	27	30
9	1/2	QPSK	2	26	28.9	54	60
10	3/4	QPSK	2	39	43.3	81	90
11	1/2	16-QAM	2	52	57.8	108	120
12	3/4	16-QAM	2	78	86.7	162	180
13	2/3	64-QAM	2	104	115.6	216	240
14	3/4	64-QAM	2	117	130	243	270
15	5/6	64-QAM	2	130	144.4	270	300 → 7.5 bit/s/Hz

802.11n Data Rates

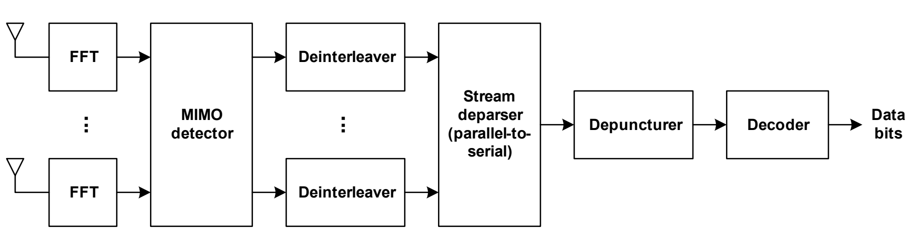
Optional MCS for 3 and 4 spatial streams

MCS	Code Rate	Modulation	Number of Spatial Streams	Data Rate in 20 MHz, 800 ns GI	Data Rate in 20 MHz, 400 ns GI	Data Rate in 40 MHz, 800 ns GI	Data Rate in 40 MHz, 400 ns GI
16	1/2	BPSK	3	19.5	21.7	40.5	45
17	1/2	QPSK	3	39	43.3	81	90
18	3/4	QPSK	3	58.5	65	121.5	135
19	1/2	16-QAM	3	78	86.7	162	180
20	3/4	16-QAM	3	117	130	243	270
21	2/3	64-QAM	3	156	173.3	324	360
22	3/4	64-QAM	3	175.5	195	364.5	405
23	5/6	64-QAM	3	195	216.7	405	450
24	1/2	BPSK	4	26	28.9	54	60
25	1/2	QPSK	4	52	57.8	108	120
26	3/4	QPSK	4	78	86.7	162	180
27	1/2	16-QAM	4	104	115.6	216	240
28	3/4	16-QAM	4	156	173.3	324	360
29	2/3	64-QAM	4	208	231.1	432	480
30	3/4	64-QAM	4	234	260	486	540
31	5/6	64-QAM	4	260	288.9	540	600 → 15 bit/s/Hz

802.11n Transmitter and Receiver



a) Transmitter



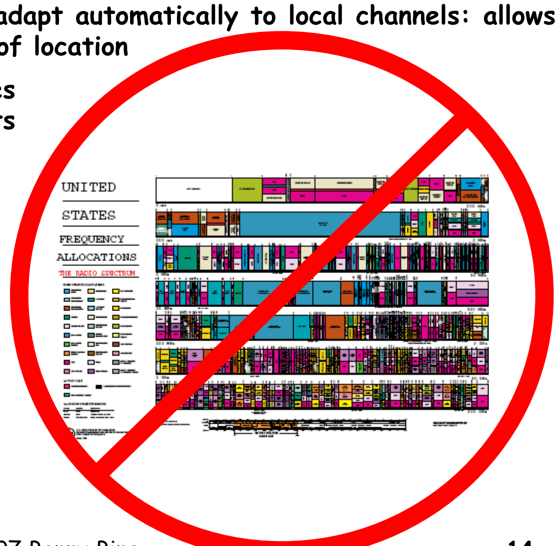
b) Receiver

A Little History of Multiple Antenna Systems

- Antenna diversity can traditionally be achieved by coding in time-frequency domain
  - Diversity can be increased further in space domain
  - Add spatially separated antennas at receiver and transmitter
- Multiple-antenna receive diversity
  - Employ signal combining techniques at access point to improve performance on uplink (i.e., transmission from wireless client to access point)
  - No additional transmit power from wireless client is required
  - Difficult to implement receive diversity on downlink (i.e., transmission from access point to wireless client)
  - Size and battery power limitations of client device
- Recent research focused on transmit diversity
  - Multiple antennas at access point transmit simultaneous data streams on downlink to client device
  - May need feedback channel for channel estimation by transmitting antennas

