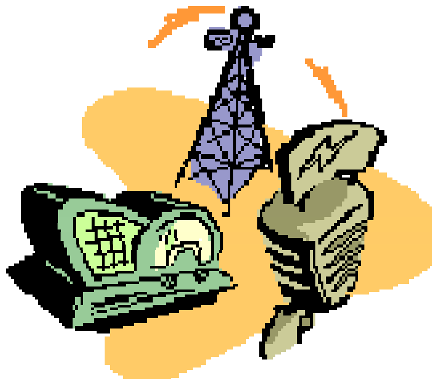
Next Generation Wireless Technologies: High Throughput WiFi , WiMAX, and UWB



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/

1. Wireless Equipment/Revenue Trends
2. Recent Developments in Wireless PHY
3. Ultra Wideband
4. High Throughput WiFi: 802.11n
5. WiMAX Overview
6. WiMAX Technology
7. Other Competing Broadband Access Technologies

1. Wireless Equipment/Revenue 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

- OFDM, OFDMA, SOFDMA
- Beamforming
- MIMO
- Turbo Codes
- Space-Time Block Codes
- Time Division Duplexing
- 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 Technology

- 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. 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.

Intentionally blank

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/

- 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
   $\Rightarrow$ 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
   $\Rightarrow$ Mobility
4. Broadband Access is growing faster than cell phones
5. Wiring more expensive than equipment
   $\Rightarrow$ Wireless Access

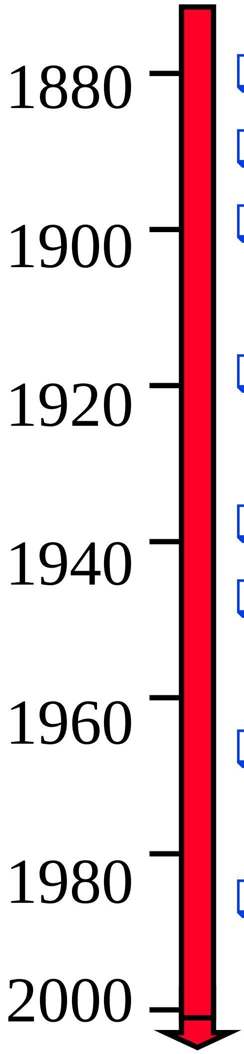
Top 10 Networking Developments (Cont)

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

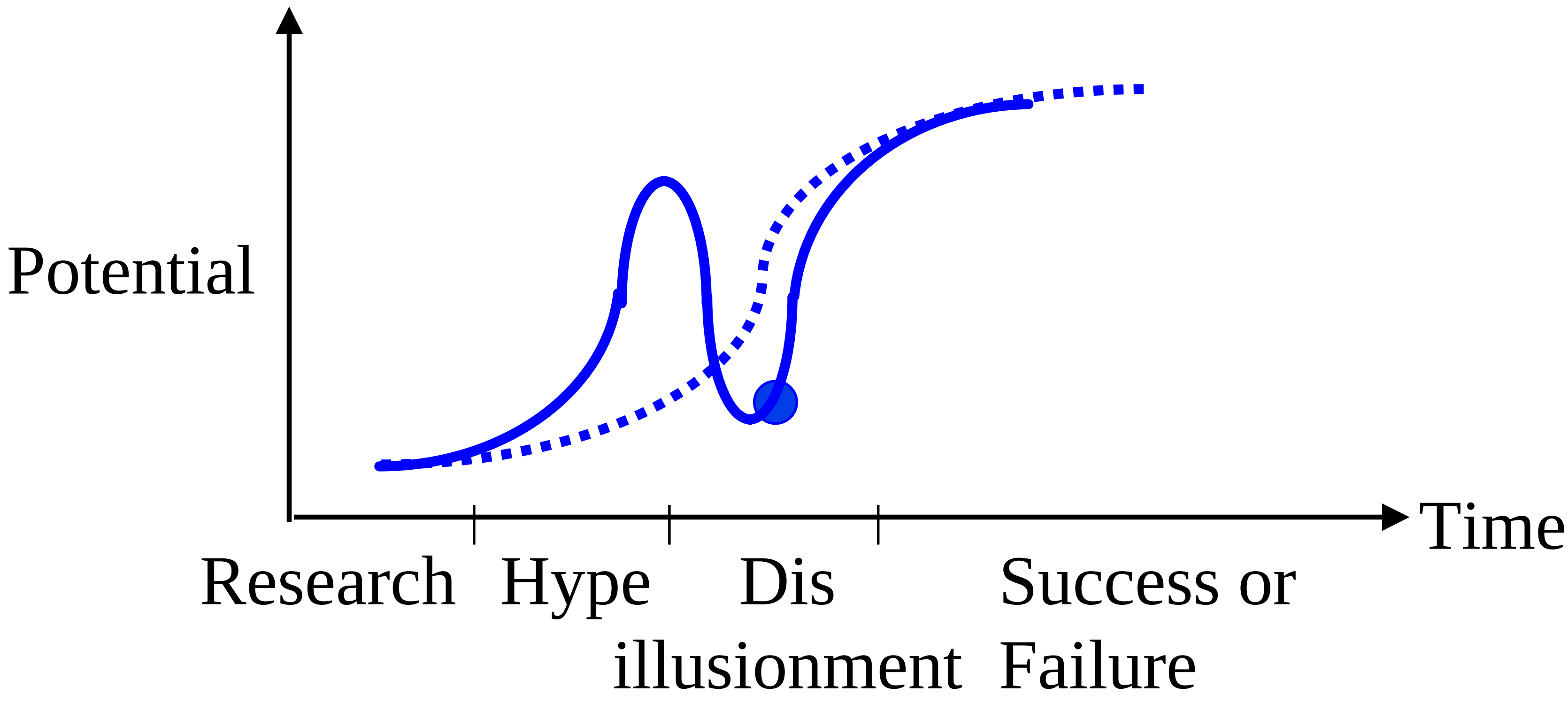
- Memory in Laptops: Megabytes to Gigabytes
- Cordless Phones: 900 Mega Hertz to 2.4/5.8 GHz
- Processors: MIPS (Mega Instructions per second) to GFIPS (Giga Flops)
- Digital Cameras: 100-500 Mega Pixels to Giga Pixels
- Office Networks: 10/100 Mega bps to 1-10 Giga bps
- Worldwide Wireless Network Users: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

Wireless: History

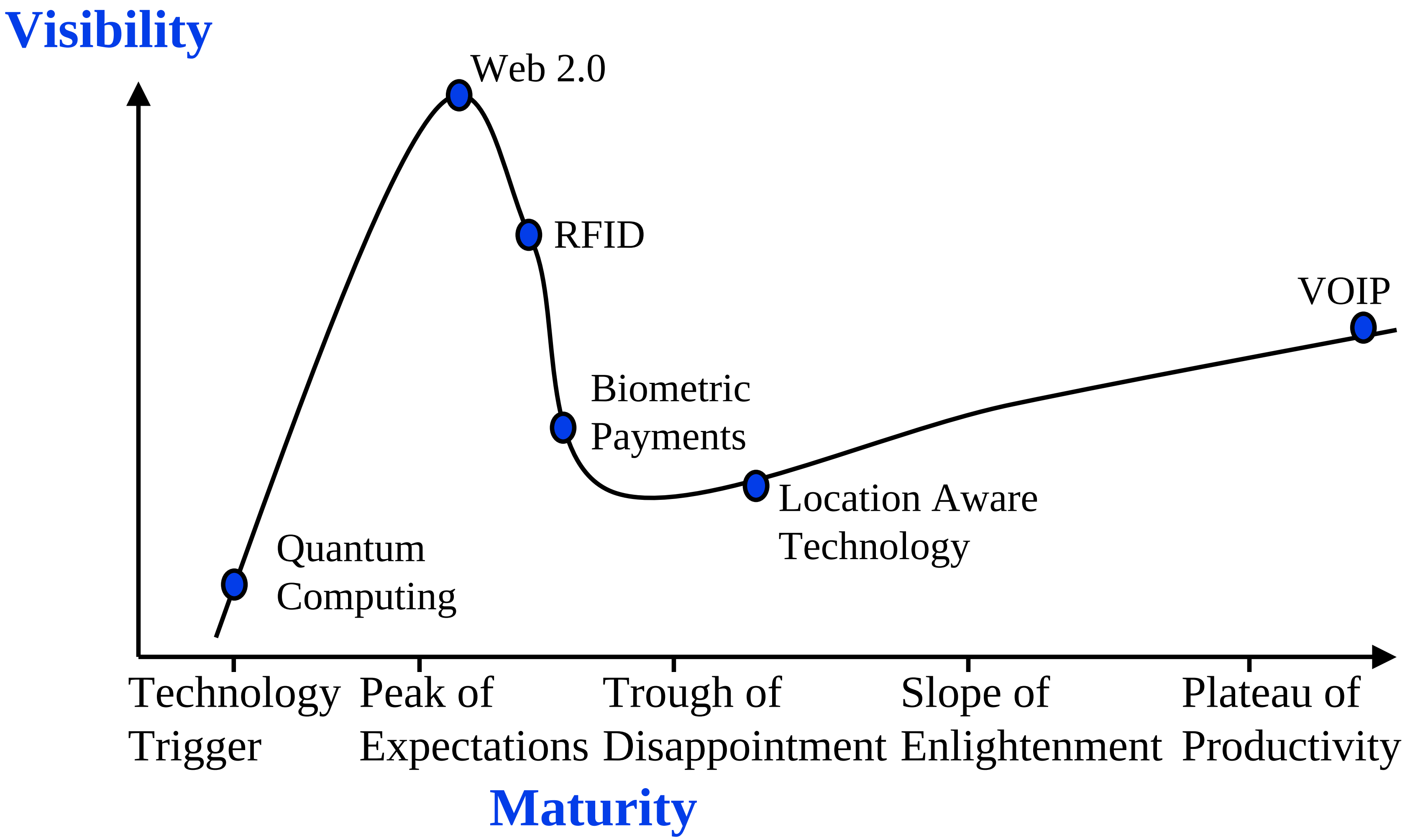


- 1880: Hertz discovered electromagnetic waves
- 1898: First commercial radio data service
- 1921: First Mobile Radio:
  Wireless dispatch system for Detroit Police
- 1946: First Mobile Telephone Service:
  In St. Louis by AT&T. Half-duplex ⇒ Push to talk.
- 1970: First Cellular Phone Service: AT&T Chicago
- 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

