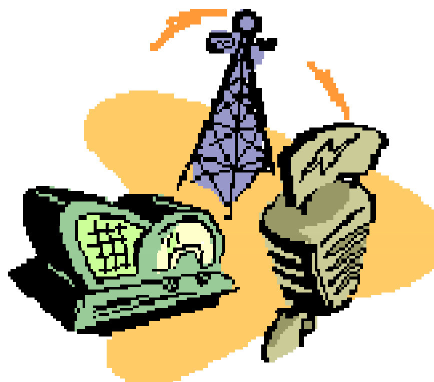
Next Generation Wireless Technologies: High Throughput WiFi , WiMAX, and UWB



Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

IEEE COMMUNICATIONS SOCIETY

IEEE

1. Wireless Networking: Issues and Trends
2. Recent Developments in Wireless PHY
3. Ultra Wideband
4. High Throughput WiFi: 802.11n
5. WiMAX Overview
6. WiMAX Technical Details
7. Other Competing Broadband Access Technologies

1. Wireless Networking: Issues and Trends

- Top 10 Recent Networking Developments
- Hype Cycles of Technologies
- Wireless Equipment/Revenue Trends
  - Home Networking Equipment Trends
  - Global Broadband Wireless Equipment
  - Broadband Market by Regions
  - Fixed vs. Mobile
  - Voice vs. Data

2. Recent Developments in Wireless PHY

1. Code Division Multiple Access (CDMA)
2. OFDM, OFDMA
3. Adaptive Antenna System (AAS)
4. MIMO
5. Turbo Codes
6. Space-Time Block Codes
7. Software defined radios

3. Ultra Wideband

- Ultra-Wideband: How it works
- FCC Rules on UWB
- Advantages of UWB
- Direct sequence (DS-UWB)
- Multi-Band OFDM
- Applications of UWB
- UWB Products

4. High Throughput WiFi: 802.11n

- Major Components of 11n
- IEEE 802.11n Status
- Sample IEEE 802.11n Products
- Hybrid 802.11 Networks: Issues

5. WiMAX Overview

- Technical and Business Challenges
- Prior Broadband Wireless Efforts
- Spectrum Options
- IEEE 802.16 – QoS Classes
- WiBro
- Sample WiMAX Products

6. WiMAX Technical Details

- IEEE 802.16 Standards
- IEEE 802.16 PHY Features
- 802.16 Frame Structure
- Scheduling and Link Adaptation
- IEEE 802.16 Activities
- WiMAX Forum Certification Profiles
- WiMAX Performance

7. Other Competing Broadband Access Technologies

- IEEE 802.11 vs. 802.16
- HSDPA, HSUPA, HSPA
- EV-DO
- WiMAX vs. 3G
- LTE
- Evolution of 3GPP2
- IEEE 802.20, IEEE 802.22

Pre-Test

Check if you know the difference between:

- CDMA vs OFDMA
- MIMO vs beam forming
- STBC vs turbo coding
- MB-OFDM vs DS-UWB
- TDD vs FDD
- UGS vs ertPS
- WiBro vs WiMAX
- WirelessMAN-OFDM vs WirelessHUMAN
- Fixed vs Mobile Profiles
- HSDPA vs HSUPA
- LTE vs EV-DO

Number of Items Checked: ____

- If you checked more than 6 items, you may not gain much from this course.
- If you checked only a few or none, don't worry. This course will cover all this and much more.

Wireless Networking: Trends and Issues

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

Overview

- Top 10 Recent Networking Developments
- Hype Cycles of Technologies
- Wireless Equipment/Revenue Trends
  - Home Networking Equipment Trends
  - Global Broadband Wireless Equipment
  - Broadband Market by Regions
  - Fixed vs. Mobile
  - Voice vs. Data

Top 10 Recent Networking Developments

1. Large investments in Security: Message Aware Networking
   ⇒ All messages scanned by security gateways
2. Wireless (WiFi) is ubiquitous (Intel Centrino)
3. More Cell phones than POTS.
   Smart Cell phones w PDA, email, video, images
   ⇒ Mobility
4. Broadband Access is growing faster than cell phones
5. Wiring more expensive than equipment
   ⇒ Wireless Access

Top 10 Networking Developments (Cont)

6. Voice over Internet Protocol (VOIP) is in the Mainstream
   VOIP over Broadband/Wi-Fi/Cellular
7. Multi-service IP: Voice, Video, and Data
8. Terabyte/Petabyte storage (Not VoD)
   ⇒ High-Speed Networking
9. Gaming: Internet and wireless based
10. 100-Mbps wireless LAN is here.
    ⇒ 100 Mbps in MAN and Gbps in design.

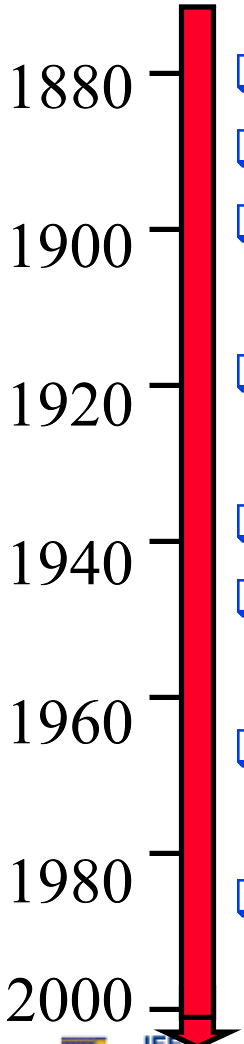
2002-2007: Mega-to-Giga Transition

- Memory in Laptops: Megabytes to Gigabytes
- Cordless Phones: 900 Mega Hertz to 2.4/5.8 GHz
- Processors: MIPS (Mega Instructions per second) to GFIPS (Giga Flops)
- Digital Cameras: 100-500 Mega Pixels to Giga Pixels
- Office Networks: 10/100 Mega bps to 1-10 Giga bps
- Worldwide Wireless Network Users: Millions to Billions

IEEE COMMUNICATIONS SOCIETY

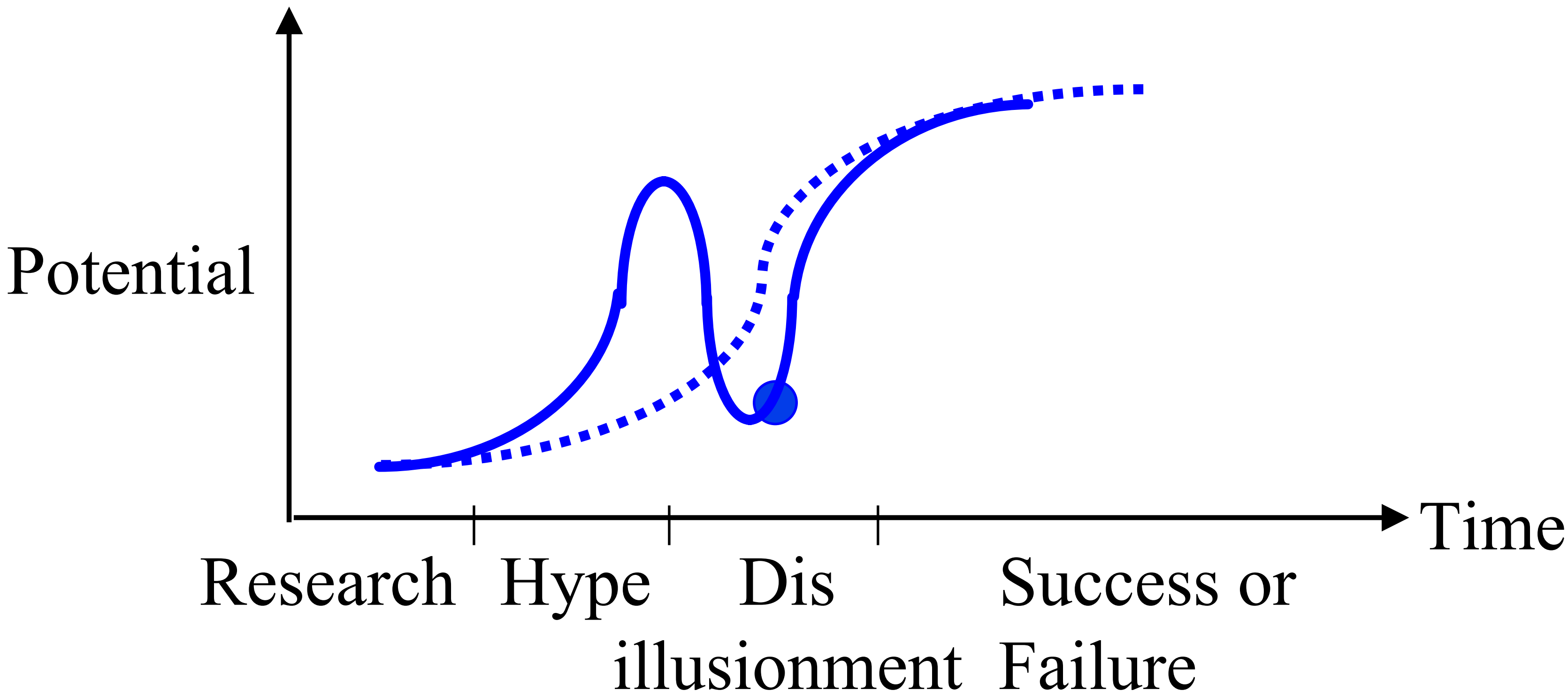
IEEE

Wireless: History

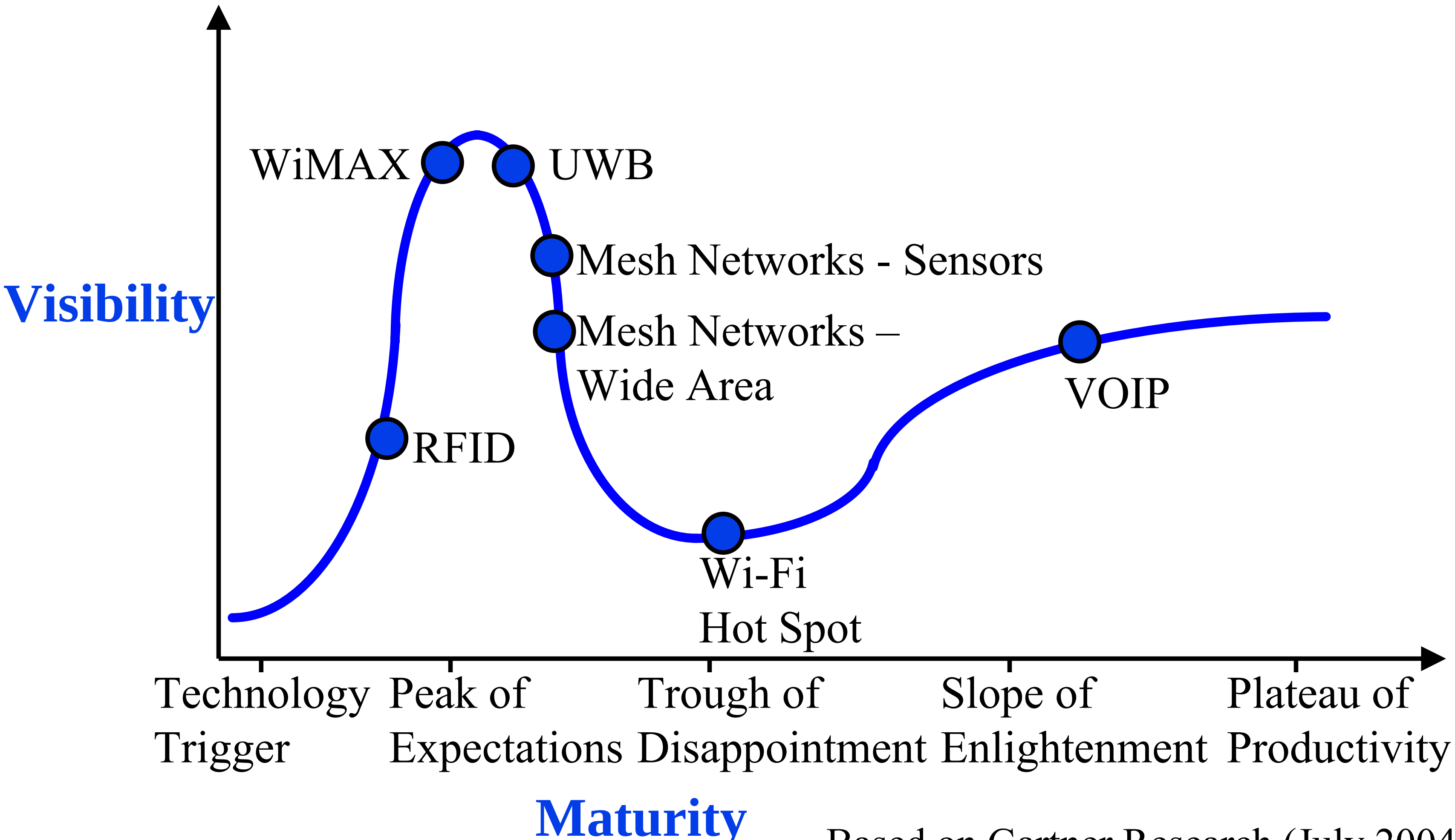


- 1880: Hertz discovered electromagnetic waves
- 1898: First commercial radio data service
- 1921: First Mobile Radio:
  Wireless dispatch system for Detroit Police
- 1946: First Mobile Telephone Service:
  In St. Louis by AT&T. Half-duplex ⇒ Push to talk.
- 1970: First Cellular Phone Service: AT&T Chicago
- 1971: First Wireless Data Network:
  Aloha at University of Hawaii
- 1990: First Commercial WLAN Product AT&T WaveLAN
- 1997: First WLAN Standard - IEEE 802.11 2Mbps

Hype Cycles of Technologies

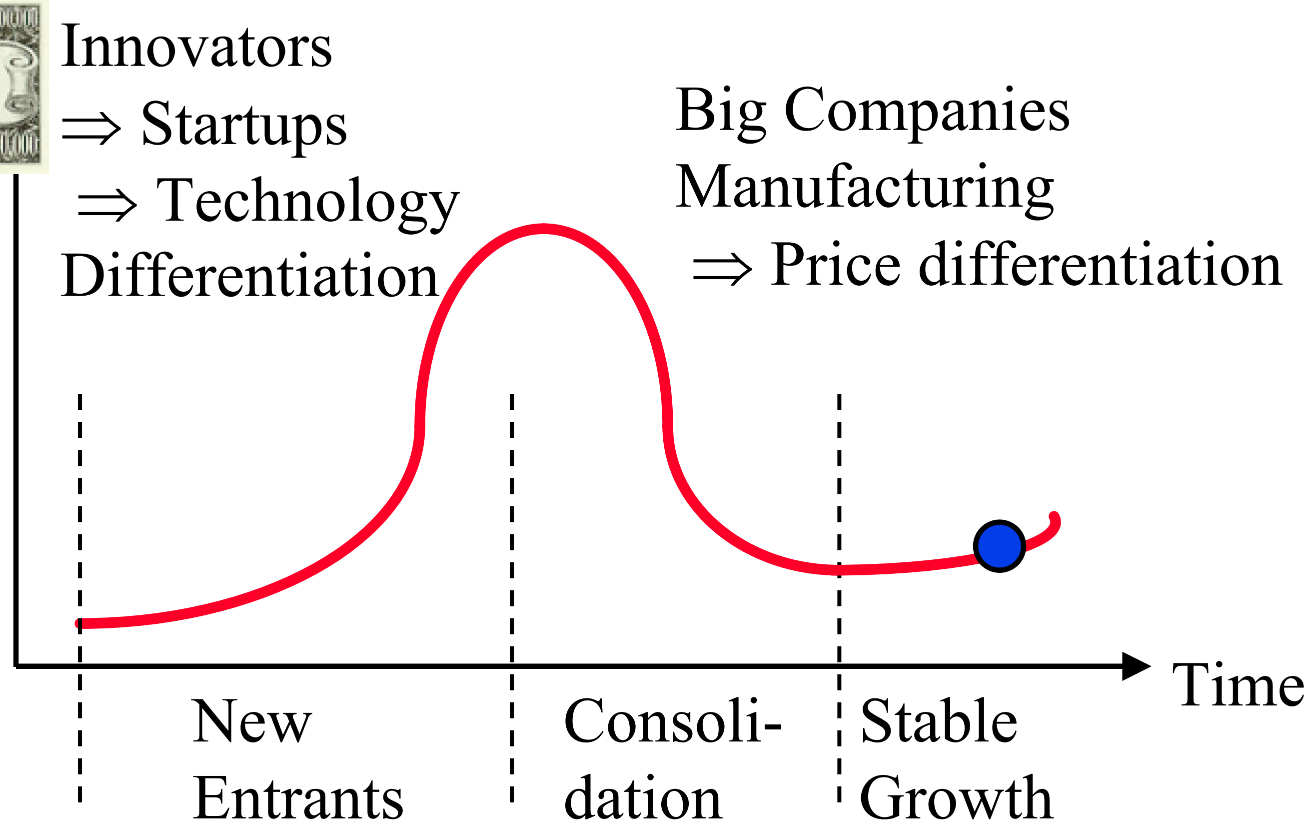


Hype Cycle 2004



Based on Gartner Research (July 2004)

Industry Growth: Formula for Success



- **10-20-70 Formula**: 10% of R&D on distant future, 20% on near future, 70% on today's products

IEEE COMMUNICATIONS SOCIETY IEEE

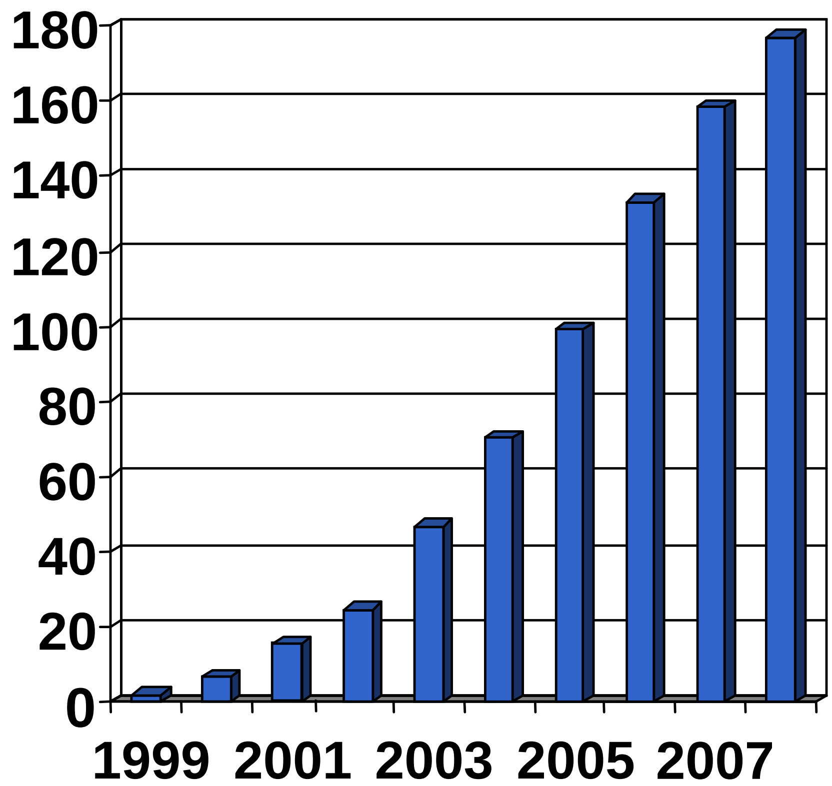
Telecom Revenue

	Revenue in Billions						
	2003	2004	2005	2006	2007	2008	Annual Growth
Video	0.2	0.3	.05	1.0	1.6	2.5	65.7%
Consumer Broadband	2.8	3.5	4.0	4.2	4.6	4.8	11.4%
Consumer long distance	20.7	18.2	16.0	13.6	11.3	9.2	-15.0%
Business local	26.3	26.7	26.4	26.1	25.8	25.5	-0.6%
Business long distance	26.1	24.5	23.0	21.3	19.7	18.2	-7.0%
Business data	44.8	45.6	46.6	47.1	46.8	45.4	0.3%
Consumer local	46.9	42.2	39.0	36.2	34.0	32.3	-7.25%
Wireless	91.5	108.7	119.2	132.8	144.5	153.6	10.9%
Total	260.7	271.5	277.0	285.0	291.3	294.9	2.5%

- Long distance is disappearing.
- Most of the revenues are going to be from wireless.
- Source: Instat/MDR (Business Week, Feb 28, 2005)

Wireless Data Connections

North American Wireless Data Connections (Millions)

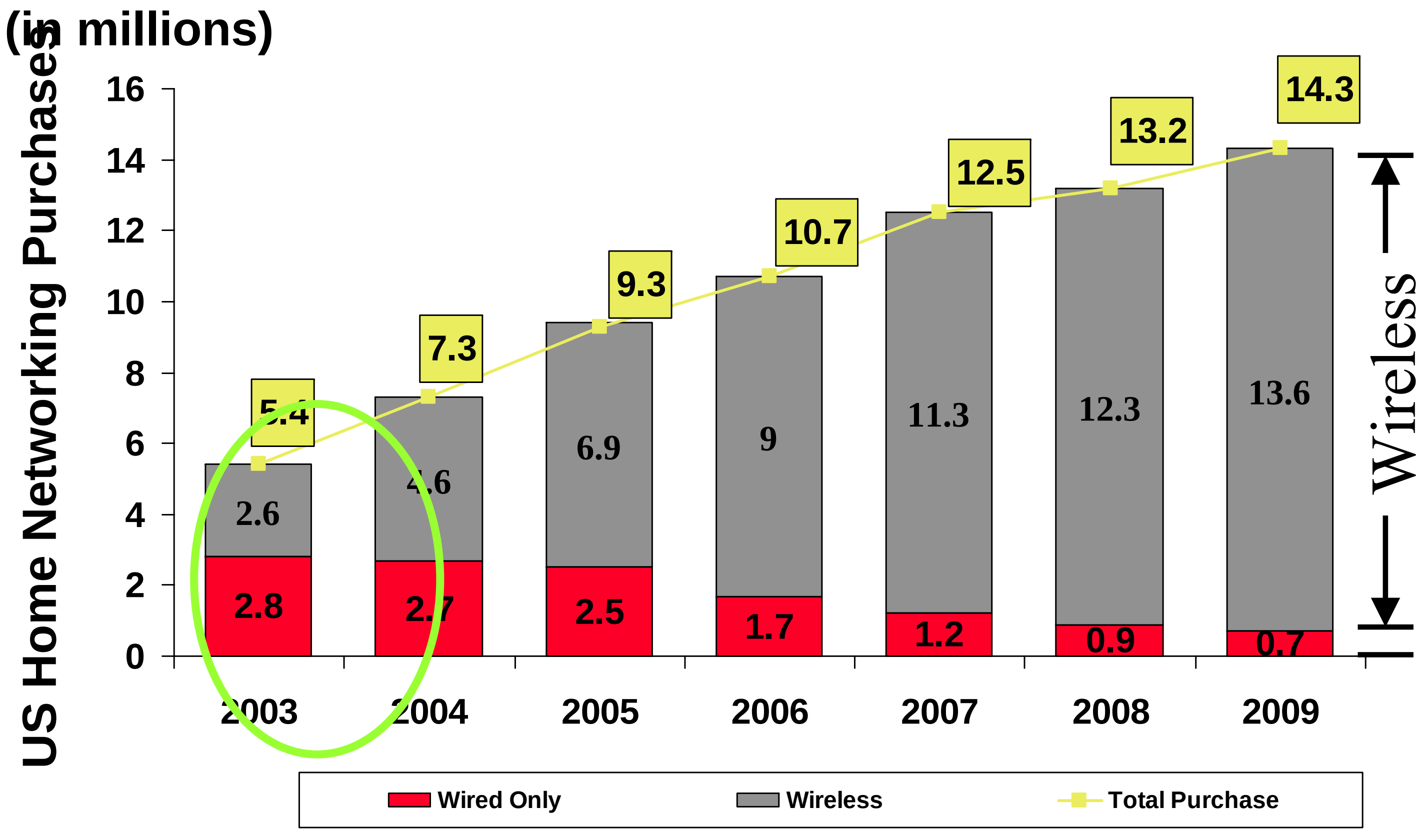


Source: Gartner, “U.S. Wireless Data Market Update, 2004”