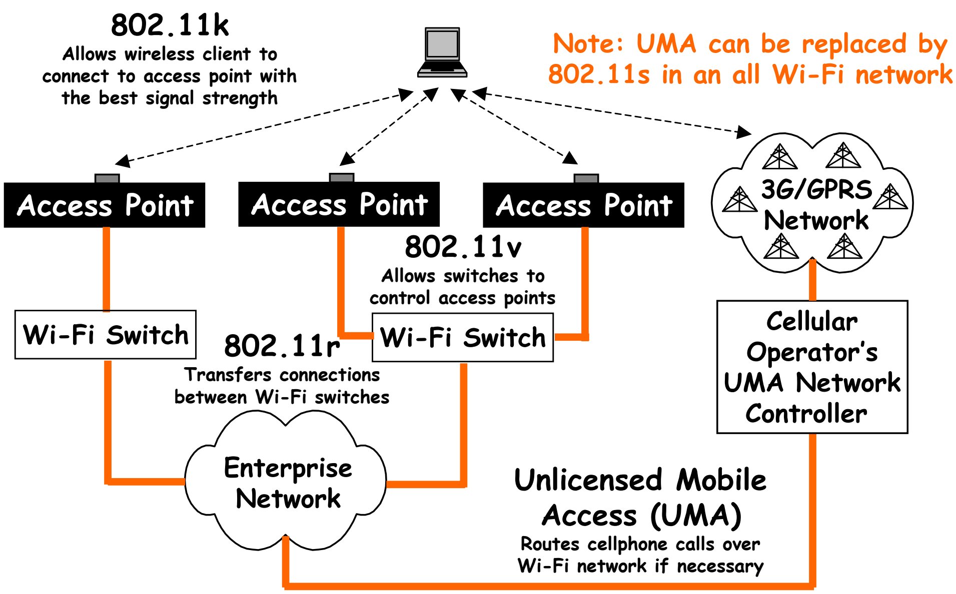
802.11k

- Exploits increasing deregulation of radio spectrum
  - Can potentially lead to unlimited wireless bandwidth: spectrum can be used and reused more efficiently and co-operatively by cognitive (smart) 802.11 devices
  - Current 802.11 client devices can adapt automatically to local channels: allows international operation, regardless of location
- In Sept 2005, Cisco Systems receives first FCC certification for its 802.11a SDR devices
- Spectrum management critical
  - Device must learn when to operate and when to interrupt service
  - Interference, retransmission must be controlled
  - 802.11's CSMA/CA (DCF) MAC provides etiquette and dynamic bandwidth acquisition
  - Difficult with centralized MAC scheduling



802.11 Roaming

- Various levels of granularity depending on span of roaming area



802.11p

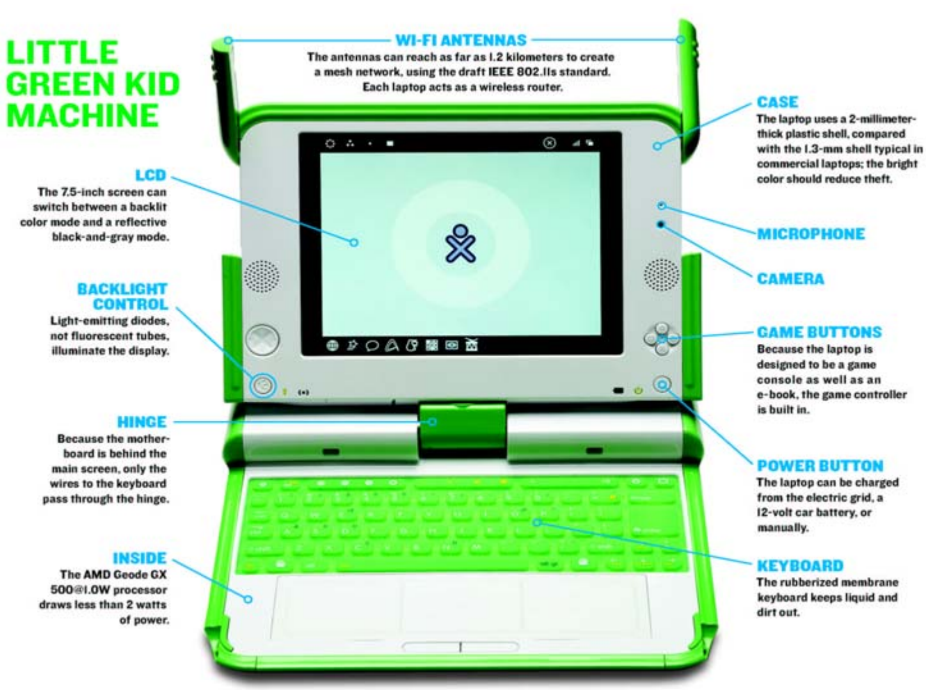
- 802.11 access in vehicular environments
  - Devices operate in 5 GHz Dedicated Short-Range Communications (DSRC) band for Intelligent Transportation Systems (ITS)
  - Provides wireless communications over line-of-sight distances (< 1000 m) between vehicles and vehicles on roadsides
  - Units with wireless interfaces can reside on high-speed vehicles (on-board units) or on roadsides (e.g., streetlamps)
  - Supports existing 802.11 and new applications e.g., road safety and emergency services
  - Reliability and low latencies critical, current 802.11 association process may exceed 100 milliseconds
  - To provide priority to public safety communications, uses different medium access strategy than standard 802.11
  - MAC/PHY enhancements considered, including smaller channel size of 10 MHz

Speed	Packet Error Rate (PER)
140 km/h	< 10% (1000-byte payload)
200 km/h	< 10% (64-byte payload)
283 km/h	< 10% (64-byte payload)

Higher speeds, shorter packets preferred

802.11s

- First draft issued on March 2006
  - Adopted new path selection protocol called Hybrid Wireless Mesh
  - Allows vendors to use interoperable *and* proprietary path selection protocols
  - Use existing 802.11 addressing format to define a multihop network with autoconfiguration capabilities
- New end-to-end multihop security mechanisms
  - 802.11i provides only single-hop link security
  - Mesh nodes need mutual authentication among themselves to create secure associations
  - Each node will act as a supplicant and authenticator for adjacent nodes
  - Distributed and centralized 802.1x authentication schemes supported
  - Reauthentication to occur rapidly for roaming nodes to preserve session
- Congestion control for nodes operating on the same channel
  - 802.11e extensions are considered to support hop-by-hop congestion control
  - Rate control is another solution
- Other capabilities
  - Topology discovery, path selection and forwarding, channel allocation, traffic and network management

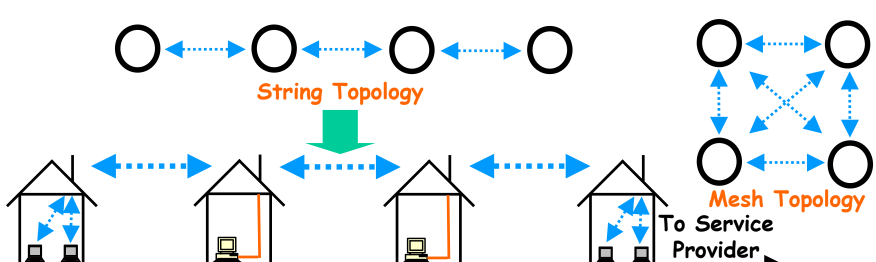


Wi-Fi Mesh Networks

- Will transform both enterprise and public networks
  - –Same MAC and PHY layers can be used throughput span of the network
  - –May see the distinction between WANs and LANs blurring for the first time in the history of computer networking
- Many cities building citywide Wi-Fi networks
  - –Networks deliver broadband services to both residents and businesses
  - –Average cost per node is currently $2,000, likely to drop even further
  - –Zero cost for CPE as many client devices now come with embedded Wi-Fi chipsets (note: an access technology may not be viable if CPE cost is > $250)
  - –Municipals provide right of way, makes it even cheaper to deploy metro Wi-Fi
  - –Likely to target dial-up users in initial market, makes it easy for them to upgrade to broadband with little or no increase in subscription cost
  - –More importantly, can also save substantial operational costs for municipals (note: cable/DSL operators normally not keen to share network)
  - –Cheap phone calls using voice over IP may become a key application, benefiting residents, businesses, tourists, and government agencies
  - –Success depends largely on strength of private-public partnership

