Broadband Wireless Access – The Next Wireless Revolution

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Outline of Talk

- Provide a comparative assessment of the key standards and technologies underpinning promising broadband wireless access solutions
- Standards
  - Long-range/multihop 802.11 (Wi-Fi)
  - 802.16 (Wi-Max)
  - Wireless DOCSIS
  - 3G/4G
  - 802.20 (mobile broadband)
  - 802.21 (media independent handoff and interoperability)
  - 802.22 (wireless regional area networks)
- Technologies
  - Licensed and unlicensed spectrum consideration
  - Reliable physical layer transmission using multiple antennas
  - Multichannel medium access protocols with QoS provisioning
  - Network topologies: point-to-point, point-to-multipoint, multihop (mesh)
  - Wireless multimedia services: wireless IP-TV, wireless VoIP
  - Cognitive radio technologies
  - Advanced wireless security
  - Wireless/wireline integration

IEEE 802 Standards

- Increasingly dominated by wireless standards

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<tr><td colspan="2">Network</td><td rowspan="4">802.1 Overview, Architecture, Management, Internetworking</td><td colspan="6"></td></tr>
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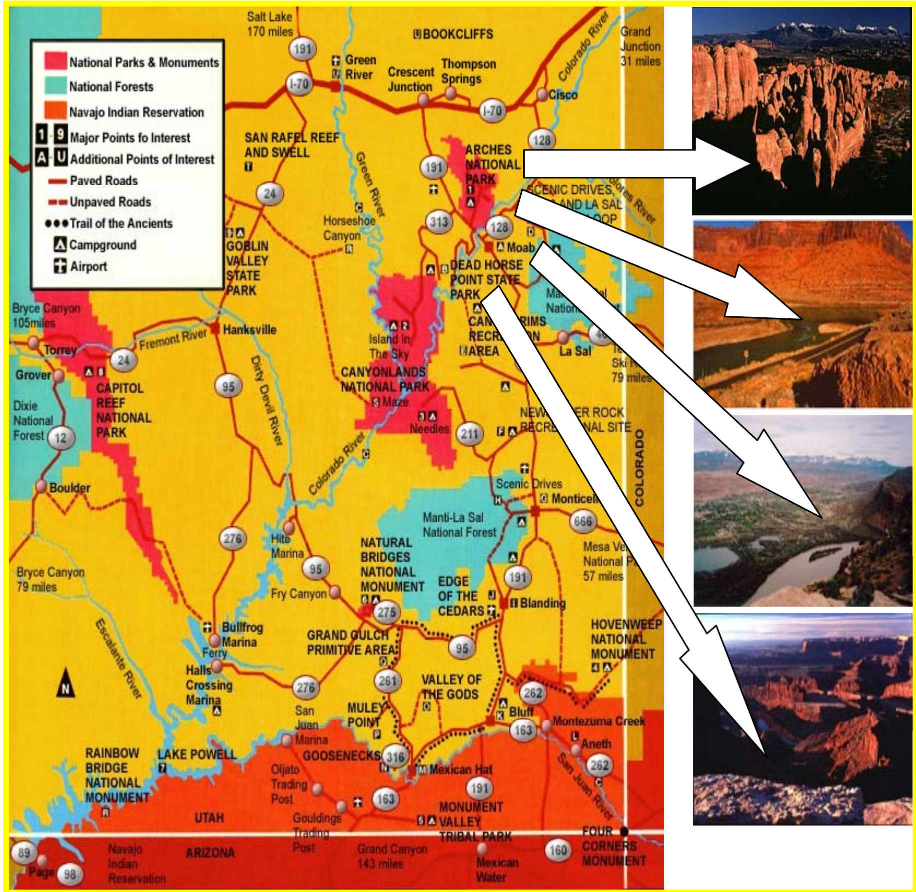
Broadband Wireless Access in Bermuda

Broadband Wireless Access in Moab, Utah



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
- Viewed by many carriers and cable operators as a "disruptive" technology and rightly so
  - Broadcast nature offers ubiquity and immediate access for both fixed and mobile users
  - Many phone companies are losing their landline business to wireless (just as they are losing business to VoIP)
- Unlike wired access (copper, coax, fiber), large portion of deployment costs incurred only when a subscriber signs up for service
  - Avoids underutilizing access infrastructure
- U.S. poised to exploit new wireless access technologies capable of pervasive high-speed connectivity despite lagging behind developed Asian countries in broadband access deployment for many years
  - An increasing number of U.S. municipal governments are financing the deployment of multihop wireless networks with the overall aim of providing ubiquitous Internet access and enhanced public services (e.g., utility, emergency, education)

Wireless Access Benefits

- Quick, low-cost alternative to installing direct cable or leased lines
  - Allows long-distance carrier to bypass local service provider, thereby cutting down subscriber costs
- Allows fixed line operators to extend broadband networks
  - Plays a very important role in completing the end-to-end broadband network
- Indispensable when wired interconnections are impractical
  - Rivers, rough terrain, private property, highways, streets, physical barriers
- Reduce network configuration complexity, dependence on gateways
- Eliminate overheads associated with moves, adds, changes
  - Removes labor, material, and equipment costs associated with cabling
  - Offers flexibility to reconfigure or add more subscribers to network without much planning effort and cost of recabling
  - Makes future expansion and growth inexpensive and easy

Direct Cable	Telephone Lines	Microwave Connection
Inflexible	High monthly subscription fees	Require licensing
High installation costs	High installation costs	Difficult to install
Government approval		Expensive equipment

Wireless Access Benefits

- Need not be less reliable than wired access
  - Can offer improved deployment reliability (compare transmission reliability)
  - No single point of failure in multihop wireless
  - In a point to multipoint network, it is not expensive to add more base stations, which improve deployment reliability by providing redundancy
  - Can be an invaluable network overlay for wired access infrastructure during emergencies and catastrophic events (e.g., hurricanes, earthquakes)
  - EchoStar capitalized on cable outages in some areas of Gulf Coast by quickly restoring its own service and sending additional resources and staff to sign up potential new customers
  - Cable TV (CATV) connection typically requires long cascades of some 30-plus trunk and line amplifiers between headend and customer premise (in addition to many passive taps), serious reliability problem since all amplifiers in series, failure of any one device results in downstream signal outage from that point
  - Fiber's reliable transmission unquestionable but deployment reliability still poses some major challenges e.g., accurate splicing

Wireless Access Limitations

- May not compete with fiber in terms of bandwidth provisioning
  - Particularly with increasing operational range
- More prone to eavesdropping, security attacks, traffic analysis
  - Security a big issue for outdoor wireless deployment
- Performance fundamentally limited by signal interference among concurrent transmissions
  - A function of timing and spatial separation of transmissions
  - For wide coverage areas, a combination of wireless and wired infrastructure may still be required
- Outdoor environmental factors need to be taken into account
  - Simple example: leaves from trees generate different operating conditions during winter/spring seasons and raining/sunny weather
- Outdoor deployment considerations
  - Earth bulges 12 ft every 18 miles (125 ft with buildings and trees)
  - To compensate for Earth's curvature, 60% of center of First Fresnel Zone to be kept free of obstacles

Multihop and Long-Range Wireless Access

- Can enable pervasive broadband access and bridge the digital divide
  - Multihop wireless simplifies private network deployment for residential users
  - Long-range wireless can act as an overlay complementing multihop technologies
  - Both technologies can compete with local Wi-Fi hotspots, 3G, integrated cellphone/Wi-Fi for revenue
- Concepts can also be applied to indoor networks
  - Wireless multihop packet routing among access points or long-range wireless eliminate need for wired backbone network
  - Allow new, large-scale enterprise networks to be set up easily
  - An alternative to wireless LAN switching

Multihop Wi-Fi

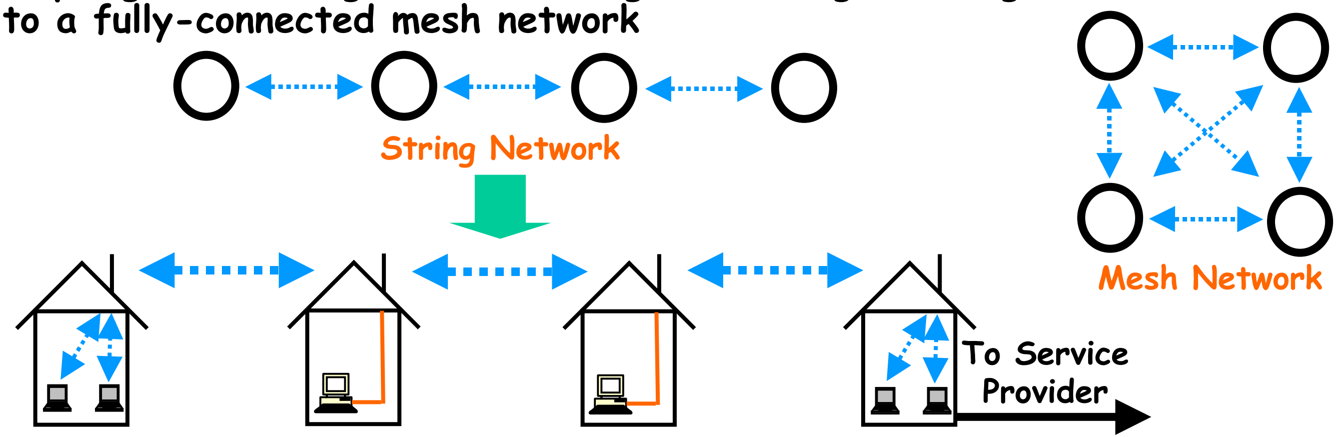
- Accelerates creation of access infrastructure for residential homes due to low overheads
  - –Network architecture very similar to Internet design (where some people still claim was originally designed to withstand a nuclear war)
- Proliferating in many cities in the U.S. and abroad
  - –Strong emergence of outdoor municipal Wi-Fi or "unwired digital cities" (www.muniwireless.com), complements existing wireless community networks such as Bay Area wireless user group, Seattle wireless, NYC wireless
  - –USA Teleservices asking Denver homeowners to put an antenna on their houses (to feed adjacent homes) in exchange for free access
  - –Philadelphia's largest U.S. hotspot (135 square miles) to provide low-cost citywide services for residents and businesses in June 2006, Earthlink is city's wireless provider (selected from 12 proposers), network will costs $15 million to build, $2.5 million a year to maintain
  - –San Francisco received 26 proposals to build its 49-square-mile city-wide network, Google among companies submitting proposals, plans free Wi-Fi service, target ads for revenue (compare free broadcast TV, ads the main source of revenue), Google Secure Access for Wi-Fi
  - –New York, Jerusalem are among cities with similar ambitions, about a quarter of Amsterdam already connected

Multihop Wi-Fi

- More unwired cities …
  - Metro-area networks installed in New Orleans, Milpitas (California), San Mateo County, city of Chaska (Minnesota) covering 16 square miles
  - City of Garland (Texas) municipal and public safety multihop wireless network allows streaming video to be transmitted, maps and large files to be downloaded from police server, and voice calls to be made between vehicles
  - City of Medford (Oregon) creating 24 square mile multihop wireless network
  - City of Houston planning to begin using its parking meters for more than regulating parking and collecting revenue for the city
    - First step is to make city's parking meters able to be "fed" not by coins, but by driver's credit card, each meter connected to a central system through Wi-Fi to verify credit card information
    - Next step is to turn these Wi-Fi-enabled meters into elements of a city-wide Wi-Fi hotzone
  - Taipei's CyberCity is world's largest project that aims to make Wi-Fi ubiquitous outdoors, 90% coverage by end-2005, access points attached to traffic and street lights
  - Nortel teaming up with service provider SimplySurf Wireless Network to offer wireless broadband through a mesh network in rural Ontario
  - City of Alpharetta (Georgia) solicited muni-wireless RFPs in late-July 2005
  - Intel's digital communities initiative supports multihop Wi-Fi

Multihop Wi-Fi

- Can be considered a concatenation of multiple hotspots
  - Forms wireless backbone network which ultimately connects service provider
  - Similar to pockets of communication islands with direct connection to mainland
- Fixed wireless access point typically mounted on rooftop of homeowner or on streetlights
  - 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 the wireless backbone
  - Topologies can range from a string network (generating the least interference) to a fully-connected mesh network



Multihop Wi-Fi

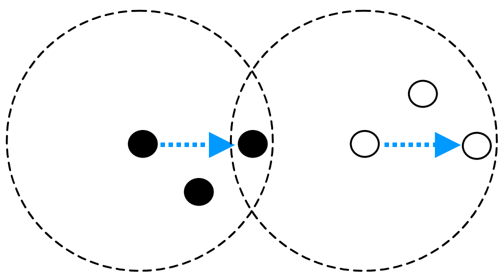
- Routing can be done by both clients and access points,
  - MeshNetworks products have this capability, guarantees < 5 ms delay per hop
  - Tropos, Strix focus on meshes of access points only but allow regular 802.11 client access (see also BelAir, Firetide, Packethop, Cheetah)
  - Predecessors include Nokia's Rooftop Solutions (using wireless IP routers) and Metricom's Ricochet network
- 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
  - Access points placed at fixed locations creates network structure, relatively stable network topology, optimized radio coverage areas
- Access points need wireless interfaces to receive and forward packets
  - Mobile client devices may also connect directly to these access points
  - Frequency reuse difficult due to limited number of non-overlapping channels (e.g., 2.4 GHz ISM band), different radio transceivers for each access point may be required e.g., two radios for full-duplex backbone routing among access points and one radio for local access by mobile clients
  - Requires additional network layer (e.g., IP layer) functionality since 802.11 standard only defines functionality for PHY and MAC layers

Multihop Wi-Fi

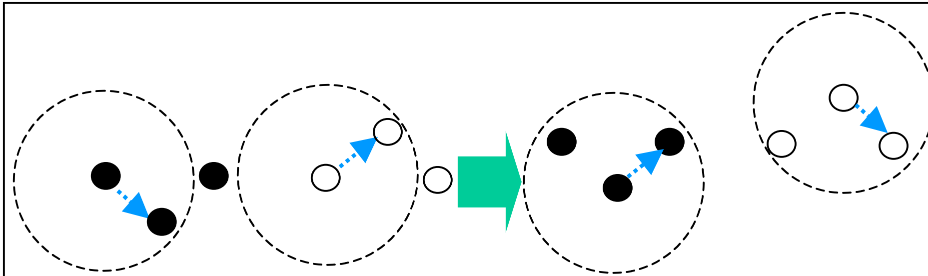
- Not completely ad-hoc
  - Some access points to act as gateways to service provider (e.g., Internet)
- Can employ less complex but more efficient packet routing protocol
  - Usually based on a variation of Open Shortest Path First (OSPF) protocol
  - May not use routing tables or rely only hop-count 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 (www.pdos.lcs.mit.edu/roofnet)
  - Champaign-Urbana Community Wireless Network (www.cuwireless.net)

Advantages of Multihop Wireless Access

- Increased capacity, improved range
  - Lower transmit power (no need to transmit information all the way back to ultimate destination), results in a corresponding reduction in interference
  - Ability to reuse limited radio spectrum efficiently
  - Overcomes range performance limit of CSMA protocols
  - Alternative to 3G/Wi-Fi integration
- Range and data rate can be scaled according to network conditions
  - Choice between a larger no. of high-speed hops or fewer lower-speed ones
  - Longer range per hop reduces data rate per hop, degrades CSMA performance, increases power requirements and interference
  - However, a smaller number of hops may improve delay and throughput performance since there is less packet forwarding and forwarding contention