Five Wireless Industry Trends

1. Wireless industry is stronger than wireline. Particularly strong growth in developing countries.
2. 48% of global telco revenues coming from wireless
3. 26% of wireless revenues coming from data (vs voice)
4. Emerging new applications: Video, Location, Remote monitoring, m-commerce, Video telephony, remote enterprise applications, remote management, Multiparty collaboration
5. Wireless outselling wired home networking gear

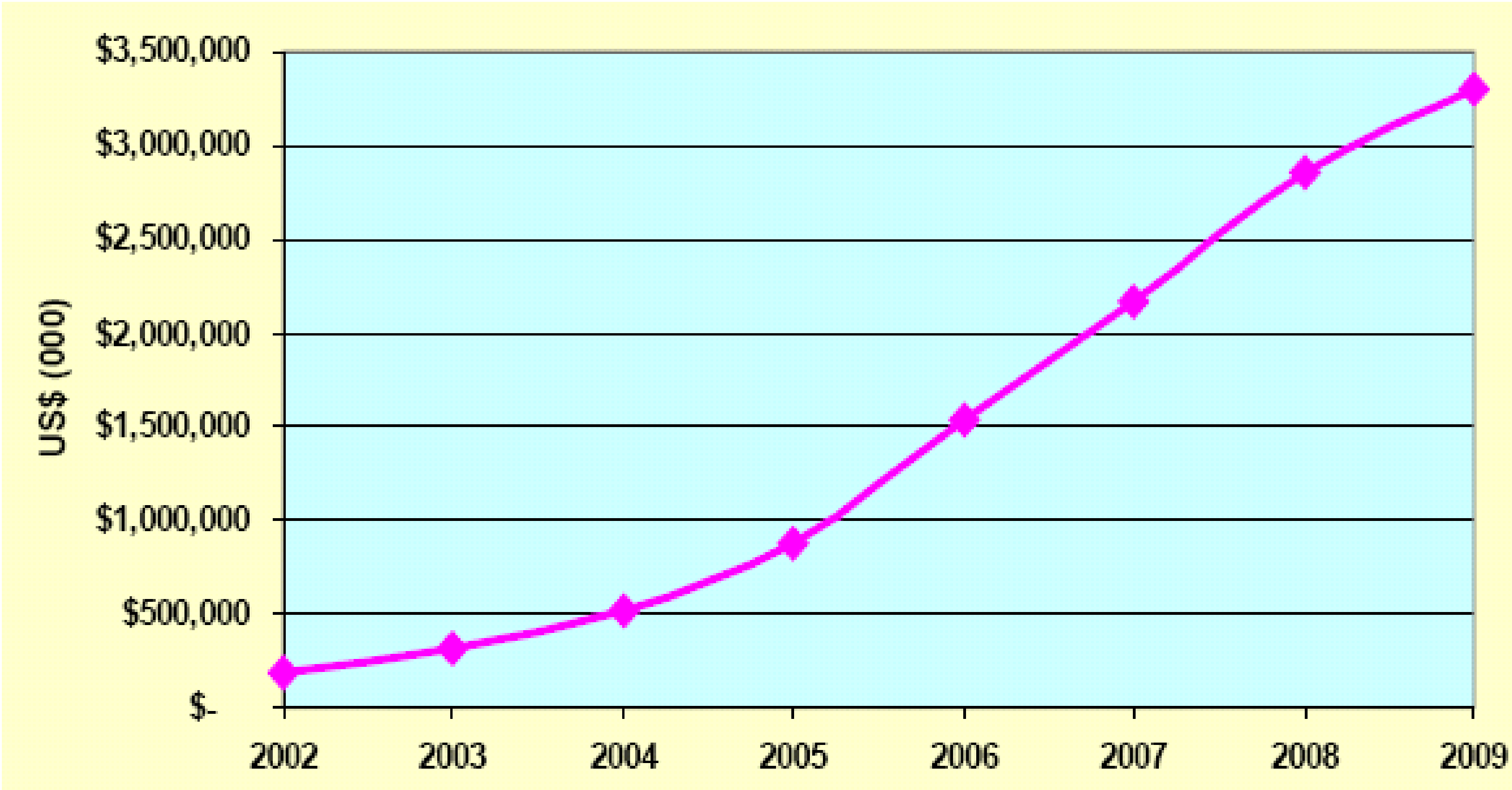
Home Networking Equipment Trends



Source: JupiterResearch Home Networking Model, 8/04 (US Only)

- Wireless outsold wired home networking gear for the first time in 2004

Global Broadband Wireless Equipment



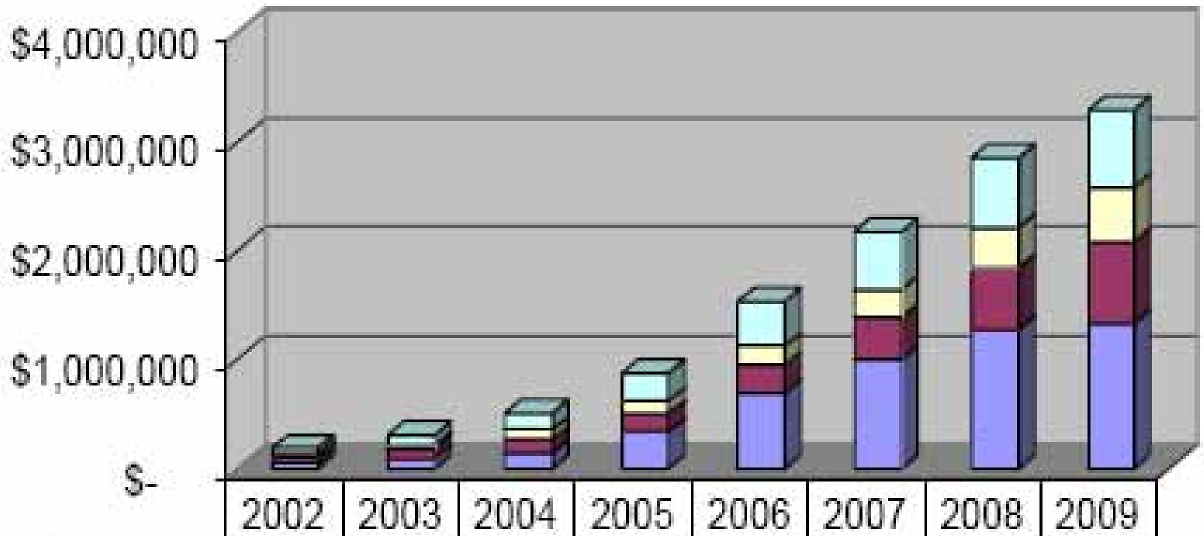
- 0-10 GHz, Base stations+Subscriber stations

Source: Skylight Research

IEEE COMMUNICATIONS SOCIETY

IEEE

Broadband Market by Regions



	2002	2003	2004	2005	2006	2007	2008	2009
EMEA	$55,3	$95,6	$160,	251,4	$406,	$527,	$637,	$721,
LAM	$21,2	$33,4	$91,2	125,3	$179,	$250,	$364,	$489,
NAM	$68,5	$100,	$122,	164,8	$254,	$386,	$577,	$746,
ASPAC	$44,6	$83,7	$140,	$336,	$688,	$1,00	$1,27	$1,33

- ASPAC and EMEA leading the growth

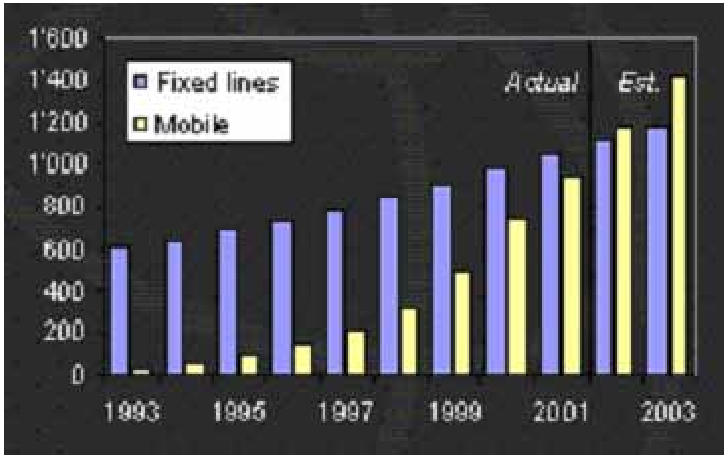
Source: Skylight Research

IEEE COMMUNICATIONS SOCIETY

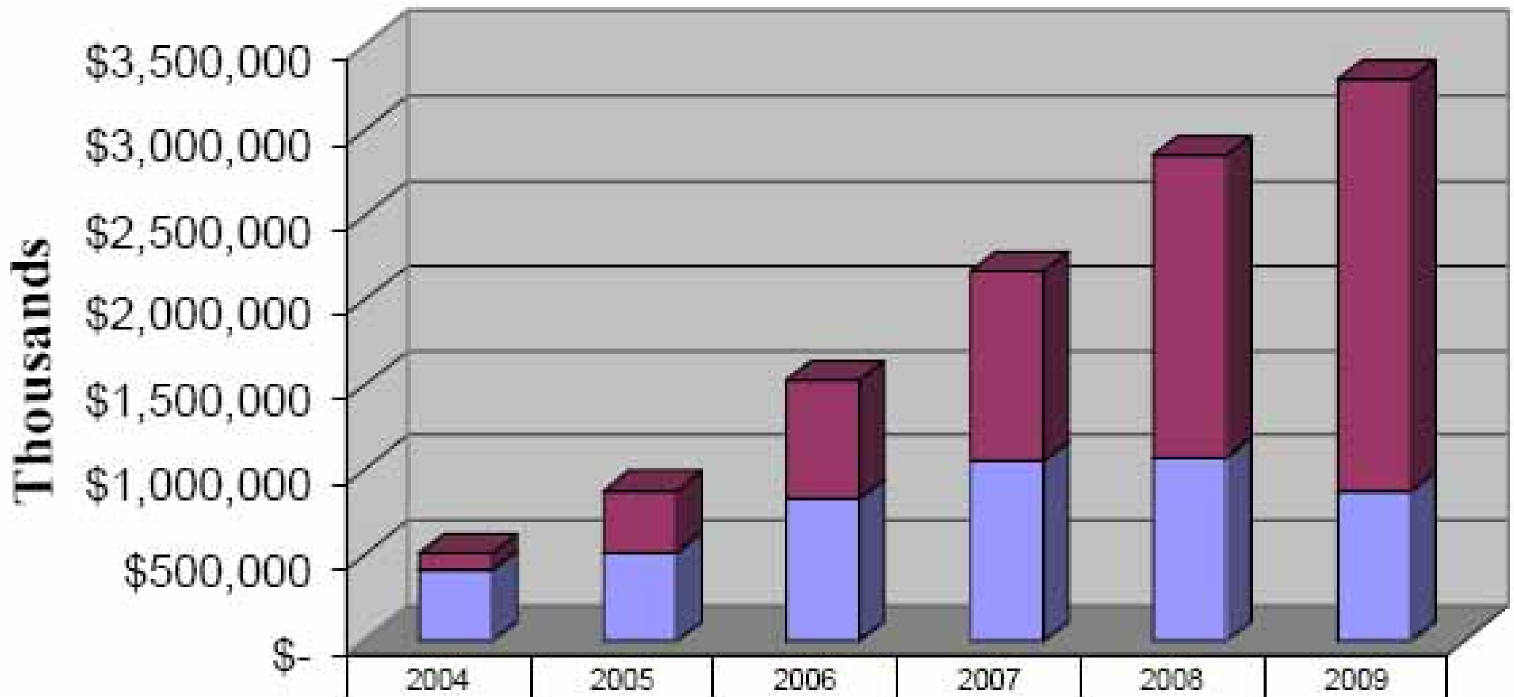
IEEE

Mobility

- 1.35 Billion mobile subscribers vs 1.2 Billion Fixed line subscribers at the end of 2003 [ITU]
- Number of wired phones in USA is declining for the first time since the Great Depression.
- 20% of world population is mobile. Need internet access. 70% of internet users in Japan have mobile access



Personal Broadband: Fixed vs. Mobile



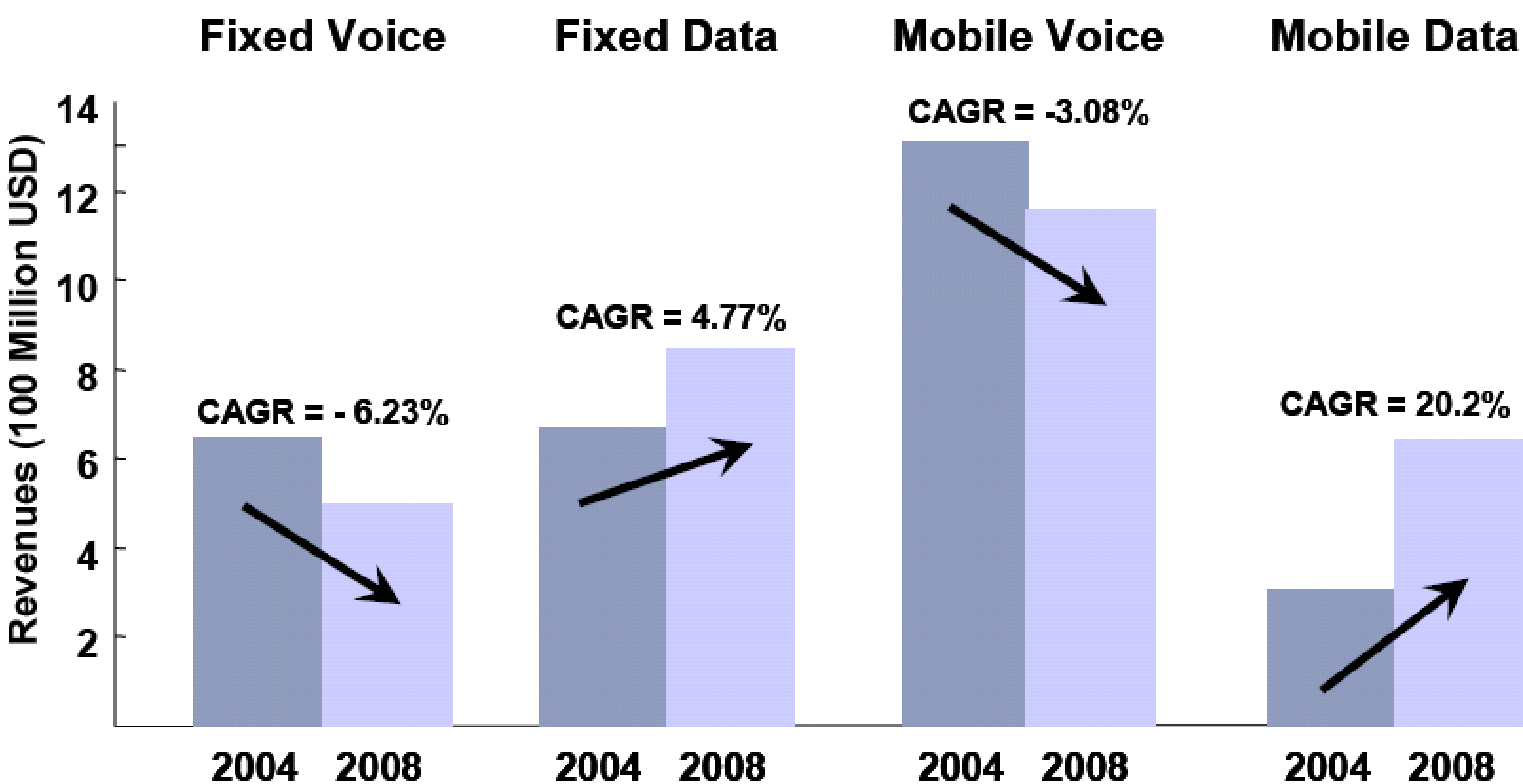
	2004	2005	2006	2007	2008	2009
Portable/Mobile wireless equipment	$100,655	$358,184	$699,616	$1,118,670	$1,776,591	$2,415,165
Fixed wireless equipment	$414,125	$519,620	$829,612	$1,051,557	$1,072,812	$878,090

Source: Skylight Research

IEEE COMMUNICATIONS SOCIETY

IEEE

Voice and Data Revenues (Korea)

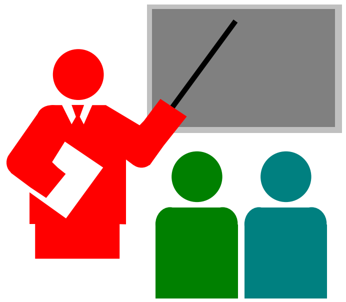


Source: KISDI 2004

IEEE COMMUNICATIONS SOCIETY

IEEE

Summary



- Security, Web 2.0, and wireless are driving the networking industry
- Wireless is the major source of carrier revenue
  $\Rightarrow$ Significant growth in Wireless networking
- Growth also in home and enterprise market
- Moving from fixed to mobile wireless
- Moving from voice to data

IEEE COMMUNICATIONS SOCIETY — IEEE

Recent Developments in Wireless PHY

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

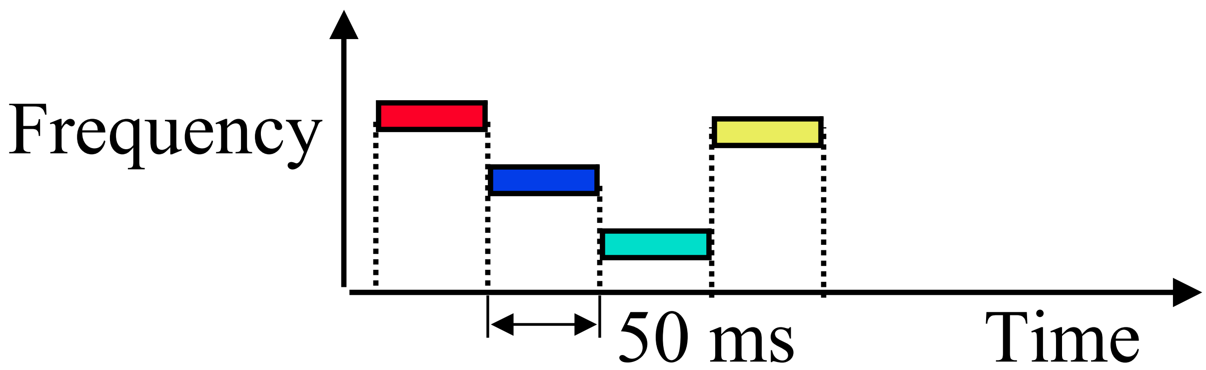
Wireless Radio Channel

- Path loss: Depends upon distance and frequency
- Shadowing: Obstructions
- Multipath: Multiple reflected waves
- Inter-symbol interference (ISI) due to dispersion
- Frequency Dispersion (Doppler Spread) due to motion
- Noise
- Interference

Recent Developments in Wireless PHY

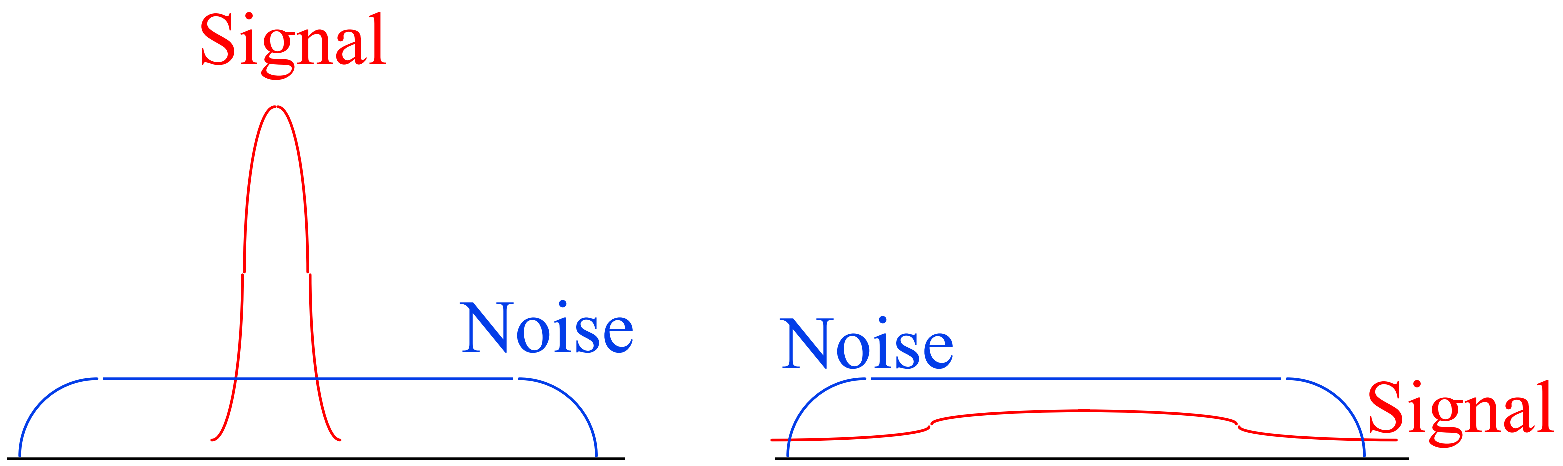
1. Code Division Multiple Access (CDMA)
2. OFDM, OFDMA
3. Adaptive Antenna System (AAS)
4. MIMO
5. Turbo Codes
6. Space-Time Block Codes
7. Software defined radios