Wi-Fi Mesh Networks

- Can be considered a concatenation of multiple hotspots
  - –Forms wireless backbone network which ultimately connects service provider
- Fixed wireless access point typically mounted on rooftop of homeowner or on streetlights or telephone poles
  - –Creates small wireless coverage area called "hop", each hop can serve a number of mobile wireless clients or wired clients within a home network
  - –Acts much like a router, automatically discovering neighboring access points and relaying packets across several hops in wireless backbone
  - –Topologies can range from string (generates least interference) to fully-connected mesh (costly to deploy but most reliable)



Wi-Fi Mesh Networks

In-built reliability and redundancy obvious from topology

Wi-Fi Mesh Networks

- Not completely ad-hoc
  - Some access points to act as gateways to service provider (e.g., Internet)
- Routing can be done by both clients and access points
  - MeshNetworks (acquired by Motorola) products have this capability, guarantees less than 5 ms delay per hop
  - Tropos, Strix focus on meshes of access points only but allow regular 802.11 client access
  - Strix and Firetide systems were originally designed for indoor networks (see also BelAir, Packethop, Cheetah)
  - Meshdynamics meshed Wi-Fi equipment are designed for military applications

Vendor	Product	Radios per Router	Radios for Client Access	Radios for Backbone (Backhaul)	Ethernet Ports
BelAir	BelAir 200	1, 2 or 4	One 802.11b/g	Up to 3 proprietary 5 GHz	8
Cisco	Aironet 1500	2	One 802.11b/g	One 802.11a	0
Firetide	HotPort 3203	1	One 802.11a/b/g	Same radio as client	2
Nortel	AP 7220	2	One 802.11b	One 802.11a	1
Strix	OWS 3600	2 to 6	Up to three 802.11b/g	Up to three 802.11a	1
Tropos	5210 Mesh	1	One 802.11b/g	Same radio as client	1

Wi-Fi Mesh Networks

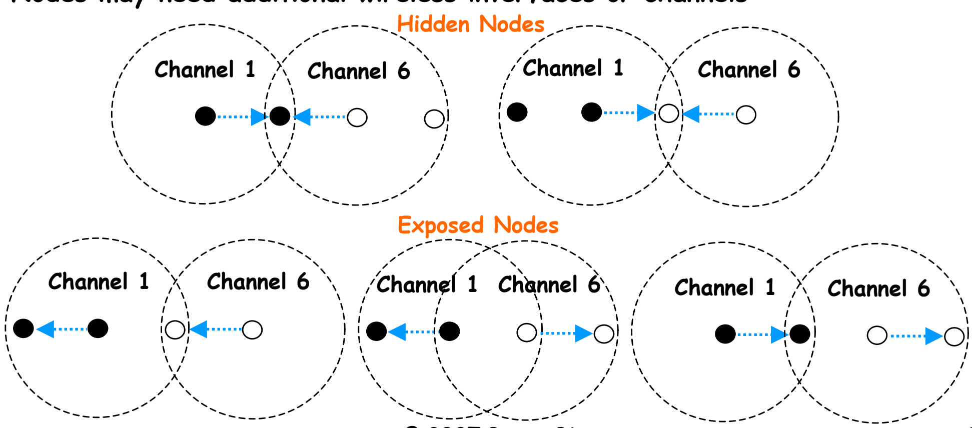
- Wireless routing among static access points more efficient and stable than routing among client devices
  - –Mobile client devices are battery-powered, need to operate in low-power sleep modes, dynamic connections between hops due to movement of individual clients
  - –Fixed access points create network structure, relatively stable network topology, optimized radio coverage areas
- Can employ less complex but more efficient packet routing protocol
  - –May not use routing tables or rely only hop-count to select transmission path
  - –Packet error rates, signal attenuation, number of active users per hop, and other network conditions are factors affecting choice of current best path
- Open source multihop wireless projects
  - –MIT Roofnet (http://www.pdos.lcs.mit.edu/roofnet)
  - –Champaign-Urbana Community Wireless Network (http://www.cuwireless.net)
  - –Mesh Networking Resource Toolkit (http://research.microsoft.com/netres/kit)

Advantages of Wi-Fi Mesh Networks

- Convenient network access
  - –Connection from virtually any open space e.g., swimming pool, backyard, etc
  - –No CPE required, reduces dependence on home gateways
- Multiple connected paths
  - –Improve network reliability (compare the Internet)
  - –Allow efficient traffic distribution (e.g., peer to peer traffic)
  - –Prevent traffic bottlenecks, avoid local interference, large-scale DoS attacks
  - –Can provide good QoS, even when operating on unlicensed bands
- Easy and convenient manual maintenance
  - –Network is located away from residential premise
- Large-scale indoor or outdoor wireless networks can be created easily
  - –Due to shorter hops, Fresnel zone impact negligible: low-lying outdoor areas do not pose problems
- Scalable network deployment
  - –Can start with minimum number of nodes (compare cellular or Wi-Max base station deployment: need to justify deployment cost for each base station)
  - –As users and traffic increase, more nodes can be installed