Forwarding contention

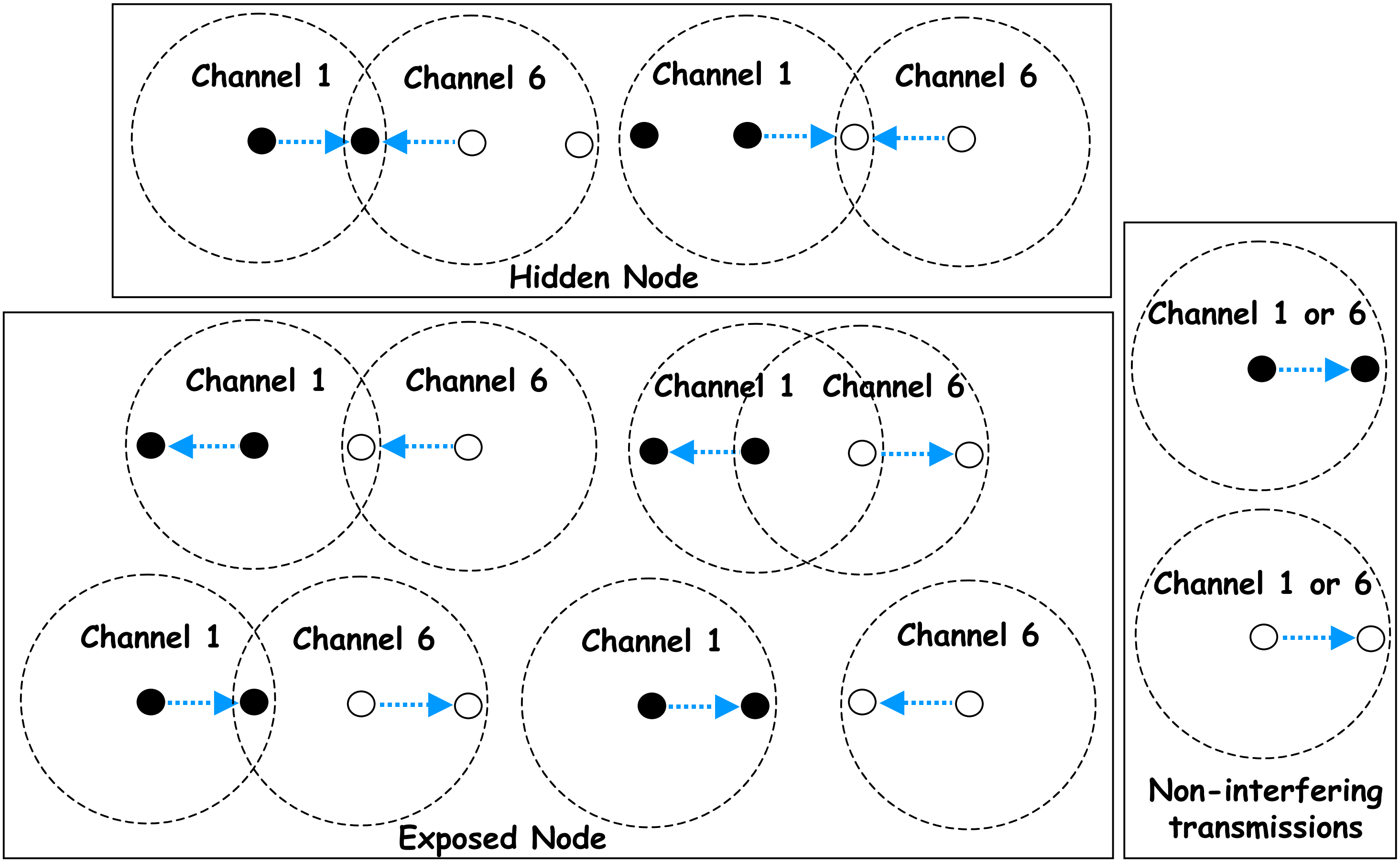


Forwarding contention eliminated using two hops

Disadvantages of Multihop Wireless Access

- Bandwidth is consumed during packet forwarding
- In some community networks, cooperation among subscribers required
  - Access point in each participating home must be "always on"
  - Difficult to guarantee security and QoS with always-on requirement
- Outdoor wireless transmission makes it easier for an intruder to impersonate as a wireless relay node
  - Current Wi-Fi security problems aggravated by soft access points that can easily store "forwarded" packets on computing devices, security of entire network compromised when connected to these access points
  - Need to authenticate all intermediate relay nodes, key distribution a big issue
- Network service cannot be guaranteed
  - Failure in a participating access point can result in a need to reroute
  - Range and data rate may need to be adjusted
- Congestion and interference may be generated by intermediate relay nodes in both upstream and downstream directions
  - Worse for nodes residing nearer to service provider in relay chain
- Low degree of concurrency among neighboring hops
  - Reduces overall network utilization, may not maintain traffic streams, including end-to-end TCP/IP flows and sessions, across all hops

Concurrent Transmissions in Multihop Wireless Access



IEEE 802.11s Task Group

- Newly-formed mesh networking group
  - To develop an efficient wireless routing protocol for wireless backbone routing and mesh networking that can improve the reach of Wi-Fi networks
  - Hopes to achieve interoperable meshing protocols in 1-2 years
  - Wireless access points will then be able to configure itself as a mesh network, similar in concept to the Internet, interconnected access points will then be able to route packets over the best available route
- Wi-Mesh Alliance (WMA) comprises hardware and software vendors
  - Nortel, Accton, Interdigital, NextHop, Thomson
  - Submitted a proposal that contains algorithm for auto discovery and routing
  - Need 802.11i extensions for key management and data encryption required in a mesh
  - Supports single radio and multiple radio configurations
- Currently one of the key working groups in 802.11, in addition to 802.11n and 802.11k
  - Proprietary solutions already generating a rich source of revenue for Wi-Fi
  - Ratified standard may dominate other wireless standards that are expected to do well e.g., 802.16, 3G

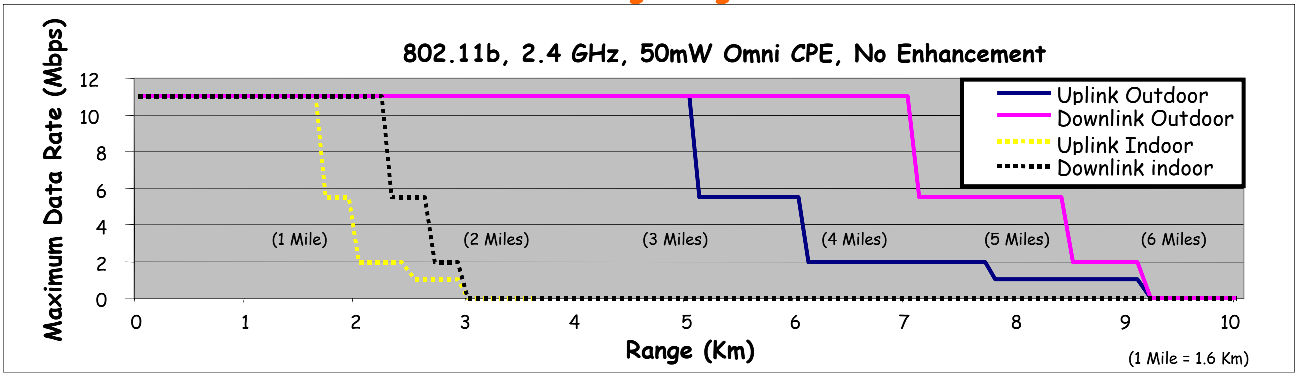
Long-Range Wi-Fi

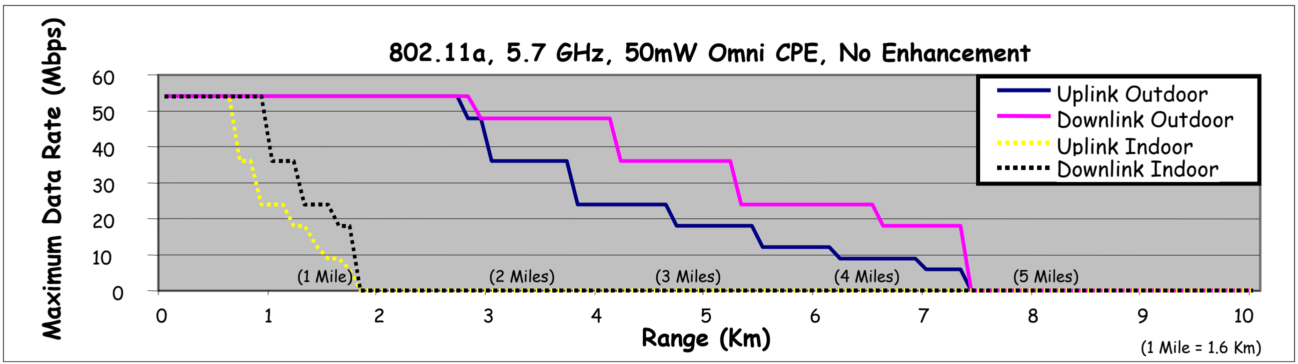
- Can provide an omnidirectional (i.e., point-to-multipoint) 5-mile radius coverage using sensitive antenna arrays mounted on fixed locations
  - Access points that service several miles can be located on a tower, a tall building's rooftop, or other elevated structure
  - Uses only tens of milliwatts of transmit power, can be solar-powered
  - If directional (i.e., point-to-point) high-gain antennas are used, then operational range can extend up to 30 miles
- Sometimes called a Hotzone: centralized antennas in hotzones are like spotlights whereas multihop wireless networks are like streetlights
  - Spotlights leave shadows (and blindspots) while streetlights illuminate them
- Advantages over other long-range solutions (e.g., Wi-Max)
  - Easily integrated with Wi-Fi home and enterprise networks
  - According to IDC, Wi-Fi will likely account for 90% of LAN equipment sales by 2005, a trend that promises to spill over into home wireless networks
  - Wi-Fi cited as most popular amenity being requested by tenants today when leasing commercial space, this was followed by food services and health clubs

Long-Range Wi-Fi

- For same transmit power, higher decay in data rate for 802.11a as range increases
  - However, more channels (23 max.) and higher transmit power levels (up to 1 W) available for 802.11a

Amazing Range!





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

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)
  - Standard completed in Oct 2001 and published on April 8, 2002
  - Unlike Wi-Fi, allows two-way simultaneous (full-duplex) communication
  - Currently, a lot of interest shown on the soon-to-be-released 802.16e mobile client standard (overlaps IEEE 802.20 charter)
- Initial focus on frequency bands between 10 to 66 GHz (line-of-sight)
  - More recent interest on 2 to 11 GHz (non line-of sight) bands led to 802.16a, which supports both unlicensed and licensed bands (ratified Jan 2003)
  - 10 to 66 GHz standard (802.11c) supports continuously varying traffic levels at many licensed frequencies (e.g., 10.5, 25, 26, 31, 38, 39 GHz)
  - Latest 802.16d (802.16-2004) for fixed access ratified on June 29, 2004: uplink performance enhancement to 802.16a, 256 OFDM carriers
  - Mobile 802.16e (802.16-2005) standard allows a maximum of 5 MHz, 1 Mbit/s throughput, 1,000-2,000 OFDM carriers, promises to support speeds of up to 80 miles/hour, asymmetrical link structure allows handheld subscriber devices e.g., laptops, PDAs, phones

Summary of IEEE 802.16 Standards

	802.16 (Oct 2001)	802.16a (Jan 2003)	802.16e (Oct 2006)
Spectrum	10-66 GHz	2-11 GHz	2-6 GHz
Channel Conditions	LOS	NLOS	NLOS
Bit Rate	32-134 Mbit/s 28 MHz Channel	Up to 75 Mbit/s 20 MHz Channel	Up to 15 Mbit/s 5 MHz Channel
Modulation	QPSK, 16QAM, 64QAM	OFDM 256 subcarriers, QPSK, 16QAM, 64QAM	OFDM 256 subcarriers, QPSK, 16QAM, 64QAM
Mobility	Fixed	Fixed	Nomadic, Portable
Channel Bandwidth	20, 25, 28 MHz	Scalable 1.75 to 20 MHz	Same as 16a with uplink subchannels
Typical Cell Radius	2-5 km	7-50 km	2-5 km

IEEE 802.16

- Time Division Multiple Access (TDMA) MAC protocol supports multiple physical layer specifications customized for frequency band of use
  - Supports circuit-switched voice connections, enabling cellular voice service
  - Accommodates voice, video, data traffic by using appropriate MAC features
  - Supports adaptive modulation, effectively balancing different data rates and link quality
- Supports both frequency and time division duplexing (FDD/TDD)
  - Both TDD/FDD alternatives support adaptive burst profiles in which modulation and coding options may be dynamically assigned on a burst-by-burst basis
  - FDD can typically transmit at a longer range than TDD

Potential of IEEE 802.16

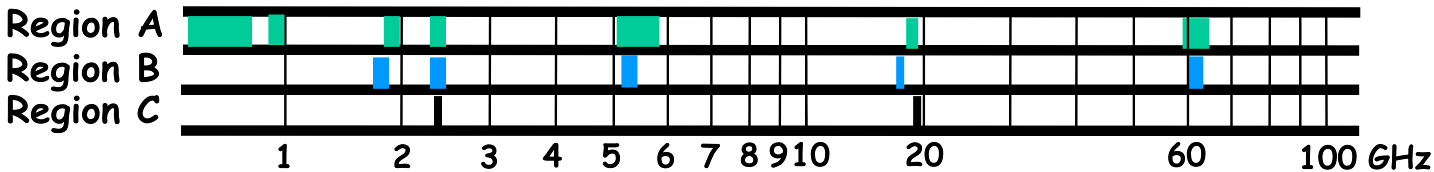
- Key application likely to be fixed wireless access
  - Initial deployments to focus on fixed wireless connections between enterprise buildings
  - Need to compete with incumbent high-speed access methods for the enterprise e.g., fiber and free-space optics
- There is uncertainty over whether the technology will eventually become popular for residential access
  - Carries some baggage from past failures, namely the limited success of the LMDS and MMDS standards
  - On the other hand, there are proprietary wireless access products that have enjoyed some measure of commercial success over the last few years, most notably Motorola's Canopy™ product (http://motorola.com/canopy)
- Strong emergence of outdoor Wi-Fi multihop access networks has clouded choices for wireless residential access
  - These developments will have implications on eventual viability of Wi-Max

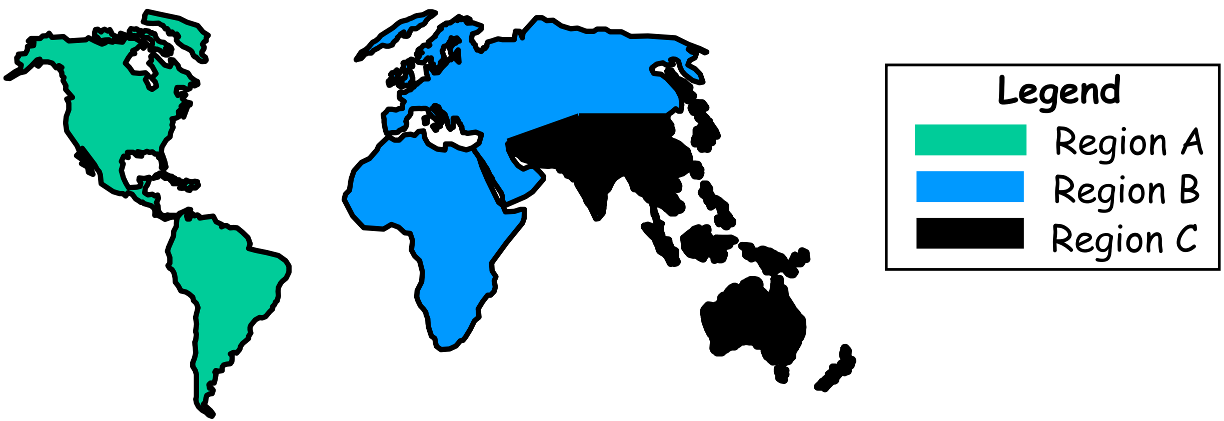
Potential of IEEE 802.16

- As for the Wi-Max standard, there are some concerns over the use of an unprecedented range of frequencies (2 to 66 GHz)
  - Will mean interoperability problems when products operating on different bands are not able to communicate
  - Raises a question of whether there is really a need for a Wi-Max standard (which could be one of the reasons why Canopy is so popular)
  - More importantly, whether this will lead to heavy reliance on a few leading players and less vendor competition, which may not drive the cost down in the long run
  - When the first Wi-Max certified products are released by wireless vendors next year (not likely to be 802.16e-based), customer premise equipment (CPE) is going to be expensive, manufacturing volume will dictate the decrease in prices and this takes time
  - Use of both licensed and unlicensed bands could mean different quality of service for different Wi-Max products, with vendors opting for licensed bands enjoying better service quality (although unlicensed bands such as 2.4 GHz and 5 GHz bands are cheaper to deploy and are therefore likely to dominate)
  - In the U.S., Sprint Nextel holds most of the licensed spectrum on Wi-Max (owns 2.5 GHz spectrum in markets covering 85 % of U.S. population)
  - In early 2006, Sprint and Samsung will launch a series of lab and field trials of 802.16e-based products offering 1 Mbit/s throughput in 2.5 GHz band

Frequency Bands

- Worldwide unlicensed frequency bands shown in figure
- 2.5 GHz and 4.9 GHz are popular licensed bands for high-speed wireless data networks e.g., Wi-Max, wireless DOCSIS