Frequency Hopping Spread Spectrum



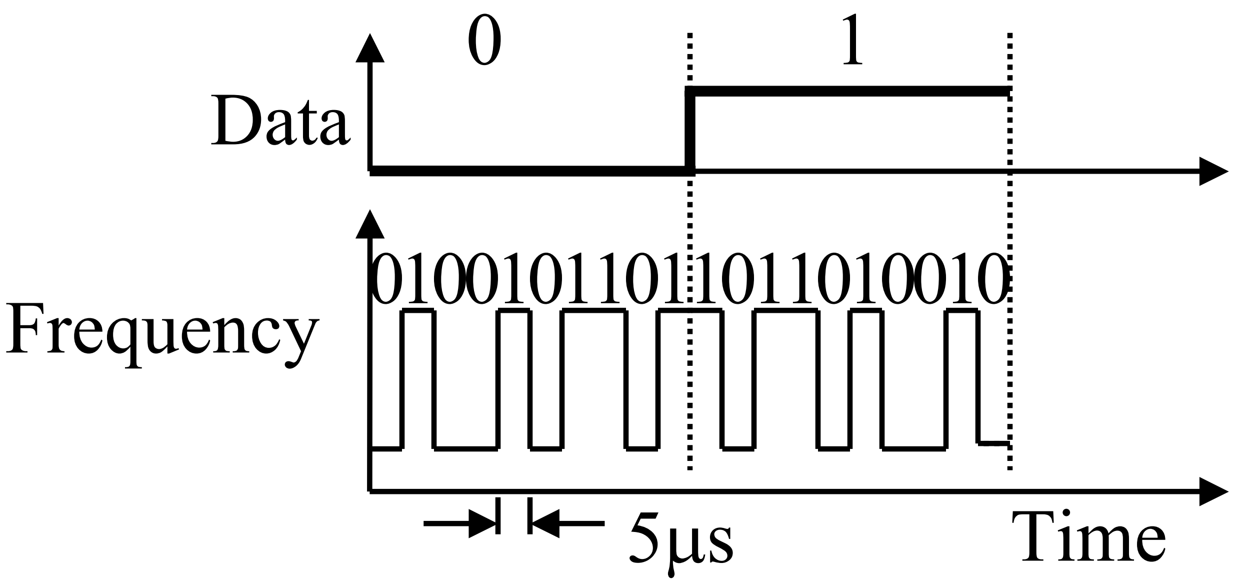
- Pseudo-random frequency hopping
- Spreads the power over a wide spectrum
  ⇒Spread Spectrum
- Developed initially for military
- Patented by actress Hedy Lamarr
- Narrowband interference can't jam

Spectrum



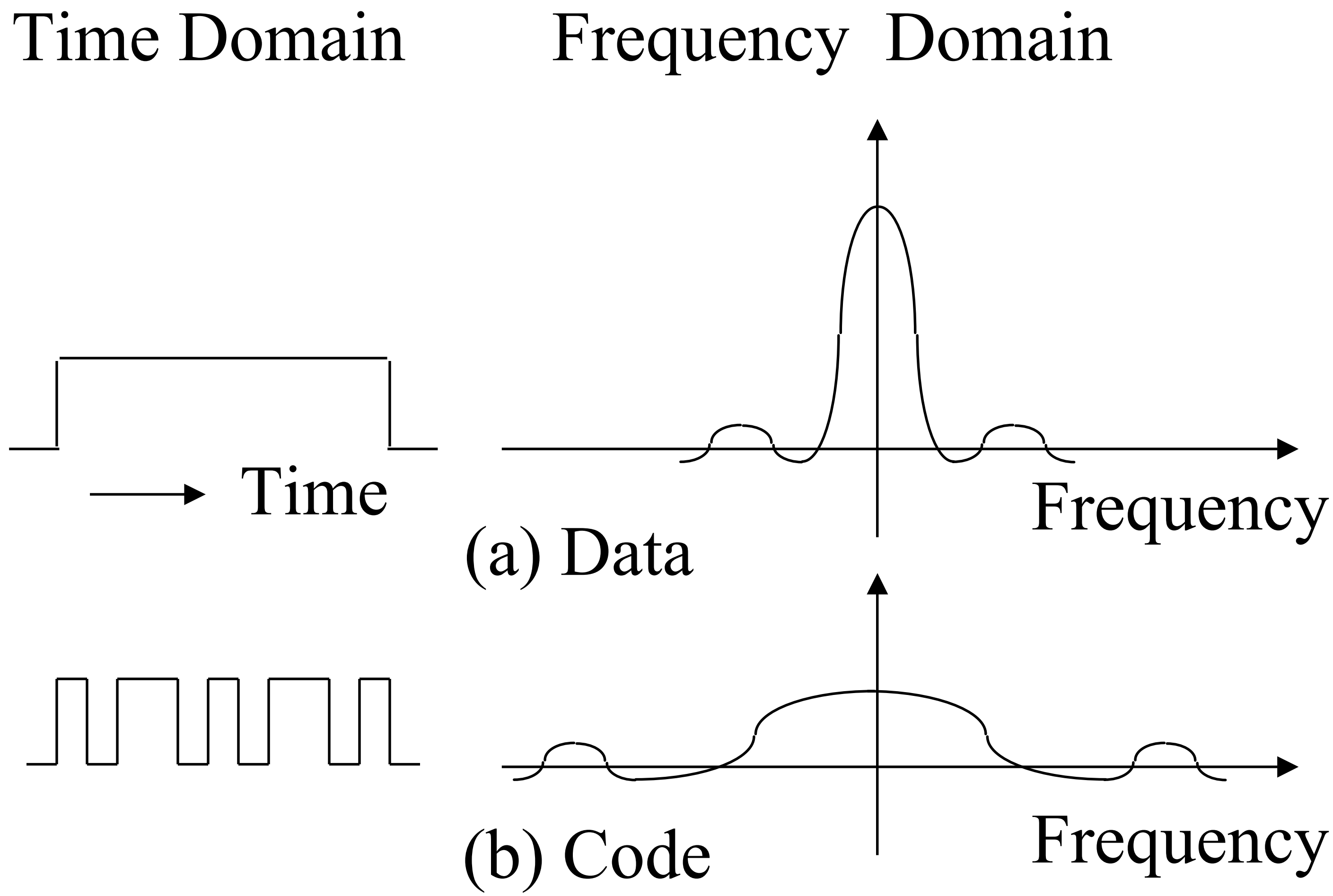
(a) Normal (b) Frequency Hopping

Direct-Sequence Spread Spectrum



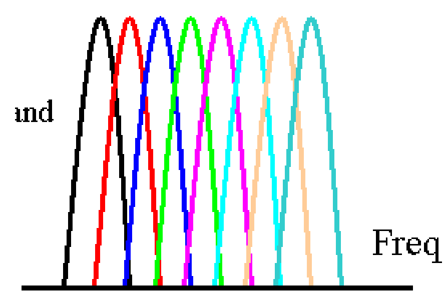
- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Correlation between codes ⇒ Interference ⇒ Orthogonal

DS Spectrum


Time Domain
Frequency Domain
Time
Frequency
(a) Data
(b) Code
Frequency

OFDM

- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel
  ⇒ Multi-carrier modulation
- Frequency band is divided into 256 or more sub-bands.
  Orthogonal ⇒ Peak of one at null of others
- Each carrier is modulated with a BPSK, QPSK, 16-QAM, 64-QAM etc depending on the noise (Frequency selective fading)
- Used in 802.11a/g, 802.16, Digital Video Broadcast handheld (DVB-H)



History of OFDM

- 1966: Chang shows multicarrier modulation solves multipath
- 1971:Weinstein and Ebert use DFT for multicarrier
- 1985: Cimini does a proof-of-concept design
- 1993: DSL adopts OFDM
- 1999: 802.11a adopts OFDM
- 2002 802.16a uses OFDM
- 2003: 802.11g uses OFDM
- 2003: Multi-band OFDM for ultra wideband

Advantages of OFDM

- Easy to implement using FFT/IFFT
- Computational complexity = O(B log BT) compared to previous $O(B^2T)$ for Equalization. Here B is the bandwidth and T is the delay spread.
- Graceful degradation if excess delay
- Robustness against frequency selective burst errors
- Allows adaptive modulation and coding of subcarriers
- Robust against narrowband interference (affecting only some subcarriers)
- Allows pilot subcarriers for channel estimation

IEEE COMMUNICATIONS SOCIETY

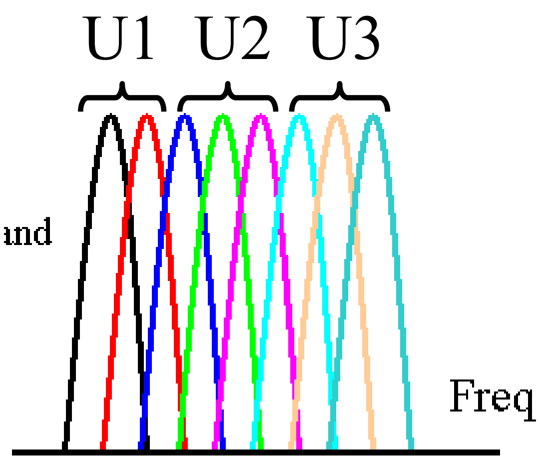
IEEE

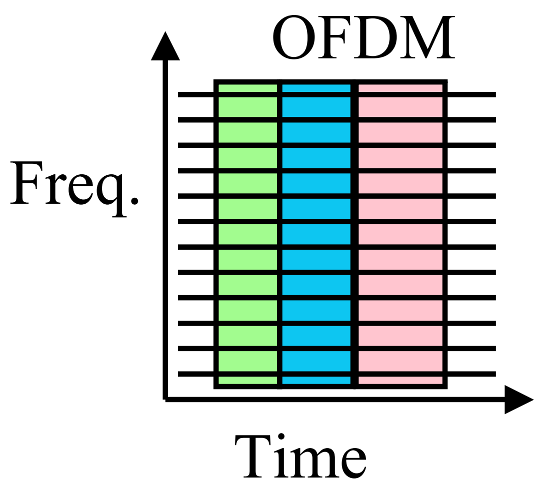
OFDM: Design considerations

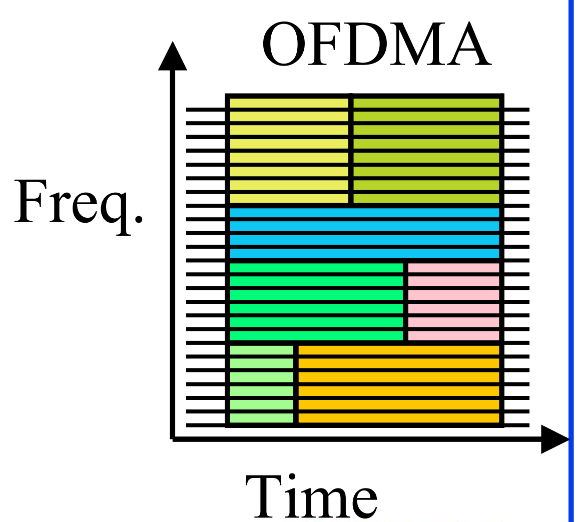
- Large number of carriers ⇒ Larger symbol duration ⇒ Less inter-symbol interference
- Reduced subcarrier spacing ⇒ Increased inter-carrier interference due to Doppler spread in mobile applications
- Easily implemented as Inverse Discrete Fourier Transform (IDFT) of data symbol block
- Fast Fourier Transform (FFT) is a computationally efficient way of computing DFT

OFDMA

- Orthogonal Frequency Division Multiple Access
- Each user has a subset of subcarriers for a few slots
- OFDM systems use TDMA
- OFDMA allows Time+Freq DMA ⇒ 2D Scheduling



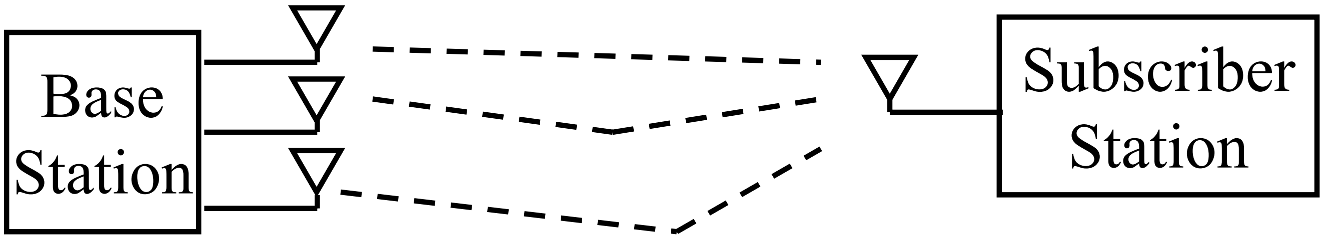




Scalable OFDMA

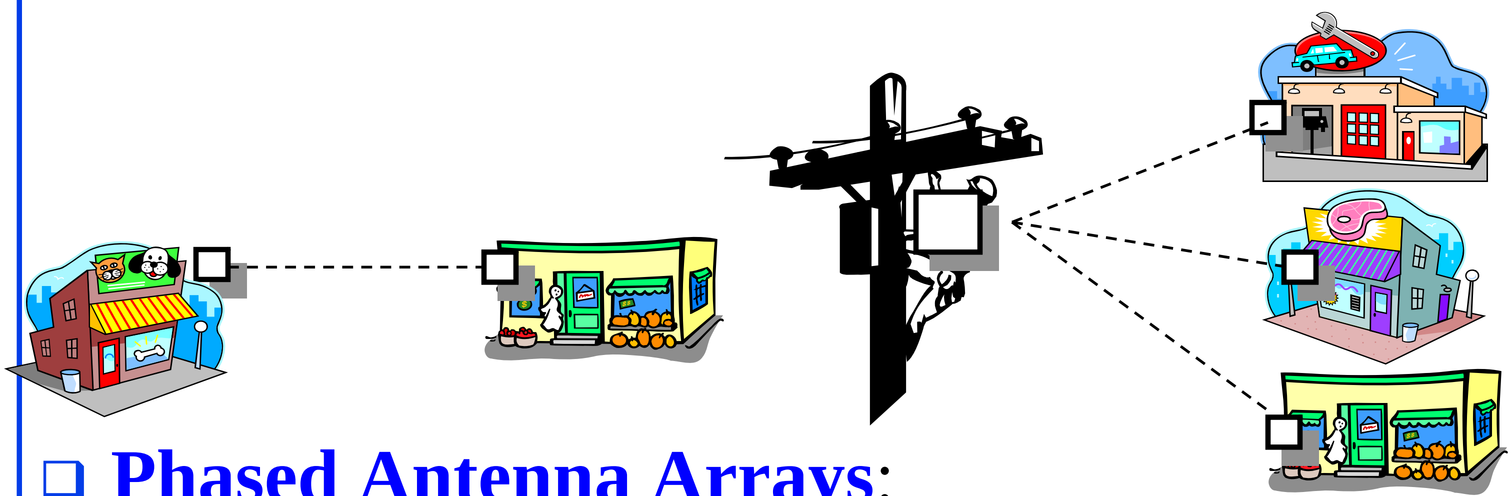
- OFDM symbol duration = f(subcarrier spacing)
- Subcarrier spacing = Frequency bandwidth/Number of subcarriers
- Frequency bandwidth=1.25 MHz, 3.5 MHz, 5 MHz, 10 MHz, 20 MHz, etc.
- Symbol duration affects higher layer operation
  ⇒ Keep symbol duration constant at 102.9 us
  ⇒ Keep subcarrier spacing 10.94 kHz
  ⇒ Number of subcarriers ∝ Frequency bandwidth
  This is known as scalable OFDMA

Adaptive Antenna System (AAS)



- Multiple antennas transmit a subset of OFDM subcarriers each
- Example: 4 Antennas. 192 data subcarriers plus 8 pilot subcarriers are divided into 4 groups of 50 subcarriers each. Each of the four antennas transmits one group.
- Receivers perform channel estimation on each beam
- Receivers feedback the channel info to xmitter
- Transmitters adjust the beam forming accordingly

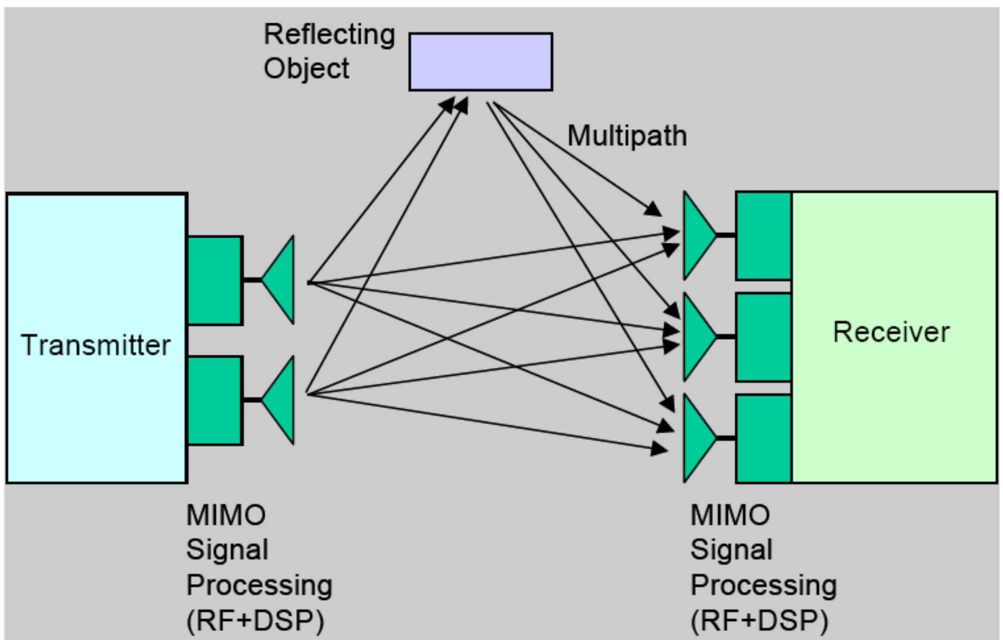
Smart Antennas



- **Phased Antenna Arrays**:
  Receive the same signal using multiple antennas
- By phase-shifting various received signals and then summing ⇒ Focus on a narrow directional beam
- Digital Signal Processing (DSP) is used for signal processing ⇒ Self-aligning

MIMO

- Multiple Input Multiple Output
- 54 Mbps/20 MHz = 2.7 bps/Hz,
  MIMO $\Rightarrow$ 108 Mbps or 5.4 bps/Hz

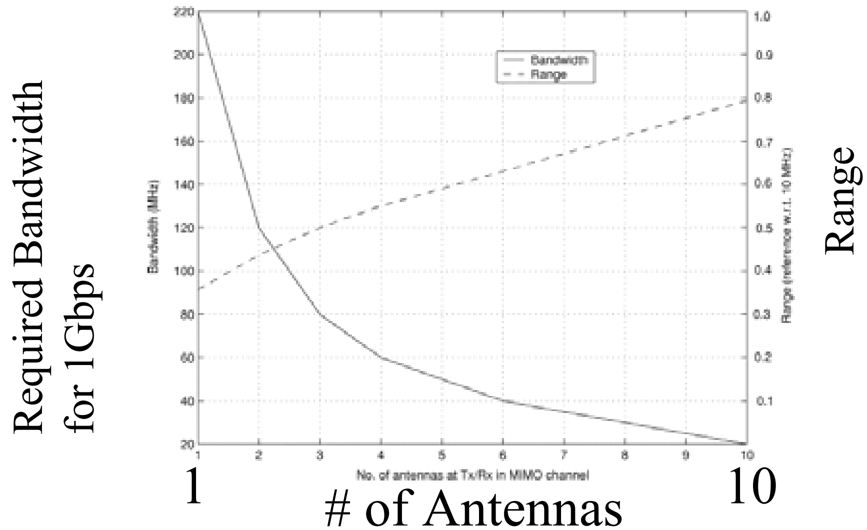


2x3

MIMO

- **Antenna Diversity**: Multiple transmit or receive antenna but a single transmit/receive chain
- **MIMO**: RF chain for each antenna ⇒ Simultaneous reception or transmission of multiple streams
  1. **Array Gain**: Improved SNR. Requires channel knowledge (available at receiver, difficult at transmitter)
  2. **Diversity Gain**: Multiple independently fading paths. Get $N_T \times N_R$th order diversity. Transmitter can code the signal suitably ⇒ Space time coding.
  3. **Spatial Multiplexing Gain**: Transmitting independent streams from antennas. Min (N_T, N_R) gain
  4. **Interference Reduction**: Co-channel interference reduced by differentiating desired signals from interfering signals

Gigabit Wireless



- Max 9 b/Hz in fixed and 2-4 b/Hz in mobile networks ⇒ Need too much bandwidth ⇒ High frequency ⇒ Line of sight
- Single antenna will require too much power ⇒ high cost amplifiers
- MIMO improves the range as well as reduces the required bandwidth
- Ref: Paulraj et al, Proc of IEEE, Feb 2004.