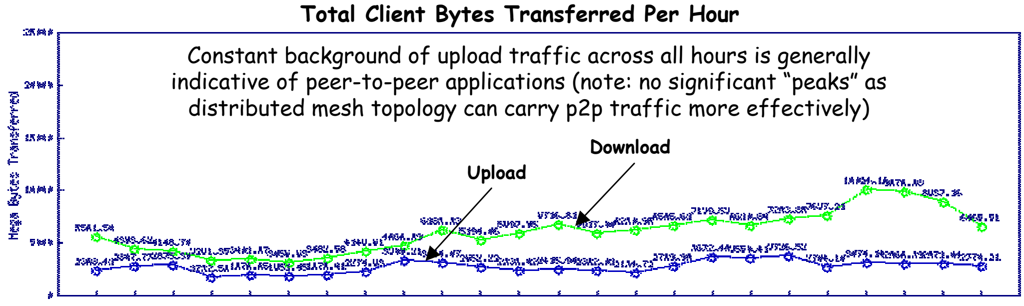
Concurrent Transmissions in Wi-Fi Mesh Networks

- Maintaining traffic streams across all hops results in maximum spatial and spectral reuse
  - Synchronous transmission and co-ordination leads to more deterministic throughput, latency, and jitter performance, requires common timing source (e.g., GPS) and possibly multiple directional antennas at each node
- Need to eliminate hidden and exposed node problems
  - Nodes may need additional wireless interfaces or channels

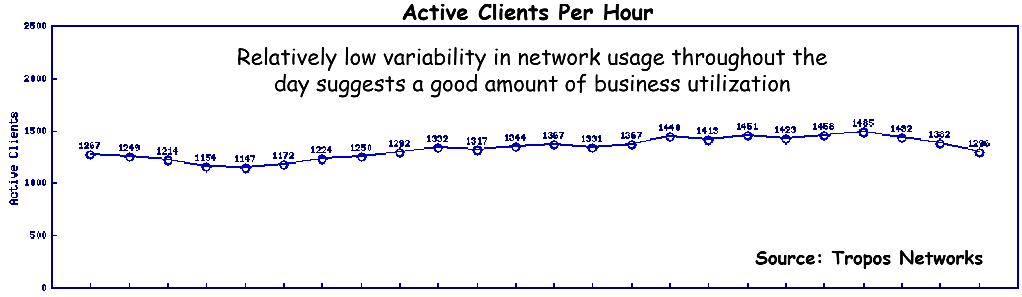


Wi-Fi Mesh Hourly Usage Pattern (For-Fee Network)

Total Client Bytes Transferred Per Hour

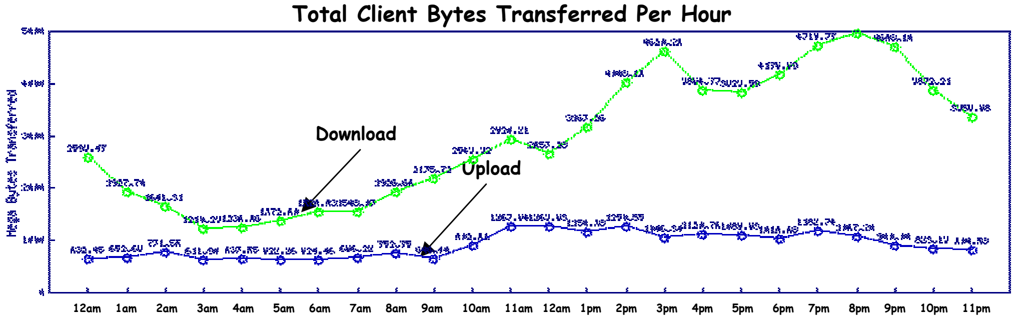


Active Clients Per Hour

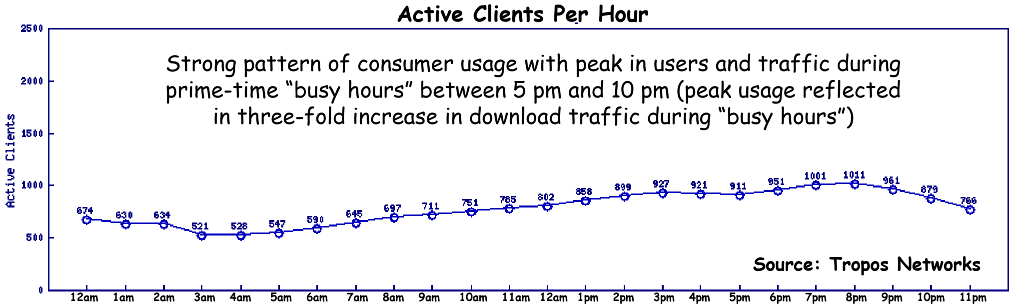


Wi-Fi Mesh Hourly Usage Pattern (Free Network)