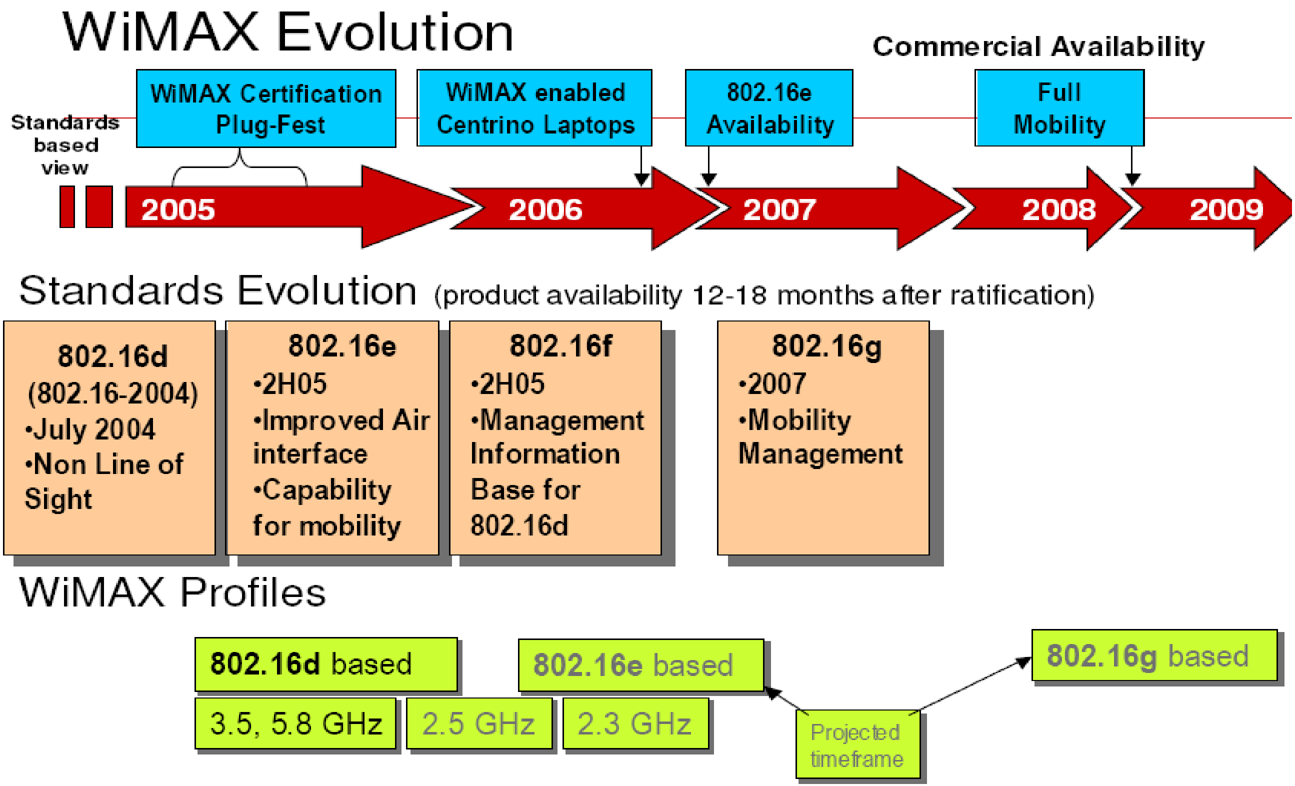




Wi-Max Forum

- Industry consortium bringing compliance and interoperability to the wireless broadband industry with its testing and certification program: WiMAX Forum Certified™
  - Stands for Worldwide Interoperability for Microwave Access
- Nonprofit association formed in June 2001 by equipment and component suppliers
  - Promotes adoption of IEEE 802.16 compliant equipment by operators of broadband wireless access systems
  - Currently has over 230 members, including leading equipment manufacturers, service providers and systems integrators
- President and chair of forum comes from Intel: Ron Resnick (Director of Marketing, Broadband Wireless Division, Intel)
  - Most powerful members are Intel, Alvarion, Nokia
  - Intel has called 802.16 "the most important thing since the Internet itself"

Beyond Wi-Max



802.16 versus 802.11 and 802.20

- 802.16 versus 802.11
  - 802.16 has embarked on several efforts similar to 802.11 (e.g., mesh networking, mobile networking)
  - Although overheads for creating fixed wireless infrastructure for residential homes using Wi-Max is much lower than traditional cable/copper/fiber methods, overheads are still higher than Wi-Fi mesh networking methods
  - As such, Wi-Fi mesh networking may yet be the dominant method for wireless residential access
- 802.16e versus 802.20
  - Both specify new mobile air interfaces for wireless broadband
  - Differences: 802.16e adds mobility in 2 to 6 GHz licensed bands, 802.20 operates in licensed bands below 3.5 GHz
  - 802.16e certified products likely to appear before 802.20 (even though 802.20 was established before 802.16e group was formed)

Wi-Bro

- A variant of 802.16e developed by South Korea's Electronics and Telecommunications Research Institute (ETRI) and several communication companies
  - In February 2002, South Korean government allocated 100 MHz of frequency spectrum in 2.3 GHz bandwidth for Wi-Bro
  - In June 2004 Phase 1 of Wi-Bro became standardized
- Samsung successfully demonstrated Wi-Bro handoff technology
  - Allows seamless connections while moving at speeds of up to 80 mph
- Main benefit of Wi-Bro is earlier completion of standard and hence, an earlier time to market products
  - Leapfrog completion of 802.16e mobile standard
  - Remains to be seen whether Wi-Max and Wi-Bro will coexist in future since Wi-Max standards such as 802.11e have yet to take off
  - Similar situation happened in China two years ago when it wanted to adopt its own homegrown WAPI security standard (ahead of 802.11i security standard, which was then in a draft stage) for 802.11 products marketed in China
  - However, because Wi-Fi has already become so pervasive globally, move was eventually thrown out

Wireless DOCSIS

- DOCSIS features can be extended for wireless access
  - Minimize overheads associated with protocol translation
  - Vendors: Aurora, Arcwave, Arris, Wireless Bypass, Xtend, Nortel, VCOM, CommScope, typically employ 5.8 GHz on downstream and upstream links except Arcwave (5.3 GHz upstream), some operate at 900 MHz (Arris)
- 2.5 GHz wireless DOCSIS from VCom
  - 27 Mbit/s TDM downstream using 64 QAM in a 6 MHz channel, or 36 Mbit/s in an 8 MHz channel
  - 256 Kbit/s to 10 Mbit/s TDMA burst upstream using QPSK or 16 QAM in 200 KHz to 3.2 MHz bandwidths
  - 4-sector upstream antennas (reduces upstream interference) and omnidirectional downstream antennas
- 5 GHz license-free U-NII wireless DOCSIS from ARCwave
  - Optimized to serve between 100 - 500 subscribers in rural, underserved areas
  - Comprises wireless CMTS and hub transceiver antenna at base station, and a subscriber transceiver antenna and modem at CPE
  - Depending on deployment needs, an ISP can implement a single-sector receiver or as many as 6 sectors to obtain full 360° coverage
  - Transmitter operates at 5.8 GHz, with 16 channels (6 MHz each) that allow for 360° of coverage for up to 4 miles at 10 Mbit/s

3G/4G

- 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
- Enhanced services of 3G expected to emulate success of cellphones
  - Expensive 3G radio spectrum a prized commodity, over $100 billion of 3G spectrum invested in Europe in early 2000
  - Wi-Fi became next wireless revolution instead
- Emergence of cellular/Wi-Fi wireless handheld smartphones
  - 3G acting alone will face severe competition from other wireless technologies
  - Key hurdles: limited data rates, expensive licensed spectrum, high user terminal/base station cost
  - Mobile carriers around the world complementing technology with Wi-Fi, so 3G might just make the cut although unlikely to displace other technologies

Data Rates of Evolving CDMA Cellular Standards

Year	1998	2000	2002	2002	2004	2005
Standard	cdmaOne	PacketOne	CDMA2000 1x	WCDMA*	1xEV-DO	HSDPA**
Max. Data Rate	14.4 Kbit/s	64 Kbit/s	307 Kbit/s	2 Mbit/s	2.4 Mbit/s	14 Mbit/s
Typical Data Rate	14.4 Kbit/s	64 Kbit/s	144 Kbit/s	384 Kbit/s	600 Kbit/s	2 Mbit/s

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

IEEE 802.21

- Tasked with developing standard that ensures co-operation among 802-type wireless networks and mobile telephony
  - Goal is to provide seamless network connectivity across a wide range of networks
  - Will formulate procedures allowing mobile devices to recognize and analyze radio environment around them
  - Different layers in software may trigger network handoffs e.g., from Wi-Fi to 3G
  - Will enable mobile VoIP and other enterprise applications to be deployed in the field as easily as they were in the office
- Key technical problems
  - How to accommodate simultaneous operation of multiple radios e.g., Bluetooth, GPRS, Wi-Fi, GPS
  - Need to resolve interference issues

IEEE 802.22

- FCC's landmark Notice of Proposed Rule Making issued in May 2004
  - Plans to open up a significant portion of the TV spectrum for unlicensed usage
  - See http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-113A1.pdf
- FCC recognizes great deal of TV white space can be exploited by unlicensed devices (see http://www.sharedspectrum.com)
  - White space mainly due to
    - Large peak-to-average ratio of many TV systems that have dedicated spectrum
    - Practical TV receiver limitations such as limited adjacent channel and image rejection
    - Spectrum demand that is not spatially uniform
- 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)
  - Chartered to develop a cognitive radio-based PHY/MAC air interface for use by low-power license-exempt devices to share spectrum in VHF/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 by Jan 2007
  - Also known as Wi-Fi TV

IEEE 802.22

- Clearly CATV-centric since it employs unused VHF/UHF TV channels between 54 and 862 MHz
  - Channels 5-36 and 38-51 generally available for unlicensed operation
  - Channels 14-20 available in most locations
  - Channels 51-69 will be available on Dec 31, 2006
  - Key difference here is the possibility of two-way communications, as opposed to one-way broadcast used in traditional broadcast TV systems
- Could be the next "lucky" 802 standard
  - Bury the myth that only 802 working groups with odd numbers are successful (e.g., 802.3, 802.11)
  - 22 is a multiple of 11!

IEEE 802.22

- Many favorable propagation characteristics inherent in TV channels
  - Prime RF channels were reserved for first broadband wireless application: TV broadcasters
  - Impairments due to Fresnel zones, environmental factors (e.g., rain, snow), and multipath effects are less significant
  - Better reliability, fast synchronization and sweep for idle channels, 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), fewer base stations will be required to cover an area compared with higher frequency bands
  - 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 (http://mrtmag.com/mag/radio_operators_crave_mhz)
- Immediate implications for fixed point-to-multipoint WRANs
  - Provide direct high-speed wireless connectivity with an in-building CPE (fixed wireless relay on rooftop not required), can potentially make IP TV pervasive
  - Serve a large subscriber base at low deployment cost, including sparsely populated areas not economically serviceable with cable or DSL
  - All-wireless network possible: 802.22 for local and metro access, satellite for backbone transport (satellite commonly used by cable networks today)

IEEE 802.22

- Challenges for deploying WRANs will be to ensure that new broadband service does not cause harmful interference to licensed incumbent services in the TV broadcast bands
  - To achieve this, mechanisms must be put in place to choose portions of spectrum by sensing what frequencies are unoccupied
  - This is facilitated by the fact that
    - TV broadcast systems use high SNRs (typically above 10 dB), which simplifies technology needed to detect if a channel is in use
    - TV channels are left on more or less continuously and changes location or frequency infrequently
    - 6 MHz bandwidth of TV channels attractive for sensing operations
    - Impact of errors when selecting unused channels would be small since only a minority of households (11.6% according to FCC estimates, which also shows that the spectrum is under-utilized) depend on over-the-air TV reception

Software Defined Radio (SDR)

- Refers to flexible radio hardware, a key technology for future wireless communications
  - Replaces conventional radio hardware with radios that are largely reconfigurable and reprogrammable by software
  - Opens the way for new services and prolongs lifespan of wireless device
  - A device with flexible radio hardware is capable of running different applications, much like PC hardware
  - A high degree of reconfiguration requires support for different system functionalities, including multi-band systems supporting more than one frequency band and multi-homing systems supporting more than one radio standard or service
  - Intel working on a form of SDR called silicon radio, which they believe will dominate the wireless world just as silicon chip has dominated the electronics/computer world for 4 decades
  - Motorola's Canopy product (as discussed previously) is based on SDR technology and can therefore allow software upgrades from its current wireless ATM design to 802.16 and beyond
- On Nov 19, 2004, FCC announced it has approved, for the first time, use of SDR devices in the U.S.
  - Cisco receives first FCC certification for 802.11a SDR devices in Sept 20, 2005 (twelve 20 MHz channels, upgradeable to 23 channels: doubling capacity)

Cognitive Radio

- Smart radio (as specified in the 802.22 charter) that leverages on SDR hardware to perform intelligent, opportunistic sharing of unlicensed radio spectrum
  - New type of radio device employs real-time interaction with its environment to determine transmitter parameters such as frequency, power, and modulation
  - Can learn when to operate and when to interrupt service
  - Relies on intelligent protocols to adapt spectrum use in response to location and operating environment e.g., unlicensed cognitive radio devices in limited bands can use higher transmit powers in rural and underserved areas
  - Lead to "plug and play" wireless systems, requiring minimum or virtually no manual intervention or frequency management during deployment
- Fundamental benefits are the ability to self-adapt, self-manage, and self-optimize under normal conditions, and the ability to self-diagnose and self-heal when unusual problems arise
  - For example, base stations can automatically adjust operating range (e.g., by controlling transmit power, receiver sensitivity, data rate, frequency channel selection) to compensate for neighboring base stations that fail
  - Contrast current wireless systems, including Wi-Max, where static frequency channels are pre-selected in advance and tedious frequency planning is mandatory to minimize interference from equipment operating in adjacent coverage areas

Cognitive Radio

- Can take advantage of the increasing deregulation of radio spectrum to provide high-speed broadband services
  - Besides the unused TV channels released by FCC for unlicensed wireless networking, there is also the Jumpstart Broadband Act where FCC allocated an additional 255 MHz of contiguous radio spectrum in 5-GHz band (5.470-5.725 GHz) for unlicensed use
  - In Britain, media and communications regulator OFCOM eyes an open market for radio spectrum, spectrum trading started in December 04 and may eventually apply to over 70% of U.K.'s radio spectrum
- Can potentially lead to virtually unlimited wireless bandwidth when spectrum is used and reused more efficiently and co-operatively
  - Capacity increase and efficiency direct result of being able to switch between momentarily idle channels in different portions of radio spectrum for short period of usage
- Can employ existing wireless transmission methods, does not preclude future ones (i.e., backward compatible and future proof)
  - Can become a more viable alternative for high-speed wireless transmission than trying to use higher frequency bands or attempting to squeeze as many bits/s/Hz out of static radio channels using complex multiple antenna systems and expensive wideband RF components

Cognitive Radio

- Can inherently avoid interference and co-exist with existing wireless systems
  - Interoperability with incompatible wireless devices could become seamless
  - Can also be used in conjunction with interference cancellation methods designed for static frequency channels to enhance performance
- Unifying theme for multiband wireless transmission (e.g., multiband OFDM)
  - Allows multiple channels to be operated simultaneously for increased bandwidth
  - Does not preclude multiple antenna systems such as MIMO
  - Even with a single antenna, can provide a degree of diversity gain similar to multiple antenna systems
- Using multiple channels simultaneously differs from using a single wideband channel
  - Similar to using multiple lanes in a highway, number of lanes can be increased to service more traffic, each lane not modified to allow existing cars to operate on them (i.e., maintain backward compatibility with existing devices)

Cognitive Radio

- In an unlicensed environment, cooperation and etiquette are key elements in minimizing interference and maintaining a level of QoS
  - Need to differentiate cooperative and non-cooperative users
  - Cooperative diversity concept: Capacity gains maximized if there is full co-operation among all users in network, can be developed in conjunction with etiquette protocols (e.g., controlling device power, transmit duration, etc)
- For cooperative approaches, users can be prioritized
  - Higher priority users can transmit higher priority traffic (e.g., time sensitive traffic such as voice, video), relevant for current and future applications
  - If licensed holders do become cooperative in the future, then these holders can be accorded the highest priority