IEEE COMMUNICATIONS SOCIETY IEEE

Shannon's Theorem

- Bandwidth = B Hz
  Signal-to-noise ratio = S/N
- Maximum number of bits/sec = B $\log_2 (1+S/N)$
- Example: Phone wire bandwidth = 3100 Hz

$$S/N = 30 \text{ dB}$$

$$10 \text{ Log}_{10} S/N = 30$$

$$\text{Log}_{10} S/N = 3$$

$$S/N = 10^3 = 1000$$

$$\text{Capacity} = 3100 \log_2 (1+1000)$$

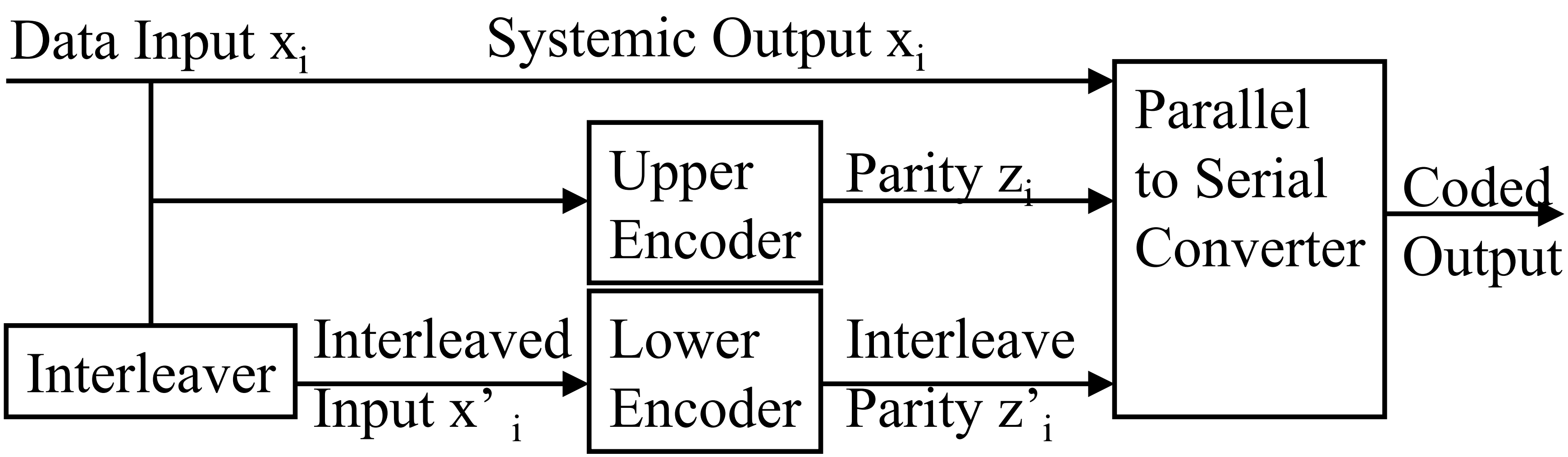
$$= 30{,}894 \text{ bps}$$

IEEE COMMUNICATIONS SOCIETY

IEEE

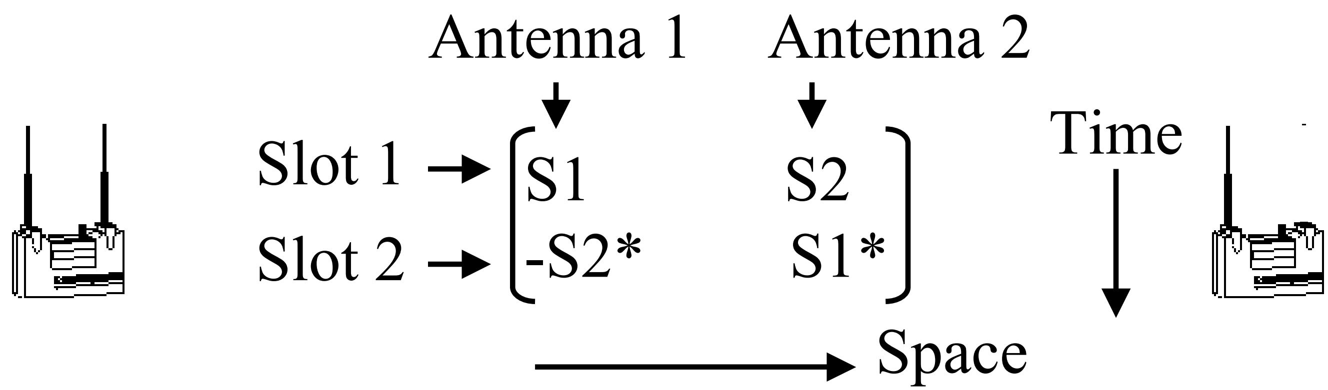
Turbo Codes

- Normal FEC codes: 3dB below the Shannon limit
- Turbo Codes: 0.5dB below Shannon limit
  Developed by French coding theorists in 1993
- Use two coders with an interleaver
- Interleaver rearranges bits in a prescribed but irregular manner



Space Time Block Codes (STBC)

- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas:

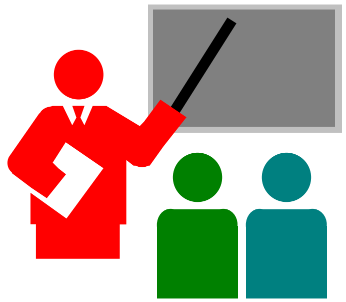


S1* is complex conjugate of S1 ⇒ columns are orthogonal

Software Defined Radio

- GSM and CDMA incompatibility ⇒ Need multimode radios
- Military needs to intercept signals of different characteristics
- Radio characteristics (Channel bandwidth, Data rate, Modulation type) can be changed by software
- Multiband, multi-channel, multi-carrier, multi-mode (AM, FM, CDMA), Multi-rate (samples per second)
- Generally using Digital Signal Processing (DSP) or field programmable gate arrays (FPGAs)
- Signal is digitized as close to the antenna as possible
- Speakeasy from Hazeltine and Motorola in mid 80's was one the first SDRs. Could handle 2 MHz to 2 GHz.

Summary



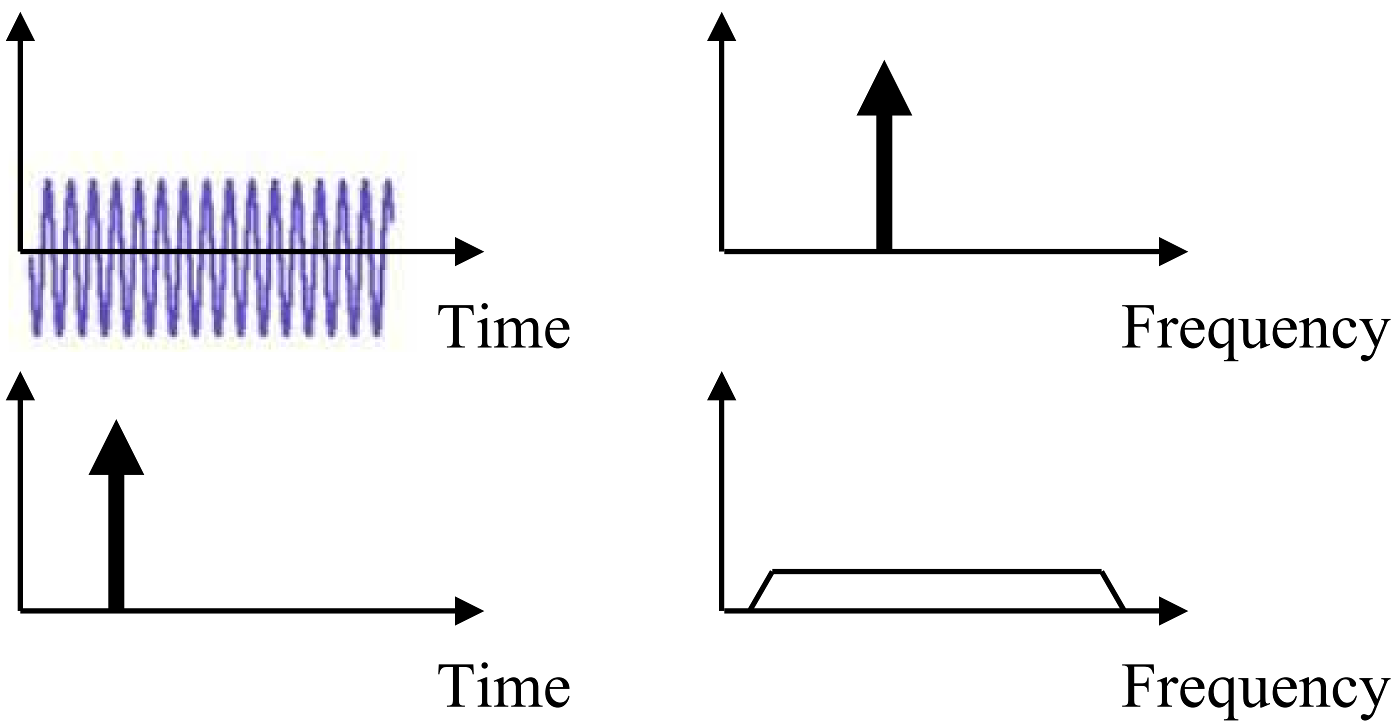
1. Frequency hopping and Direct Sequence are two methods of code division multiple access or spread spectrum
2. OFDM splits a band in to many orthogonal subcarriers. OFDMA = FDMA + TDMA
3. Turbo codes use two coders and a interleaver and operate very close to Shannon's limit
4. Space-time block codes use multiple antennas to transmit related signals
5. MIMO use multiple antennas for high throughput

Ultra Wideband (UWB)

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

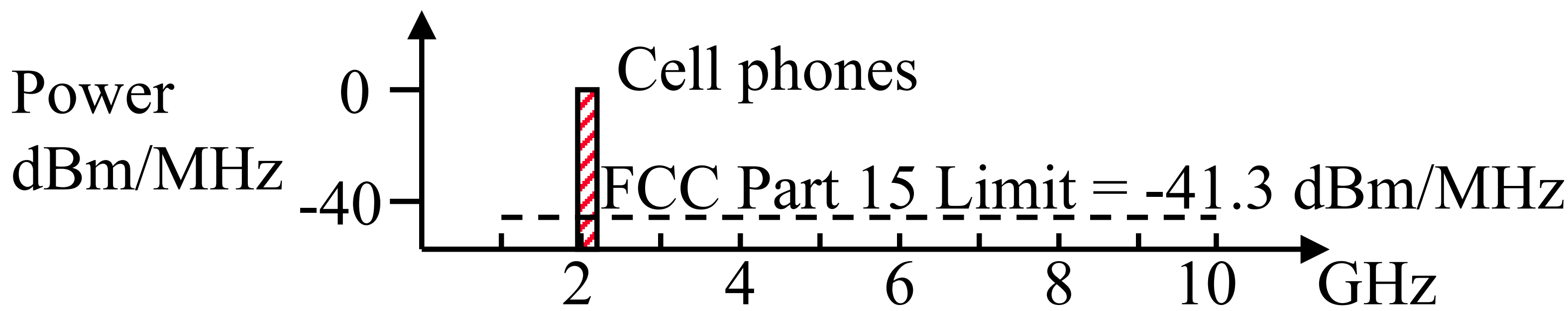
- Ultra-Wideband: How it works
- FCC Rules on UWB
- Advantages of UWB
- Direct sequence (DS-UWB)
- Multi-Band OFDM
- Applications of UWB
- UWB Products

Ultra-Wideband



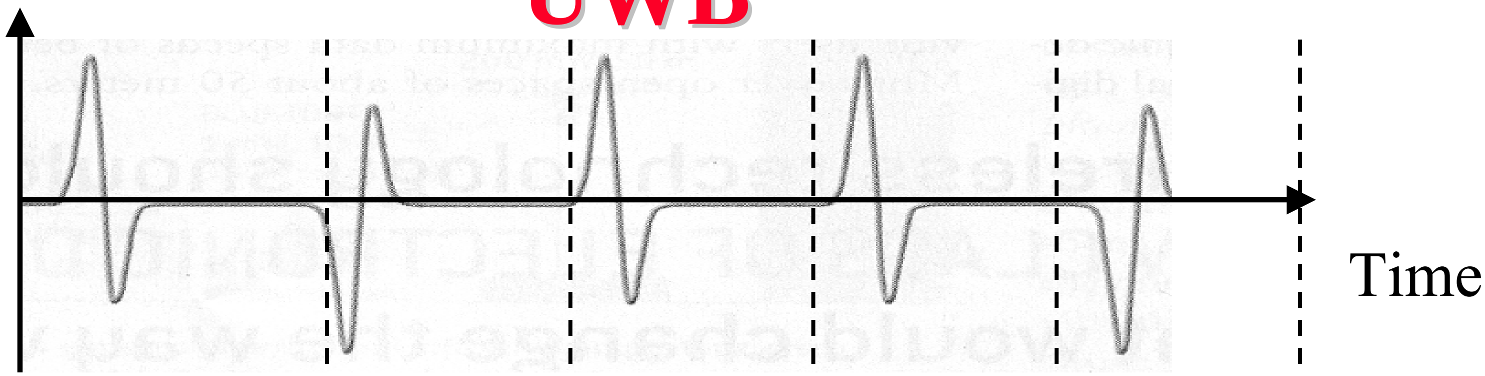
- An impulse in time domain results in a ultra wide spectrum in frequency domain and essentially looks like a white noise to other devices

Ultra-Wideband (UWB)



- FCC rules restrict the maximum noise generated by a wireless equipment (0 dBm = 1mW, -40 dBm = 0.1 mW)
- Very short (sub-ns) pulses ⇒ Spectrum below the allowed noise level ⇒ Get Gbps w 10 GHz spectrum
- FCC approved UWB operation in 2002
- High-speed over short distances ⇒ Wireless USB
- UWB can see through trees and underground (radar) ⇒ collision avoidance sensors, through-wall motion det

UWB



- Sub-nanosecond impulses are sent many million times per second. Pulse width = 25 to 400 ps
- 0.25 ns Impulse ⇒ 4 B pulses/sec ⇒ 100's Mbps
- Became feasible with high-speed switching semiconductor devices
- May be position, amplitude, or polarity modulated

History of UWB

- Oldest wireless communication technology
- Late 1800: Hertz used a spark gap generator to generate a *short pulse* of electromagnetic signal
- 1910: Low spectral efficiency of spark gap
  ⇒ Narrow band communication
- 1960: Military radar required short pulses to determine distance to objects
- Early 1990s: Multiple users can use short pulses to share the medium
- 2002: FCC allowed UWB between 3.1GHz and 10.6GHz ⇒ Within 2 years 200 companies in UWB
- 2005: Japanese and Europeans allowed UWB

IEEE COMMUNICATIONS SOCIETY

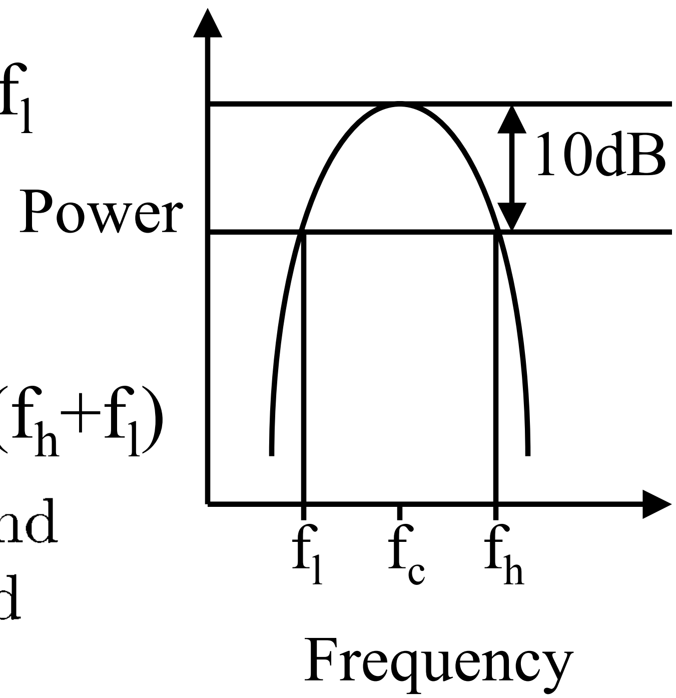
IEEE

FCC Rules on UWB

- Between 3.1GHz and 10.6GHz
- Power spectral density < -41.3 dBm/MHz
- The power masks are different for indoor and outdoor
- Some imaging systems are allowed higher power
- Through the wall surveillance systems can use 1.99 GHz to 10.6 GHz and below 960 MHz.
- 24-29 GHz for vehicular radar systems
- More than 500 MHz bandwidth or more than 20% fractional bandwidth

Fractional Bandwidth

- 10dB cut-off frequencies f_h and f_l
- Absolute bandwidth = $f_h - f_l$
- Center Frequency $f_c = (f_h + f_l)/2$
- Fractional Bandwidth = $2(f_h - f_l)/(f_h + f_l)$



$$b_f = \begin{cases} < 1\% & \rightarrow \text{Narrowband} \\ 1 \text{ to } 20\% & \rightarrow \text{Broadband} \\ > 20\% & \rightarrow \text{Wideband} \end{cases}$$

- 802.11 and Bluetooth have b_f 0.8% and 0.04%, resp.

UWB Challenges

- Pulse-shape distortion: non-sinusoidal pulses
- Channel estimation is complicated
- A jitter of 1ns can cause problem ⇒ Highly accurate timing circuit
- Interference from other UWB users
- Low transmission power

Advantages of UWB

- Shares spectrum with other applications
- Large bandwidth
- Low signal-to-noise ratio
- Low probability of intercept and detection
- Resistance to jamming
- Superior penetration properties at low frequency spectrum
- Simple transceiver architecture. All digital. Low cost.

Advantages of UWB (Cont)

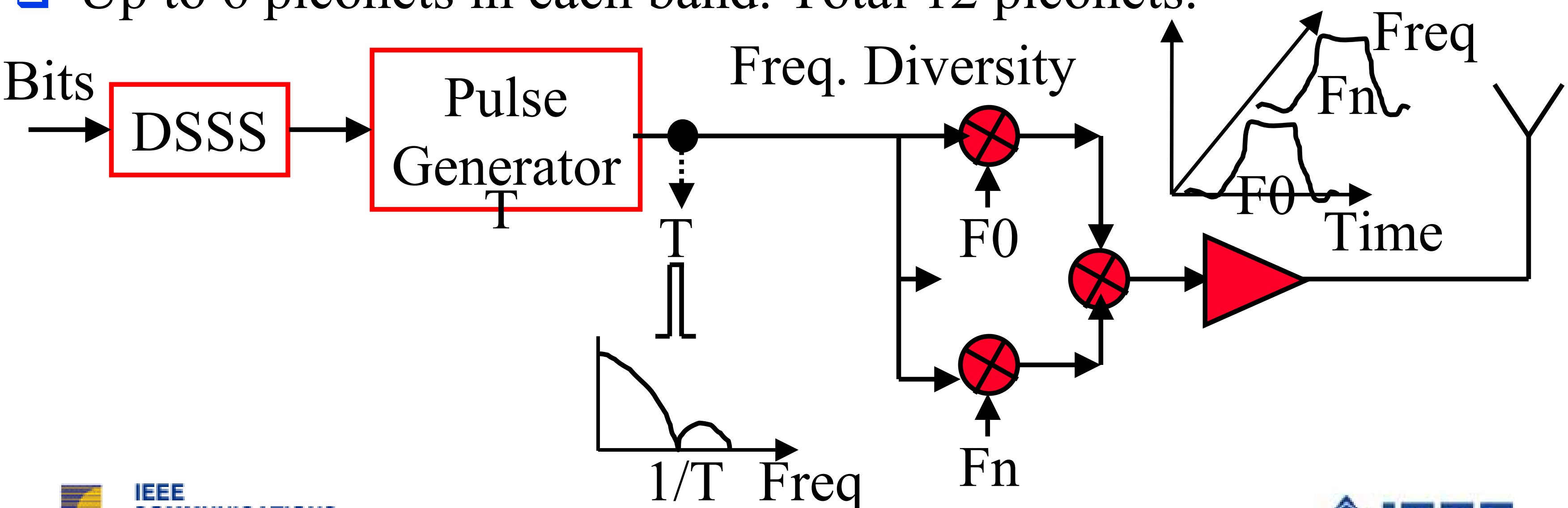
- Very low energy consumption: Good Watts/Mbps
- Line of sight not required. Passes through walls.
- Sub-centimeter resolution allows precise motion detection. Track high-value assets
- Pulse width much smaller than path delay
  ⇒ Easy to resolve multipath
  ⇒ Can use multipath to advantage

IEEE 802.15 History

- 1999: 802.15.1 started. First WPANs.
- 1999: 802.15.3 started. Higher data rate 2.4 GHz WPANs.
- 2000: UWB PHY proposed at IEEE but no regulatory support.
- 2001: 802.15.3a High Data rate UWB started
- 2002: FCC allows UWB
- 2003: 802.15.3 standard approved.
- 2006: 802.15.3a UWB group disbanded

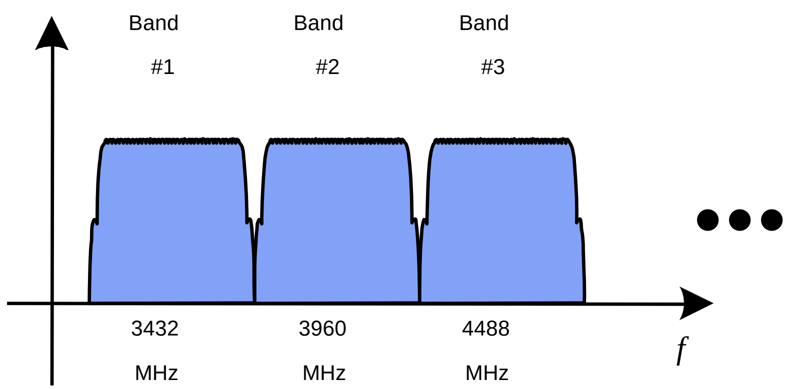
Direct sequence (DS-UWB)

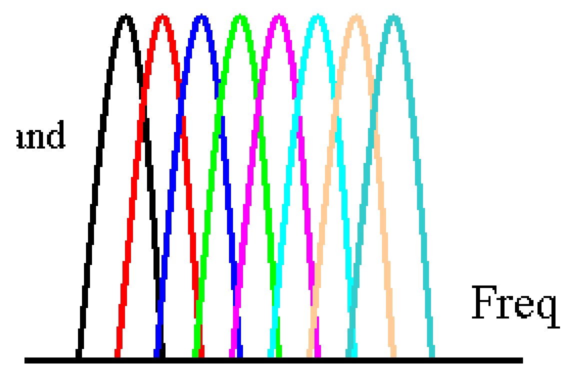
- Championed by UWB Forum (Motorola/XtremeSpectrum)
- Uses CDMA with multiple chips per bit
- Chips are encoded using pulses
- 28 Mbps to 1320 Mbps depending upon the distance
- Two bands: Low (3.1-4.9 GHz), High (6.2-9.7 GHz)
- Up to 6 piconets in each band. Total 12 piconets.



Multi-Band OFDM

- WiMedia Alliance. Originally by TI. Now many companies
- Divide the 3.1-10.6 GHz spectrum in 14x528 MHz bands (FCC requires min 500 MHz use for UWB)
- Spectrum shaping flexibility for international use
  Move off the band if interference
- Disable a few sub-carriers if required to meet local laws
- ECMA-368, 369 Standard, 2005.





IEEE COMMUNICATIONS SOCIETY

IEEE

Multi-Band OFDM PHY

- 14 528-MHz bands in 5 groups
- 128 subcarriers in one band ⇒ 4.125 MHz spacing
- 100 data + 12 pilots + 10 Guard + 6 Null
- Every 11th tone is a pilot for carrier and phase tracking
- Guard tones at the edges replicate edge data tones
- First generation (Mode 1) devices will use 1st group
- Mode 1 devices hop in 3 bands of 1st group ⇒ 4 piconets
- Group 1-4 can support 4 piconets each with frequency hopping
- Group 5 can support 2 piconets ⇒ Total 18 piconets
- 312.5 ns in each band
- Data can be duplicated in frequency or time domain ⇒ Redundancy ⇒ Lower rate 55 Mbps to 480 Mbps.