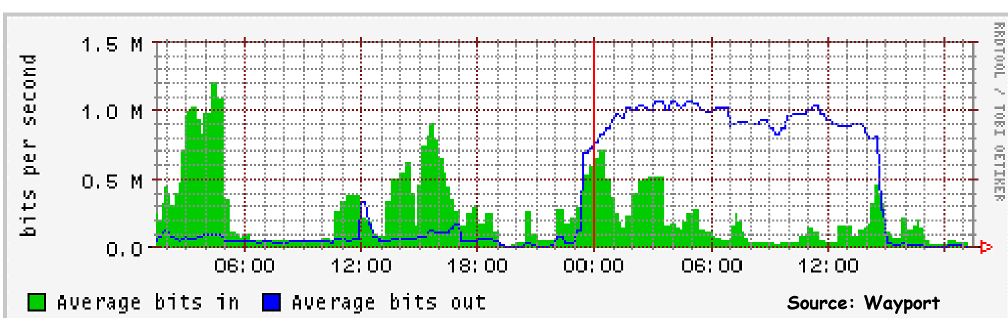
Total Client Bytes Transferred Per Hour



Active Clients Per Hour



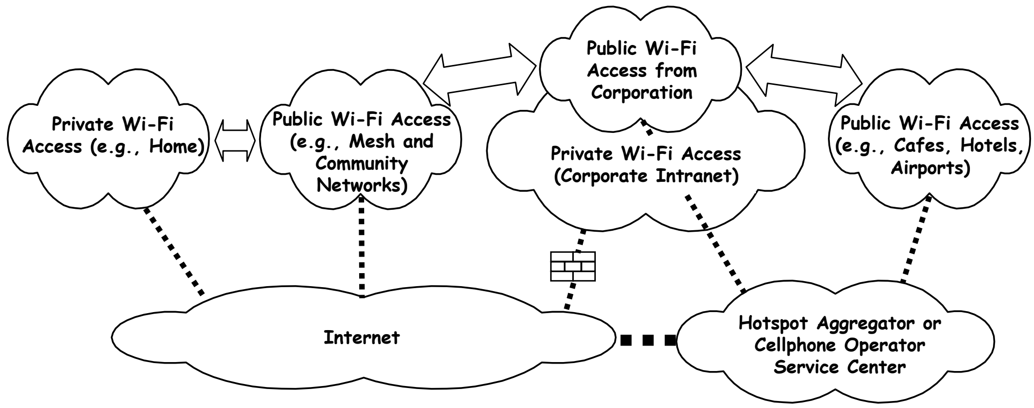
Wi-Fi Hotspot Hourly Usage Pattern



Bandwidth use at a hotel where a BitTorrent session started around 0:00, rapidly transferring files upstream (consuming over 1 Mbps), session ended about 12 hours later

Note: Unlike Wi-Fi Mesh, lower bandwidth usage from 5 pm to 10 pm

Ubiquitous Wi-Fi Access



IEEE 802.16

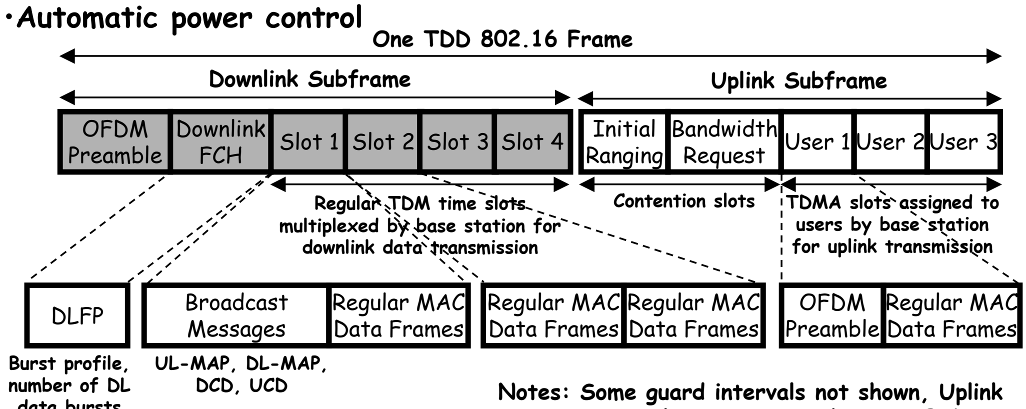
- Working Group started in August 1998
  - Specifies wireless metropolitan area network air interface for fixed, portable, mobile broadband wireless access (http://WirelessMAN.org)
  - Unlike Wi-Fi, allows two-way simultaneous (full-duplex) communication
  - Data rates can be lowered if longer operating range is desired
  - Essentially a cellular standard

Summary of IEEE 802.16 Standards

	802.16 (Oct 2001)	802.16a (Jan 2003)	802.16d (Jul 2004)	802.16e (Oct 2005)
Description	Based on LMDS	Based on MMDS and HiperMAN	Uplink enhancement to 802.16a	Adds handoff, power save to 802.16d
Frequency	10-66 GHz	2-11 GHz	2-11 GHz	2-6 GHz
Propagation Conditions	Line of Sight (LOS) Urban Settings, More Obstacles	Non-LOS Rural Areas, Big Cell Coverage	Non-LOS (<110μs delay spread)	Non-LOS
Bit Rate	32-134 Mbit/s at 28 MHz channelization	Up to 75 Mbit/s at 20 MHz channelization	Up to 75 Mbit/s at 20 MHz channelization	Variable 15 Mbit/s at 5 MHz channelization
Channel Bandwidth	20, 25 MHz (U.S) 28 MHz (Europe)	Scalable multiples of 1.25, 1.5, 1.75 MHz, up to 20 MHz	Scalable multiples of 1.25, 1.5, 1.75 MHz, up to 20 MHz	Similar to 802.16d but with subchannelization
Modulation	Single carrier, BPSK, QPSK, 16QAM, 64QAM	256-OFDM, BPSK, QPSK, 16QAM, 64QAM	256-OFDM, 2048-OFDMA, BPSK, QPSK, 16QAM, 64QAM	256-OFDM, scalable 128/512/1024/2048-OFDMA
MAC Protocol	TDMA	TDMA	TDMA using 256-OFDM, inherent in 2048-OFDMA	Same as 802.16d
Mobility	Fixed	Fixed	Fixed and Nomadic	Fixed and Mobile
Network Topology	Point to Point and Point to Multipoint	Point to Point and Point to Multipoint	Point to Point, Point to Multipoint, Mesh	Point to Point, Point to Multipoint, Mesh
Typical Cell Radius	1 - 3 miles (2 - 5 km)	3 - 30 miles (5 - 50 km)	3 - 30 miles (5 - 50 km)	1 - 3 miles (2 - 5 km)

IEEE 802.16-2004 MAC Frame Format

- All services are connection-oriented
  - Even connectionless services are mapped to a connection
- Automatic retransmission request
- Automatic power control



Notes: Some guard intervals not shown, Uplink contention slots transmitted using QPSK