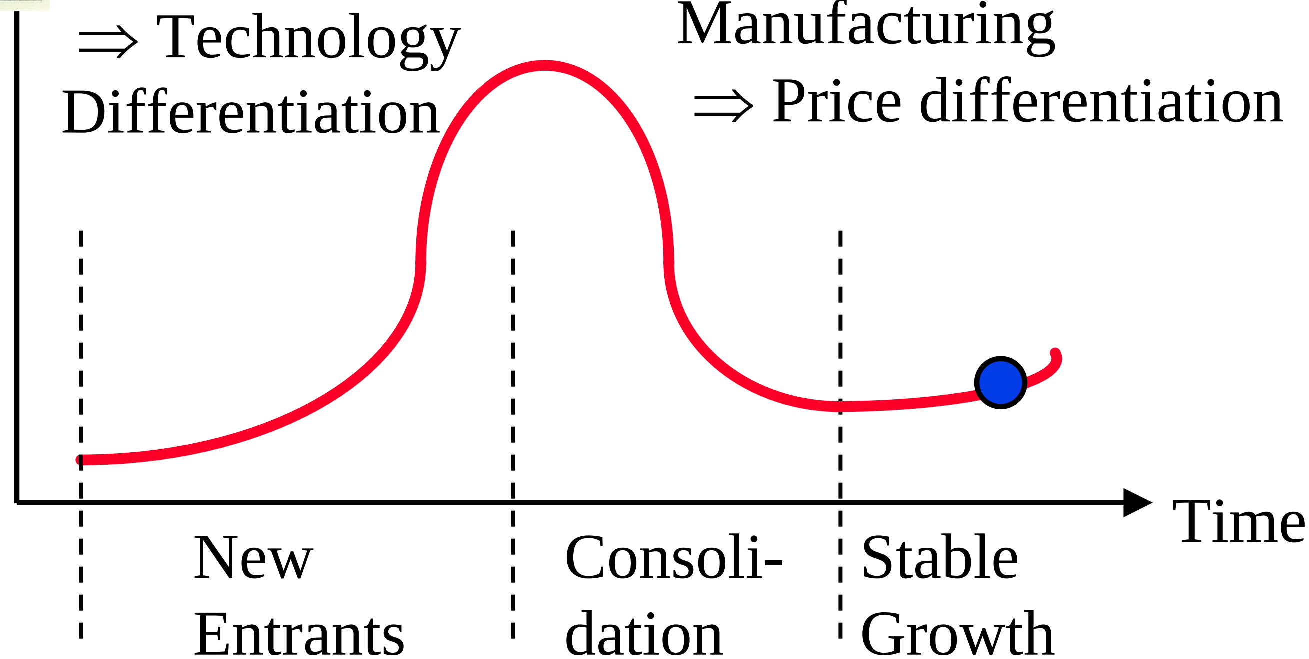


Networking Hype Cycle 2006



Based on Gartner Research (July 2006)

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

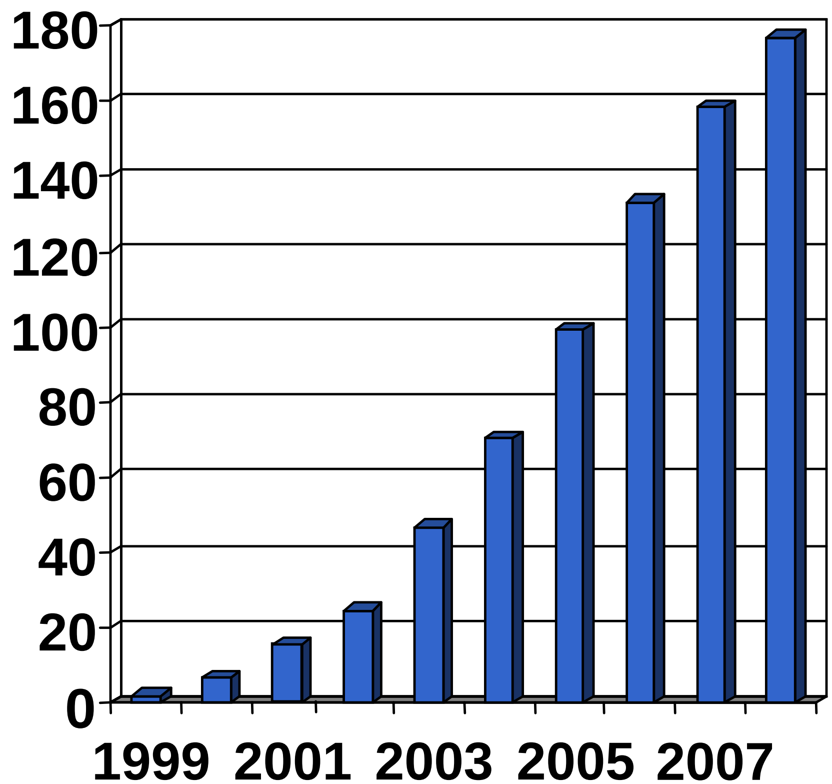
Telecom Revenue

	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%

- 48% revenues are from wireless.
- 26% of revenue from data (vs. voice)
- Source: Instat/MDR (Business Week, Feb 28, 2005)

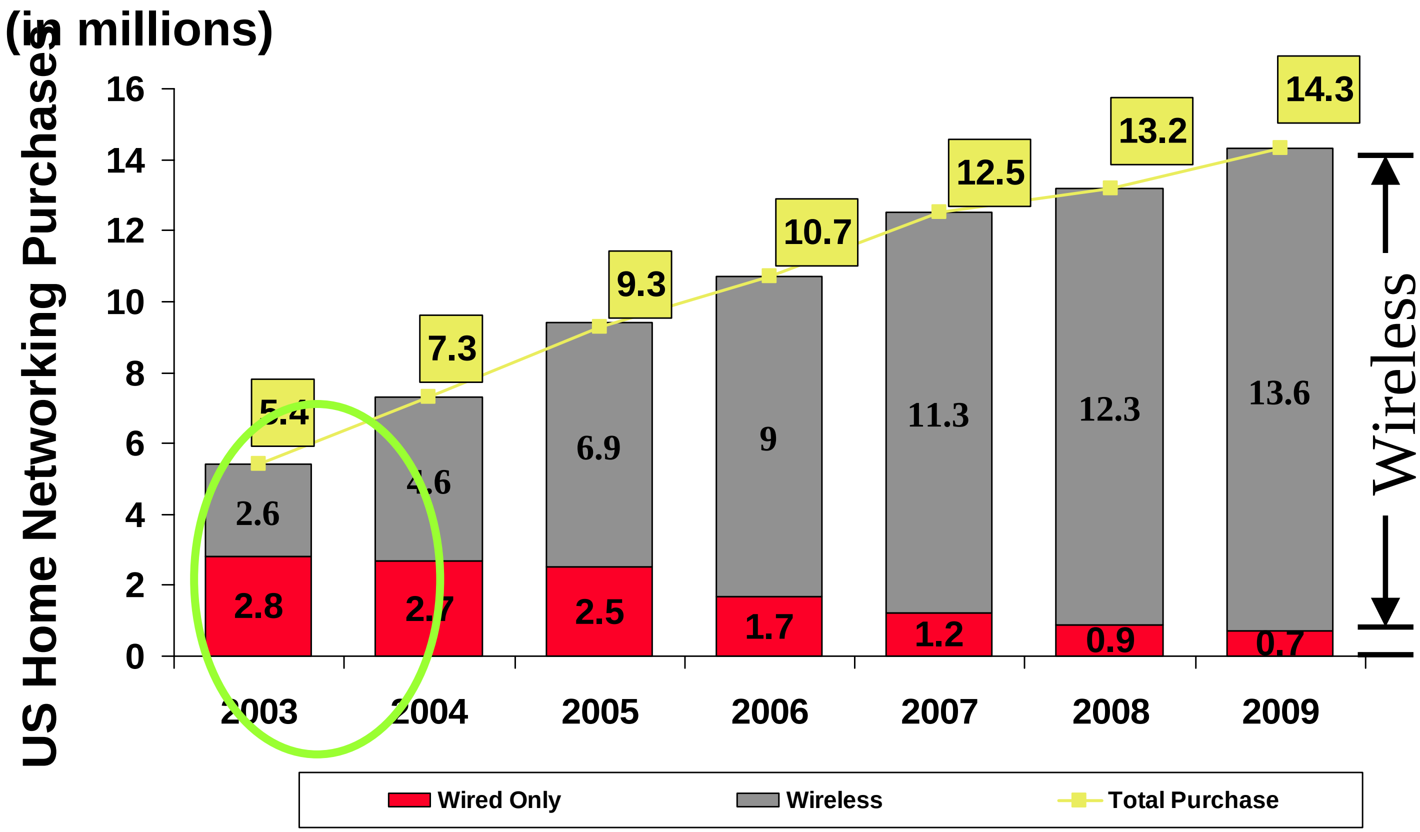
Wireless Data Connections

North American Wireless Data Connections (Millions)