Applications of UWB

1. **Data communication**:
   High bandwidth ⇒ High data rate;
   Low spreading factor + Low power ⇒ Short distances ~= 10 m ⇒ PAN

   HDTV transmission from set top box or DVD player to TV

   Wireless USB = 480 Mbps
2. **Sensor Networks**: Baseband ⇒ No down conversion ⇒ All digital ⇒ Low cost;

   Low data rate ~a few kbps, longer ranges ~=30 to 100m

   IEEE 802.15.4a is developing a impulse radio based standard

   Very precise location of sensor nodes possible via UWB
3. **Location aware communication**: Precise location possible ⇒ Firefighters communicating thru burning obstacles.

Applications of UWB (Cont)

4. **Body area networks**: Small size and very low power.
   Home automation ⇒ change channel as you walk in,
   Automatically lock/unlock doors
   Identification ⇒ Friend or Foe
5. **UWB Radar**: Short pulse ⇒ Precise position location;
   Can penetrate walls and ground
6. **Ground Penetration Radar**:
   Multi-path resolution ⇒ Locate underground pipes, landmines
7. **Through-Walls Imaging**: Surveillance, urban warfare, locate concealed contrabands in hidden compartments in boats
8. **Vehicular collision avoidance radar**. Adaptive cruise control (match speed to car ahead).

Applications of UWB (Cont)

9. **Biological imaging**: Movement of heart, lungs, bowls, chest, bladder, or fetus. Better than MRI.
   Detection of lumps ⇒ Breast cancer
10. **Localization**: Prisoner tracking, inventory tracking, personnel identification

UWB Products

- **XtremeSpectrum Inc/Motorola**: Trinity chipset Trinity=Low power, low cost, and high data rate. DS-UWB based high speed PAN.
- **Time Domain Corp**: PulseON chipset. I-UWB with Pulse position modulation. 9.6 Mbps at less than 20m.
- **Multispectral Solutions Inc (MSSI)**:
  - Short and long range military communication systems.
  - Cordless communication systems for use in aircrafts.
  - Precision asset location (PAL) system, originally for tracking soldiers and containers. Now commercial FCC compliant use.
  - Micro air vehicle collision avoidance systems. MAVs are aircrafts less than 6 inches in any dimension for monitoring.

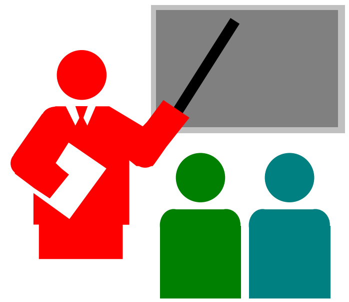
UWB Products (Cont)

- **Aether Wire and Location Inc**: Pager sized units with centimeter localization over several kms in networks of thousands of nodes.
- Wireless USB from Staccato Communications
- UWB antennas from Omran
- Click n' Share Wireless USB Flash Memory Drives from Memsen
- UWB chips from Intel, Artimi, and Wisair
- Locating bodies in disaster situations by Ultravision
- Mini-PCI UWB radio modules and evaluation kits from Focus Semiconductor

Sample UWB Products (Cont)

- Wireless video in cars using Focus UWB radio
- Wireless High-Definition Multimedia Interface (HDMI) solutions form Tzero, Analog Devices, and Gefen
- Wireless HD gaming over UWB by Pulse-Link
- Ref: http://www.ultrawidebandplanet.com/products/

Summary



- Impulses in time domain result in a wideband frequency spectrum
- FCC requires min 500 MHz band and 20% fractional bandwidth
- The average power is below the noise level ⇒ Shares spectrum with current spectrum users
- Applications in communications, positioning (radar, surveillance), and multi-path imaging

High Throughput WiFi: 802.11n

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

- Major Components of 11n
- IEEE 802.11n Status
- Sample IEEE 802.11n Products
- Hybrid 802.11 Networks: Issues

Wi-Fi

- "Last Feet" standard
- 54 Mbps to 100 ft (11a/g)
- 1000 ft with highest power allowed
- Operates over 20 MHz
- Pro: Wide availability of terminals (Notebooks, PDAs, phones, media players)
- con: CSMA - inefficient ⇒ 20-25 Mbps max
- Not designed for high-speed mobility

IEEE 802.11n

- Trend: HDTV and flat screens are taking off
  Media Center Extenders from Linksys and other vendors
- Application: HDTV and streaming video (over longer distances than permitted by 802.15.3 WPANs)
- IEEE 802.11n = Next Generation of 802.11
- At least 100 Mbps at MAC user layer
  $\Rightarrow$ 200+ Mbps at PHY $\Rightarrow$ 4x to 5x faster than 11a/g
  (802.11a/g have 54 Mbps on air and 25 Mbps to user)
- Pre-11n products already available

11n Technology

- Uses multiple input multiple output antenna (MIMO)
- Data rate and range are enhanced by using spatial multiplexing (N antenna pairs) plus antenna diversity
- Occupies one WLAN channel, and in compliance with 802.11
- Backwards compatible with 802.11 a,b,g
- One access point supports both standard WLAN and MIMO devices

Major Components of 11n

1. Better OFDM: Higher code rate gives 65 Mbps instead of 54 Mbps
2. Space Division Multiplexing: Up to 4 spatial streams
3. Diversity: More receive antennas than the number of streams. Select the best subset of antennas.
4. Beam Forming: Focus the beam directly on the target antenna
5. MIMO Power Save: Use multiple antennas only when needed
6. 40 MHz Channels
7. Aggregation: Transmit bursts of multiple data packets
8. Reduced Inter-Frame Spacing
9. Greenfield Mode: Optionally eliminate support for a/b/g

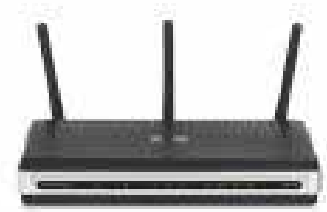
IEEE 802.11n Status

- Enhanced Wireless Consortium (EWC) was formed in October 2005 to accelerate the development
- WWise, TGnSync and EWC proposals were merged and a draft was accepted in January 2006.
- IEEE 802.11n draft v2.03 in May 3, 2007
- Final IEEE publication scheduled for April 2008
- Intel, Broadcom, Marvel have pre-11n chip sets
- Wi-Fi Alliance is planning to certify products based on draft 2.0 of the standard.

Sample IEEE 802.11n Products

- Linksys, Belkin, D-Link, Netgear have pre-11 wireless routers
- Not compatible with each other
  Not guaranteed to be upgradeable to full 802.11n
  Actual throughputs up to 40 Mbps
- Wi-Fi Alliance will certify pre-11n products

Belkin



D-Link

Linksys

IEEE COMMUNICATIONS SOCIETY   IEEE

Hybrid 802.11 Networks: Issues

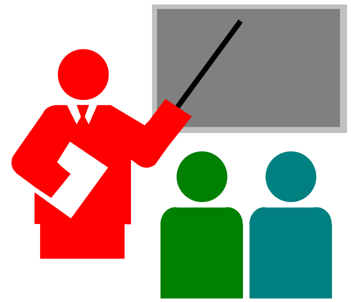
Parameter	802.11b	802.11a	802.11g	802.11n
Data Rate (Mbps)	11	54	54	130 or 270
Modulation	CCK or DSSS	OFDM	CCK, DSSS or OFDM	CCK, DSSS OFDM
Band (GHz)	2.4	5	2.4	2.4 or 5
Spatial streams	1	1	1	4
Channel (MHz)	20	20	20	20 or 40

- You need 11n at both ends to benefit
- A single 802.11b station can force 802.11n AP to operate with CCK or DSSS modulation ⇒ Reduced performance
- 802.11n can consume 2 of 3 non-overlapping channels in 2.4 GHz band ⇒ Can degrade existing 802.11b/g networks ⇒ Move to 5 GHz and 802.11a

Hybrid Networks Issues (Cont)

- Most of the benefits of 802.11n are in 5 GHz band. Enterprise networks are moving from 11b to 11a.
- Upgrade from 11b/a/g to 11n is a forklift upgrade.
- Need gigabit Ethernet backbone with 802.11n

Summary



1. 11n gets 100+ Mbps by MIMO, OFDM and wider channels
2. 11b devices can prohibit use of OFDM and may decrease the performance for everyone
3. Wider channels practical only in 5 GHz band ⇒ 11a/n
4. You need 11n at both ends to really benefit

IEEE COMMUNICATIONS SOCIETY

IEEE

WiMAX Overview

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

- Technical and Business Challenges
- Prior Broadband Wireless Efforts
- Spectrum Options
- IEEE 802.16 – QoS Classes
- WiBro
- Sample WiMAX Products

Broadband Wireless: Tech Challenges

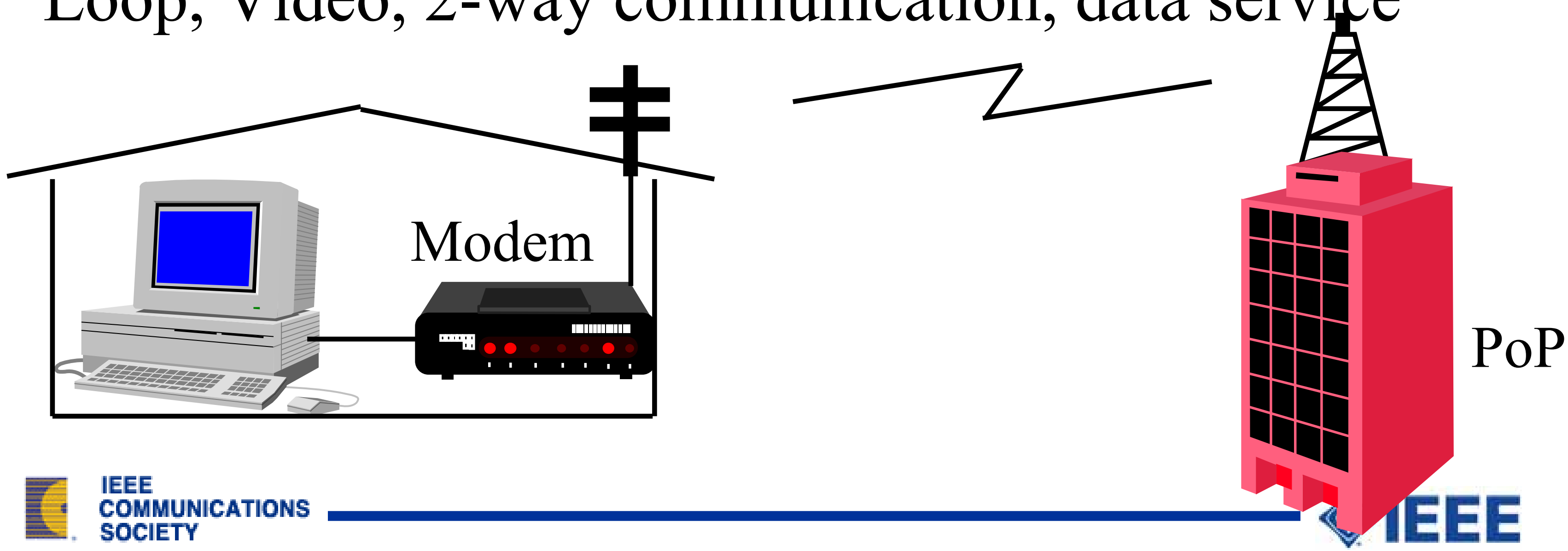
- Reliable transmission
- Non-line of Sight
- High spectral efficiency
- QoS
- Seamless handover and roaming
- Low power consumption
- Robust Security

Business Challenges

- Compete with DSL
- Global spectrum availability
- Competition from 3G
- Subscriber devices:Computers, MP3 Players, Video players, ...

Prior Broadband Wireless Efforts

- Local Multipoint Distribution Service (LMDS)
- Local ⇒ Within one cell. 2 to 5 miles range.
- Multipoint ⇒ Broadcast from base. Point-to-point from subscriber.
- Distribution ⇒ Multiple services = Wireless Local Loop, Video, 2-way communication, data service



LMDS (Cont)

- 1.3 GHz around 28 GHz band (Ka Band)
  28 GHz ⇒ Rain effects
- 1 Gbps downstream and 200 Mbps upstream
  Most commercial offerings T1/E1
- FCC auctioned LMDS spectrum in 1998.
  A Block: 27.5-28.35GHz, 29.10-29.25GHz
  B Block: 31.00-31.075 GHz, 32.225-32.300 GHz
- Using TDMA, FDMA, or CDMA
- CellularVision offered 49-channel cable TV service using LMDS in NYC.
- NextLink, Teligent, and Winstar offered ATM-based service
- Issues: Equipment too expensive, Roof top antennas, short range

IEEE COMMUNICATIONS SOCIETY IEEE

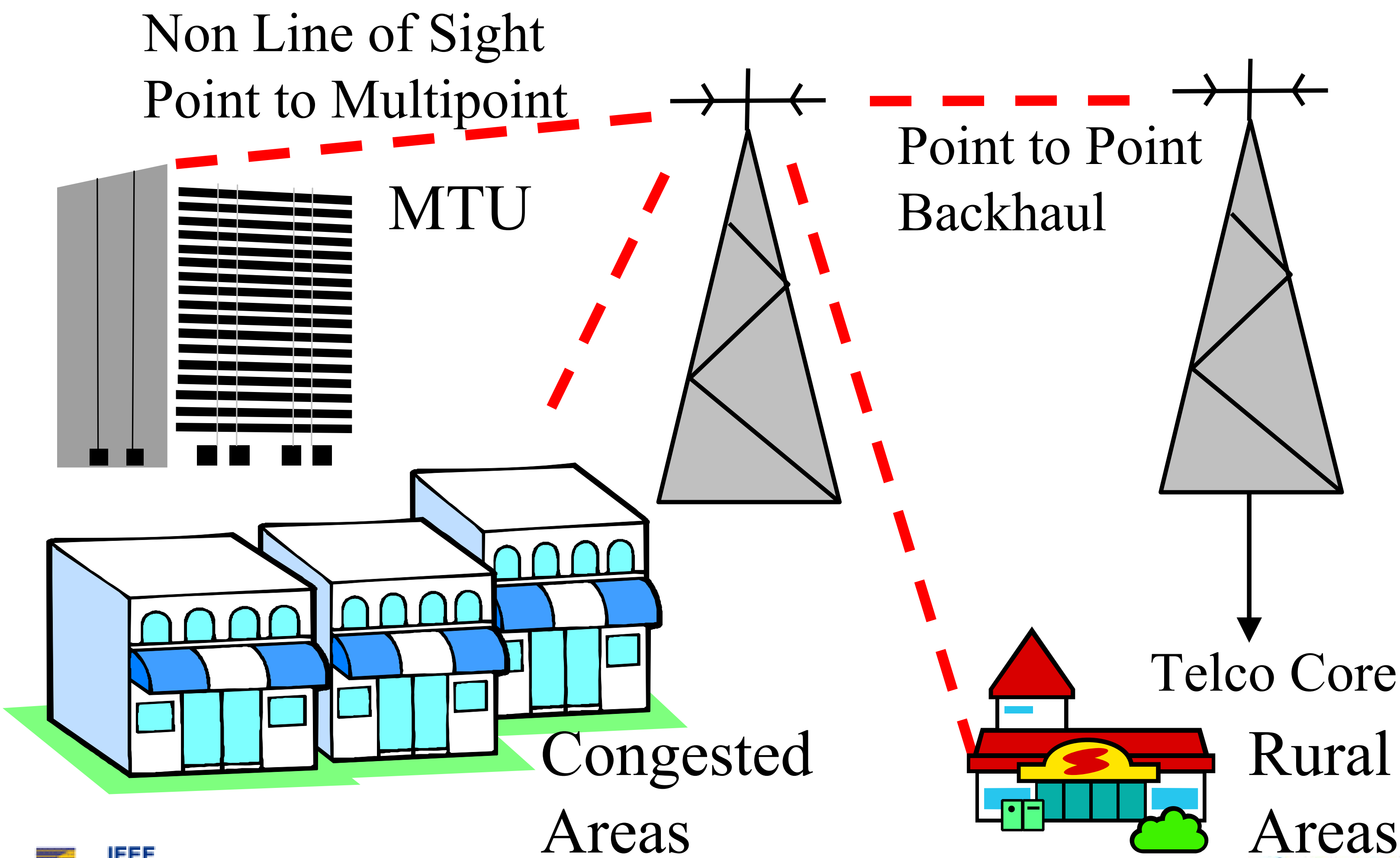
MMDS

- Multi-channel Multipoint Distribution Services
- 2.1, 2.5-2.7 GHz Band ⇒ Not affected by rain
- Reused the towers used for wireless Cable TV
  Omni-directional or sectorized antennas on TV towers
- Outdoor subscriber antenna with clear LoS

MMDS (Cont)

- Line of sight. Alternative to DSL
- Wireless cable for internet access in rural areas
- 35-mile radius protected service areas or 3850 sq. miles per base
- 99 data streams at 10 Mbps each
- April 1999-October 2001: MCI and Sprint offered MMDS
- Issue: Outdoor LoS antenna, Too small capacity for 35 Miles

Broadband Wireless Access



History of WiMAX

- Jul 1999 IEEE 802.16 group's first meeting
- Jun 2001 WiMAX Forum established
- Dec 2001 IEEE 802.16 SC 11-60 GHz standard
- Feb 2002 Korea allocates 2.3 GHz for WiBro
- Jan 2003 IEEE 802.16a with NLOS in 2-10 GHz
- Jun 2004 IEEE 802.16-2004 (802.16d) completed
- Sep 2004 Intel ships first WiMAX chipset
- Dec 2005 IEEE 802.16e with scalable OFDMA
- Jan 2006 First WiMAX Forum Certified product announced
- Jun 2006 WiBro Commercial Services Launched in Korea
- Aug 2006 Sprint Nextel announces WiMAX plans in USA
- Q1 2007 Mobile WiMAX Certification started

IEEE 802.16: Key Features

- Broadband Wireless Access
- Up to 50 km or Up to 70 Mbps.
- Data rate vs Distance trade off w adaptive modulation. 64QAM to BPSK
- Offers non-line of site (NLOS) operation
- 1.5 to 28 MHz channels
- Hundreds of simultaneous sessions per channel
- Both Licensed and license-exempt spectrum
- Centralized scheduler
- QoS for voice, video, T1/E1, and bursty traffic
- Robust Security

IEEE COMMUNICATIONS SOCIETY

IEEE

WiMAX

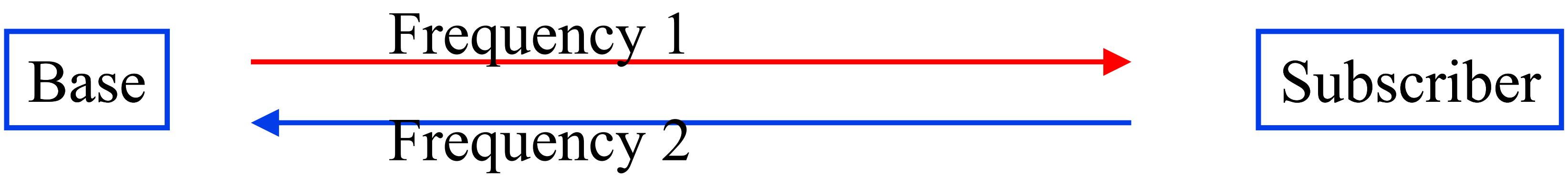
- Worldwide Interoperability for Microwave Access
- 420+ members including Semiconductor companies, equipment vendors, integrators, service providers. Like Wi-Fi Alliance
- Established June 2001
- Narrowed down the list of options in 802.16
- Plugfests started November 2005
- WiMAX forum lists certified base stations and subscriber stations from many vendors
- http://www.wimaxforum.org

IEEE COMMUNICATIONS SOCIETY

IEEE

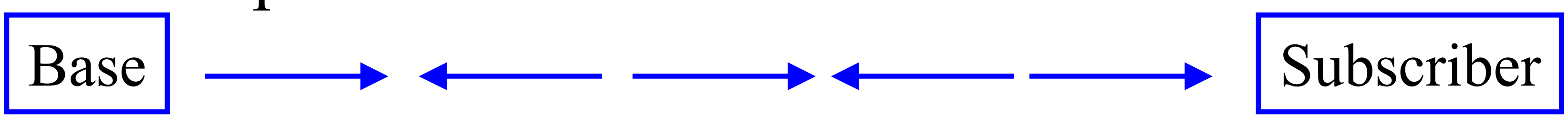
Duplexing Options

- Duplex = Bi-Directional Communication
- Full-Duplex = Both directions at the same time



This is known as Frequency division duplexing (FDD)

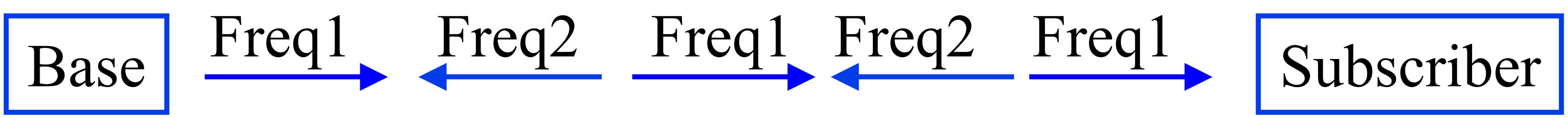
- Half-duplex = One direction at a time



This is known as Time division duplex (TDD)

Duplexing Options (Cont)

- Half-Duplex FDD (HFDD): Two frequencies.
  But either transmitter or receiver is on.