FCH: Frame Control Header

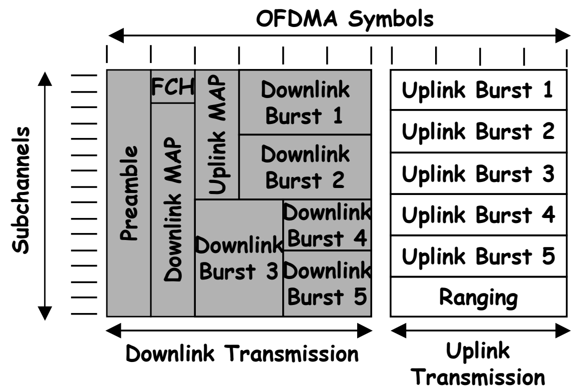
MAP: Bandwidth Allocation Messages

DCD: Downlink Channel Descriptor

UCD: Uplink Channel Descriptor

IEEE 802.16-2005 MAC Frame Format

- Scalable bandwidth allocation
  - Greater flexibility and granularity: duration and bandwidth of up and down link data bursts can be varied via subchannelization



Note: Downlink data is transmitted first

Orthogonal Frequency Division Multiple Access (OFDMA)

- Main feature of mobile IEEE 802.16e standard
  - Simplifies MAC operation on uplink, facilitates high-speed mobility
  - Can assign different subsets of subcarriers to different users (as opposed to all subcarriers to same user, as employed by 802.11a/g)
  - Allows smaller transmit power from end-user device
  - Allows more transmit power per OFDM subcarrier, improving uplink link budget
  - Lower training overhead
  - Subcarrier allocation can be dynamic (i.e., can vary in each burst)
  - Can potentially allow a frequency reuse of 1 (i.e., all wireless coverage areas or cells employ same frequency channel but different subchannels, much like CDMA networks employing same frequency channel but different PN codes)
- Less helpful on the downlink
  - Transmit power per subcarrier from base station remains the same
  - Can prioritize near and far users (can reduce interference by transmitting less power to closer users)
- Time and frequency alignment crucial
  - Need to maintain orthogonality of signals between signals from different users

Potential of IEEE 802.16

- Key application likely to be fixed wireless access
  - Initial deployments to focus on fixed wireless connections between enterprise buildings and backhaul operations
  - Also useful in places where there is no infrastructure (in order not to compete with DSL and cable), popular in developing countries such as India
  - Some proprietary fixed wireless access products have enjoyed some measure of commercial success e.g., Motorola's Canopy™
- Uncertainty over viability of 802.16 for residential access
  - Strong emergence of outdoor municipal 802.11 mesh networks has clouded choices for wireless residential access
- Business model for 802.16e still unclear
  - Likely to compete more directly with 3G cellular than Wi-Fi
  - Cellular has strong existing subscriber base and incremental network evolution (e.g., 2G, 2.5G, 3G) that facilitates subscriber upgrades
  - Wi-Max needs new infrastructure and new customers
- In the U.S., Sprint Nextel holds most of the licensed spectrum
  - Owns 2.5 GHz spectrum in markets covering 85% of U.S. population
  - Sprint, Comcast, Cox, Time Warner team up to offer Wi-Max services

IEEE 802.22

- FCC's landmark Notice of Proposed Rule Making issued in May 2004
  - Plans to open up a significant portion of TV spectrum for unlicensed use by secondary (cognitive) devices
  - Motivated by transition from analog to digital TV
  - See http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-113A1.pdf
  - FCC recognizes great deal of TV white space spectrum can be exploited by unlicensed devices
- Proposed rule making led to formation of IEEE 802.22 working group
  - Latest IEEE 802 working group formed in October 2004, focuses on Wireless Regional Area Networks (WRANs)
  - To develop a cognitive radio-based air interface for use by low-power license-exempt devices to share spectrum in UHF TV bands
  - Maximum output power for fixed devices: 1 W, for portable devices: 100 mW
  - Working group expects to complete a specification for balloting in 2008
  - Unofficially known as Wi-Fi TV

IEEE 802.22

- Many favorable propagation characteristics inherent in UHF channels
  - –Prime RF channels were reserved for first broadband wireless application: TV broadcasting
  - –Impairments due to environmental factors (e.g., rain, snow) less significant
  - –Deeper wall penetration in buildings and houses than microwave frequencies used by other wireless access technologies
  - –Lower signal attenuation results in wider coverage (*omnidirectional* coverage of at least 25 miles from a well-sited base station, 33 km typical range, 100 km max. range)
  - –Trial broadband network in Washington D.C. at 700 MHz covers entire metro area with 10 sites, compared to 400 sites for 4.9 GHz
  - –Can support high-bandwidth and high-speed mobility: "HDTV Mobile Reception in Automobiles", *Proceedings of IEEE*, Jan 2006
  - –NASA's new onboard Electra UHF relay transceiver provides faster data rates required for all future orbiters, landers, and rovers

3G/4G Cellular and LTE

- Likely to appeal to traveling professionals
  - –Pre-4G technologies like HSDPA can provide smoother video telephony and download of large multimedia files from virtually anywhere, even on the road
- 3GPP's Long Term Evolution (LTE) provides upgrade path for 3G
  - –Enhances and optimizes the Universal Terrestrial Radio Access (UTRA) architecture
  - –Targets peak downlink rate of 100 Mbit/s and uplink rate of 50 Mbit/s using 20 MHz bandwidth

Data Rates of Evolving CDMA Cellular Standards

Year	1998	2000	2002	2002	2004	2005
Standard	cdmaOne	PacketOne	CDMA2000 1x	WCDMA*	1xEVDO**	HSDPA***
Max. Data Rate	14.4 Kbit/s	64 Kbit/s	384 Kbit/s	2 Mbit/s	2.4 Mbit/s	14.4 Mbit/s
Typical Data Rate	9.6 Kbit/s	32 Kbit/s	144 Kbit/s	384 Kbit/s	600 Kbit/s	2 Mbit/s

* In Europe, also known as UMTS   ** 1.25 MHz bandwidth   *** High-Speed Downlink Packet Access

Mobile TV and Digital Video Broadcast (DVB)