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

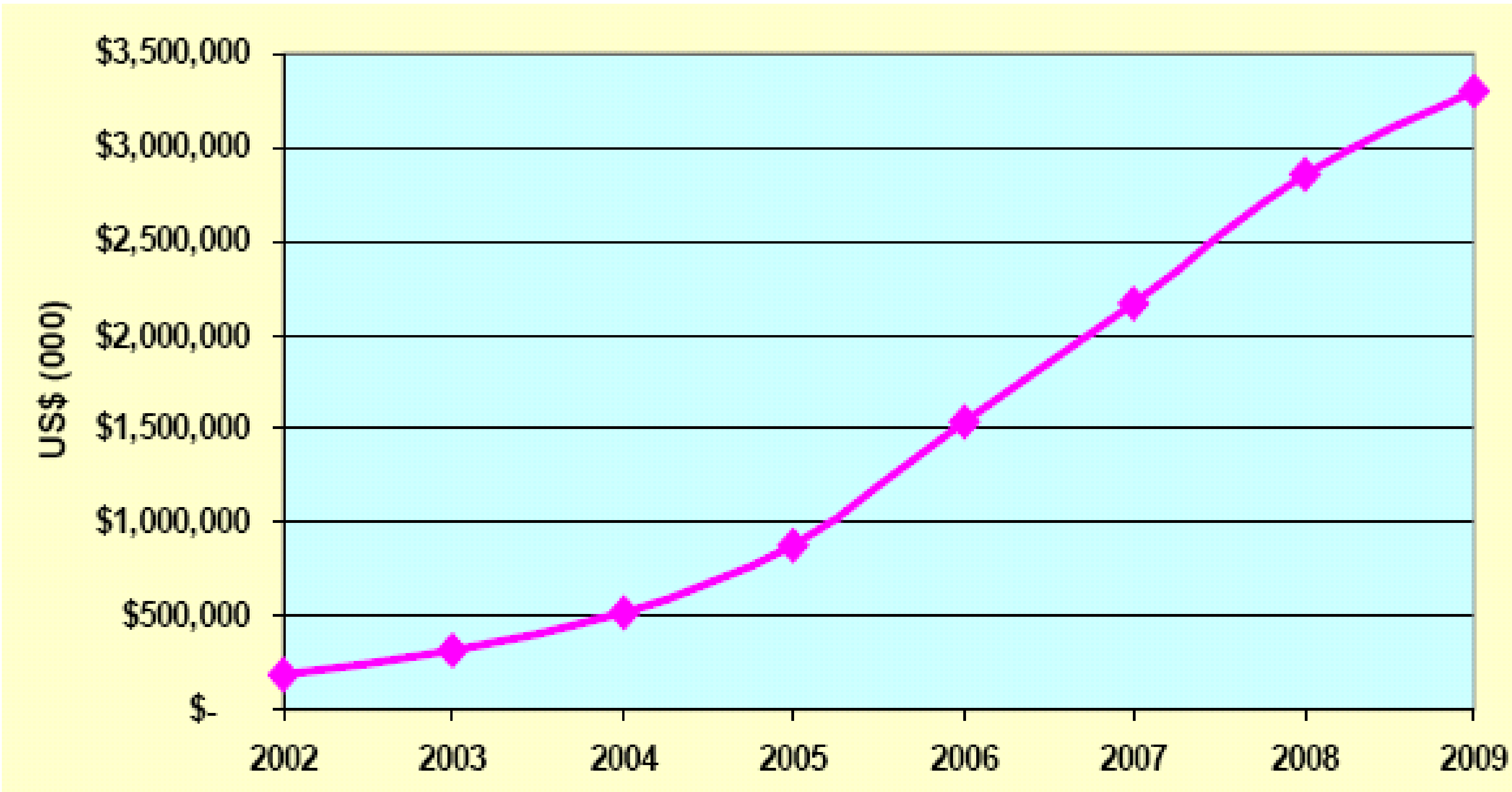
Home Networking Equipment Trends



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

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

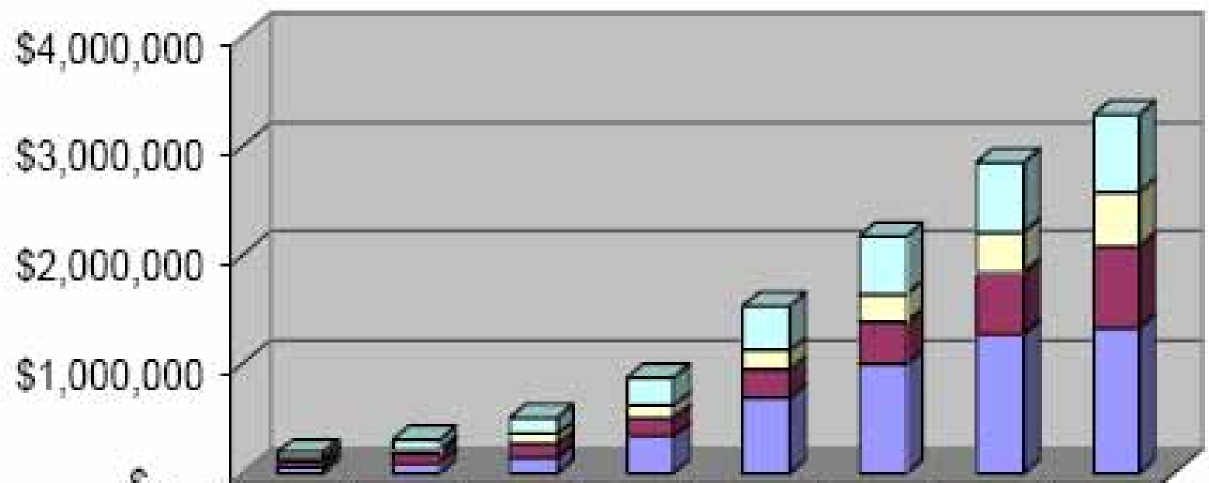
Global Broadband Wireless Equipment



- 0-10 GHz, Base stations+Subscriber stations

Source: Skylight Research

Broadband Market by Regions

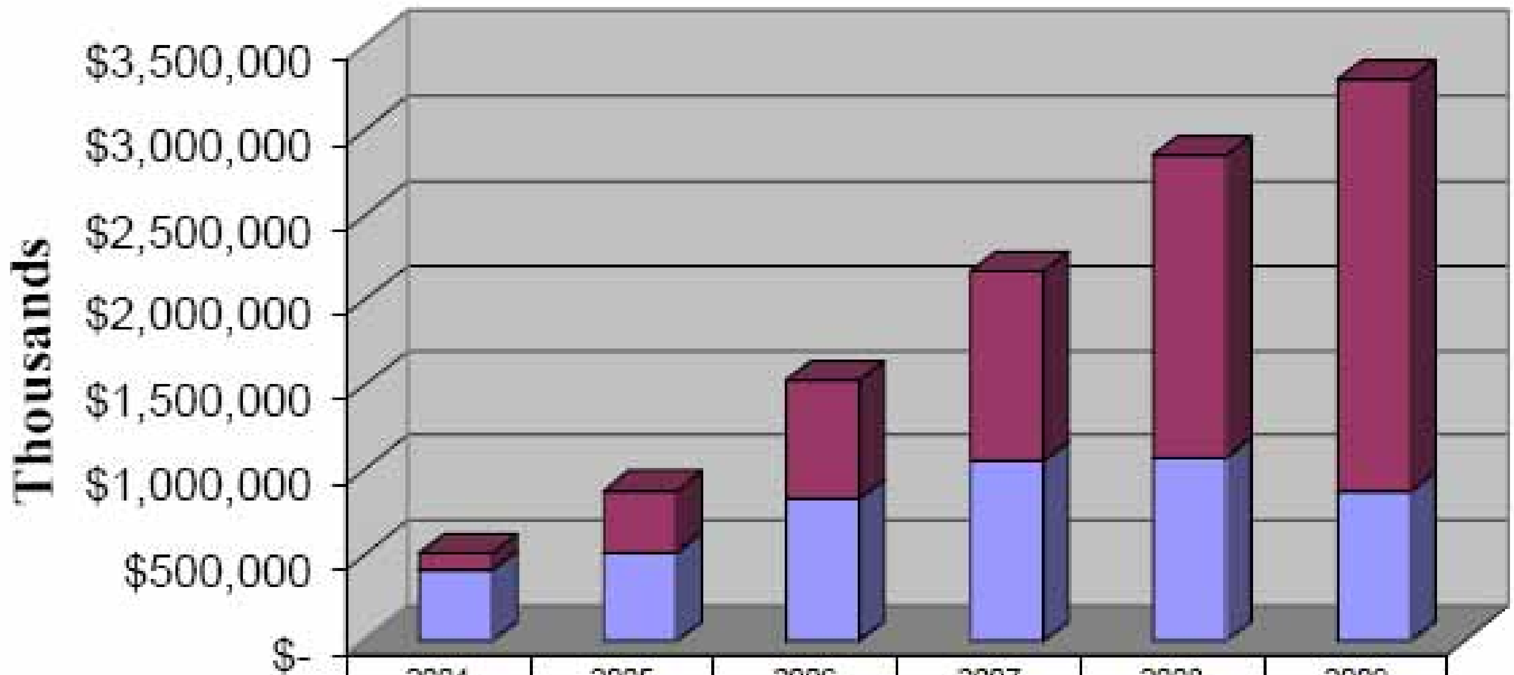


	2002	2003	2004	2005	2006	2007	2008	2009
EMEA	$55,3	$95,6	$160,	251,4	$406,	$527,	$637,	$721,
LAM	$21,2	$33,4	$91,2	125,3	$179,	$250,	$364,	$489,
NAM	$68,5	$100,	$122,	164,8	$254,	$386,	$577,	$746,
ASPAC	$44,6	$83,7	$140,	$336,	$688,	$1,00	$1,27	$1,33

- ASPAC and EMEA leading the growth

Source: Skylight Research

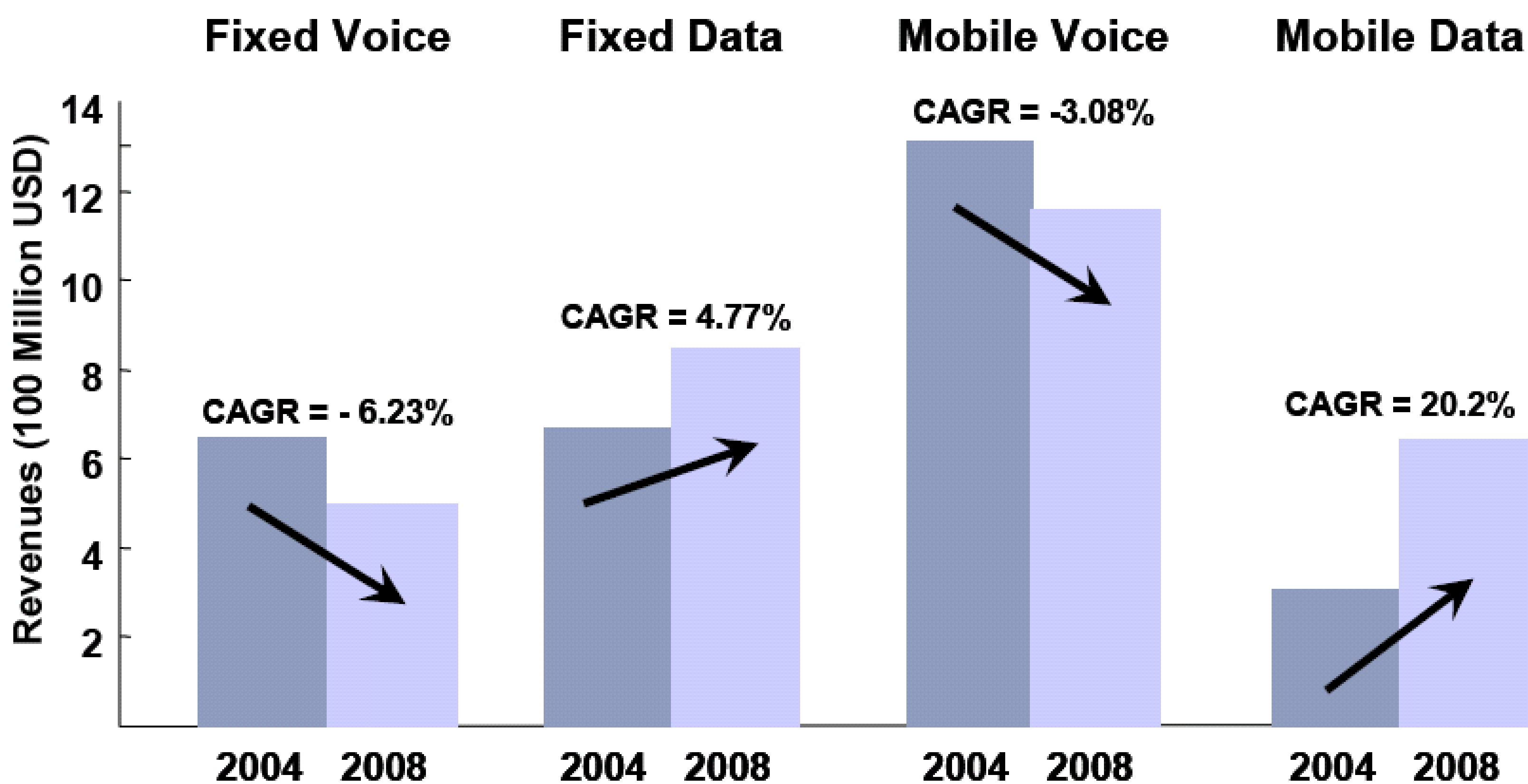
Personal Broadband: Fixed vs. Mobile



	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

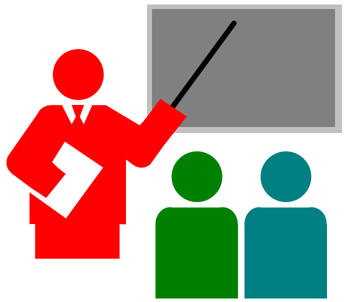
Source: Skylight Research

Voice and Data Revenues (Korea)