- Most WiMAX deployments will use TDD.
  - Allows more flexible sharing of DL/UL data rate
  - Does not require paired spectrum
  - Easy channel estimation Þ Simpler transceiver design
  - Con: All neighboring BS should time synchronize

IEEE 802.16 – QoS Classes

Connection oriented: one or more unidirectional connections between subscriber and base

Five Service Classes:

1. Unsolicited Grant Service (UGS): CBR traffic like voice
2. Enhanced Real-time Service (ertPS): Silence suppressed voice.
3. Real-Time Polling Services (rtPS): rtVBR like MPEG video
4. Non-Real-Time Polling Service (nrtPS): nrtVBR, e.g., FTP
5. Best Effort (BE)

Spectrum Options

Designation	Frequency GHz	Bandwidth MHz	Notes
3.5 GHz	3.4-3.6; 3.3-3.4; 3.6-3.8	200 Total. 2×(5 to 56)	Not in US. Considering 3.65-3.70 for unlicensed
2.5 GHz	2.495-2.690	194 Total. 16.5+6 paired.	In USA.
2.3 GHz	2.305-2.320; 2.345-2.360	2×5 paired. 2×5 unpaired.	US, Kr, Au, Nz
2.4 GHz	2.405-2.4835	80 Total	Lic exempt. World-wide.
5 GHz	5.250-5.350; 5.725-5.825	200 MHz	Worldwide.
700 MHz	0.698-0.746; 0.747-0.792	30+48	US
Adv W. Serv.	1.710-1.755; 2.110-2.155	2×45 paired	Used for 3G

IEEE COMMUNICATIONS SOCIETY

IEEE

WiBro

- Mobile broadband access standard for Korea
- A pre-standard version of 802.16e
  Will conform to 802.16e in the near future
- Standardized 1H04, Licenses issued 1H05, Service starts 1H06
- Up to 60 km/h mobility, 1km cells
- Spectral efficiency:
  Max: 6 bps/Hz/sector UL/ 2 bps/Hz/sector DL
  Avg: 2 bps/Hz/sector UP/ 1 bps/Hz/sector DL

IEEE COMMUNICATIONS SOCIETY

IEEE

WiBro (Cont)

- 10 MHz channel in 2.3 GHz band
- OFDMA with QPSK, QAM16, QAM64 modulation
- Per Subscriber Data rate:
  DL/UL = 3 Mbps/1 Mbps (max) = 512 kbps/128 kbps (mobile)
- Handoff $\leq$ 150 ms

Status of WiMAX

- WiBro service started in Korea in June 2006
- More than 200 operators have announced plans for WiMAX
- About half are already trialing or have launched pre-WiMAX
- Two dozen networks in trial or deployed in APAC
- 15 in Western Europe
- Sprint-Nextel in 2.3/2.5 GHz with equipment supplied by Intel, Motorola, Samsung, Nokia, and LG
- Initial deployment in Washington DC and Chicago
- Intel will sample a multi-band WiMAX/WiFi chipset in late 2007
- M-Taiwan

Sample WiMAX Subscriber Stations

Alvarion

Airspan

Axxcelera

Siemens

Aperto

Redline

SR Telecom

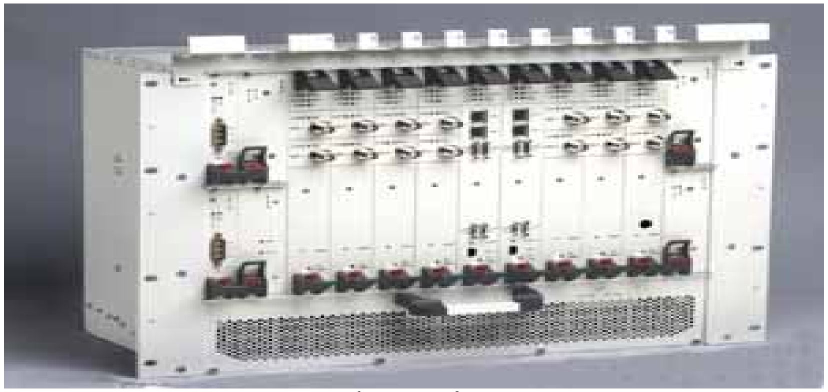
Telsima

IEEE COMMUNICATIONS SOCIETY

IEEE

Sample WiMAX Base Stations

Axxcelara



Alverian

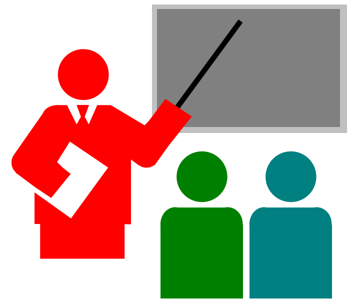
Redline

Airspan

Aperto

SR Telecom

Summary



1. Previous broadband access technologies had problems with antenna placement and cost
2. WiMAX allows indoor, non-line of sight operation
3. Many different spectral bands are possible.
   WiMAX forum is working on a worldwide band.
4. WiBro service in Korea started. Sprint/Nextel starting in USA next year.
5. Key features: TDD, OFDMA, MIMO, centralized scheduling, QoS

IEEE COMMUNICATIONS SOCIETY

IEEE

WiMAX Technology

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

IEEE COMMUNICATIONS SOCIETY

IEEE

- IEEE 802.16 Standards
- IEEE 802.16 PHY Features
- 802.16 Frame Structure
- Scheduling and Link Adaptation
- IEEE 802.16 Activities
- WiMAX Forum Certification Profiles
- WiMAX Performance

802.16 Standards

	802.16-2001	802.16-2004	802.16e-2005
Band GHz	10-60	2-11	2-11 for fixed; 2-6 for Mobile
Application	Fixed LoS	Fixed NLoS	Fixed and Mobile NLoS
Carriers	Single	SC + 256 OFDM + 2048 OFDM	128, 512, 1024, 2048 SOFDMA
Multiplexing	TDMA	TDMA	OFDMA
Channel MHz	20, 25, 28	1.75, 3.5, 7, 14, 1.25, 5, 10, 15, 8.75	1.75, 3.5, 7, 14, 1.25, 5, 10, 15, 8.75
Air Interface	WirelessMAN-SC	WirelessMAN-SCa, WirelessMAN-OFDM, WirelessMAN-OFDMA, WirelessMAN-HUMAN	WirelessMAN-SCa, WirelessMAN-OFDM, WirelessMAN-OFDMA, WirelessMAN-HUMAN
WiMAX	None	256 OFDM	SOFDMA

IEEE 802.16 PHYs

	Function	LOS	Freq. Band	Carrier	Duplexing
WirelessMAN SC	Pt-to-pt	LOS	10-66 GHz	Single	TDD, FDD
WirelessMAN SCa	Pt-to-pt	LOS	2-11 GHz Licensed	Single	TDD, FDD
WirelessMAN OFDM	Pt-to-mpt	NLOS	2-11 GHz Licensed	256	TDD, FDD
WirelessMAN OFDMA (16e)	Pt-to-mpt	NLOS	2-11 GHz Licensed	2048	TDD, FDD
WirelessHUMAN (High-speed Unlicensed)	Pt-to-mpt	NLOS	2-11 GHz License Exempt	1/256/ 2048	TDD Dynamic Freq. Sel.

IEEE 802.16 Activities

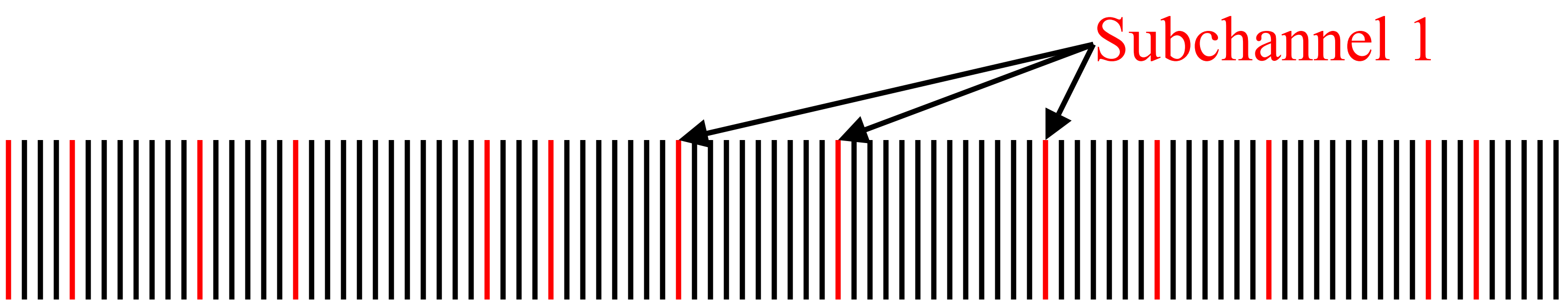
- P802.16g: Management Plane Procedures and Services
- P802.16i: Mobile MIB
- P802.16k: 802.1D bridging
- P802.16j: Mobile Multihop Relay (MMR)
- P802.16h: License-exempt channel coordination
- P802.16m: Advanced Air Interface

IEEE 802.16 PHY: Other Features

- Adaptive Modulation and Coding
- Space Time Block Codes (STBC)
- Adaptive Antenna System

Subchannelization

- Subchannel = Group of subcarriers
- Each user is given one or more subchannel.
- Subcarriers of a subchannel can be contiguous or distributed



- Contiguous
  ⇒ Subchannels allocated based on use's SINR
  ⇒ AMC ⇒ Not suitable for mobile applications

Subcarrier Permutations

- 1024 subcarriers for 10 MHz
  ⇒ 30 subchannels down and 35 subchannels up
- Each subchannel has some data+pilot subcarriers
- Subcarriers are randomly assigned to a channel and changed every few symbol times

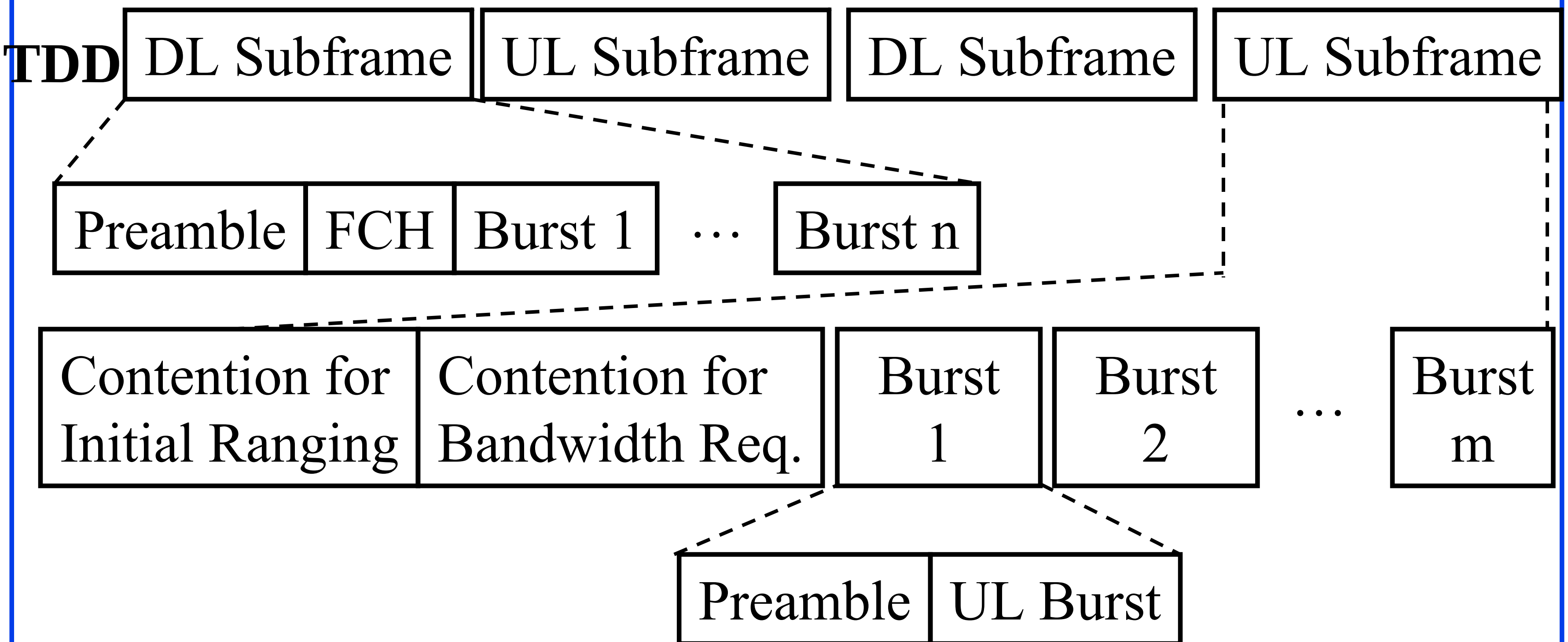
WiMAX OFDM Parameters

Parameter	Fixed	Mobile			
Channel width MHz	3.5	1.25	5	**10**	20
FFT	256	128	512	**1024**	2048
Subcarriers spacing KHz	15.625	**10.94**			
Data Subcarriers[1]	192	72	360	**720**	1440
Pilot Subcarriers	8	12	60	**120**	240
Null/Guard Subcarriers	56	44	92	**184**	368
OFDM Symbol Duration	72μs	**102.9** μ**s**			
Cyclic Prefix/Guard Time T_g/T_b	1/32, 1/6, **1/8**, 1/4				
Guard Time assuming 1/8	8 μs	**11.4** μ**s**			
Useful Symbol Time	64 μs	**91.4** μ**s**			
OFDM Symbols in 5ms Frame	69	**48**			

[1]Assuming downlink PUSC for Mobile profiles

Bold ⇒ Initial WiMAX Profiles

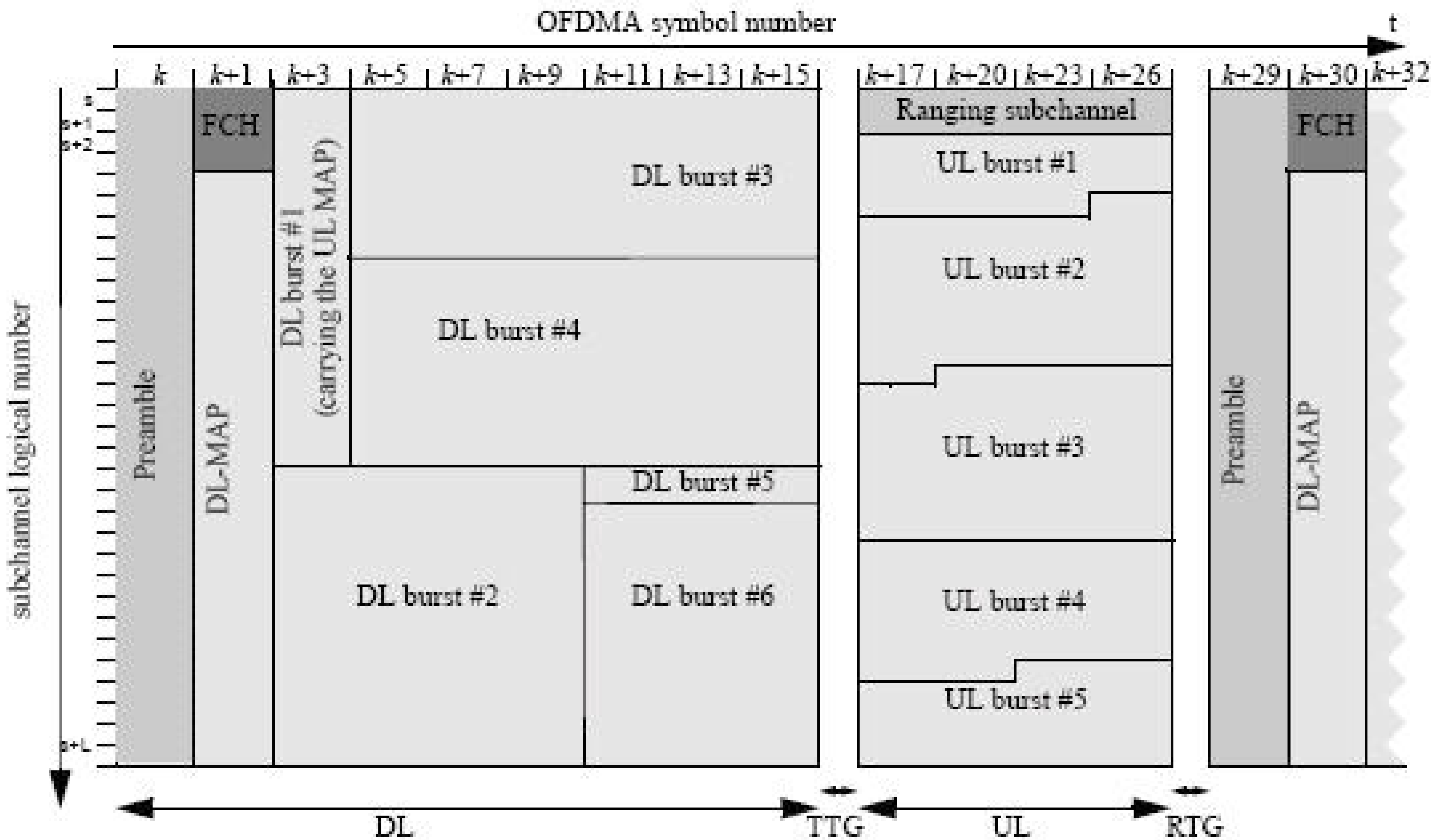
802.16 Frame Structure



TDD = Time Division Duplexing
DL = Downlink (Base to subscriber)
FCH = Frame control header:
Burst Profile, Down-link map, Uplink map, DL channel descriptor, etc.

FDD = Freq Div Duplexing
UL = Uplink

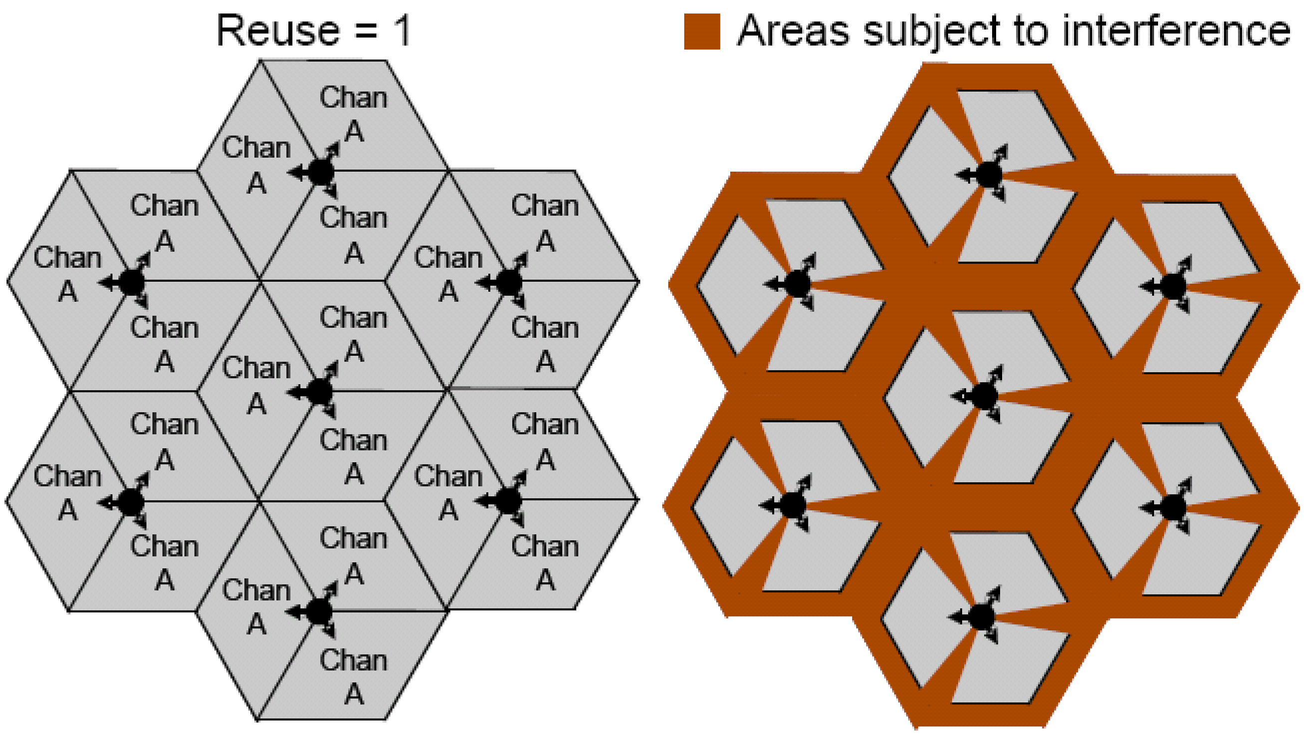
Mobile WiMAX Frame



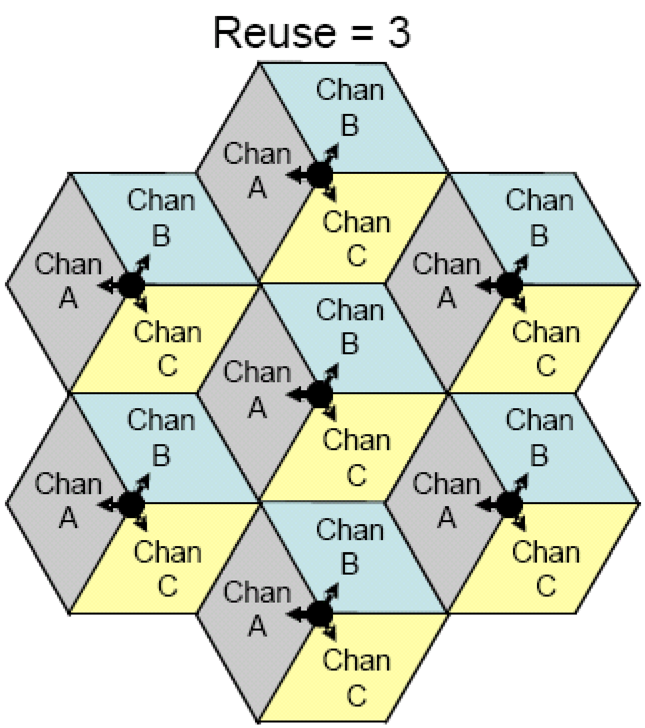
Frame Structure

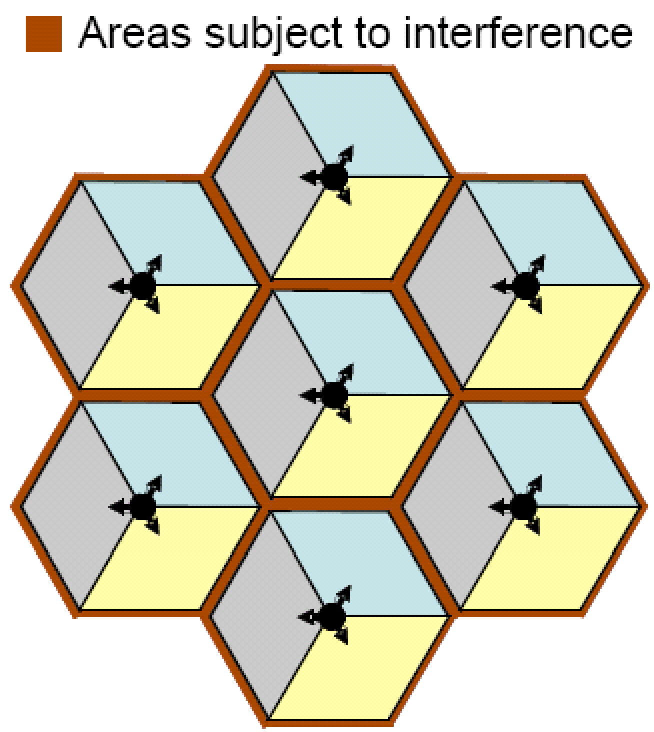
- **DL Preamble**: Time and frequency synchronization
- **Frame Control Header (FCH)**: MAPs lengths, modulation and coding, usable subcarriers
- **Downlink MAP**: Burst profile (time, frequency, modulation, coding) to each user
- **Uplink MAP**: Burst profile for transmission from each user. MAPs can be compressed
- **Contention-based region**: Ranging, bandwidth request, best-effort data
- **Ranging Channel**:
  - Closed loop frequency, time, and power adjustments
  - Channel quality indicator channel (CQICH)
  - **Ack Channel**: subscriber stations
- Initially, 5 ms frames only.