- **Bring entertainment away from the home**
  - U.S. was home to 40 million multimedia cellphones in September 2005, up from 20 million in January 2005
  - TV phone sales revenue to soar from $5 billion in 2006 to more than $30 billion by 2010
  - According to IDC, by 2009, more than 30 million wireless subscribers will be watching commercial TV and video on a handheld device
  - Strategic Alliance estimates that more than 25% of the 179 million digital devices sold in 2010 will be cellphones
- **Mobile TV not a substitute for traditional television**
  - Most obvious difference is in usage patterns and length of viewing sessions
  - Audio quality and synchronization with video are particularly important
  - Helps viewers follow the plot in situations when image quality is degraded
- **Network deployment based on overlay solutions**
  - 700 MHz solutions are popular
- **Sling Media a popular application**

DVB: Advanced Television Systems Committee (ATSC)

- **Broadcast both standard and high-definition TV channels**
  - 4 HD and 20 SD channels available for free viewing in Atlanta!
  - No CPE

Hauppauge WinTV

Digital Video Broadcast-Handheld (DVB-H)

- **Mobile TV and IP datacast standard (http://www.dvb-h-online.org)**
  - Adopted by European Telecommunications Standards Institute (ETSI) in Nov 2004 for broadcasting TV transmissions to handsets
  - Has ability to receive up to 15 Mbit/s in an 8 MHz channel in 700 MHz band
  - Can be tailored to work with 5 MHz bandwidth in L-band (1670 - 1675 MHz)
  - Employs coded OFDM and OFDMA
  - Transforms digital TV into IP packets which are transmitted in short 100 ms time slots
  - Allows receiver to power off in inactive periods, results in significant reduction of battery power consumption

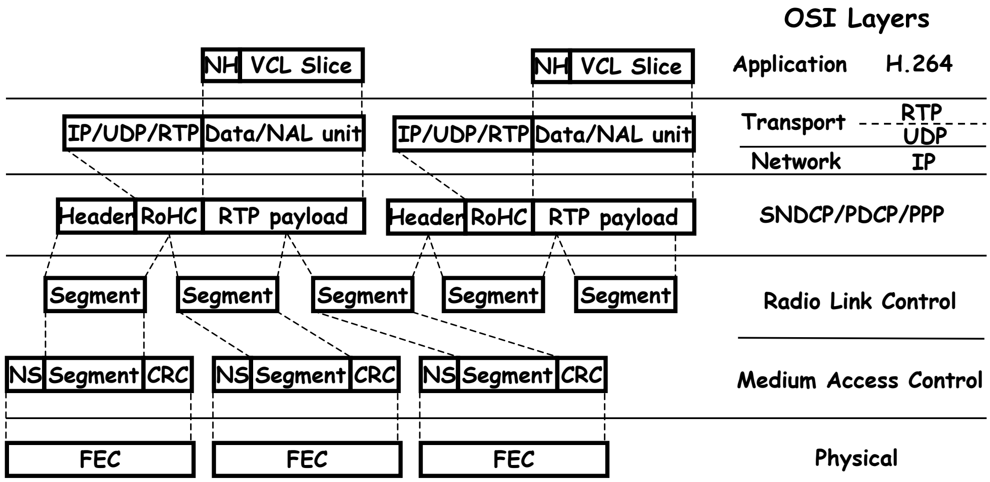
MediaFLO Media Distribution System

- **Utilizes 700 MHz spectrum for which Qualcomm holds U.S. licenses with a nationwide footprint**
  - Qualcomm and its subsidiary MediaFLO are working together with Verizon Wireless to bring its customers real-time mobile video over the MediaFLO multicasting network in the U.S.
  - Qualcomm and Verizon Wireless expect to launch mobile TV services over the MediaFLO network in approximately half of the markets already covered by Verizon Wireless' CDMA2000 1xEV-DO-based network

Wireless Video

- Video encoder generates data units containing compressed video stream, possibly stored in an encoder buffer before transmission
  - Wireless medium might delay, lose or corrupt individual data units
  - May have significant impact on perceived video quality due to spatio-temporal error propagation
  - H.263, MPEG-4 Visual Simple Profile currently popular in handheld products
- H.264/AVC video codec will become important in near future
  - Recommended codec for all 3GPP video services
  - Improves compression efficiency over prior standards (>2 over MPEG-2)
  - Addresses needs of different applications
  - Provides bit rate adaptivity
  - Comprises 2 layers: video coding layer (VCL), network abstraction layer (NAL)
    - VCL functions: motion compensation, transform coding of coefficients, entropy coding
    - NAL is an interface between codec and transport network

Wireless Video Packetization in 3GPP Framework



FEC : Forward Error Correction
NH: Network Abstraction Layer (NAL) header
PDCP: Packet Data Convergence Protocol
PPP: Point to Point Protocol

RoHC: Robust header compression
SNDCP: Sub Network Dependent Convergence Protocol
VCL: Video Coding Layer

Note: RLC similar to Wi-Max

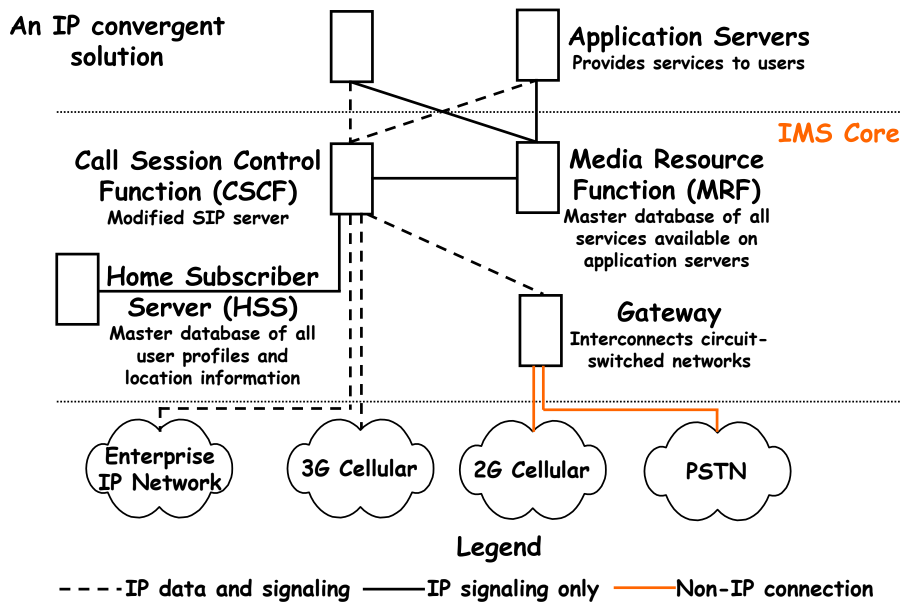
Error Robustness in Wireless H.264 Transmission