Source: KISDI 2004

Summary: Wireless Revenue Trends



- Wireless is the major source of carrier revenue
  ⇒ Significant growth in Wireless networking
- Growth also in home and enterprise market
- Moving from fixed to mobile wireless
- Moving from voice to data

Intentionally blank

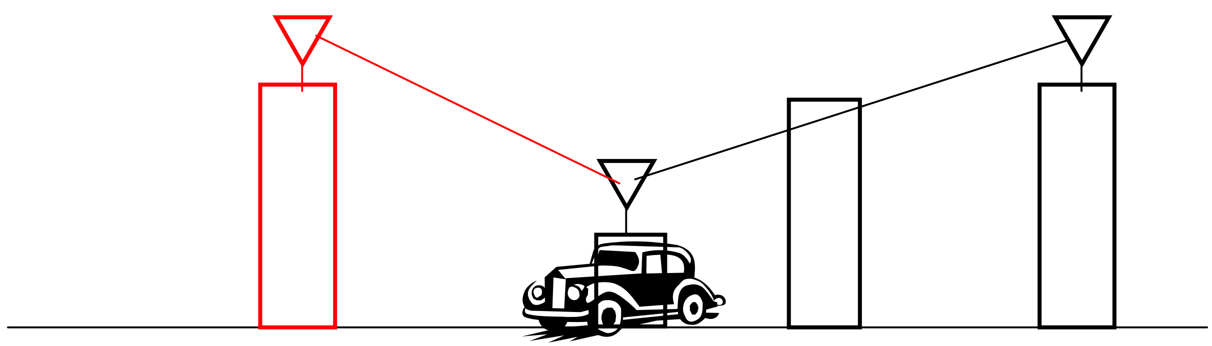
Recent Developments in Wireless PHY

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/

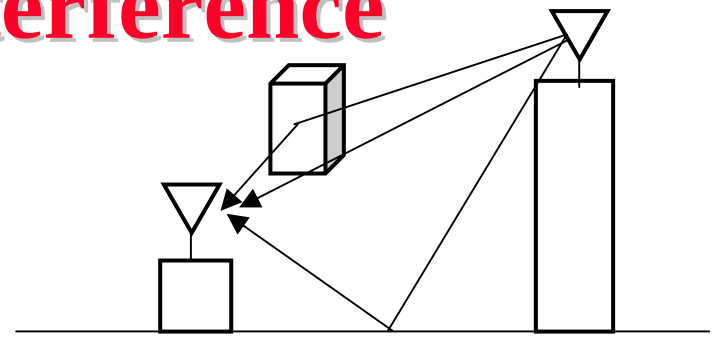
1. OFDM, OFDMA, SOFDMA
2. Beam forming
3. MIMO
4. Turbo Codes
5. Space-Time Block Codes
6. Time Division Duplexing
7. Software defined radios

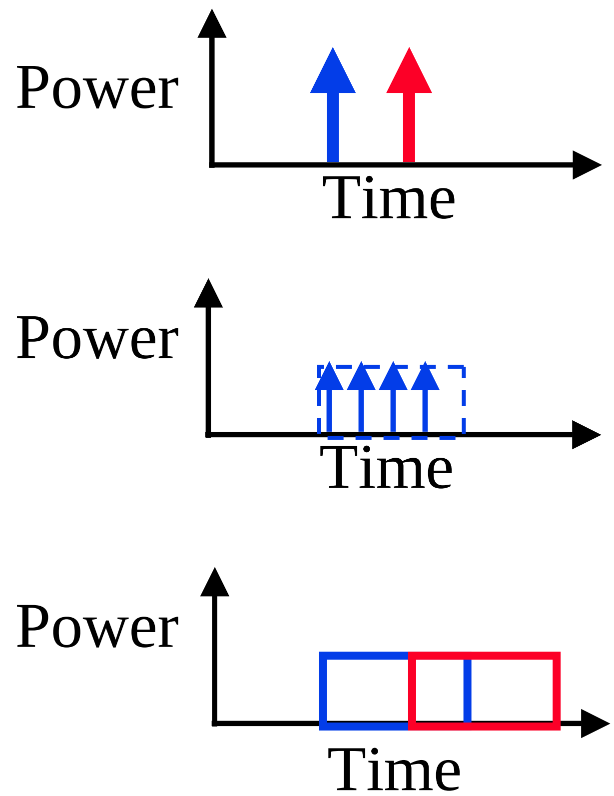
Wireless Radio Channel

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



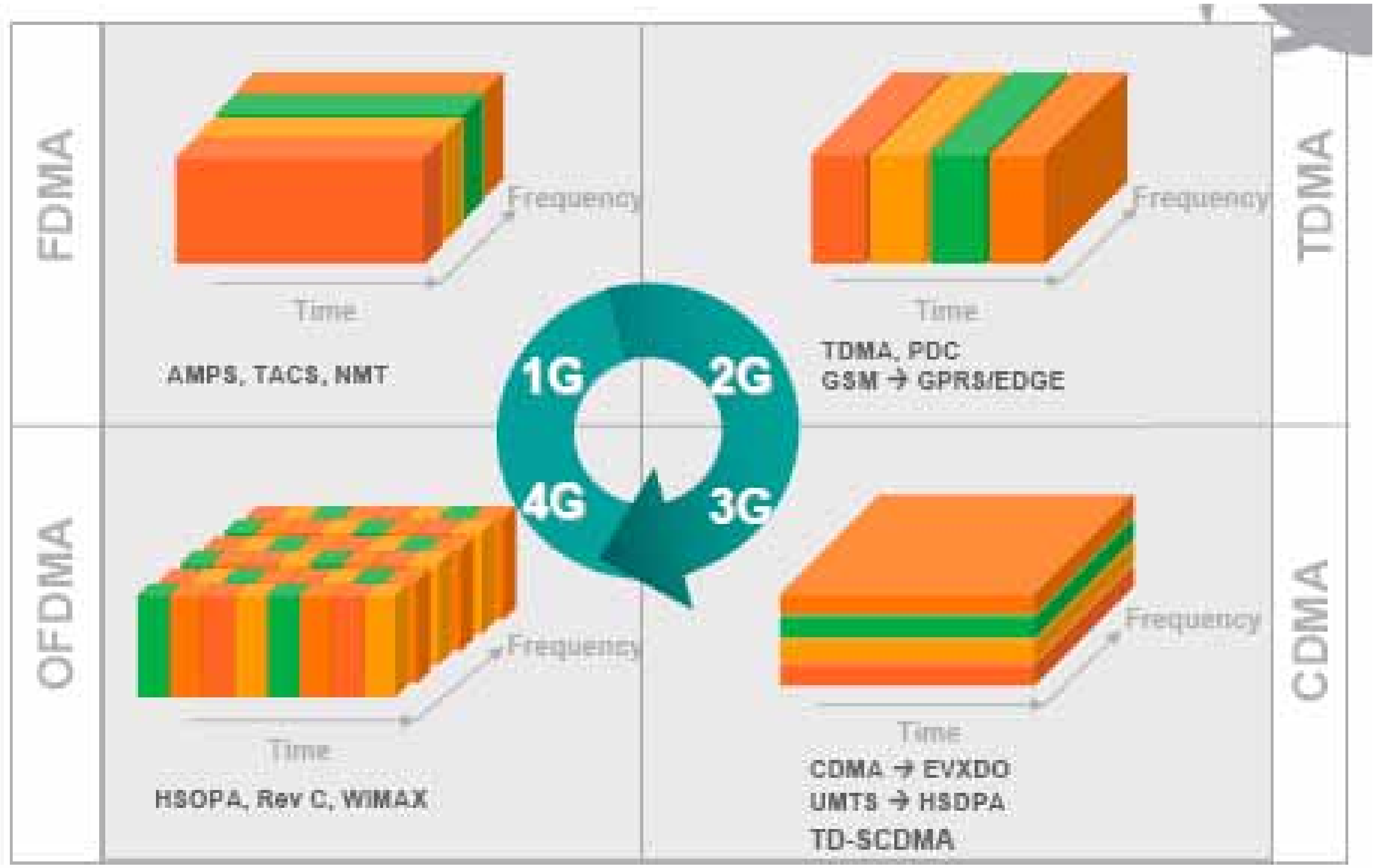
Inter-Symbol Interference





- Symbols become wider
  ⇒ Limits the number of bits/s

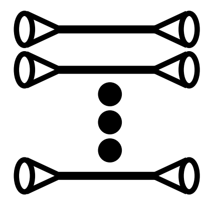
Multiple Access Methods



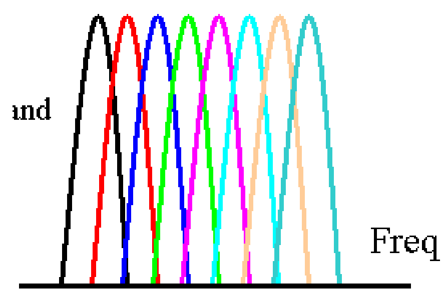
Source: Nortel

1. OFDM

- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel
  $\Rightarrow$ Multi-carrier modulation



- Frequency band is divided into 256 or more sub-bands.
  Orthogonal $\Rightarrow$ 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)
- Easy to implement using FFT/IFFT



Advantages of OFDM

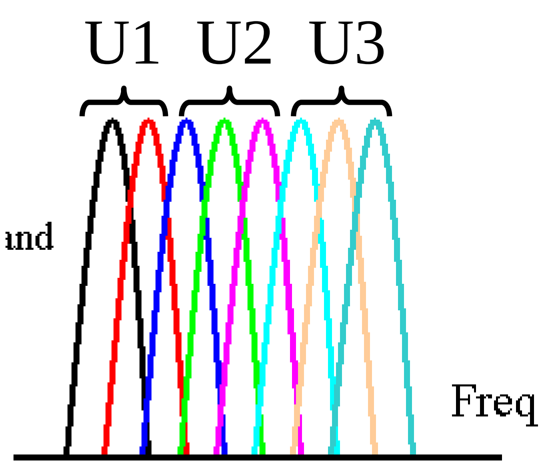
- Easy to implement using FFT/IFFT
- Computational complexity = O(B log BT) compared to previous O(B^2T) for Equalization. Here B is the bandwidth and T is the delay spread.
- Graceful degradation if excess delay
- Robustness against frequency selective burst errors
- Allows adaptive modulation and coding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