Cognitive Radio

- Sharing of licensed bands by cognitive radio devices
  - Two major impediments for such a scenario to happen: (1) current spectrum licensing policy has to allow such sharing (2) licensed devices need to know if licensed spectrum is being shared by cognitive devices
  - Even if cognitive device is able to perform an ultra-fast switchover of frequency channels, they do not know when to do the switchover
  - Non-cooperative approaches will not work because current licensed holders expect zero interference from non-licensed users
  - To do a clean switchover with zero interference, licensed devices will still need to communicate, in a co-operative manner, on impending use of spectrum to all other users
  - Service providers (e.g., cellular providers) who have paid huge sums of money to secure spectrum for their exclusive use may be reluctant to do that unless given very strong incentives

Cognitive Radio

- Sharing of licensed bands by cognitive radio devices
  - As another example, when FCC opened TV channels for unlicensed use by cognitive devices, they also recognized that TV broadcasters, being "uncognitive" or "un-cooperative", are likely to lead to TV receivers suffering from occasional interference from transmissions arising from cognitive users
  - However, they performed a study and found out even if such interference occurs, it is only going to affect an estimated 11.6% of people using over the air TV reception
  - Cannot apply the same principle to cellular bands, even if these bands are under-utilized.
  - Power used by cellular base stations is significantly lower than TV broadcasters and as such, sensing operations cannot be done as reliably as in the TV bands, which will result in more interference
  - Key point these examples is that interference (large or small) is inevitable in a network that has non-cooperative users

xG's XMax Technology

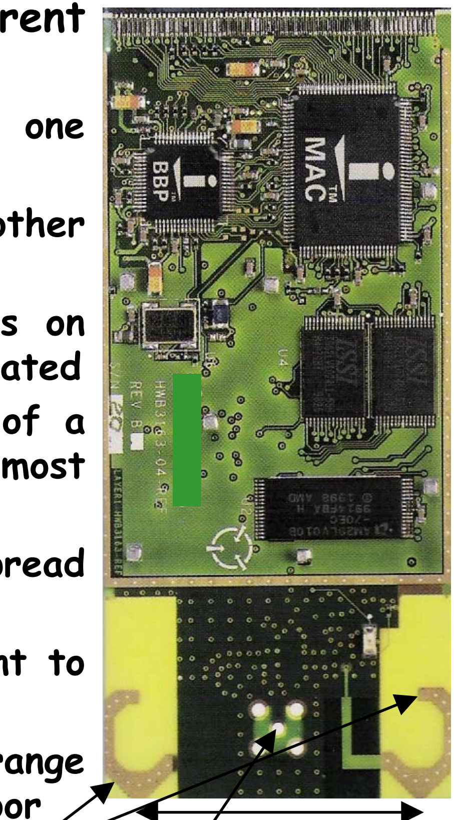
- Uses single cycle modulation, needs much less power than other technologies (http://www.xgtechnology.com)
  - Flash signal modulation alters frequency of individual cycles of carrier wave, which has the effect of introducing very low power sidebands to the signal
  - Conventional communications systems require a receiver to modulate thousands, or millions, of RF cycles for each bit of information
  - Flash signal scheme accomplishes the feat in just one RF cycle.
  - Capable transmitting 7.4 Mbit/s per MHz per Watt, 2 Mbit/s over 40 ft, using 3 nW
  - Power levels are 10,000 times below the FCC's power limits for ultrawideband (UWB) transmissions (25 to 45 dB advantage), traditionally weak signals become usable, battery life of mobile devices can improve dramatically
- Receiver includes a passive wavelet path filter that tunes only to single-cycle waveforms, all other RF signals are ignored
  - Reduces interference considerably, permits effective communication even at very low power levels
- Two pending patents available from the following link - http://www.techworld.com/mobility/news/index.cfm?NewsID=4722&inkc=0

Reliable Wireless Transmission Using Multiple Antennas

- Wireless channel response at any given time and frequency (i.e., channel dimension or "degree of freedom") a random variable
  - Hence, essential that each bit of information is spread over several dimensions
  - Traditionally, this can be achieved by coding in time-frequency domain
- Number of channel degrees of freedom for diversity can be increased further in the space domain
  - Add spatially separated antennas at receiver and transmitter
- Conventional multiple-antenna receive diversity employ signal combining techniques at receiver to improve performance on uplink (i.e., transmission from wireless client to base station)
  - In this case, receive diversity preferable to transmit diversity since no additional transmit power from wireless client is required
- Difficult to implement receive diversity on downlink (i.e., transmission from base station to wireless client)
  - Size and battery power limitations of client device
- Recent research focused on transmit diversity where multiple antennas at base station are able to broadcast on downlink to client device
  - May need feedback channel for channel estimation by transmitting antennas

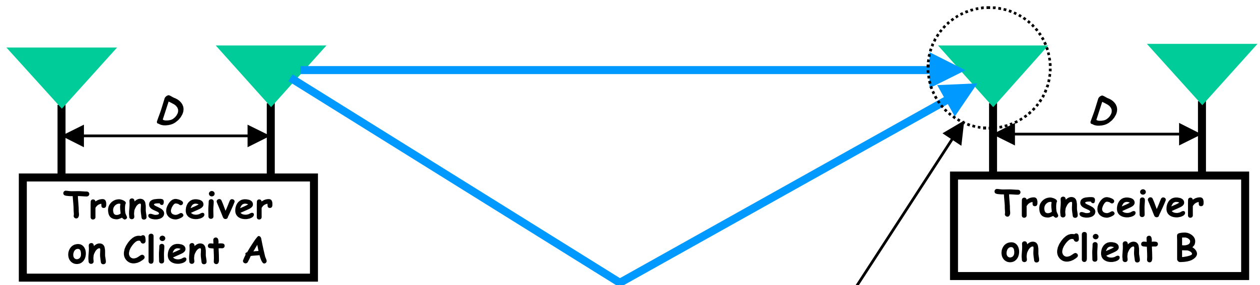
Switched Antenna Diversity

- Simple, hence commonly employed by current 802.11 WLANs
  - Can be compared to a simple switch that selects one antenna or another, never both at the same time
  - Single receiver switches from one antenna to another only when antenna is in a fade
  - Best diversity gains obtained when received signals on different antennas are uncorrelated or slightly correlated
  - Two antennas separated by about an odd multiple of a quarter of a wavelength are enough to cause almost independent fades at receiving antennas
  - Amount of separation depends on amount of delay spread to be mitigated
  - At 2.4 GHz, quarter wavelength is roughly equivalent to 3 cm (as illustrated in wireless NIC picture)
  - Note that if one external antenna is used instead, range is extended but multipath mitigation impact can be poor



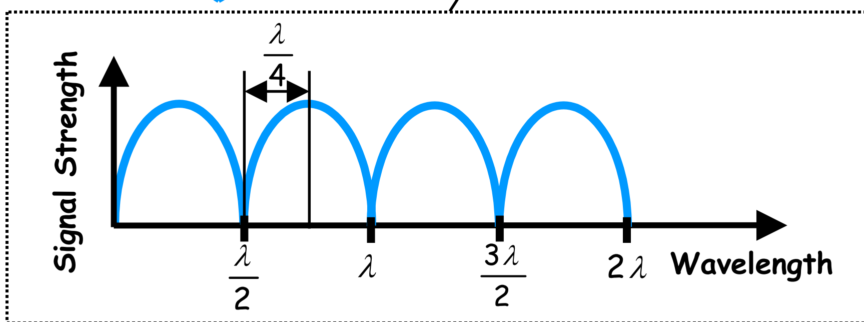
Selection Antenna Diversity

- Requires signal strength at each antenna to be monitored by an individual receiver
  - Best signal from multiple reflections selected from two or more antennas
  - Maximal ratio combining can be employed: signals received by different antennas are weighted and combined to produce best signal-to-noise ratio



$$D = \frac{n\lambda}{4} \text{ where } n = 1, 3, 5, \ldots$$

Note: Also applies to switched antenna diversity

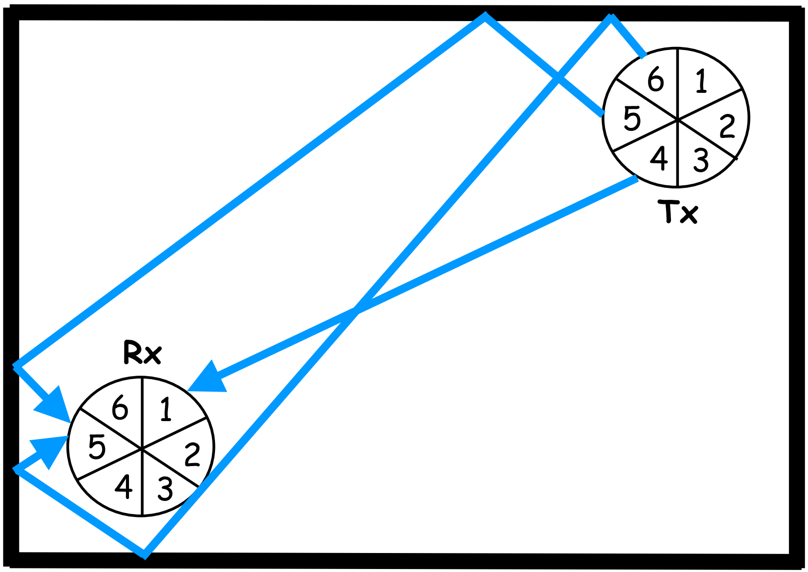


Beamforming and Phased Antenna Arrays

- Employ directional antenna beams from multiple antenna arrays that radiate only in specific directions
  - Angular segregation of wanted signal from interferers
  - Attempts to logically partition wireless link into non-interfering sets: provides gain along intended direction and attenuation in undesired directions
  - In doing so, wireless coverage area is broken down into smaller areas called sectors, each serviced by a directional antenna
  - Equivalent to increasing number of communication links, which increases system capacity
  - Also helps enlarge signal coverage area while reducing interference and transmit power requirements
  - Requires uncorrelated channels
- Identical information transmitted simultaneously from all antennas arrays when performing antenna selection
  - Selection algorithms at antennas assess received signal strength and quality from different paths
  - Gives system a high probability of finding a path that is not corrupted by fading or interference

Beamforming and Phased Antenna Arrays

- Antenna arrays can be made adaptive
  - When employed by an access point, these antennas are able to track the locations of mobile users
  - Vivato product uses adaptive beamforming phased arrays to improve range performance



Antenna Selection Table

Rx \ Tx	1	2	3	4	5	6
1				Best		
2						
3						
4						
5					Better	Good
6						

Multiple Input Multiple Output (MIMO) Systems

- 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
  - Motorola Labs tested 20-MHz OFDM channel with 300 Mbit/s downlink speeds on a mobile network
  - Agere demonstrated 162 Mbit/s 3x3 MIMO system in 2002, proposed 4x4 MIMO at 500 Mbit/s in 802.11n
  - Toshiba and Airgo chipset vendors have demonstrated that MIMO can boost current 802.11 data rates to over 100 Mbit/s
  - Intel committed to include MIMO into its future WLAN products and push for inclusion of MIMO in IEEE 802.11n (successor to 802.11a, b and g)
  - Netgear's 108 Mbit/s router has three MIMO antennas, offers better range, and is compatible with 802.11b/g

Multiple Input Multiple Output (MIMO) Systems

- Improves spectral efficiency by using multiple channels simultaneously transmitted over multiple antennas at both transmitter and receiver
  - Spatial multiplexing schemes at multiple receive antennas separate interfering streams while improving signal processing capabilities (compare human ears)
  - Different from directional antennas which try to cancel multipath
  - Overall signal power equally split among transmit antennas
  - Accurate channel knowledge needed (channel sounding methods typically used to estimate channel response)
  - Receiver decoding complexity critical in determining actual performance
- Spectral efficiency improves in proportion to number of antennas used at both transmitter and receiver
  - Pioneering research of Foschini and Telatar shows that capacity increases linearly with $min(m, n)$ where m is the number of transmit and n the number of receive antennas, but only logarithmically with signal to noise ratio (SNR)
  - Sufficient RF signal scattering in multipath environment assumed (need not always apply in an outdoor environment)
  - In addition, both diversity and coding gains can be achieved using multidimensional space time coding (STC) or Bell Laboratories layered space-time (BLAST) coding

Multiple Input Multiple Output (MIMO) Systems

- In BLAST coding, each antenna transmits an independently modulated signal simultaneously and on the same carrier frequency
- Alternatively, redundancy between transmitting antennas can be increased to improve robustness by using STC
  - Typically employs a smaller number of receive antennas than BLAST
  - Redundancy reduces throughput performance of STC compared to BLAST
- Both BLAST coding and STC make use of space (multiple antennas) and time domains in encoding/decoding data symbols
  - Key is to efficiently map data symbols to various signals transmitted by individual antenna elements using a code matrix
  - In general, rank and determinant of code matrix determines diversity gain and coding gain respectively
  - Diversity gain dominates bit error probability at high SNR and should therefore be maximized before coding gain

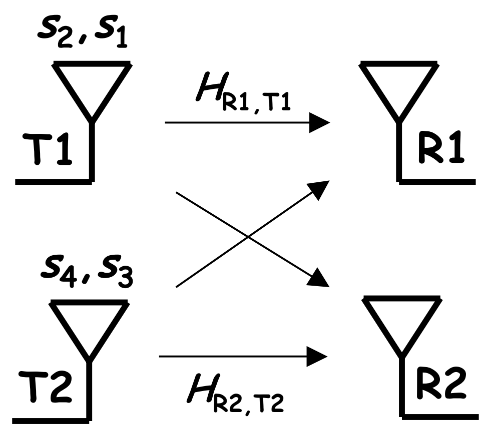
2 x 2 MIMO Systems

- Can be generalized to $n \times m$ MIMO systems
  - s_1, s_2 mapped into PSK or QAM constellation
  - X also known as a *code matrix* that attempts to maximize diversity gain, coding gain, and channel capacity (data rate)

Bell Laboratories layered space-time (BLAST) coding

$$X = \begin{bmatrix} s_1 & s_2 \\ s_3 & s_4 \end{bmatrix}$$

Rate = 2



$$Y = HX + N$$

Y = Received Signals
X = Transmitted Signals
H = Channel Response
N = Channel Noise

BLAST Coding

- Exploits rich scattering in multipath environment by simultaneously transmitting independent data streams from different antennas
  - At a given symbol interval, two signals (namely s_1 from T1 and s_3 from T2) are simultaneously transmitted from two antennas
  - In next symbol interval, signal s_2 is transmitted from T1 and signal s_4 is transmitted from T2
- Minimizes redundancy among multiple antenna signals to maximize data rate (i.e., channel capacity)
  - Obvious from code matrix when compared to STC (e.g., Alamouti STBC, STTC)
  - Spatially multiplexed data streams are separated by multiple receive antennas using interference cancellation, improving peak throughput of system
  - Hence, number of receive antennas should not be less than number of transmit antennas
  - Reduced diversity due to lack of redundancy across antennas, results in poor bit error performance, may reduce achievable throughput at low SNR
  - Employs nonlinear receivers (e.g., maximum likelihood detectors) to achieve better performance at the expense of substantially increased complexity

Space Time Coding

- First introduced by Tarokh, et al from AT&T Research Labs (1998)
  - Combines channel coding with modulation and diversity at transmitter to improve data rates and reliability of communication
  - Introduces redundancy among multiple antenna signals to maximize spatial diversity gain and minimize bit error rate
  - Well-constructed space time codes achieve a fair amount of coding gain in addition to diversity gain
- Spatial diversity available if individual transmission paths from transmit to receive antennas fade more or less independently
  - Probability of all paths fading at the same time significantly smaller than probability of a single path experiencing fading
  - Correlation between paths can be introduced by small antenna spacing at transmitter and receiver, lack of scattering, strong line-of-sight component
- Unlike BLAST coding, multiple antennas at receiver are optional
  - An advantage for asymmetric links where high downlink rates are crucial
  - Most designs work for any number of receive antennas: extra receive antennas provide receive diversity gain in addition to the transmit diversity gain
- Can be broadly classified under space time block coding (STBC) and space time trellis coding (STTC)
  - STBC, STTC can achieve same diversity gain as maximal ratio receive combining

Space Time Block Coding (STBC)

- Buffers a block of data symbols and then forms a code matrix from these symbols
  - Can be applied independently to each OFDM subcarrier
  - Several examples of STBC code matrices for various number of transmit and receive antennas are shown below
  - Note that the use of 3 receive antennas can place heavy demands on mobile terminals although this helps to create more symmetrical data rates