Frequency Reuse of 1



Frequency Reuse of 3





Scheduling and Link Adaptation

- Scheduling:
  - Base schedules usage of the air link among the SSs
  - Packet schedulers at the base and subscribers give transmission opportunities to multiple connection Qs
- Link Adaptation: Base determines
  - Contents of the DL and UL portions of each frame
  - Appropriate burst profile (code rate, modulation level and so on) for each subscriber
  - Bandwidth requirements of the individual subscribers based on the service classes of the connections and on the status of the traffic queues at the base and subscriber.

WiMAX Forum Certification

- Fixed WiMAX certification started in January 2006
- Mobile WiMAX certification starting in Q1 2007
- Initially PCMCIA cards, Laptop and PDA modules, Indoor modems
- Phones and consumer devices in 2008
- Initially, 2.3-2.4 GHz, 2.496-2.69 GHz, and 3.4-3.6 GHz
- **Release 1 Wave 1**: Mobility, throughput, coverage, real-time
- applications, security, power save
- **Release 1 Wave 2**: MIMO, Beam forming, Multicast broadcast service, Ethernet IO
- Conformance (Meets the specifications) & Interoperability
- Multiple Profiles based on band (e.g., 2.3-2.4 GHz), channelization (e.g., 10 MHz), and duplexing (e.g., TDD)

IEEE COMMUNICATIONS SOCIETY IEEE

WiMAX Forum Cert. Profiles: Fixed

Band Index	Frequency Band	Channel Width	OFDM FFT	Duplexing	Notes
1	3.5	3.5	256	FDD	1
		3.5	256	TDD	
		7	256	FDD	
		7	256	TDD	
		10	256	TDD	
2	5.8	10	256	TDD	

1. Products already certified

WiMAX Cert. Profiles: Mobile

Band Index	Frequency Band	Channel Width	OFDM FFT	Duplexing	Notes
1	2-3-2.4	5	512	TDD	2
		10	1024	TDD	2
		8.75	1024	TDD	
2	2.305-2.320	3.5	512	TDD	
		5	512	TDD	
		10	1024	TDD	
3	2.496-2.690	5	512	TDD	2
		10	1024	TDD	2
4	3.3-3.4	5	512	TDD	
		7	1024	TDD	
		10	1024	TDD	
5	3.4-3.8	5	512	TDD	
	3.4-3.6	7	1024	TDD	
	3.6-3.8	10	1024	TDD	

2. Both bandwidths must be supported by mobile station.

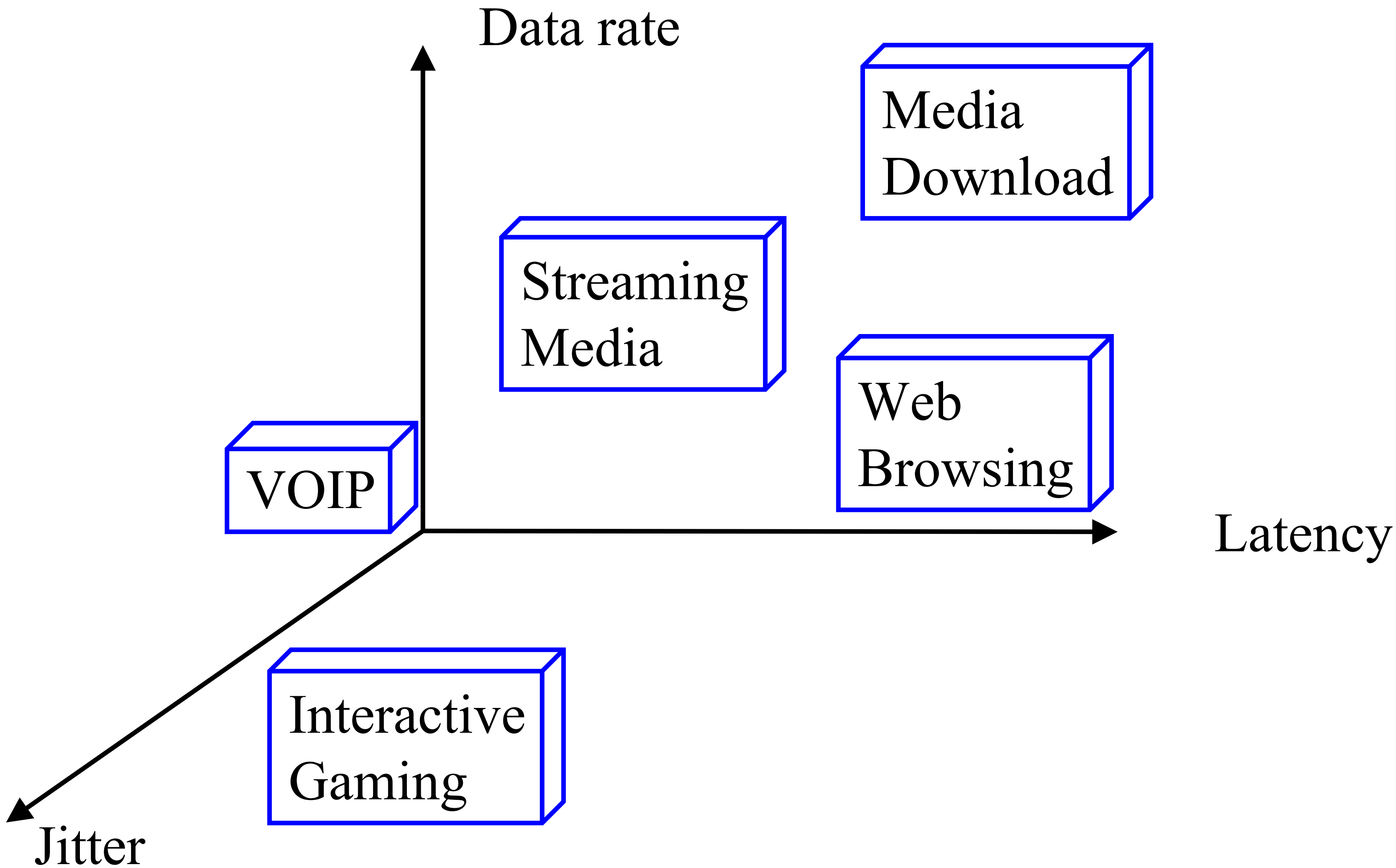
WiMAX AWG Application Classes

Class	Application	Data Rate		Latency		Jitter	
1	Interactive Gaming	Low	50 kbps	Low	80 ms		
2	VOIP	Low	6-32 kbps	Low	160 ms	Low	<50 ms
3	Streaming Media	Mod	<2 Mbps			Low	<100 ms
4	Instant Messaging/ Web Browsing	Mod	2 Mbps				
5	Media download	High	10 Mbps				

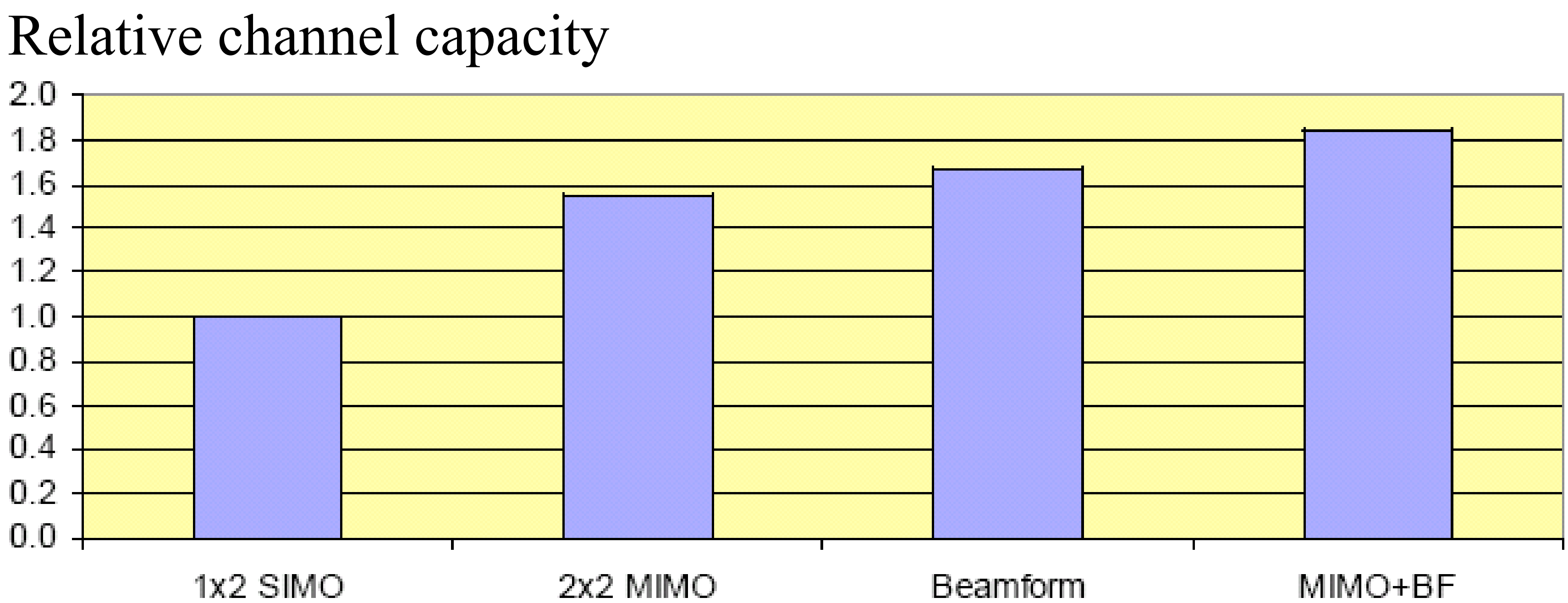
IEEE COMMUNICATIONS SOCIETY

IEEE

WiMAX AWG Classes (Cont)

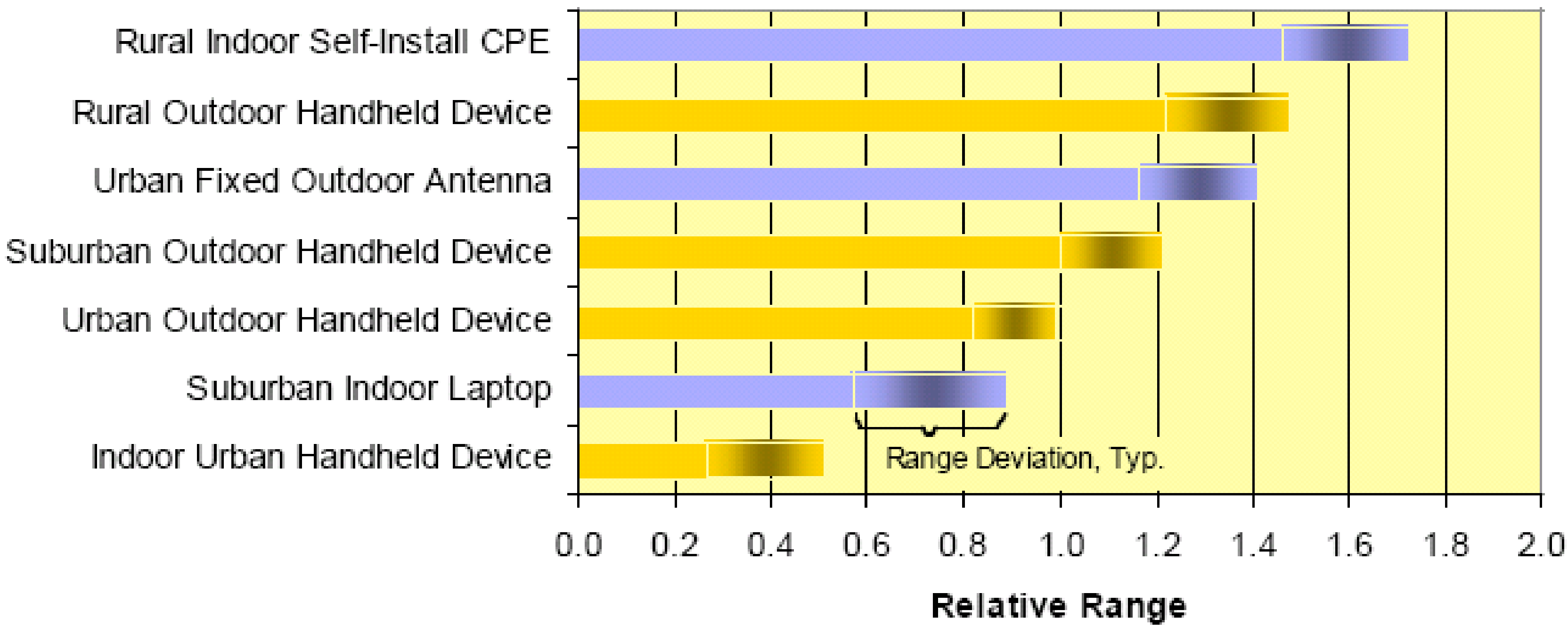


Effect of MIMO on Capacity



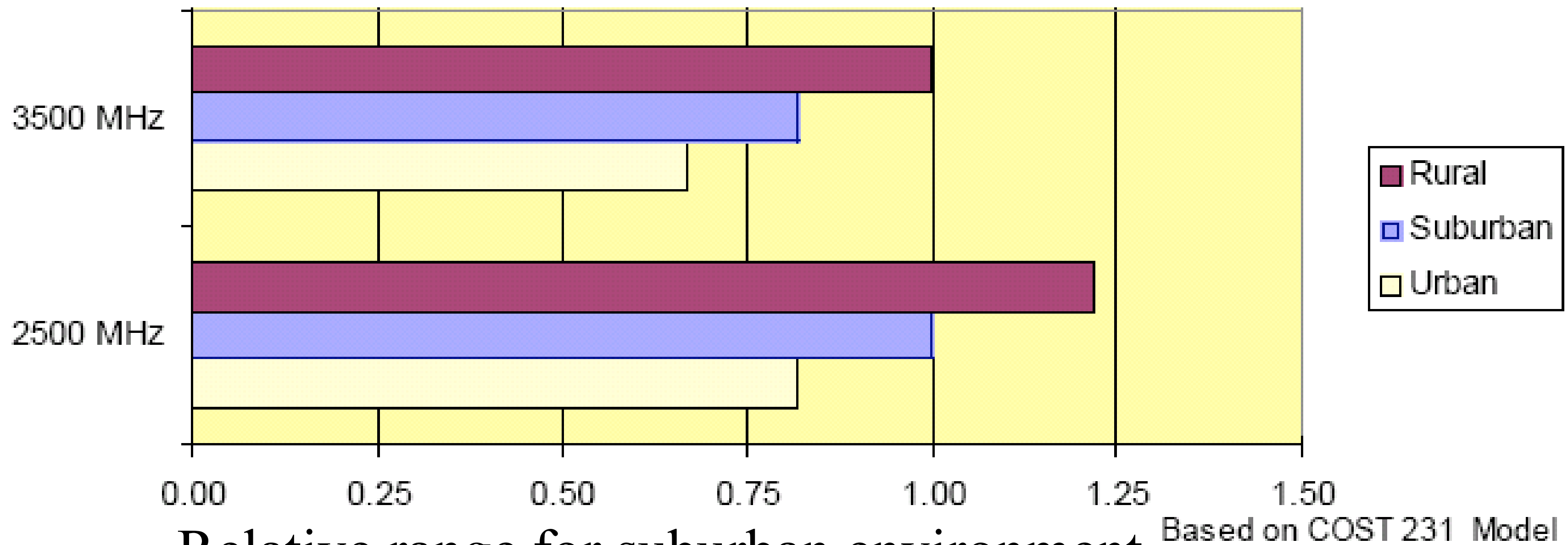
- Ref: WiMAX Forum, "A Comparative Analysis of Mobile WiMAX Deployment Alternatives in the Access Network," White paper, May 2007.

Effect of Location and Device Type



- Ref: WiMAX Forum, "A Comparative Analysis of Mobile WiMAX Deployment Alternatives in the Access Network," White paper, May 2007.

Effect of Wavelength



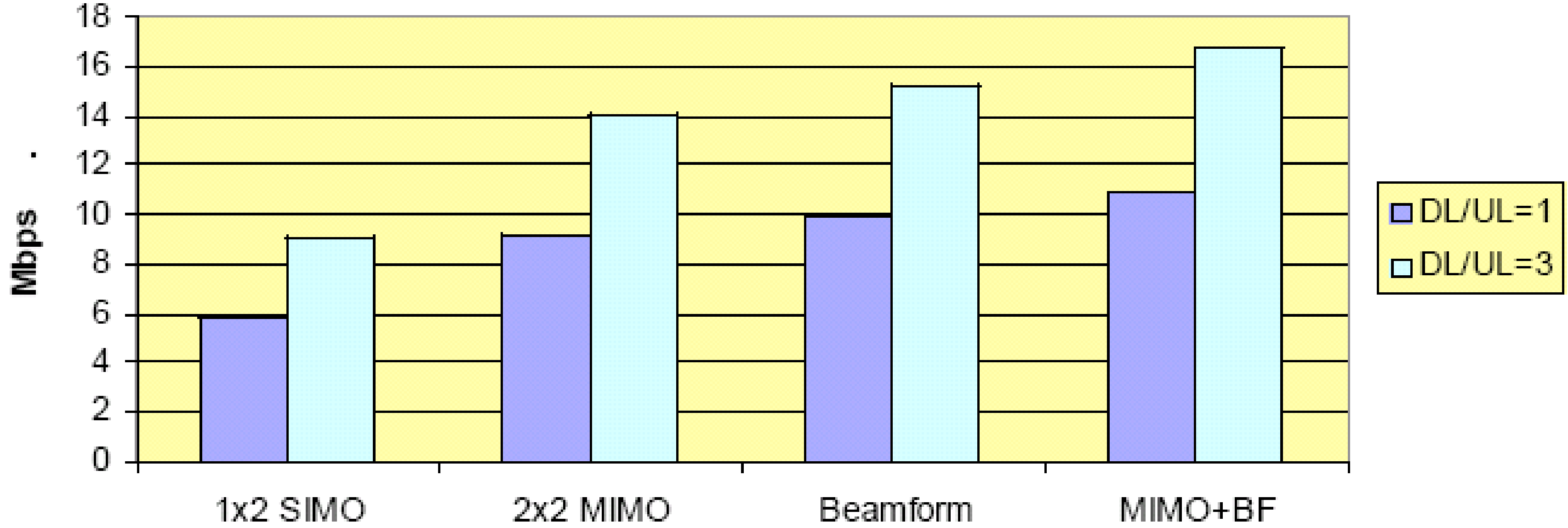
Relative range for suburban environment

- Antenna gain is inversely proportional the square of the operating wavelength.
- Ref: WiMAX Forum, "A Comparative Analysis of Mobile WiMAX Deployment Alternatives in the Access Network," White paper, May 2007.

Effect of TDD

- Same channel both ways
  ⇒ Base station can optimize beam forming for DL
- Easily adopt to asymmetric traffic 1:1 to 3:1 (FDD = 1:1)

Downlink Throughput

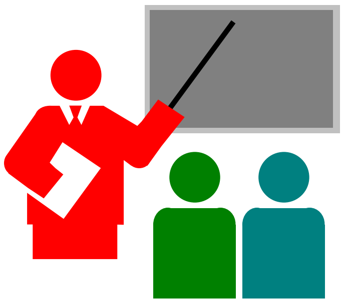


TDD with 10 MHz

Ref: WiMAX Forum, Comparative Analysis whitepaper

IEEE COMMUNICATIONS SOCIETY

Summary: WiMAX Technical Solutions



Issue	Solution
Multipath fading	OFDM
Noise	Coding
Interference	Sectorization; dynamic frequency selection
High spectral efficiency	Adaptive modulation and coding; diversity, spatial multiplexing, Cellular architecture
Radio resource management	Efficient scheduling
QoS	Classes of service
Mobility	Scalable OFDMA
Seamless Handover	Roaming database
Long battery life	Sleep/idle modes; power efficient modulation
Security	Encryption; Authentication and access control
Low cost	IP based architecture

Other Broadband Access Technologies

Raj Jain
Department of Computer Science and Engineering
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

IEEE COMMUNICATIONS SOCIETY
IEEE

- IEEE 802.11 vs. 802.16
- HSDPA, HSUPA, HSPA
- EV-DO
- WiMAX vs. 3G
- LTE
- Evolution of 3GPP2
- IEEE 802.20, IEEE 802.22

IEEE 802.11 vs. 802.16

	802.11	802.16
Application	In-Building, Enterprise	Service providers => Carrier Class
Range	Optimized for 100m	Optimized for 7-10 km Up to 50 km
Range Spread	No near-far compensation	Handles users spread out over several kms
# Users	10's of users	Thousands of users
Coverage	Optimized for indoor	Optimized for outdoor. Adaptive modulation. Advanced Antenna
Bands	License exempt	License and license exempt bands Allows Cell Planning
Channels	Fixed 20 MHz Channel	1.5 MHz to 20 MHz Channels Size chosen by operator
Spectral Efficiency	2.7 bps/Hz ⇒54 Mbps in 20 MHz	3.8 bps/Hz ⇒ 75 Mbps in 20 MHz 5 bps/Hz ⇒ 100 Mbps in 20 MHz
Delay Spread	Designed to handle indoor multipath Delay spread of 0.8 μs	Designed for longer multipaths. Multipath delay spread of 10 μs.