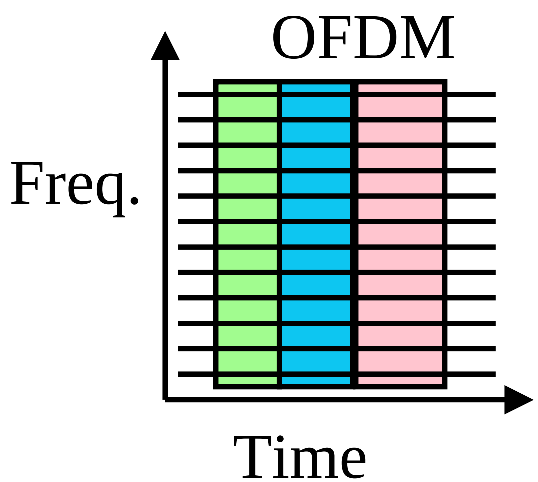
OFDM: Design considerations

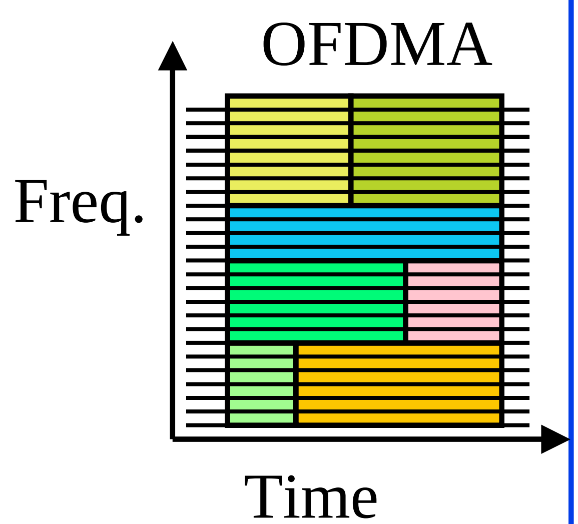
- Large number of carriers ⇒ Larger symbol duration ⇒ Less inter-symbol interference
- Reduced subcarrier spacing ⇒ Increased inter-carrier interference due to Doppler spread in mobile applications
- Easily implemented as Inverse Discrete Fourier Transform (IDFT) of data symbol block
- Fast Fourier Transform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



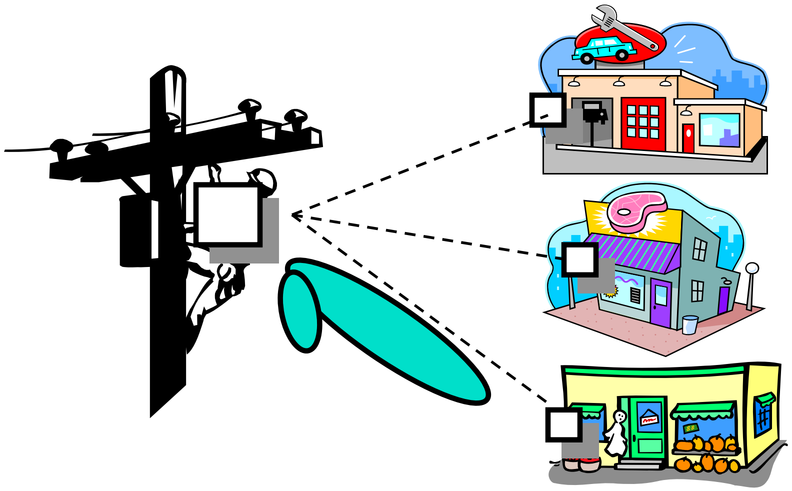




Scalable OFDMA (SOFDMA)

- 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
  $\Rightarrow$ Keep symbol duration constant at 102.9 us
  $\Rightarrow$ Keep subcarrier spacing 10.94 kHz
  $\Rightarrow$ Number of subcarriers $\propto$ Frequency bandwidth
  This is known as scalable OFDMA

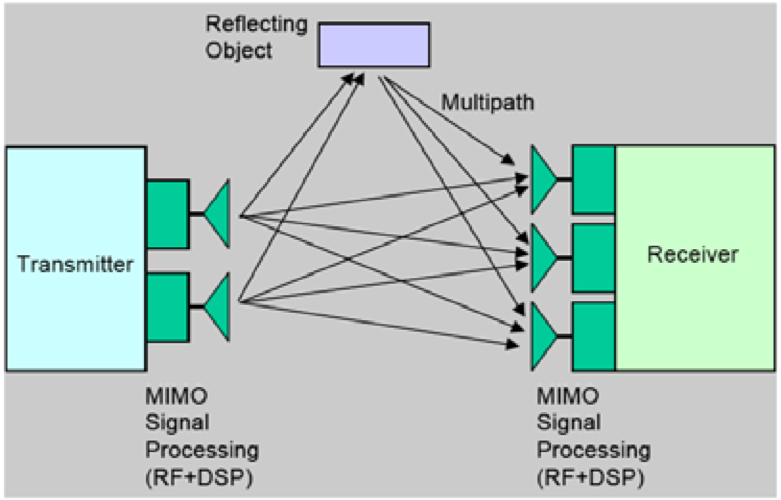
2. Beamforming



- 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

3. MIMO

- Multiple Input Multiple Output
- RF chain for each antenna
  ⇒ Simultaneous reception or transmission of multiple streams



2x3

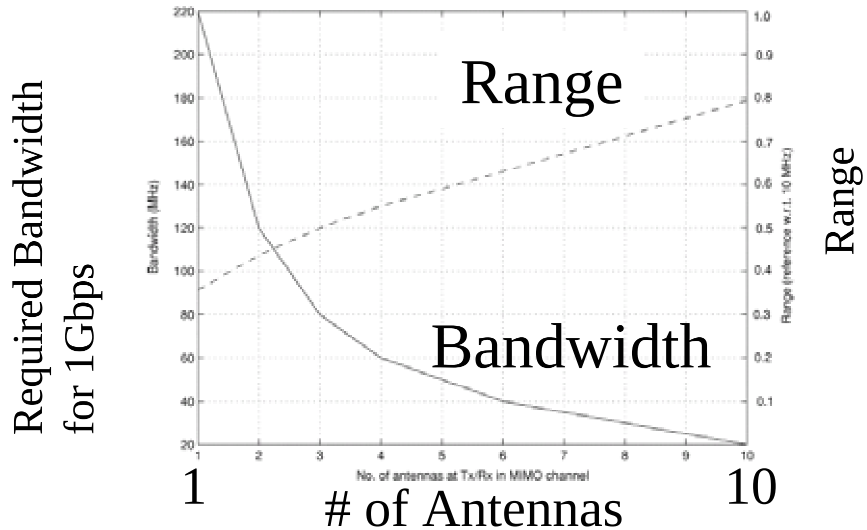
802.16e at 2.5 GHz, 10 MHz TDD, D:U=2:1

T:R	1x1	1x2	2x2	2x4	4x2	4x4
b/Hz	1.2	1.8	2.8	4.4	3.7	5.1

MIMO

- **Antenna Diversity**: Multiple transmit or receive antenna but a single transmit/receive chain
- **MIMO**: RF chain for each antenna $\Rightarrow$ 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 $\Rightarrow$ 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

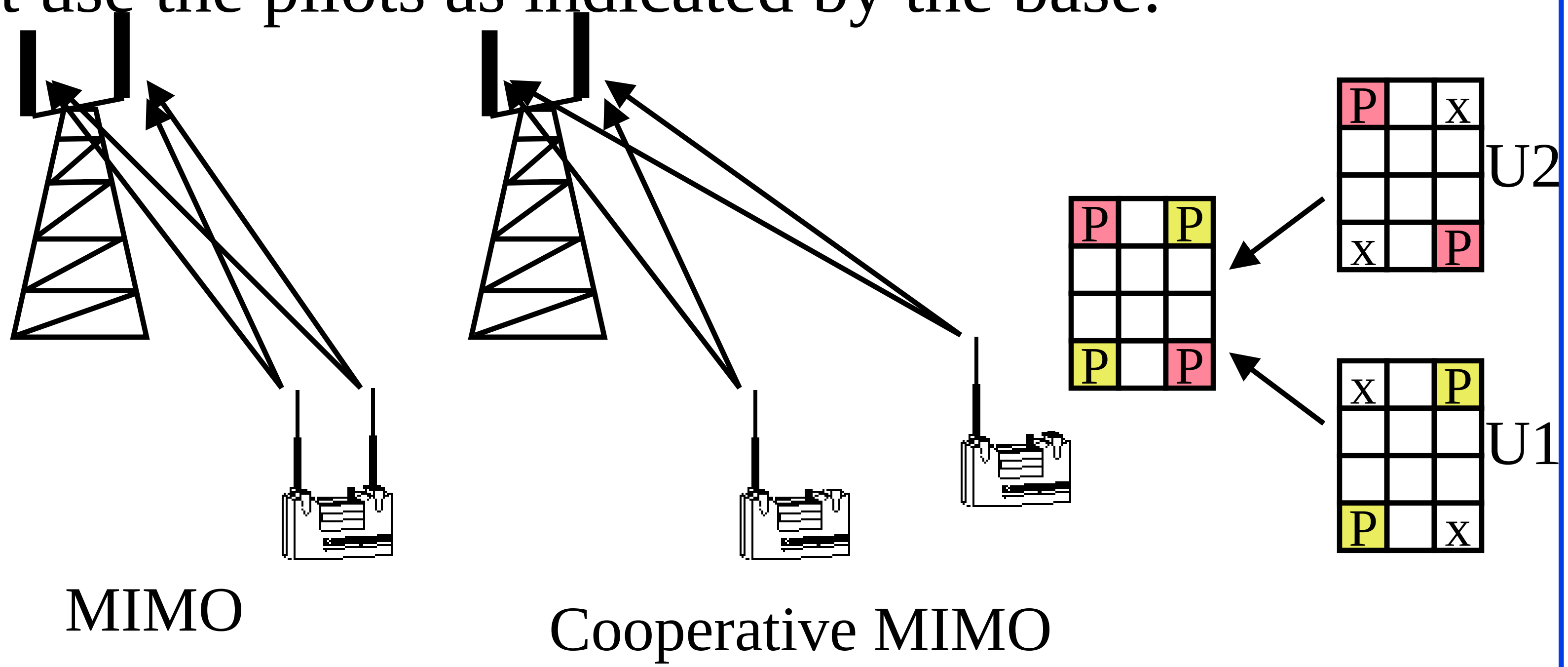
Gigabit Wireless



- 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.

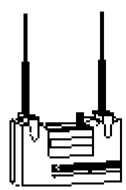
Cooperative MIMO

- Two subscribers with one antenna each can transmit at the same frequency at the same time
- The users do not really need to know each other. They just use the pilots as indicated by the base.