2x1	t_1	t_2
T1	s_1	s_2
T2	$-s_2^*$	s_1^*

Alamouti STBC

3x2	t_1	t_2
T1	s_1	s_2
T2	$-s_2^*$	s_1^*
T3	s_3	s_4

4x2	t_1	t_2
T1	s_1	s_2
T2	$-s_2^*$	s_1^*
T3	s_3	s_4
T4	$-s_4^*$	s_3^*

Two concatenated Alamouti STBCs

4x3	t_1	t_2
T1	s_1	s_2
T2	$-s_2^*$	s_1^*
T3	s_3	s_4
T4	s_5	s_6

Concatenated Alamouti STBC and 2x2 BLAST

Alamouti STBC

- Special case of STBC using 2 transmit and 1 receive antennas (2 x 1)
  - At a given symbol interval, two signals (namely s_1 from T1 and $-s_2^*$ from T2) are simultaneously transmitted from two antennas, where * denotes complex conjugation
  - In next symbol interval, signal s_2 is transmitted from T1 and signal s_1^* is transmitted from T2
  - Code matrix becomes

$$X = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

Rate = 1

  - Note that $XX^T = \alpha I_{2x2}$, where X^T is transpose of X, α is a constant, I_{2x2} is a 2x2 identity matrix
- Employs orthogonal channels, requires least channel assumptions
  - Transmitted signals are decoupled and can be decoded independently
  - Optimum decoding using simple linear processing possible although this may result in severe noise enhancement
  - Contrast complexity of maximum likelihood detection, which requires signals to be decoded jointly
  - Provides excellent performance in highly correlated channels

Alamouti STBC

- Consider the following Alamouti code matrix transmitted over a MIMO channel:

$$X = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

- Receiver buffers the received symbols (r_1, r_2) for two symbol periods and are given by:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \begin{bmatrix} s_1 h_1 + s_2 h_2 + n_1 \\ -s_2^* h_1 + s_1^* h_2 + n_2 \end{bmatrix}$$

- Taking conjugates for r_2 (this operation does not introduce any correlation for the noise entities), we obtain:

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}$$

- Recovered symbols s_1, s_2 are decoupled and can be decoded independently

Space Time Trellis Coding (STTC)

- Same data symbol transmitted at different symbol intervals by different antennas to obtain diversity gain
  - For the same number of transmit and receive antennas, STTC diversity gain equals STBC diversity gain
  - Trellis encoding provides additional coding gain, improving error performance
  - Need for soft Viterbi decoder increases decoding complexity at receiver
  - Decoding complexity increases exponentially with number of transmit antennas (just like maximum likelihood decoding) and number of trellis states
- Block of data symbols is fed into space time trellis encoder
  - Output symbols transmitted from multiple antennas
  - Tail of zeros appended to input data stream to reset encoder to zero state at end of transmission burst

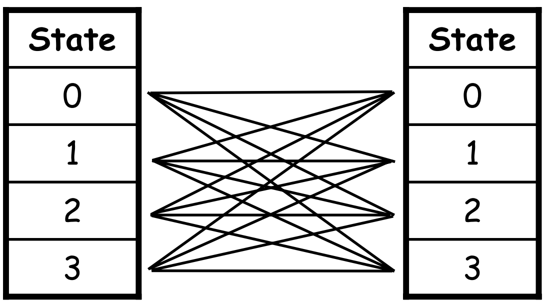
STTC with Two Transmit Antennas

- Data symbol to be transmitted depends on current input and current encoder state
  - If encoder is in initial state *0* and input data is *1*, then output symbol *0* is transmitted from first antenna
  - Output symbol *1* is transmitted from second antenna
  - Hence, if input data stream is *1 3 0 1 2*, resultant code matrix *X* is

Initial encoder state →

$$X = \begin{bmatrix} 0 & 1 & 3 & 0 & 1 & 2 \\ 1 & 3 & 0 & 1 & 2 & 0 \end{bmatrix}$$

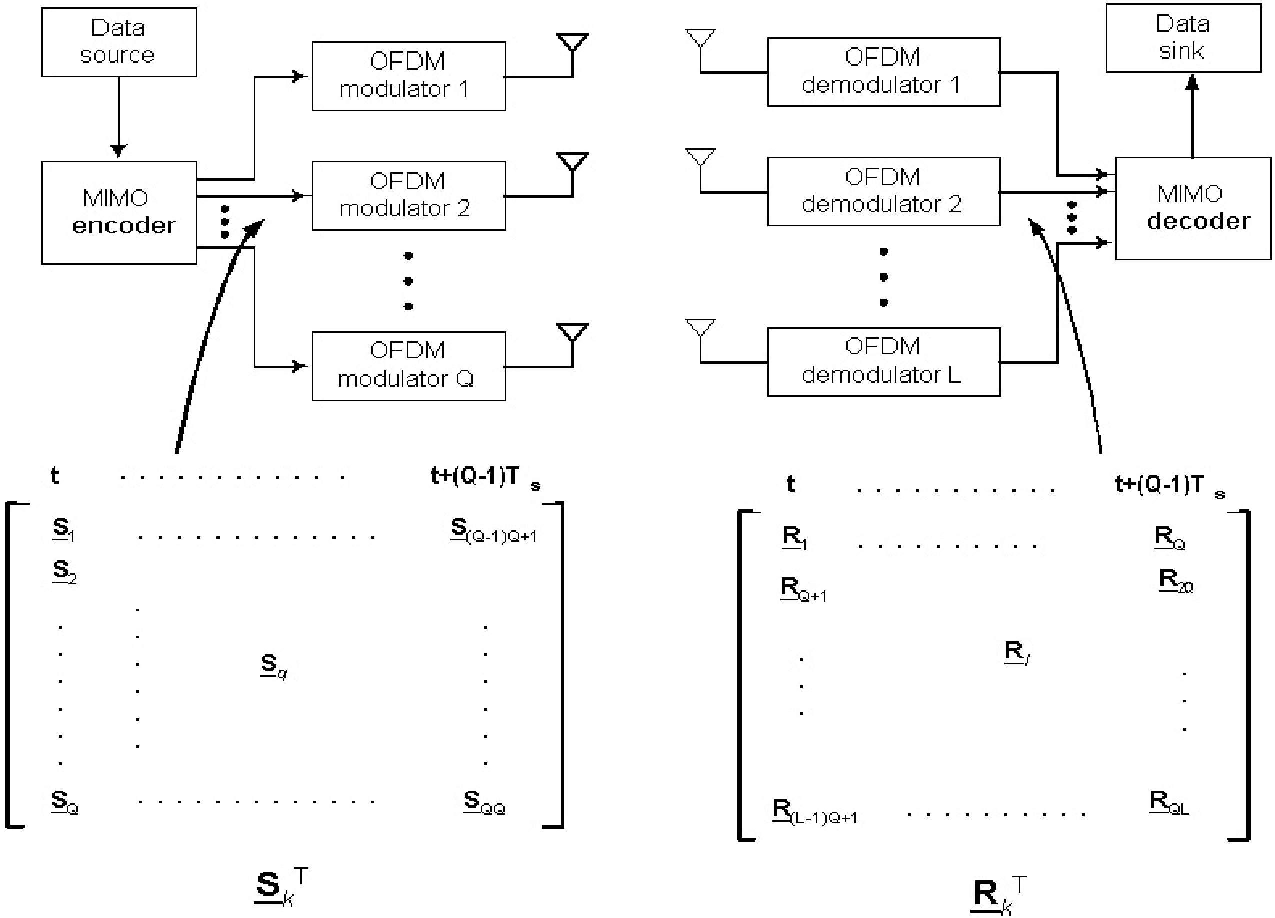
← Padded zero(s) to reset encoder



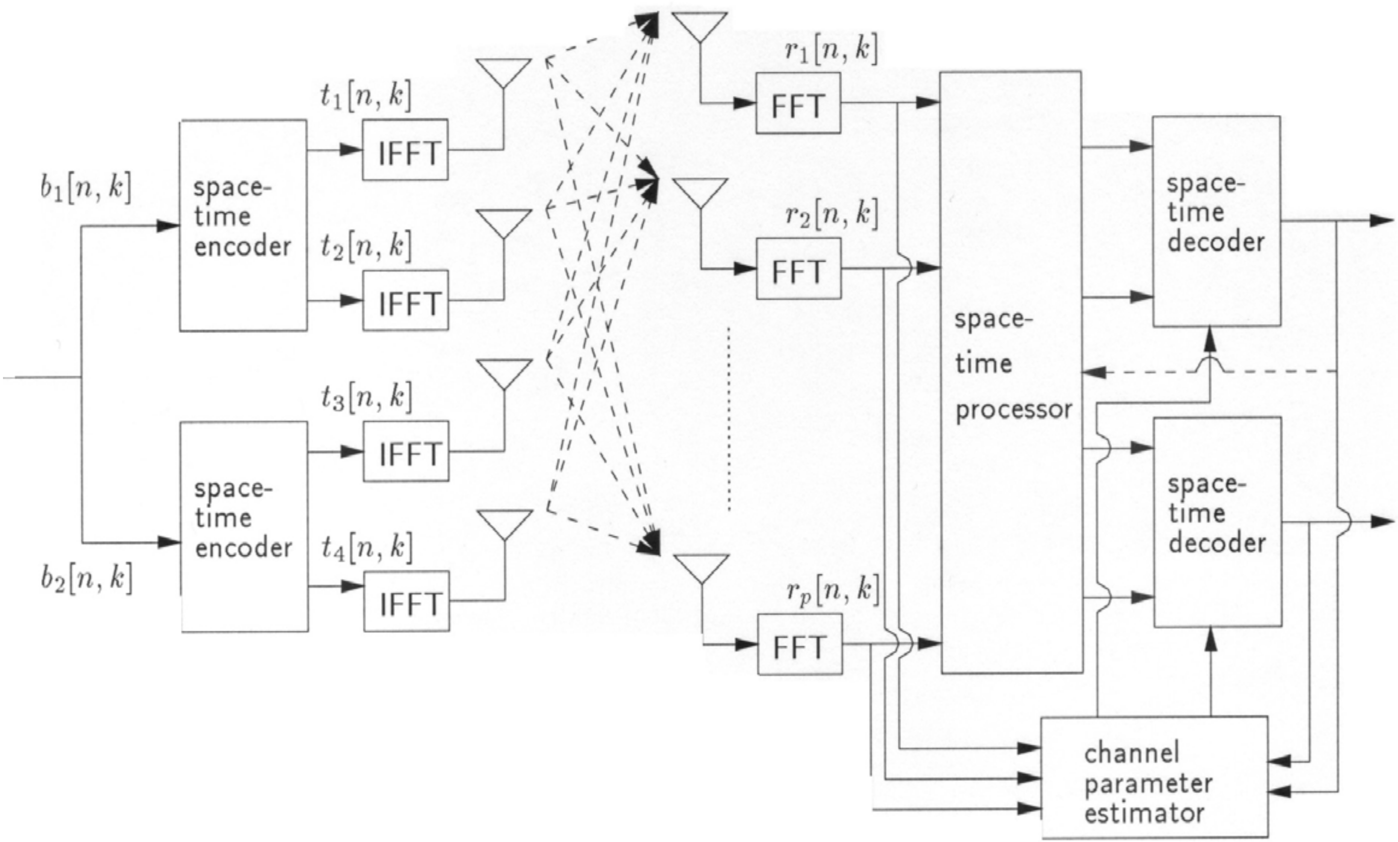
4-state QPSK Constellation

Output Data Symbols			
Input 0	Input 1	Input 2	Input 3
00	01	02	03
10	11	12	13
20	21	22	23
30	31	32	33

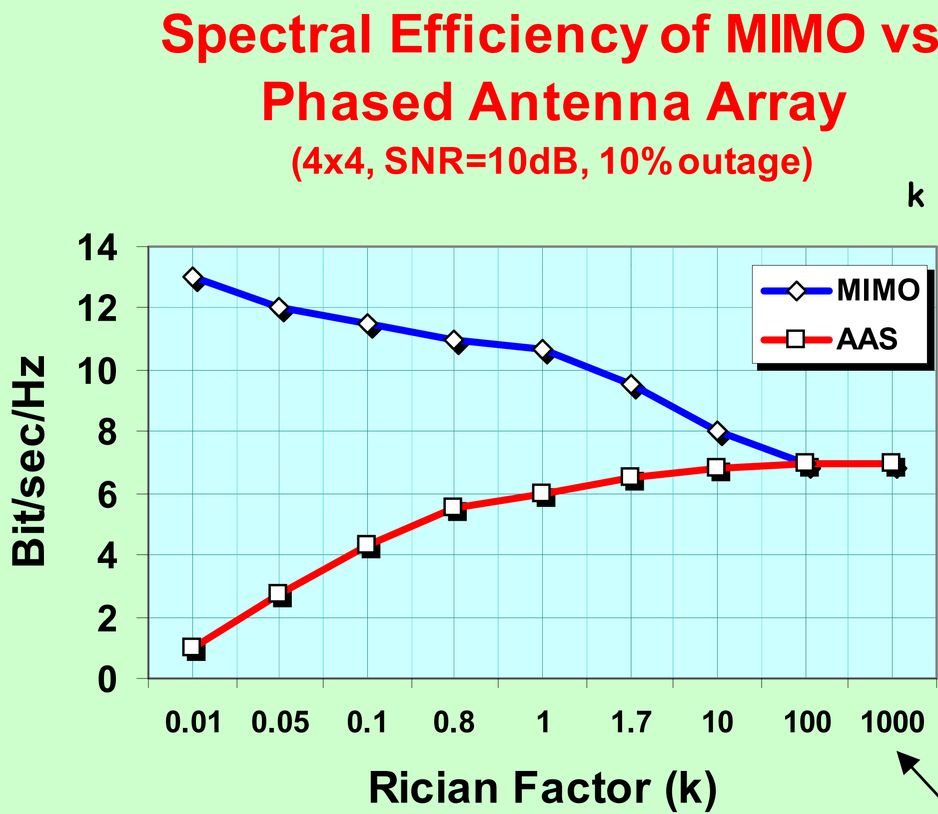
Q-Transmit L-Receive MIMO OFDM System



MIMO OFDM Transmitter and Receiver Structure



MIMO versus Phased Antenna Array



$$k = \frac{\text{direct path power}}{\text{diffuse power}}$$

Dominant LOS path

Source: Nortel, Lucent " MIMO" ITU-R 229/8

AAS: Adaptive Antenna System

Multichannel Medium Access Control

- Need to co-ordinate multiple channels, multiple users and possibly multiple antennas
  - First step to efficient bandwidth utilization is to choose bandwidth of each channel appropriately (20 MHz seems a good value)
  - Second step to decide whether to co-ordinate channels using a single MAC or multiple MAC layers
  - Conventional protocols such as CSMA, TDMA needs to be modified in multichannel environment, especially if fully symmetric wireless channels are involved
  - Synergy with other emerging standards such as DOCSIS 3.0 cable standard
- Cross-layer design with physical layer becoming increasingly popular
  - Protocol layering an important abstraction, reduces network design complexity, not well suited for wireless networks, nature of wireless medium makes it difficult to decouple layers
  - Need to evaluate performance tradeoff between use of OFDM, MIMO, phased arrays, spread spectrum for 700 MHz, 2.4 GHz, 5 GHz bands

QoS and Network Availability

- Usable throughput will always be a key performance metric for wireless networks
  - Due to higher overheads needed for wireless transmission, especially as new wireless technologies operate at increasingly higher data rates
  - While these overheads are sometimes unavoidable, network performance can be improved by implementing appropriate QoS algorithms that utilize available radio spectrum in the best possible way depending on traffic requirements
- A more sensitive issue for wireless networks that operate on unlicensed radio spectrum e.g., Wi-Fi and some Wi-Max standards
  - Such networks are prone to denial of service (DoS) attacks where the airwaves are jammed by a client that transmits packets endlessly, preventing all other clients from transmitting and disrupting network operation
  - However this can be avoided using intelligent spectrum management techniques that switch to unaffected frequency channels
  - Deployment of multihop networking will also limit the impact of DoS attacks to only certain parts of the network
  - If the mesh network is dense enough, the disruptive impact of such attacks can be virtually eliminated since alternative paths can be found easily