- Most codecs apply error resilience features at the expense of compression efficiency
  - Shannon's separation principle: Combine compression efficiency with link layer features that completely avoid losses such that compression and transport can be completely separated
- H.264/AVC provides various levels of defense against errors
  - Loss correction below codec layer that minimizes losses in wireless channel without sacrificing video bit rate using
    - application layer FEC
    - selective application layer retransmission
    - low bit rate feedback channel for loss control/management messages e.g., real-time TCP (RTCP)
  - Error detection: If errors are unavoidable, detect and localize erroneous data
  - Loss prioritization methods: If losses are unavoidable, then minimize loss rates for important data (e.g., control)
  - Error resilience tools based on slice structure, data partitioning (i.e., compressed data units of different importance), flexible macroblock ordering

Converged Broadband Networks

- High performance access networks promise enabling of new services
  - Services include IP-TV, video-on-demand, Web-based multimedia conferencing
  - Bandwidth pipes can be dynamically provisioned and released based on users' initiated demands
- Next generation access networks will offer telecommunications, broadcasting, Internet access from a variety of devices
  - Broad areas of convergence will take place
    - Convergence of wired and wireless networks
    - Convergence of heterogeneous wireless networks
    - Convergence of telecommunications and broadcasting (e.g., mobile TV, TiVo lets subscribers record or schedule TV shows via Verizon cellphones)
- For efficient service provisioning, well-designed network operations and management functions with traffic engineering are crucial
  - Key challenges include end-to-end QoS-guarantees, seamless connectivity, and effective policy management

IMS Architecture



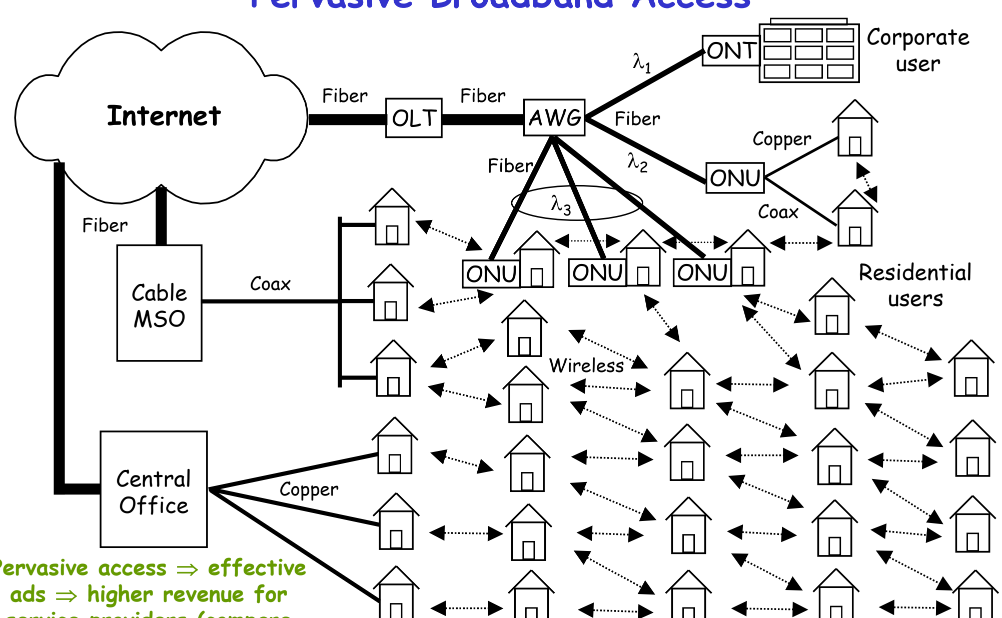
Summary for Broadband Wireless

- **Multihop "mesh" networks are growing**
  - Removes bottleneck, latency, single point of failure in many access networks
- **Wi-Fi will continue to pervade outdoor access networks**
  - Evidenced by cellular/Wi-Fi integration, increasing number of hotspots
  - Many municipals chose Wi-Fi over other wireless access options
- **Traffic management crucial in supporting emerging applications**
  - Interesting interplay of network layer and application layer services
  - VoIP, IP TV, p2p voice, p2p video streaming
- **Choice of frequency band critical for wireless broadband**
  - Determines coverage area, data rate, ability to communicate in-building *and* outdoors, which determines need for CPE
  - M Law: network value increases to square of number of things connected to it
- **Efficient spectrum utilization**
  - Multiple antenna/multichannel operation, interference avoidance methods, spectrum sensing algorithms, co-operative diversity
- **Cognitive radio a key technology enabler for future wireless broadband**
  - Enhances spectrum management, capacity, interoperability of wireless systems
  - Unlicensed band device can achieve performance close to licensed band device

Final Analysis for Broadband Access

- Wireless most pervasive
  - Over 50% of backbone Internet traffic now start and end with wireless
- Powerline is pervasive but not as pervasive as wireless
  - Network outlet and CPE still required
  - Can support nomadic operations but not seamless mobility
- Fiber access driven by HDTV and DVR
  - Note that cable and satellite operators are already offering such services
  - Need to compete with "VoD" suppliers such as NetFlix ($4.99/month with free shipping)
  - Wire medium still difficult to deploy: there are seldom two cable or two DSL operators competing in the same residential neighborhood

Pervasive Broadband Access



Pervasive access ⇒ effective ads ⇒ higher revenue for service providers (compare free broadcast TV, ads the main source of revenue)