4. Space Time Block Codes (STBC)

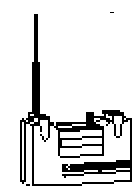
- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas:



$$\begin{array}{c} \\ \text{Slot 1} \rightarrow \\ \text{Slot 2} \rightarrow \end{array} \begin{array}{c} \begin{array}{cc} \text{Antenna 1} & \text{Antenna 2} \\ \downarrow & \downarrow \end{array} \\ \begin{bmatrix} S1 & S2 \\ -S2^* & S1^* \end{bmatrix} \end{array}$$

Time ↓

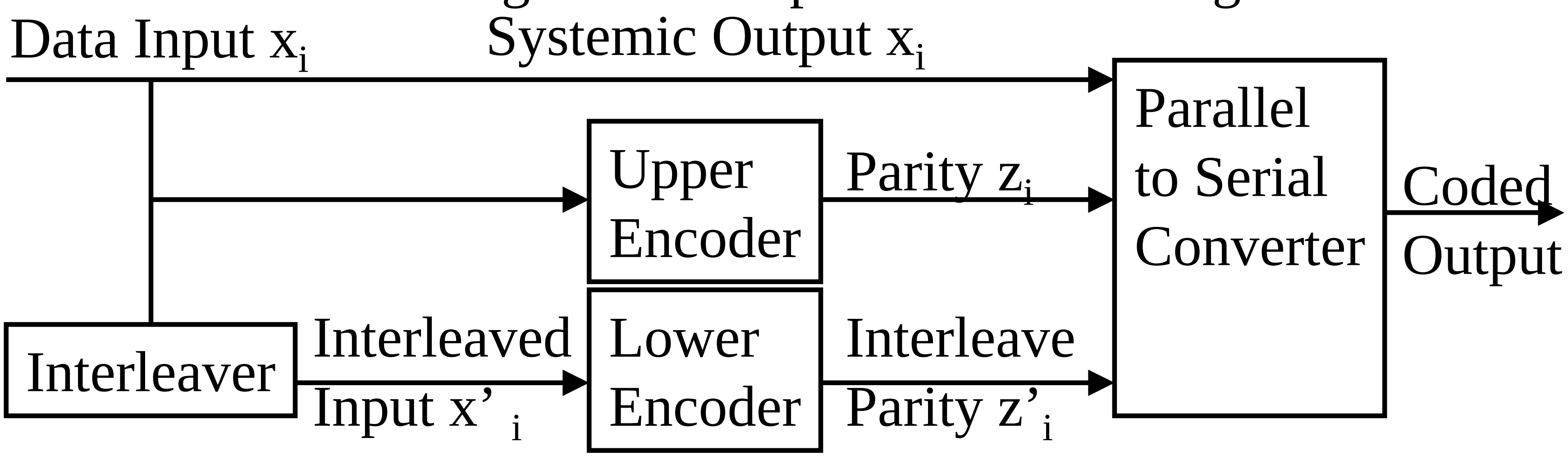
Space →



S1* is complex conjugate of S1 ⇒ columns are orthogonal

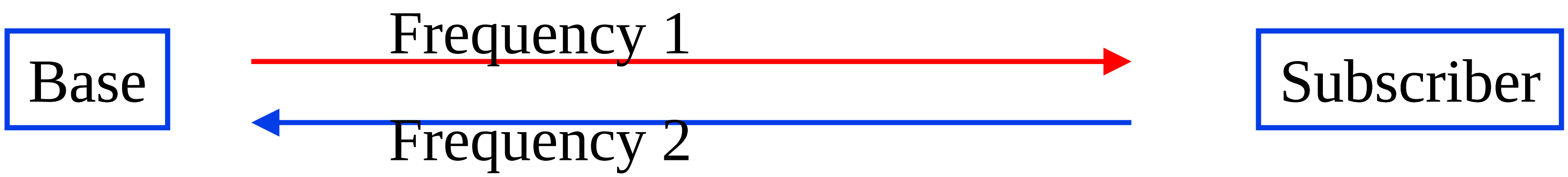
5. Turbo Codes

- Shannon Limit:= B $\log_2$ (1+S/N)
- 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

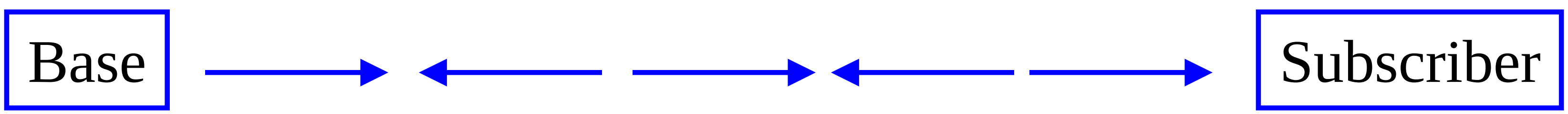


6. Time Division Duplexing (TDD)

- Duplex = Bi-Directional Communication
- Frequency division duplexing (FDD) (Full-Duplex)



- Time division duplex (TDD): Half-duplex

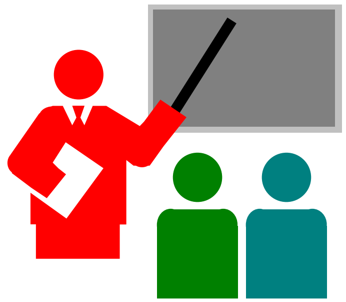


- Most WiMAX deployments will use TDD.
  - Allows more flexible sharing of DL/UL data rate
  - Does not require paired spectrum
  - Easy channel estimation ⇒ Simpler transceiver design
  - Con: All neighboring BS should time synchronize

7. 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: Wireless PHY



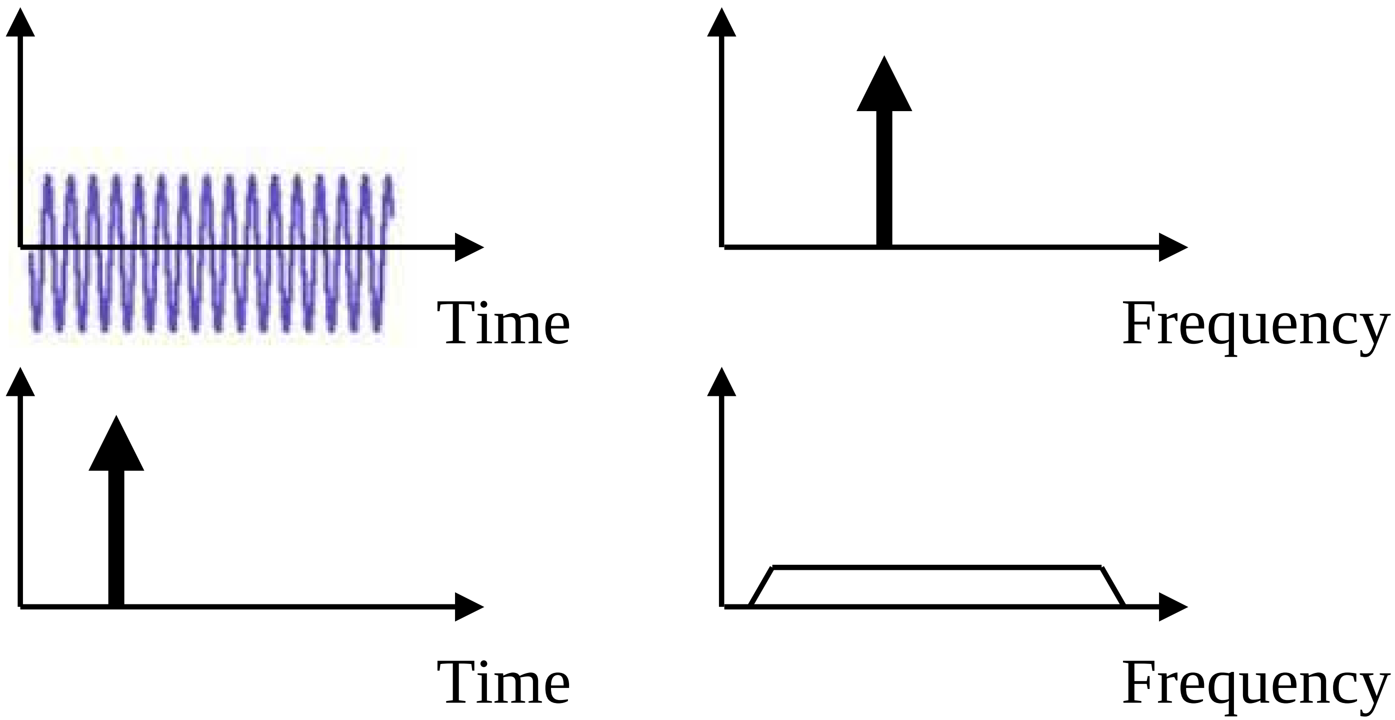
1. OFDM splits a band in to many orthogonal subcarriers. OFDMA = FDMA + TDMA
2. Turbo codes use two coders and a interleaver and operate very close to Shannon's limit
3. Space-time block codes use multiple antennas to transmit related signals
4. MIMO use multiple antennas for high throughput

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

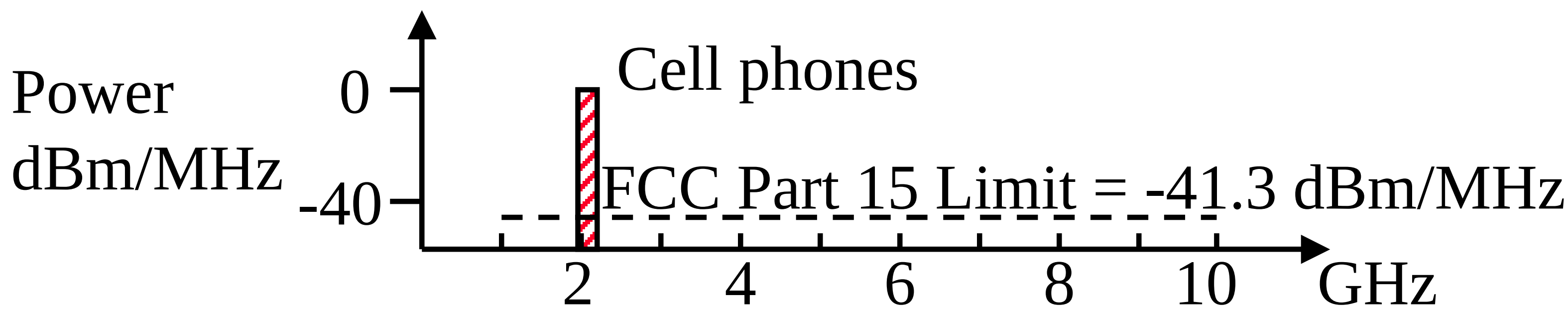


- An impulse in time domain results in a ultra wide spectrum in frequency domain and essentially looks like a white noise to other devices