QoS Scheduling and Surplus Bandwidth

- Takes into account packet error probability (due to unreliable wireless medium) in addition to packet drop probability
- Single packet transmission
  - If channel causes independent errors from packet to packet and error probability is constant for all packets of same length
  - Probability of dropped packet after n retransmissions is $p_{drop} = (p_e)^{n+1}$ where p_e is packet error probability in a single transmission attempt
  - If $p_e = 0.1$ and $p_{drop} = 10^{-8}$, then $n = 7$, scheduler to accommodate 7 TXOPs
- Multiple packet transmission
  - Suppose N packets need to be transmitted correctly and packet error probabilities are Bernoulli distributed
  - Then

$$p_{\text{drop}} = \sum_{k=N_{ex}}^{N+N_{ex}} \binom{N+N_{ex}}{k} (p_e)^{N_{ex}} (1-p_e)^{N+N_{ex}-k} = \mathrm{B}_{p_e}(N_{ex}, N+1)$$

  - Where B( ) is the Incomplete Beta Function, assuming N is large
  - If $N = 100$, $p_e = 0.1$, $p_{drop} = 10^{-8}$, then $N_{ex} = 38$
  - Surplus bandwidth allowance, $S = N_{allocated}/N_{payload} = (N + N_{ex})/N = 1.38$
  - If $N = 100{,}000$, $p_e = 0.1$, $p_{drop} = 10^{-8}$, then $N_{ex} \approx 12{,}000$, $S \approx 1.12$
  - Surplus bandwidth decreases as N increases
  - For infinite packet stream with no delay constraints, S approaches lower bound of 1.111

Mobility: Mobile IP

- Originally designed to allow communication using a permanent home IP address while being connected to foreign wireless or wireline network
  - Has been extended to allow roaming between wireless subnets while maintaining active connections, defined in IETF RFC 3344
  - Employs home agent to maintain binding between client's home IP address and the care-of address in its current location
  - Problem of triangular routing: packet to mobile host travels via home agent, whereas packet from mobile host is routed directly to destination
  - Can be expected to be aggravated in a wide area network, when the distance increases between the different entities
  - Relies on dedicated servers to maintain tables of remote mobile clients, "anticipated" location of each mobile client must be manually entered into system by administrator (tedious process), servers represent a single point of failure, if server fails, no mobile client will be able to roam
  - Licensed software to be purchased and loaded on all end-user devices
- Like IP tunneling, can be classified as a macromobility solution
  - Virtual wireless subnets can be created to track users, avoids creating a physical subnet for wireless devices
- Micromobility protocols localize mobility information
  - Reduces handoff latency and signaling load

Mobility: Session Initiation Protocol (SIP)

- Originally designed to provide virtual "dialtone" over the Internet
  - Allows one computer user to know if another user is online and available for communication (just like regular telephony over public switched network)
  - Has been extended to provide application-layer mobility (both personal and device mobility) as opposed to network layer mobility using mobile IP
  - Does not require changes to the operating system of any of the participants and thus can be easily deployed on a wider scale than mobile IP
  - Does not have mobile IP's triangulation routing problem
- Mobile IP and SIP mobility not suitable for fast or small-scale (micro) mobility
  - Fast handoffs needed for fast mobility should be supported by lower layers
  - One suggestion is to employ cellular IP together with mobile IP or SIP

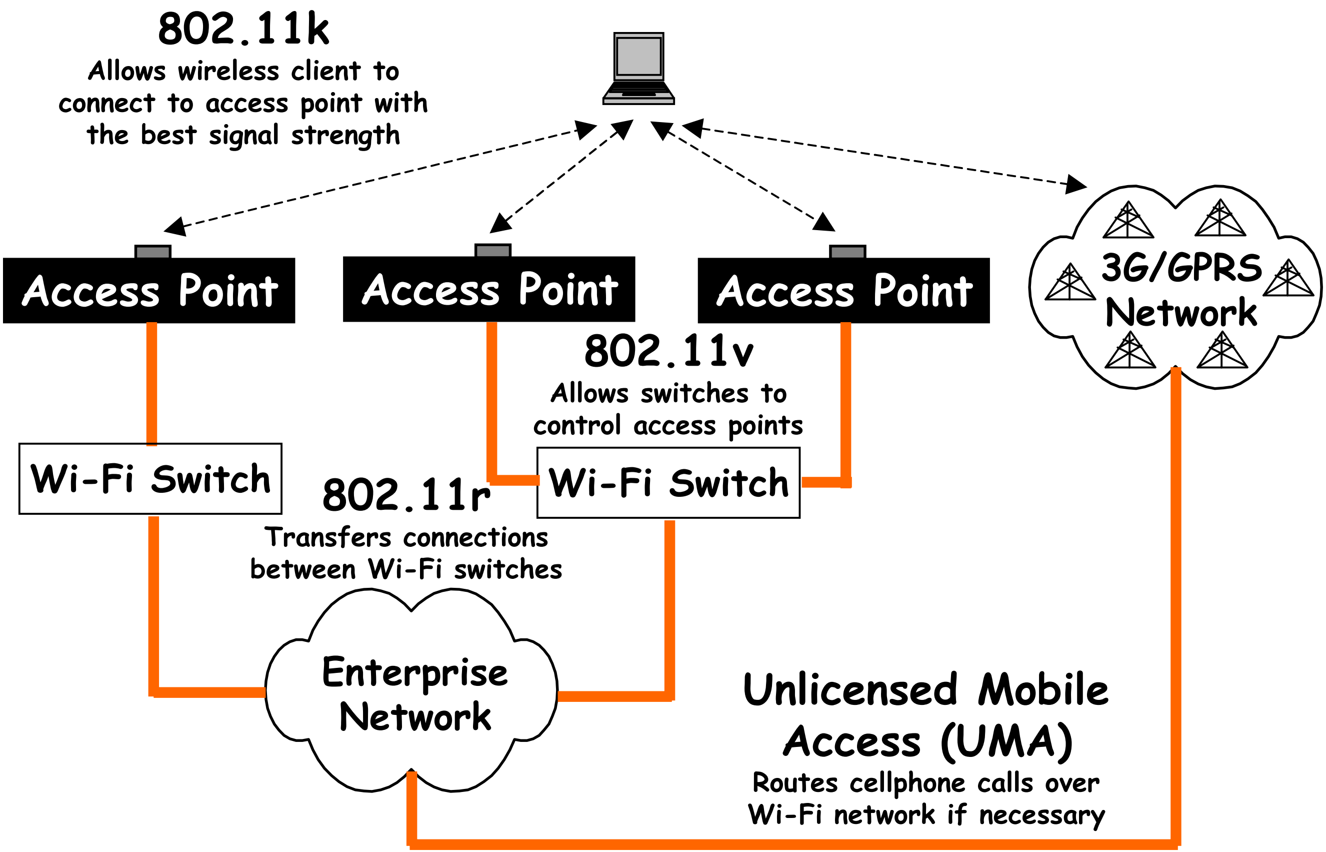
Mobility: Wireless Access in Vehicular Environments

- Latest WAVE draft (802.11p version 1.1) issued on January 2005
  - Operational mode used by 802.11 devices in Dedicated Short-Range Communications (DSRC) band allocated for Intelligent Transportation Systems (ITS) communications
  - Provides wireless communications over line-of-sight distances of less than 1000 m between units on high-speed vehicles (on-board units) or on roadsides (e.g., streetlamps), each unit provides an wireless interface for client devices operating at vehicular speeds
  - Supports existing uses for 802.11, includes new applications such as roadway safety (e.g., vehicle collision avoidance) 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

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)

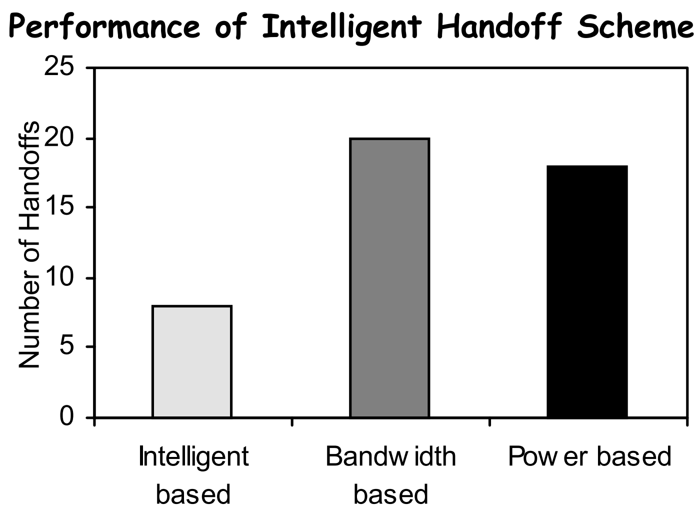
Higher speeds, shorter packets preferred

Mobility: Integrated Cellphone/Wi-Fi Roaming



Mobility: Intelligent Handoff Minimization

- Heterogeneous wireless networks have varying radio resources
  - For instance, Wi-Fi vs 3G vs Wi-MAX; 802.11a vs 802.11b/g; Wi-Fi hotspot service A vs Wi-Fi hotspot service B; wireless VoIP vs cellphone; UWB vs Wi-Fi
  - Need to minimize handoffs since they are disruptive due to changing channel and service quality when a mobile device changes mode (even within the same type of wireless network)



Security: Extensible Authentication Protocol (EAP)

- An extension to Remote Access Dial-In User Service (RADIUS)
  - RADIUS's vendor specific attribute (VSA) allows vendor to extend RADIUS operation to fit its own products without conflicting existing RADIUS attributes or other companies' VSAs
  - Originally defined in IETF RFC 2284, updated in RFC 3748, enhanced by Diameter RFC 3588
  - Security framework enables multiple authentication methods (e.g., passwords, tokens, kerberos, digital certification) to be activated in sequence if desired
  - Creates new key for every user and every new session
  - Provides centralized security management of thousands of users
  - Ideal for organizations with large user base
  - By itself, does not provide mutual authentication (e.g., EAP-MD5)
- EAP framework can be extended to wired LANs
  - Enables an enterprise to use *single* security architecture for every access method (wireless and wired)
- 802.1x encapsulates lightweight version of EAP for port-based network access control
  - Ratified in June 2002, also known as EAP over LAN (EAPOL)
  - Part of 802.11i security

Security: Versions of EAP

- Security protocol developed by Microsoft for XP OS
  - Provides mutual authentication with non-repudiation, encryption, secure key exchange between two endpoints, integrity protected cipher negotiation, keyed message integrity checking (MIC)
  - Resides on OS, thereby allowing different client hardware
- Protected EAP (PEAP)
  - Simplified version of EAP-TLS
  - Authenticates server only and hence avoids having to distribute user certificates for every client
  - Provide mutual authentication between EAP client and server
- EAP with Tunneled Transport Layer Security (EAP-TTLS)
  - Developed by Funk Software to enable EAP attribute exchanges within an encrypted TLS authentication tunnel (setup at Layer 2)
  - Robust, scalable, flexible
- EAP-SIM6
  - Used in IPv6
- EAP-MD5
  - Used in Point-to-Point Protocol (PPP) connections to the Internet over telephone lines

Security: Wireless Security Trends

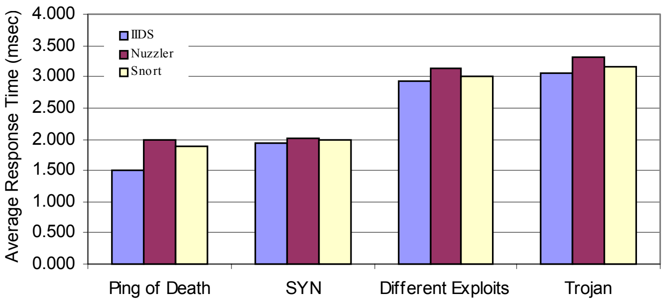
- Converging towards an extended form of TLS (for wireless data networks) and SIM (for cellular networks) using EAP
  - EAP a flexible scheme that allows multiple user-authentication methods to be encapsulated under a unified security protocol
  - This in turn provides flexibility in the choice of user authentication, ensuring seamless compatibility when deployed in heterogeneous wireless networks
  - More importantly, EAP can multiplex several authentication methods in sequence (i.e., serial authentication)
  - This capability can be exploited in new security approaches that allow user to authenticate network before revealing its identity
  - Allows mobile user to quickly re-authenticate network and maintain connections as it roams across different networks
- Besides seamless integration with both wired and wireless networks, EAP also compatible with many popular operating systems of mobile computing devices

Content Security: Digital Rights Management

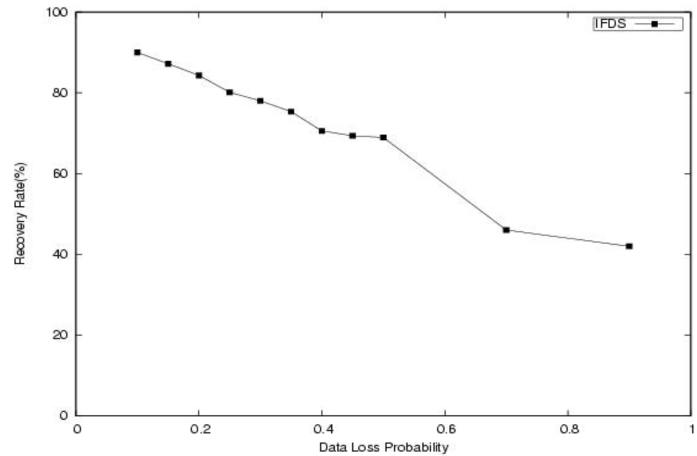
- Both IP TV and p2p video provide a cost-effective and unified way of distributing video content
  - –However, there is a fear that such video content distribution could be abused if no proper digital rights management (DRM) solutions are put in place
  - –It can be shown that the distributed nature of p2p video streaming achieves better performance and scalability than IP TV
  - –Key question here is how to control video content, will ultimately help increase availability of high fidelity multimedia content
  - –KaZaA (a dominant online music swapping platform) has forced big recording labels to agree to offer music downloads for as little as $1 a song
- DRM solutions based on information hiding can increase both security *and* reliability levels when distributing p2p video and IP TV content
  - –Key motivation is to prevent video content from being changed, intentionally or unintentionally, by both legitimate and non-legitimate users
  - –When used properly, also makes it almost impossible to trace the author and recipient of a message, allowing conversations to be submerged in a flow of information in a manner that no one can know if a conversation exists at all
  - –Potential applications to DRM include video content authentication, proof of ownership, copyright protection, usage control, distribution tracing, authorized access control

Intelligent Wireless Security

- Unified security architecture using intelligent algorithms
  - Key components: EAP and information hiding
  - EAP crucial for integrating wireless data and cellular voice security
  - Information hiding increases both security *and* reliability levels of transmitted information, information can be protected from wireless DoS attacks



Performance of an Intelligent Intrusion Detection System (IIDS)



Performance of Information Hiding using an Intelligent Fuzzy Decoding System (IFDS)