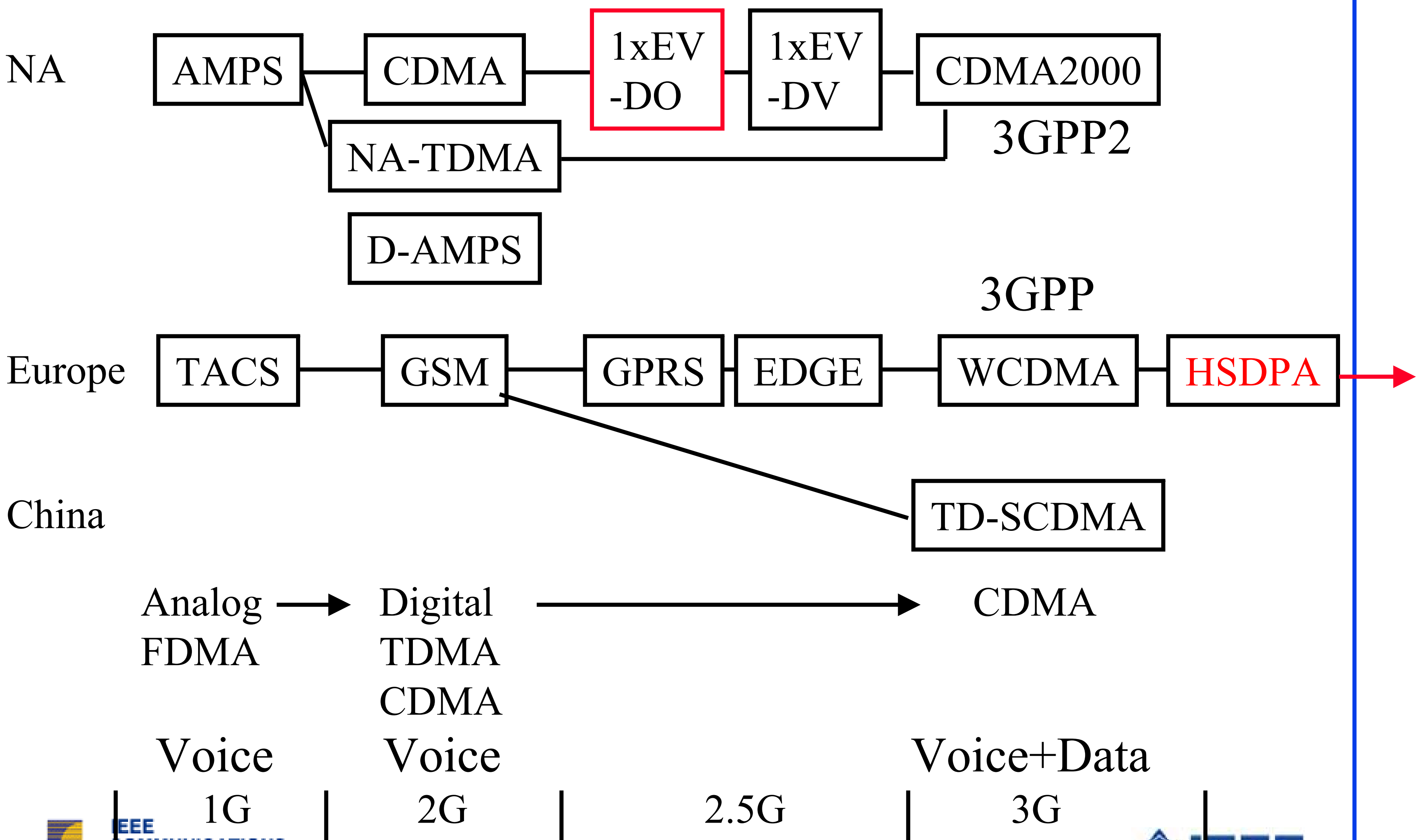
IEEE COMMUNICATIONS SOCIETY

IEEE

IEEE 802.11 vs. 802.16 (Cont)

	802.11	**802.16**
Duplexing	TDD only - Asymmetric	TDD/FDD/HFDD – Symmetric or asymmetric
MAC	Contention based. Distributed control.	Grant based. Centralized control.
QoS	No delay or throughput guarantees	Guarantees QoS
User Differentiati on	All users receive same service	Different users can have different levels of service. T1 for businesses. Best effort for residential.
Security	WEP, WPA, WPA2	128-bit 3DES and 1024-bit RSA

Cellular Telephony Generations



HSDPA

- High-Speed Downlink Packet Access for WCDMA
- Defined in 3GPP UMTS Release 5 specs
- Improved spectral efficiency for downlink ⇒ Asymmetric
- 14.4 Mbps using 5 MHz using all 15 codes
- Typical 250 kbps to 750 kbps
- Uplink 40-100 kbps (Max 384 kbps)
- Adaptive modulation and coding (AMC)
- Multi-code (multiple CDMA channels) transmission
- Fast physical layer (L1) hybrid ARQ (H-ARQ)
- Advanced packet scheduling techniques
  ⇒ user data rate can be adjusted to match the instantaneous radio channel conditions.

HSUPA

- High-Speed Uplink Packet Access
- 3GPP Release 6
- 5.8 Mbps
- To be deployed in 2007
- HSPA=HSDPA+HSUPA

1x EV-DO

- Update from 2G CDMA by 3GPP2
- Evolution – data only
- Max 2.4 Mbps down with 1.25 MHz
- Typical 100 to 200 kbps
- Rev A of 1x EV-DO gives max 3.1 Mbps up 1.8 Mbps down
- Rev B gives max 4.9 Mbps up and 1.8 Mbps down
- Rev B can also give 73 Mbps down 27 Mbps up with 20 MHz
- Rev C plans 70-200 Mbps down 30-45 Mbps up with 20 MHz (Expected after 2010)

Broadband Access Technologies: Comparison

Parameter	16e	HSPA	1x EVDO	11n
Peak DL/UL Mbps	46/7[1]	7.2/1.4[2]	3.1/1.8	$x/100-x$
Bandwidth	3.5, 5, 7, 8.75, 10 MHz	5 MHz	1.25 MHz	20/40 MHz
Max Mod.	64-QAM	16-QAM	16-QAM	64-QAM
Multiplexing	OFDMA	CDMA	CDMA	CSMA
Duplexing	TDD/FDD	FDD	FDD	TDD
Freq. GHz	2.3, 2.5, 3.5	.8/.9/1.8/1.9/2.1	.8/.9/1.8/1.9	2.4, 5
Coverage	≤2 miles	1-3 miles	1-3 miles	≤1000 ft
Mobility	Mild	High	High	Low

[1] Assumes 10 MHz, 3:1 DL:UL ratio, 2×2 MIMO

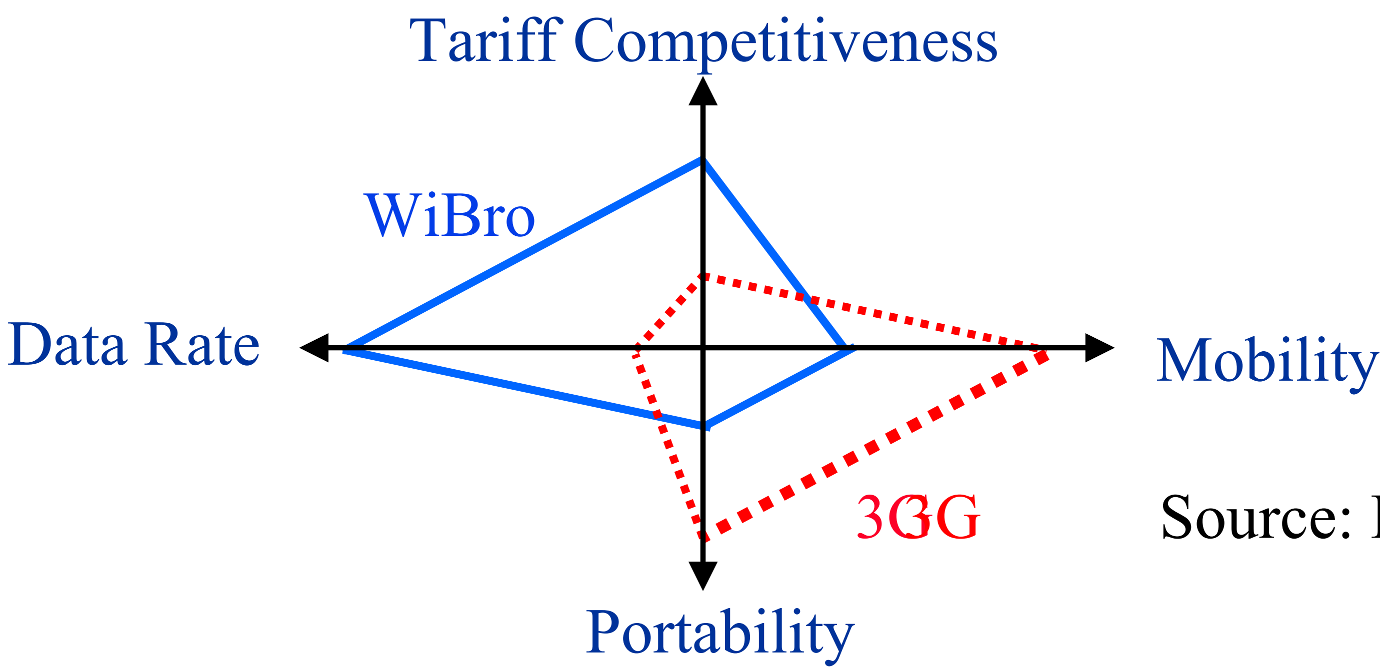
[2] With 10 codes

Source: Andrews 2007

IEEE COMMUNICATIONS SOCIETY

IEEE

Wibro vs. 3G

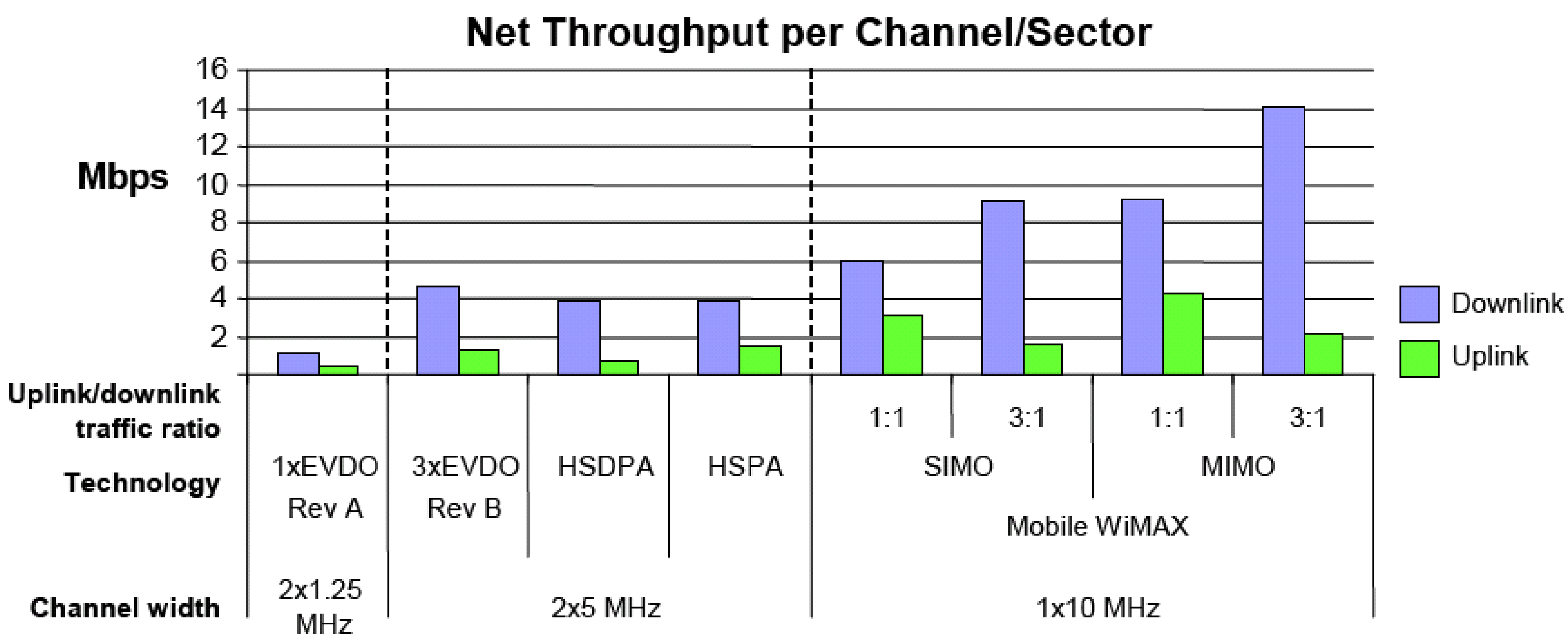


Source: KT

IEEE COMMUNICATIONS SOCIETY

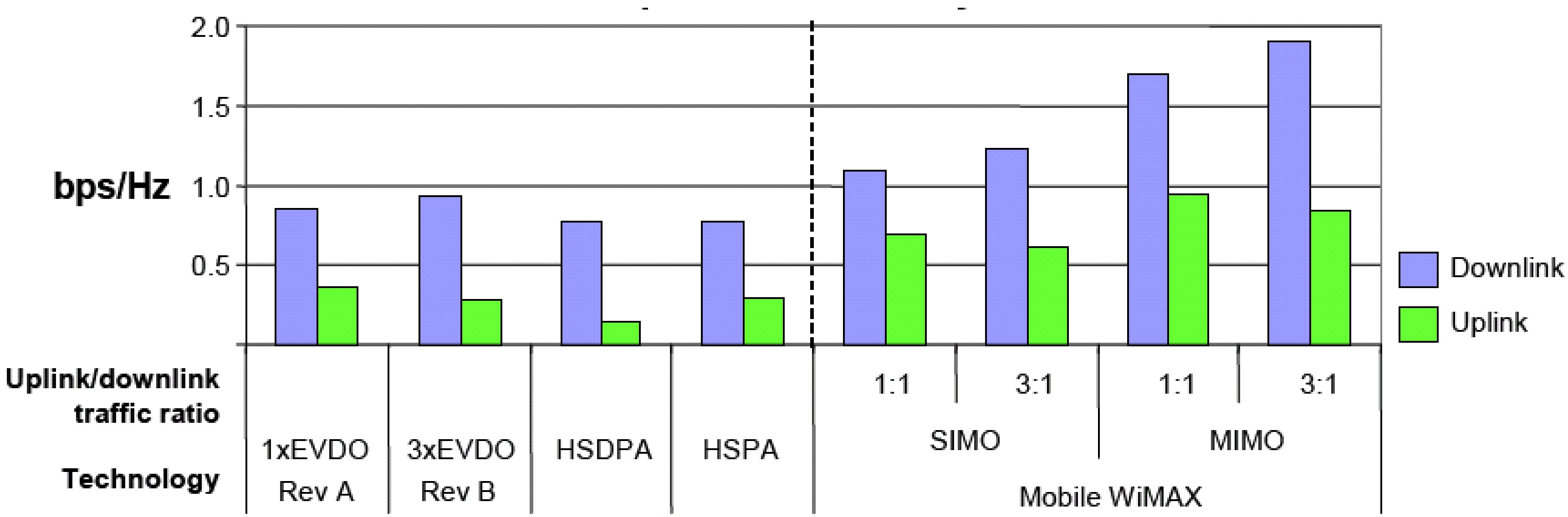
IEEE

3G vs. WiMAX: Throughput



- Source: WiMAX Forum, "Mobile WiMAX: The best personal broadband experience" June 2006

3G vs. WiMAX: Spectral Efficiency



- Source: WiMAX Forum, "Mobile WiMAX: The best personal broadband experience" June 2006

3G vs. WiFi vs. WiMAX

Feature	3G	Wi-Fi	WiMAX
Bandwidth	5 MHz	20 MHz	Selectable 1.25 Mhz-20 Mhz
Duplexing	FDD	TDD	TDD or FDD
Down:up Ratio	1:1	Variable	Selectable
Multiplexing	Need Code spreading	No such restriction	No such restriction
Higher Layers	3G	IP	IP
QoS	Good	Poor	Good
Mobility	Good	Poor	Good
Coverage	Long	Short	Long
Data Rate	Kbps	Mbps	Mpbs
Roaming	Proven	To be proven	To be proven

- Royalty on WCDMA phones = 10-15% of average selling price

LTE

- Long term evolution for 3GPP
- A.k.a. Super 3G
- Expected after 2010
- 100 Mbps down 50 Mbps up
- Low latency
- Spectral efficiency of 3 to 4 times of Release 6 HSPA
- Will use OFDMA, MIMO (Similar to WiMAX)
- Specs to be finalized in 2007

Evolution of 3GPP2

- System requirement document (SRD) for next air interface for CDMA2000 approved in May 2006
- Scalable bandwidths up to 20 MHz
- Peak 100 Mbps down and 50 Mbps up in Mobile
- Peak 500 Mbps down 150 Mbps up in stationary indoor
- Reduced system latency for VOIP
- DL uses OFDMA, MIMO, Spatial division multiple access (SDMA)
- UL uses quasi-orthogonal OFDMA with non-orthogonal user multiplexing with Layered-superimposed OFDMA (LS-OFDMA) and also supports CDMA for control and low-rate low-latency traffic

IEEE 802.20

- Mobile Broadband Wireless Access (MBWA)
- Vehicular mobility up to 250 Km/h
- Optimized for IP data transport
- Licensed band below 3.5 GHz
- >1 Mbps data rate
- Designed for green field wireless data providers
- Intel and Motorola vs. Qualcomm and Kyocera
- Stopped operation on June 8, 2006. Restarted Sept 19, 2006.

IEEE COMMUNICATIONS SOCIETY

IEEE

IEEE 802.22

- Wireless Regional Area Networks (WRAN)
- Cognitive radio using unused TV channels
- VHF and low UHF bands
- FCC will require cognitive radios
- Early stages of development

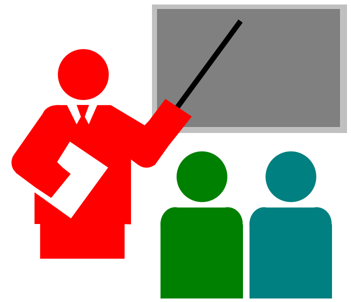
WiMAX Competition: Summary

1. IEEE 802.11 and 802.16 are complementary
2. 3G is currently CDMA based
   Limited by 5MHz channel bandwidth
3. Next generation of 3G is evolving.
   Taking the best of WiMAX: OFDMA, MIMO
4. Next generation WiMAX 802.16m will run at 100 Mbps

IEEE COMMUNICATIONS SOCIETY

IEEE

Overall Summary



1. Wireless is the major source of carrier revenue
   ⇒ Significant growth in Wireless networking
2. CDMA is past. OFDM/OFDMA is taking over.
3. OFDM splits a band in to many orthogonal subcarriers.
   OFDMA = FDMA + TDMA
4. MIMO uses multiple antennas for high throughput
5. Impulses in time domain result in a wideband frequency spectrum ⇒ UWB

IEEE COMMUNICATIONS SOCIETY

IEEE

Overall Summary (Cont)

6. The average UWB power is below the noise level
   $\Rightarrow$ Shares spectrum with current spectrum users
7. UWB applications in communications, positioning (radar, surveillance), and multi-path imaging
8. 11n gets 100+ Mbps by MIMO, OFDM and wider channels
9. 11b devices can prohibit use of OFDM and may decrease the performance for everyone
10. You need 11n at both ends to really benefit
11. Previous broadband access technologies had problems with antenna placement and cost
12. WiMAX allows indoor, non-line of sight operation

Overall Summary (Cont)

14. WiMAX works on many different spectral bands. WiMAX forum is working on a worldwide band.
15. Key WiMAX technical features: TDD, OFDMA, MIMO, centralized scheduling, QoS
16. WiMAX products with fixed profile are available. Mobile profile certification is just beginning.
17. IEEE 802.11 and 802.16 are complementary
18. 3G is currently CDMA based
    Limited by 5MHz channel bandwidth
19. Next generation of 3G is evolving.
    Taking the best of WiMAX: OFDMA, MIMO
20. Next generation WiMAX 802.16m will run at 100 Mbps

References

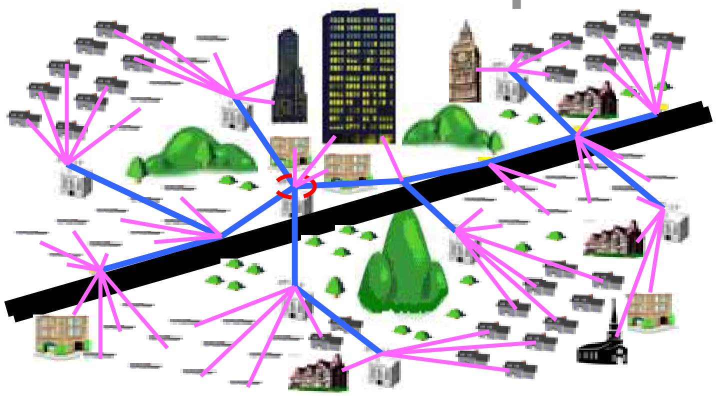
- See http://www.cse.wustl.edu/~jain/refs/icc07.htm

IEEE COMMUNICATIONS SOCIETY

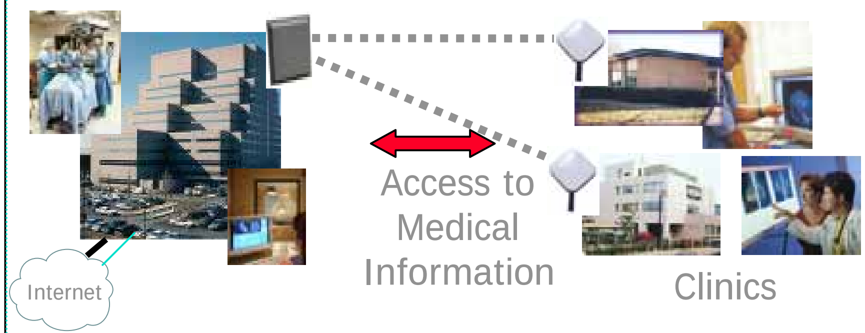
IEEE

WiMAX Applications

Carriers/Municipal



Distributed Enterprises



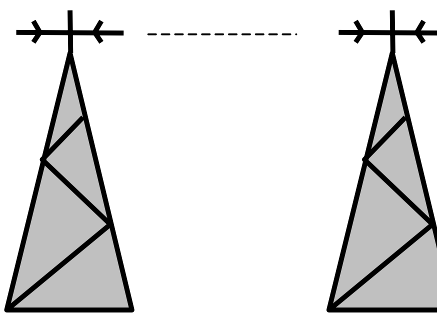
Virtual Medical Centers

High-Velocity Deployments

Disaster Recovery Offshore Drilling

Construction sites, Emergency Relief

Cellular Backhaul



IEEE COMMUNICATIONS SOCIETY

IEEE