History of UWB

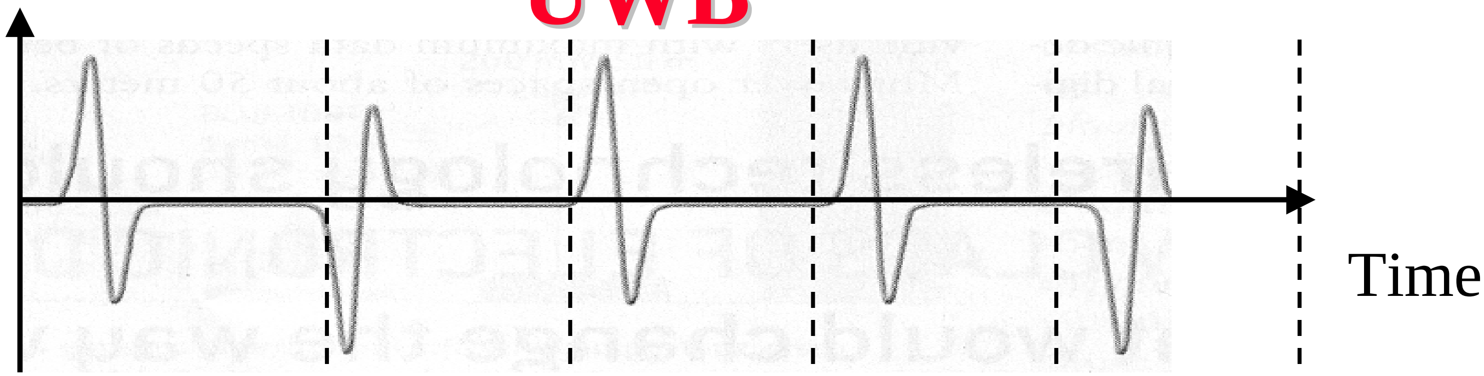
- Oldest wireless communication technology
- Late 1800: Hertz used a spark gap generator to generate a *short pulse* of electromagnetic signal
- 1910: Low spectral efficiency of spark gap
  $\Rightarrow$ Narrow band communication
- 1960: Military radar required short pulses to determine distance to objects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

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
  - Between 3.1GHz and 10.6GHz
  - More than 500 MHz bandwidth or more than 20% fractional bandwidth
- High-speed over short distances ⇒ Wireless USB

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

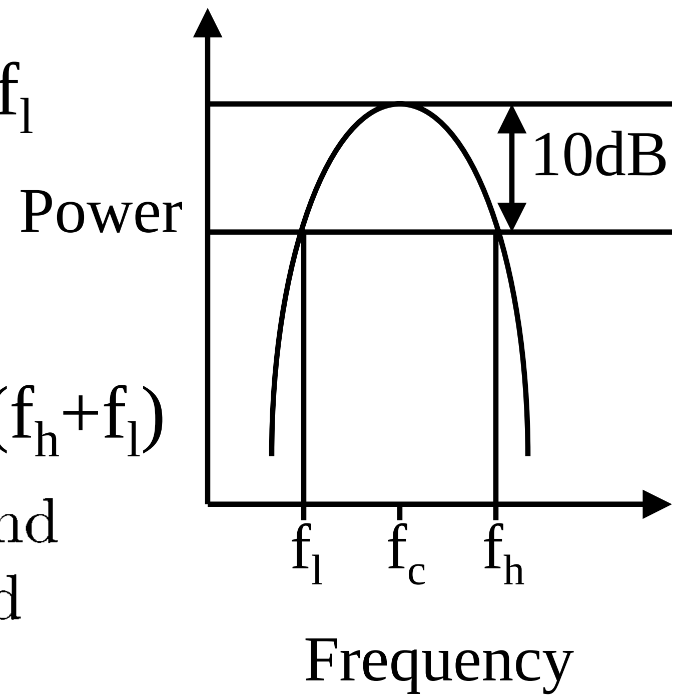
FCC Rules on UWB

- 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.

Advantages of UWB

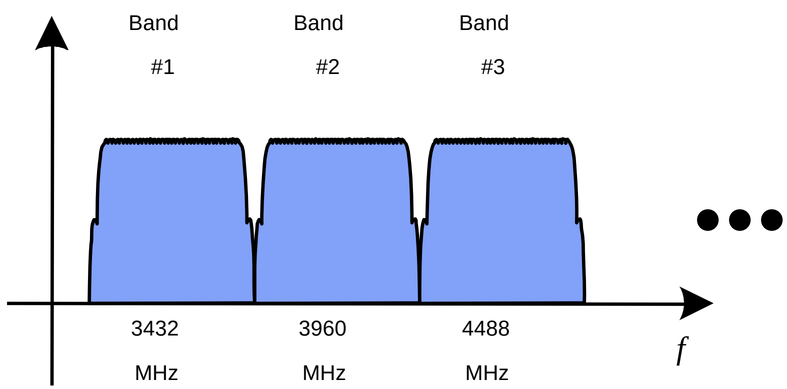
- Shares spectrum with other applications
- Large bandwidth
- Low signal-to-noise ratio
- Low probability of intercept and detection
- Resistance to jamming
- Superior penetration properties at low frequency spectrum
- Simple transceiver architecture. All digital. Low cost.

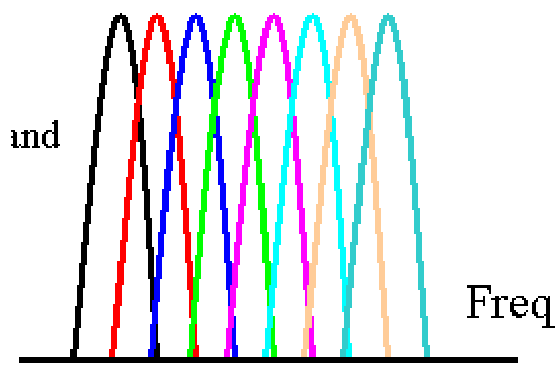
Advantages of UWB (Cont)

- 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
  $\Rightarrow$ Easy to resolve multipath
  $\Rightarrow$ Can use multipath to advantage

Multi-Band OFDM

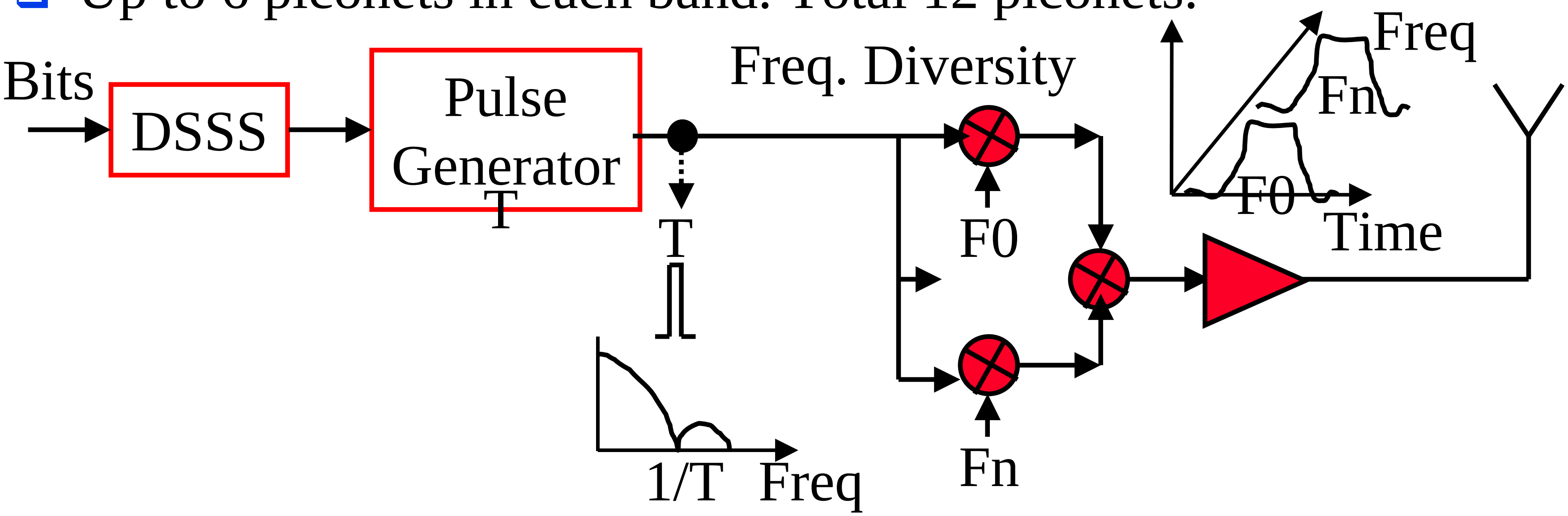
- WiMedia Alliance. Originally by TI. Now many companies
- Divide the 3.1-10.6 GHz spectrum in 14x528 MHz bands (FCC requires min 500 MHz use for UWB)
- Spectrum shaping flexibility for international use
  Move off the band if interference
- Disable a few sub-carriers if required to meet local laws
-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





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.



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

- UWB chips from Intel, Artimi, and Wisair ~$10
- Wireless USB from Staccato Communications and Alereon
- Lenovo Thinkpad T61p has UWB option along with 11n (July 2007).
- Wireless High-Definition Multimedia Interface (HDMI) solutions form Tzero, Analog Devices, Gefen, and Monster
- Mini-PCI UWB radio modules and evaluation kits from Focus Semiconductor
- Y-E Data make four-port ultrawideband hub YD-300
- Click n' Share Wireless USB Flash Memory Drives from Memsen

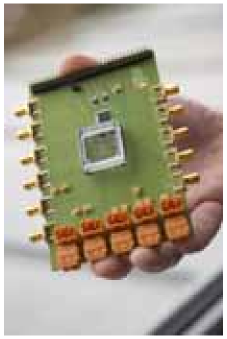
UWB Products (Cont)

- Aether Wire and Location Inc: Pager sized units with centimeter localization over several kms in networks of thousands of nodes.
- UWB antennas from Omran
- Locating bodies in disaster situations by Ultravision
- Wireless video in cars using Focus UWB radio
- Wireless HD gaming over UWB by Pulse-Link
- Ref: http://www.ultrawidebandplanet.com/products/

UWB Products (Cont)

Belkin
Wireless USB

Toshiba UWB
Docking Station



IMEC
UWB Chip

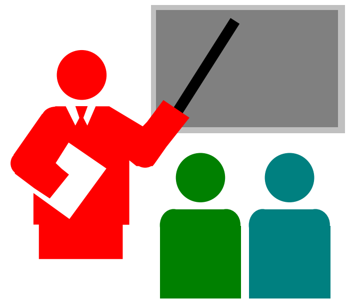
Cell phone with
Infineon UWB

LeCroy UWB
Protocol Analyzer

Haier's UWB-based
HDTV Media Server

UWB Products Plans

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 $\Rightarrow$ 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 $\Rightarrow$ 20-25 Mbps max
- Not designed for high-speed mobility

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 v3.0 in October 6, 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

Hybrid 802.11 Networks: Issues

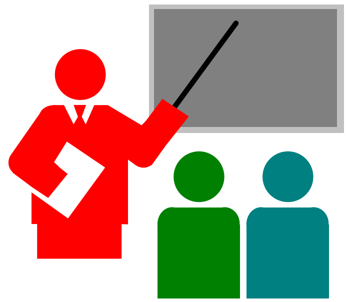
Parameter	802.11b	802.11a	802.11g	802.11n
Data Rate (Mbps)	11	54	54	130 or 270
Modulation	CCK or DSSS	OFDM	CCK, DSSS or OFDM	CCK, DSSS OFDM
Band (GHz)	2.4	5	2.4	2.4 or 5
Spatial streams	1	1	1	4
Channel (MHz)	20	20	20	20 or 40