Wireless/Wireline Integration: IMS

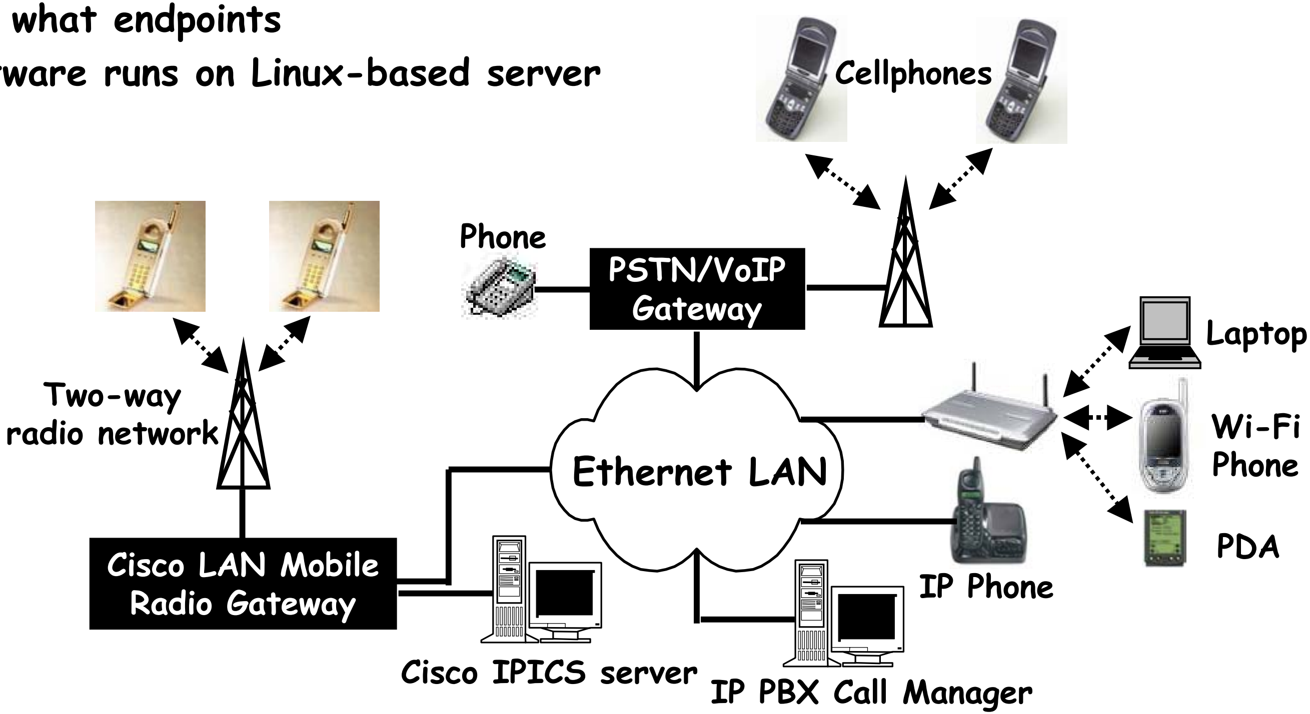
- IP multimedia subsystem (IMS) is an IP convergent solution
  - Reference IP core network architecture defined by 3GPP and 3GPP2 standards, targeted towards 3G wireless networks
  - Based on IETF Internet protocols, originally promoted by Lucent
  - Access independent as it supports IP connectivity over wireline IP, 802.11, CDMA, packet data GSM/EDGE/UMTS and other packet data applications
  - Unifying framework for both network and application layers
- Key elements
  - Lucent's softswitch manages IP voice and multimedia communications
  - Lucent's Super Distributed Home Location Register (S-DHLR) maintains user location, subscriber profiles (one profile for all services) on mobile networks
  - Lucent's Mi-Life applications suite personalizes service delivery and billing
  - IBM Websphere middleware, eServer BladeCenter, Service Provider Delivery Environment
- Alcatel announced on Sept 26, 2005 that it has achieved a world first by demonstrating delivery of IMS-based services over Wi-MAX
  - Demonstration utilized key components of Alcatel's IMS solution connected over three different access technologies: DSL, 3G/UMTS, WiMAX
  - Demonstration clearly showed the IMS promise of rich multimedia services delivered over any kind of access network

Wireless/Wireline Integration: Iobi and One

- Verizon's Iobi is a network-based convergent solution
  - Integrates on a single device fixed/mobile telephony and any computing device (e.g., PCs, laptops, and PDAs)
  - Real time call management including programmable call forwarding so that calls can be directed to user's telephone, cellphone or PC
  - Multimodal communications: regardless of how a message is sent, customer can decide how to receive it (e.g., email, voicemail, SMS)
- Verizon's One is a top end cordless telephone
  - Touch screen computer has built in DSL modem (enabling broadband access) and WLAN router (allows wireless connections to all home PCs)
  - Combined with Verizon Iobi, Verizon One can synchronize calls emails, calendars, voicemails
- Combination of Iobi and One represents a strong convergent solution for residential customers
  - Will build on success of Verizon's 'Freedom' bundles of flat rate fixed, mobile, and DSL services

Wireless/Wireline Integration: IPICS

- Cisco's IP Interoperability and Collaboration System (IPICS)
  - Integrates disparate networks e.g., two-way public safety radio, cellular, wireless LANs, traditional analog/digital phones, wired/wireless IP telephony
  - With all traffic converted to IP, server controls what traffic can communicate with what endpoints
  - Software runs on Linux-based server



Wireless/Wireline Integration: Key Issues

- IP the unifying network layer framework
  - AT&T recently passed 1.7 peta bytes of daily IP traffic on their network: testament to importance of IP
- Ethernet encapsulation
  - Ubiquity of Ethernet deployment, including gigabit Ethernet LANs, metro Ethernet, and wireless Ethernet such as Wi-Fi
- Seamless end-to-end IP QoS on an Ethernet platform
  - Key to success will be the integration of resource allocation algorithms and individual SLA enforcement across heterogeneous access networks and core backbone networks and services
  - QoS maintenance: channel/speed mismatch, broadcast versus point to point
  - Wireless MAC scheduler the key: how to move packets from wireline to wireless domain seamlessly (at the Broadband Institute, we have done some work on integrating DOCSIS with Wi-Fi)

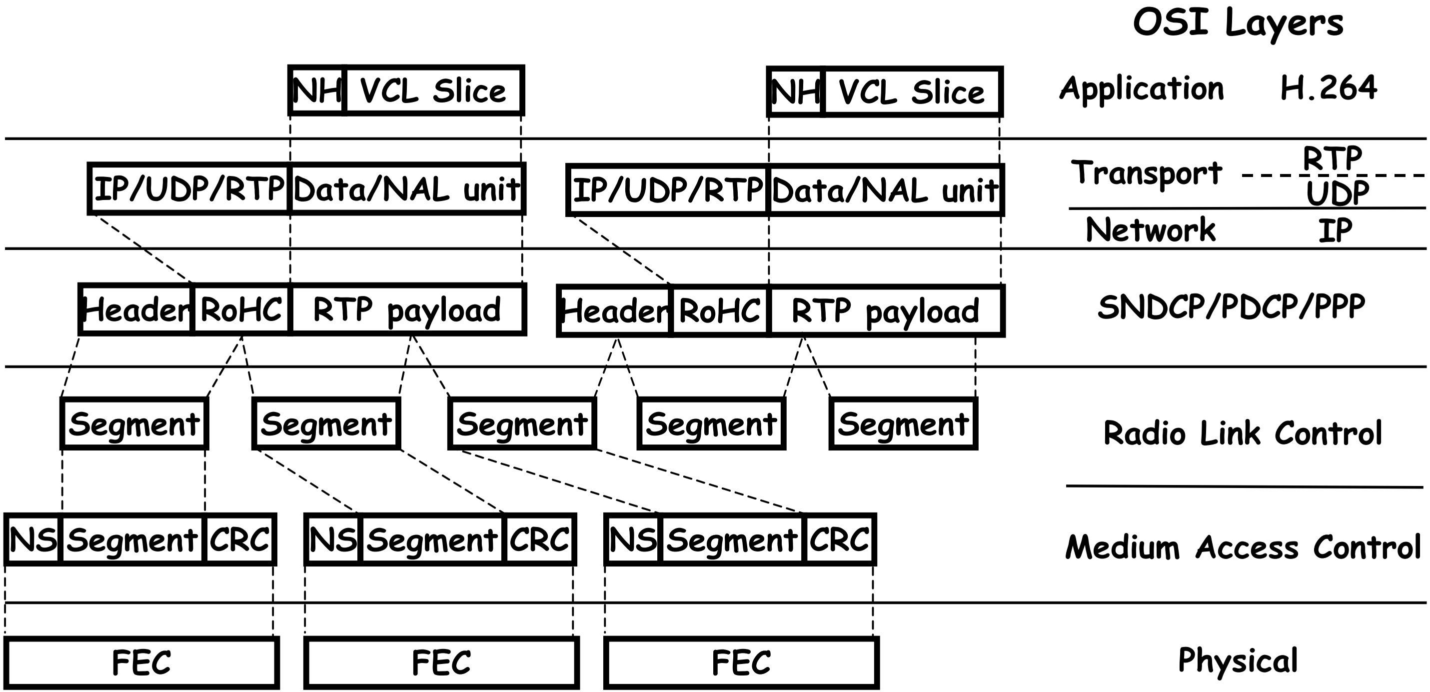
Wireless VoIP

- Packet-voice transmission over the Internet (VoIP) has revolutionized the way telephony traffic is carried over networks
  - Although sensitive to network congestion and delay, technology is driven by tremendous reduction in deployment costs regardless of distance
  - Service is popular with consumers because it offers a high quality voice connection for a fraction of the cost of traditional lines on a public switched telephone network (PSTN)
- Becoming significant driver for VoIP in general
  - Allow wireless Internet connections to double up as inexpensive phone lines
  - Will present challenge to both fixed line and mobile (cellphone) operators e.g., how do you protect cellular revenue from being eroded by VoIP?
- Voice over Wi-Fi also becoming a big phenomenon
  - Business-wise this makes sense since Voice over Wi-Fi marries two potent technologies: Wi-Fi and VoIP
  - More cost effective than cellular VoIP
  - With integrated cellular/Wi-Fi phones emerging, wireless VoIP may become the more significant driver for VoIP than wireline VoIP

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 and MPEG-4 Visual Simple Profile commonly used in handheld products
  - However, H.264/AVC video codec will become important in the near future
  - Recommended codec for all 3GPP video services
  - Excellent for wireless transmission: (a) compression efficiency improvement by at least a factor of two over prior standards (b) can be easily integrated into existing and future networks (c) addresses needs of different applications (d) provides bit rate adaptivity
  - Codec processes network abstraction layer (NAL) units that can be encapsulated into different transport protocols and file formats e.g., MPEG2 transport stream, real-time transfer protocol (RTP) and MPEG4 file format
  - RTP payload supports 3 modes: (a) single NAL unit transported in single RTP packet, (b) non-interleaved mode where several NAL units of the same picture is packetized in single RTP packet, (c) interleaved mode where several NAL units from different pictures are packetized into single RTP packet, not necessarily in their decoding order

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

Wireless Video Applications for 3GPP

Application	3GPP	Max. delay	Encoder buffering requirements	Transport feedback	CSI	Encoding
Download and play	MMS	NA	None	Yes	NA	Offline
On-demand, pre-encoded streaming	PSS	1 s	Yes	Yes	Partly	Offline
Live streaming	PSS	200 ms	Yes	Partly	Partly	Online
Multicast	MBMS	1 s	Limited	Limited	Limited	Both
Broadcast	MBMS	2 s	None	None	None	Both
Conferencing	PSC	250 ms	Limited	None	Limited	Online
Telephony	PSC	200 ms	Yes	Limited	Partly	Online

CSI: Customized Applications for Mobile network Enhanced Logic (CAMEL) Subscription Information

MBMS: Multimedia Broadcast/Multicast Service

MMS: Multimedia Messaging Service

PSC: Primary Synchronization Code

PSS: Packet Switched Stream

Error Robustness in Wireless Video Transmission

- Most codecs apply error resilience features at the expense of compression efficiency
  - –Apply Shannon's separation principle: Combine compression efficiency with link layer features that completely avoid losses such that compression and transport can be completely separated
- Encoder-decoder mismatch avoidance
  - –Prevents error propagation
- Error recovery and concealment
  - –In case of losses, minimize visual impact of losses on actual distorted image
- H.264/AVC provides various levels of defense against errors
  - –Loss correction below codec layer: Minimize losses in the wireless channel without completely sacrificing the video bit rate using (a) application layer FEC, (b) selective application layer retransmission, (c) low bit rate feedback channel for loss control and management messages e.g., real-time TCP (RTCP)
  - –Error detection: If errors are unavoidable, detect and localize erroneous data
  - –Prioritization methods: If losses are unavoidable, at least minimize loss rates for important data (e.g., control)

Peer-to-Peer (p2p) Broadband Access

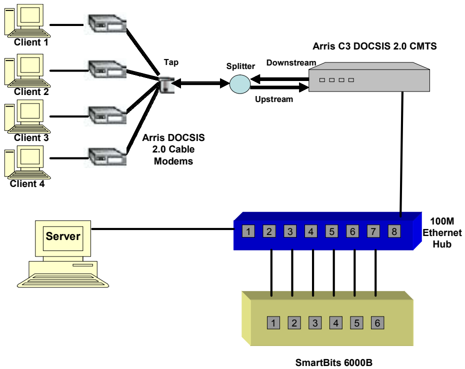
- p2p file sharing accounts for over 80% of Internet backbone traffic
  - Disruptive technology, just like wireless access
  - Overcomes current lack of IP multicasting support by major ISPs
- With p2p gaining popularity, new business models may be required
  - Concept of cable companies controlling headend may be coming to an end
  - p2p voice applications such as Skype (www.skype.com) are challenging traditional VoIP (2 million Skype users first 3 months, 1 million simultaneous subscribers 1 year later, partnered Boingo to provide voice over Wi-Fi service for 18,000 hotspots, bought by Ebay for US$2.6 billion in Sept 2005)
  - FCC considering regulating VoIP but Skype remains unregulated
- Live p2p streaming provides integrated services without current limitations of Internet television (i.e., IP TV)
  - TV over Internet growing fast (Google "Free Internet TV": 65 million hits)
- Allows information to be downloaded from multiple computers (peers) as opposed to one server in ftp
  - Communications essentially involve two kinds of network nodes: peers download and upload data, tracker is a server that assists peers to find other peers
  - Information broken down into smaller blocks of fixed length, each downloaded piece reported by all participating peers

Peer to Peer Experiments at Broadband Institute

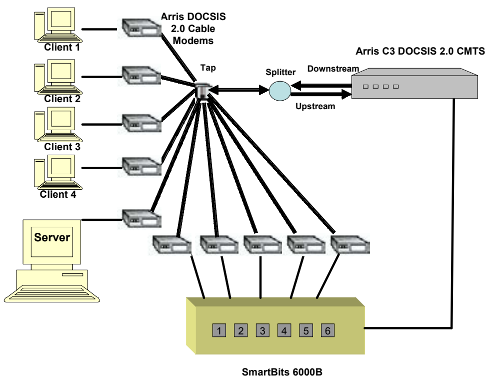
- p2p voice, video, data file sharing and streaming
  - File sharing and streaming experiments performed using DOCSIS 2.0 equipment (symmetrical upstream/downstream data rates)
  - Demonstrated that p2p file sharing achieves higher throughputs for each peer than ftp
  - Demonstrated that p2p video streaming is more scalable and performs better than IP-TV when the number of users increases
  - Performance can be enhanced using delta compression (fast compression based on file or packet comparison) or data streaming techniques
- p2p content distribution with digital rights management
  - Distributed content security using information hiding
  - Allows carriers and cable MSOs to leverage on the advantages of p2p networks while protecting content distribution
- p2p communications in multihop wireless networks
  - Distributed nature of p2p traffic matches multihop wireless networks
  - Local p2p traffic can be isolated from global p2p traffic, improving network performance

Peer to Peer File Sharing

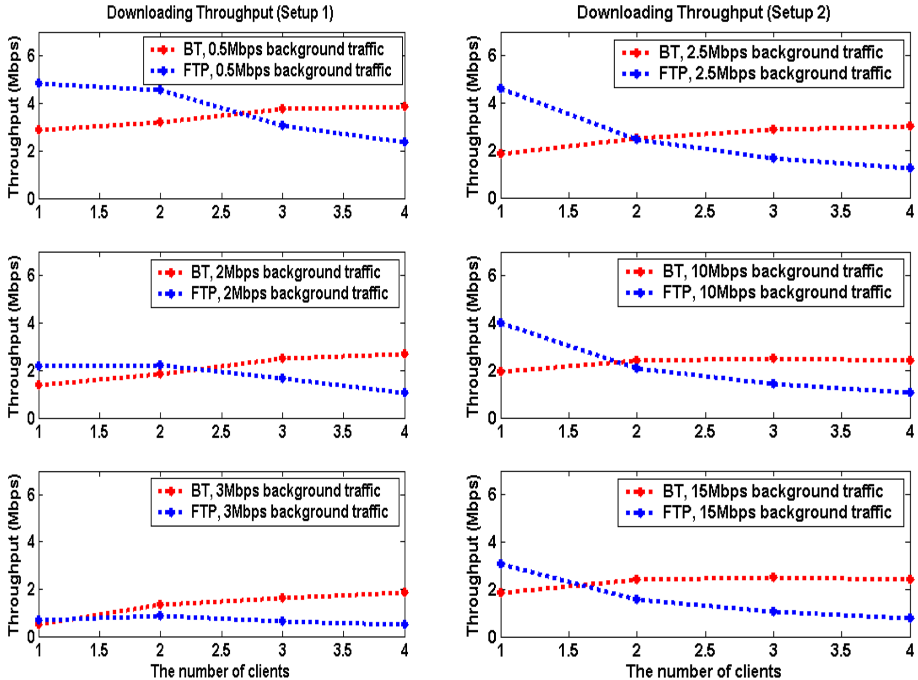
BitTorrent (BT) peer-to-peer file distribution performs better than the conventional file transfer protocol (ftp) when (1) the background traffic increases (2) the number of clients (users) increases



Experimental Setup 1: Background Traffic on the Backbone

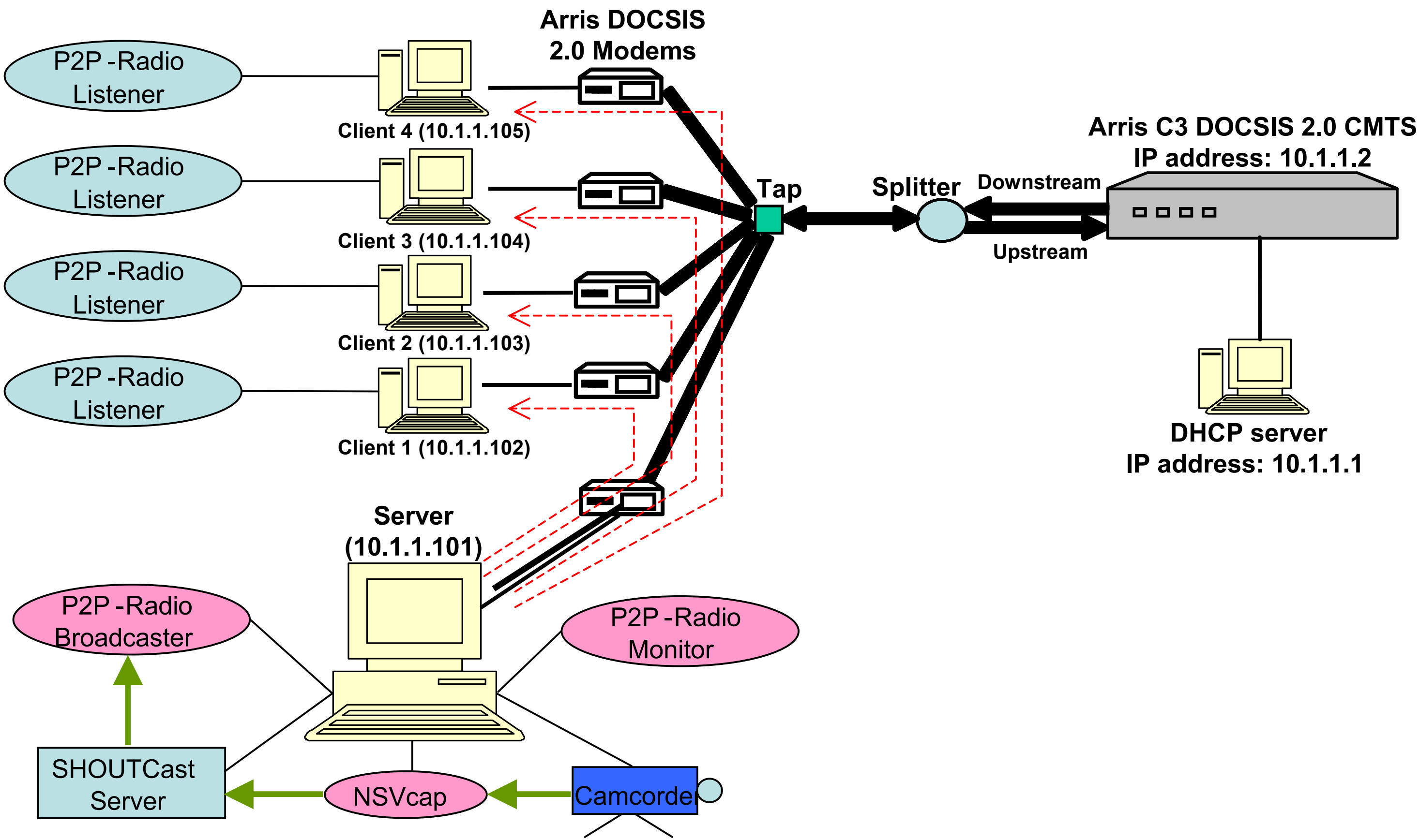


Experimental Setup 2: Background Traffic on the Upstream

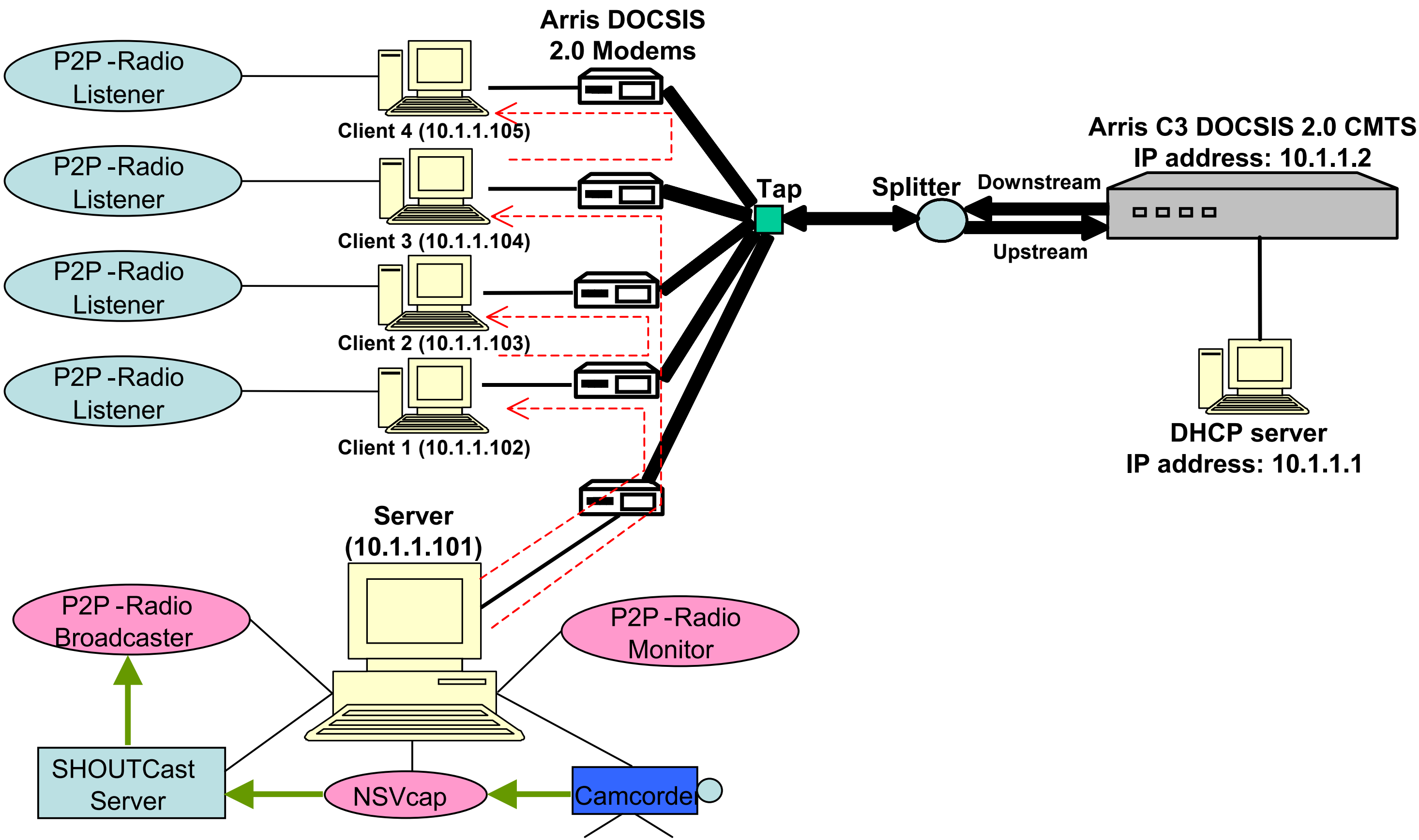


Throughput is computed by averaging the overall traffic load with the number of clients. Individual traffic load variance is negligible. Overall traffic load for BT and ftp are the same.

Unicast IP-TV Communication Paths



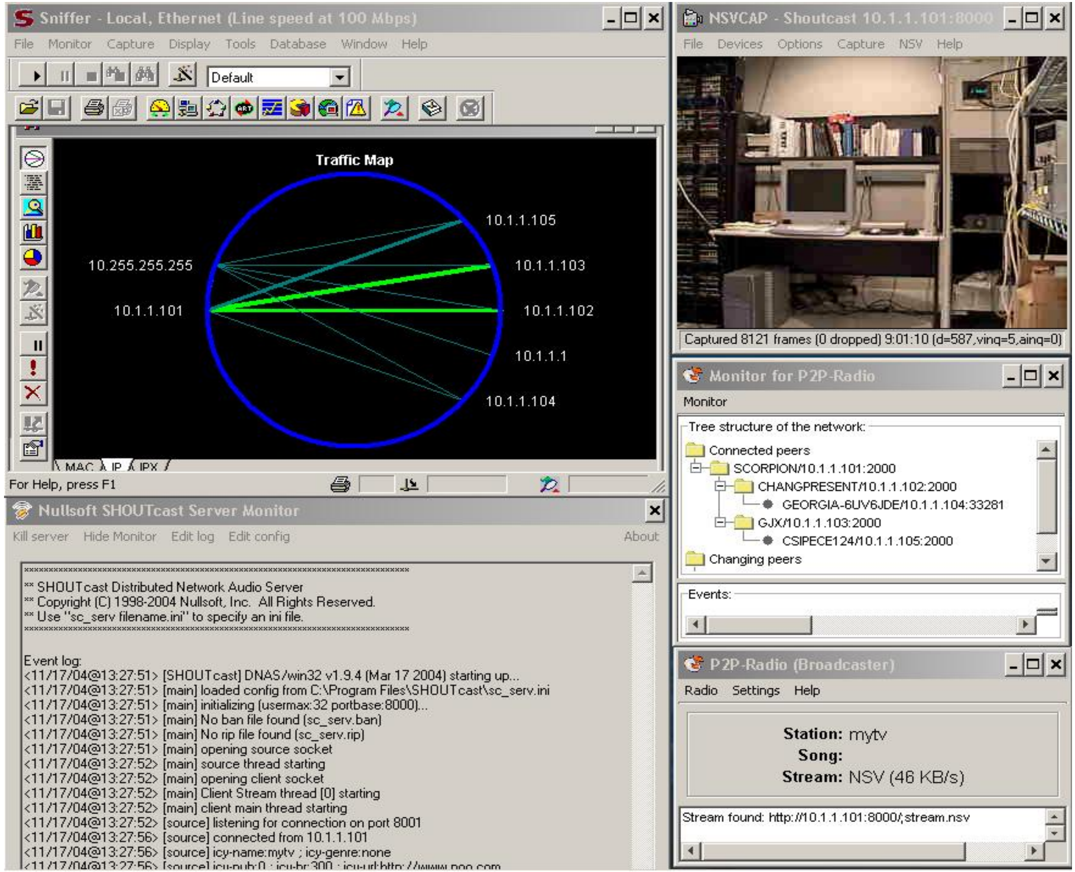
Peer to Peer Video Streaming Communication Paths



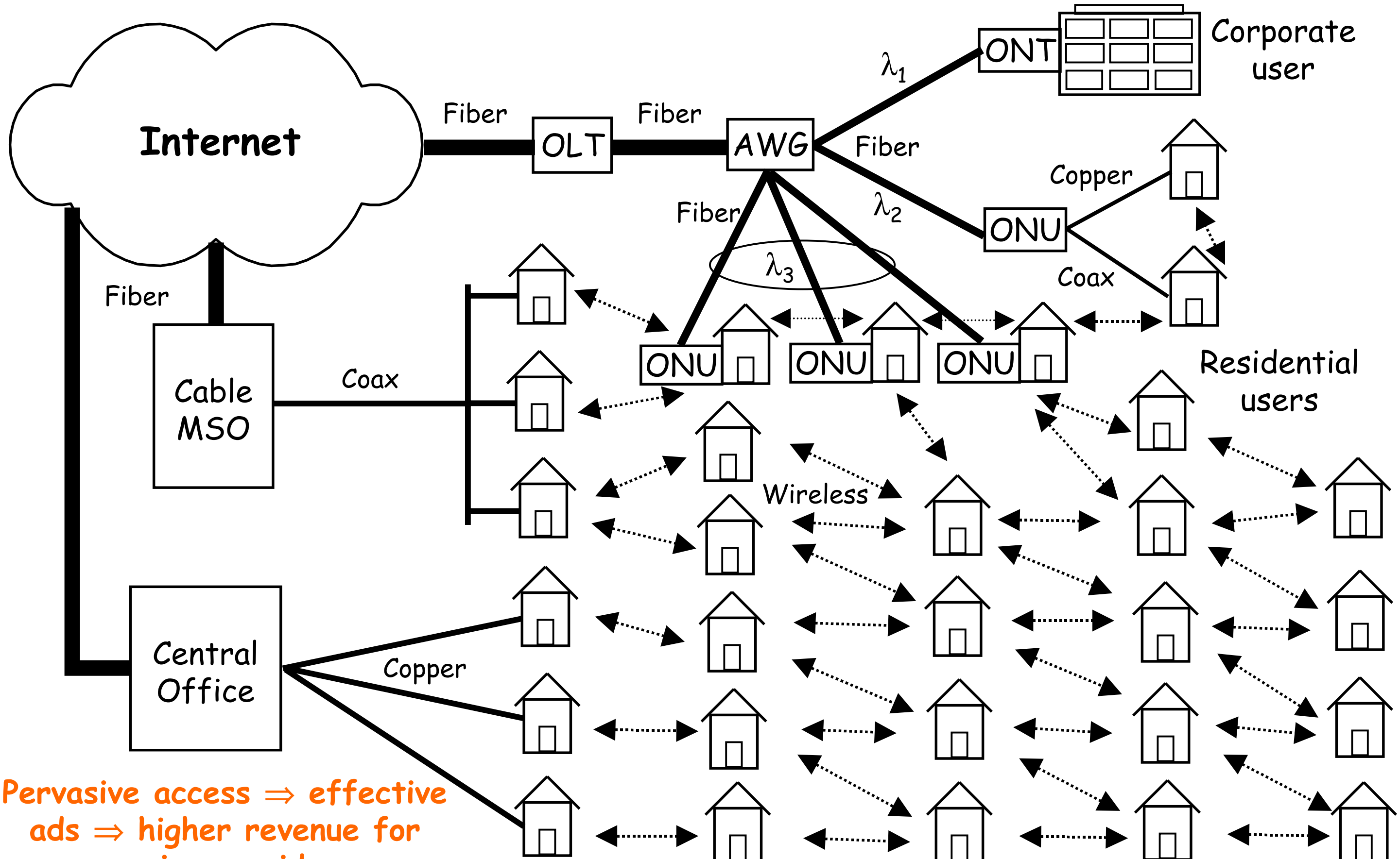
Peer-to-Peer Video Streaming Snapshot

- Live p2p streaming experiment performed on symmetrical broadband access network

Computer	IP Address
Peer 1 (Sender)	10.1.1.101
Peer 2	10.1.1.102
Peer 3	10.1.1.103
Peer 4	10.1.1.104
Peer 5	10.1.1.105



A Pervasive Broadband Access Architecture



Pervasive access ⇒ effective ads ⇒ higher revenue for service providers

Summary

- Access networks have long embraced a centralized model that holds the potential for bottlenecks, latency, and a single point of failure
  - Multihop "mesh" networks are growing: multihop routing is an alternative to wireless switching, longer range provides an alternative to cellphone/Wi-Fi integration, multiple connected paths help provide network reliability, prevent traffic bottlenecks, avoid large-scale DoS attacks
  - Many municipals are absorbing significant portions of the costs for deploying multihop networks with the overall aim of bridging the digital divide: providing residential neighborhoods in cities with ubiquitous Internet access
  - Improved public emergency services (e.g., fire, police) are increasingly dependent on such networks for high bandwidth, real time services that cannot be supported by wireless technologies of the past
- Wi-Fi will continue to pervade outdoor access networks
  - Evidenced by 3G/Wi-Fi integration, multihop Wi-Fi
- Cognitive radio a key technology enabler for broadband wireless access
  - Efficient spectrum utilization requires studies on multiple antenna/multichannel operation, interference avoidance methods, spectrum sensing algorithms, co-operative diversity
- Wireless access networks will need to support emerging applications
  - Interesting interplay of network layer and application layer services: VoIP, IP TV, p2p voice (Skype), p2p video streaming

Final Analysis

More detailed information is available in the book "All in a Broadband Wireless Access Network: A Comprehensive Workbook on the Next Wireless Revolution", 2005, ISBN 0976675218