- 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: 802.11n



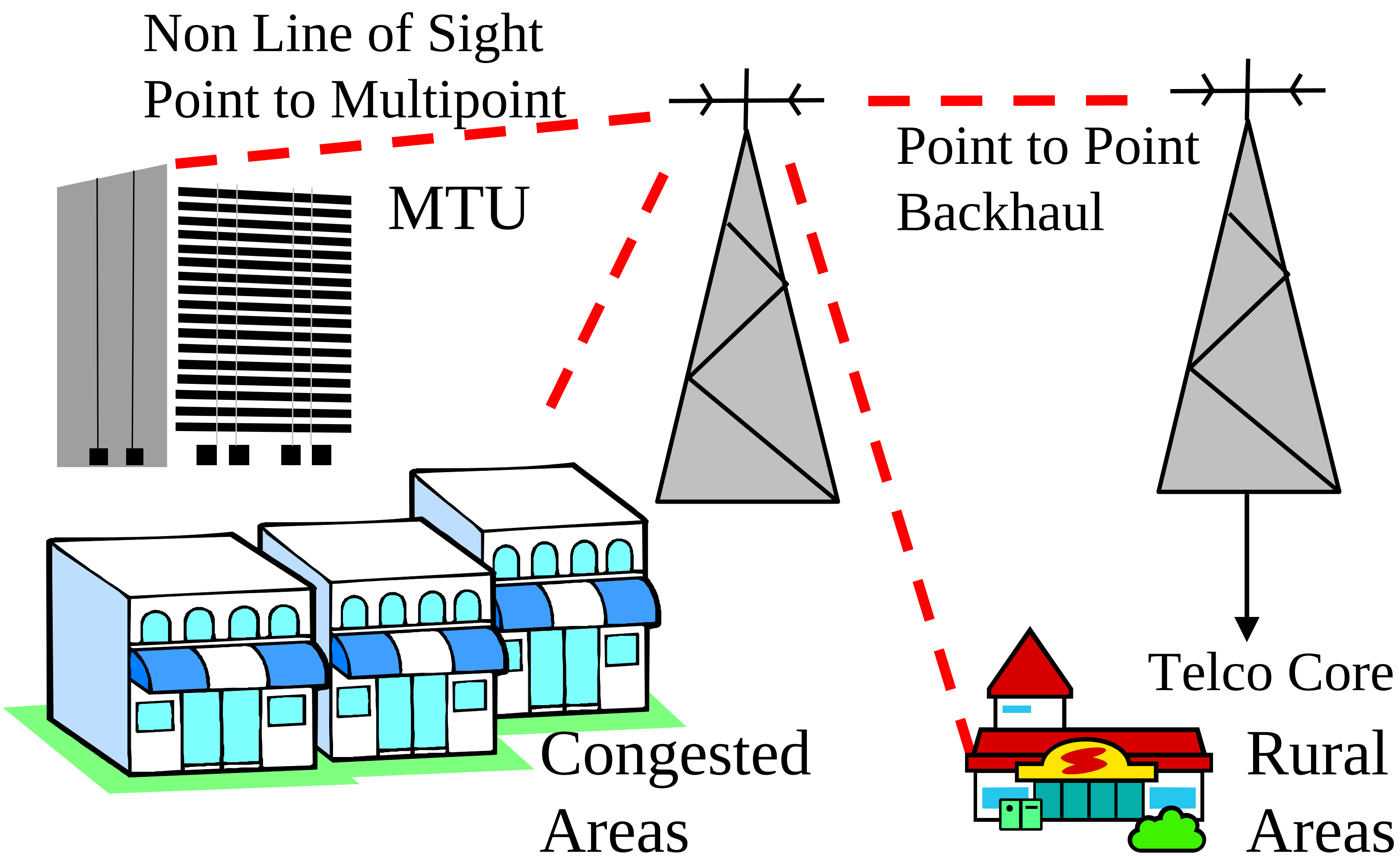
1. 11n gets 100+ Mbps by MIMO, OFDM and wider channels
2. 11b devices can prohibit use of OFDM and may decrease the performance for everyone
3. Wider channels practical only in 5 GHz band $\Rightarrow$ 11a/n
4. You need 11n at both ends to really benefit

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

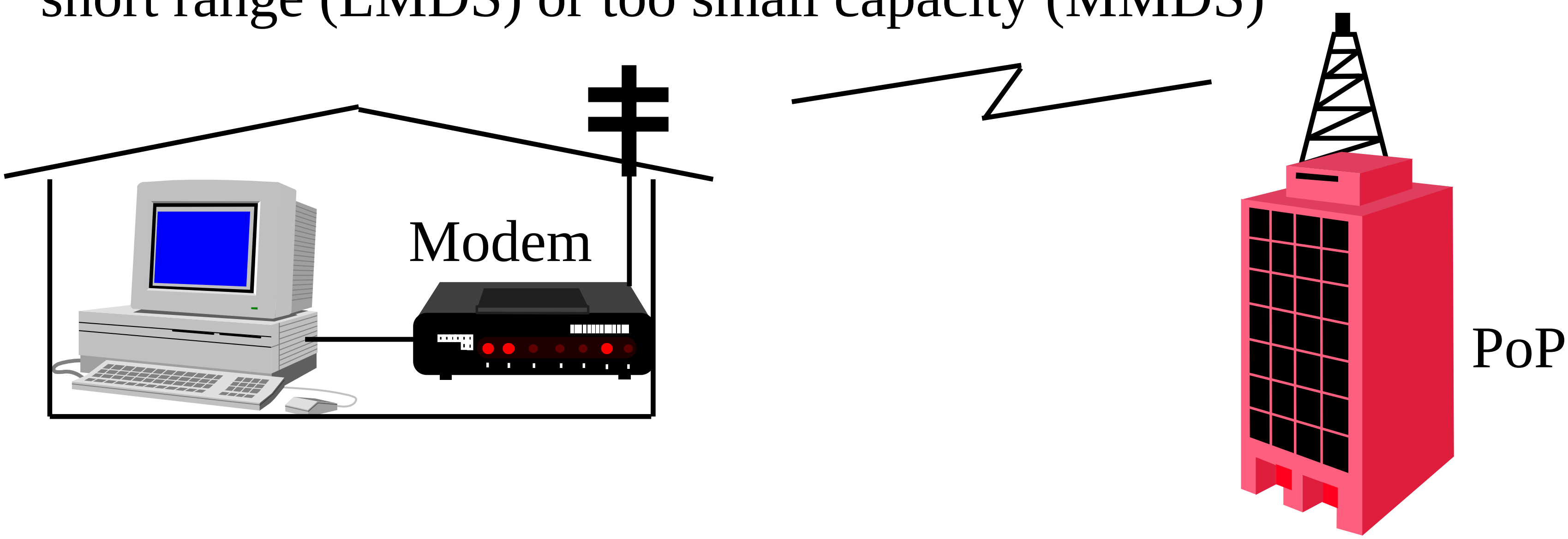
Broadband Wireless Access



Prior Attempts: LMDS & MMDS

- Local Multipoint Distribution Service (1998)
- 1.3 GHz around 28 GHz band (Ka Band)
  28 GHz ⇒ Rain effects
- Multi-channel Multipoint Distribution Services (1999-2001)
- 2.1, 2.5-2.7 GHz Band ⇒ Not affected by rain

Issues: Equipment too expensive, Roof top **LoS** antennas, short range (LMDS) or too small capacity (MMDS)



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

WiMAX

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

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. $2\times(5$ 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

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

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

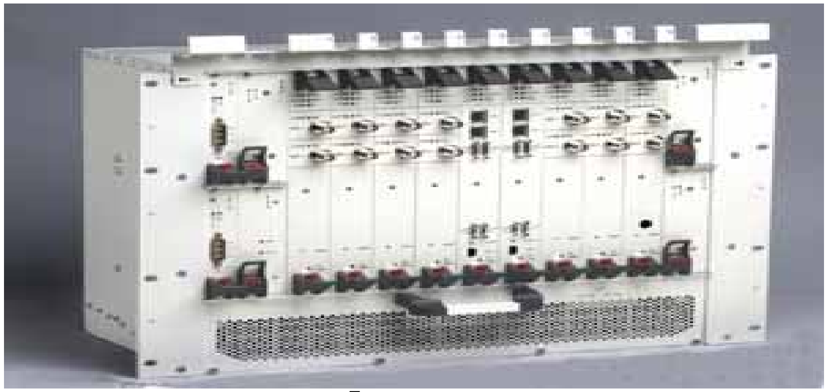
Redline

SR Telecom

Telsima

Sample WiMAX Base Stations

Axxcelara



Alverian

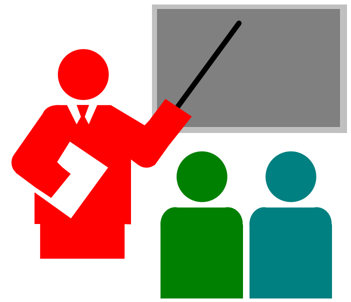
Redline

Airspan

Aperto

SR Telecom

Summary: WiMAX



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

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 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

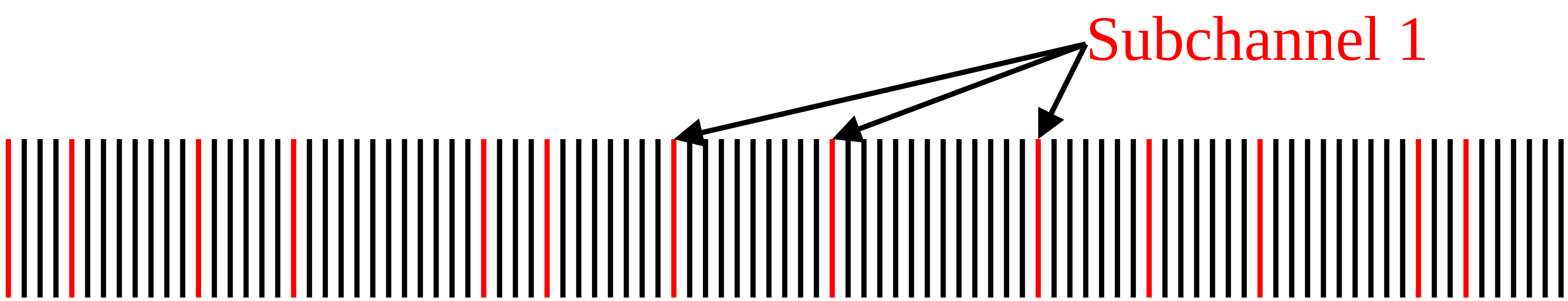
	Function	LOS	Freq. Band	Carrier	Duplexing
WirelessMAN SC	Pt-to-pt	LOS	10-66 GHz	Single	TDD, FDD
WirelessMAN SCa	Pt-to-pt	LOS	2-11 GHz Licensed	Single	TDD, FDD
WirelessMAN OFDM	Pt-to-mpt	NLOS	2-11 GHz Licensed	256	TDD, FDD
WirelessMAN OFDMA (16e)	Pt-to-mpt	NLOS	2-11 GHz Licensed	2048	TDD, FDD
WirelessHUMAN (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

Subchannelization

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

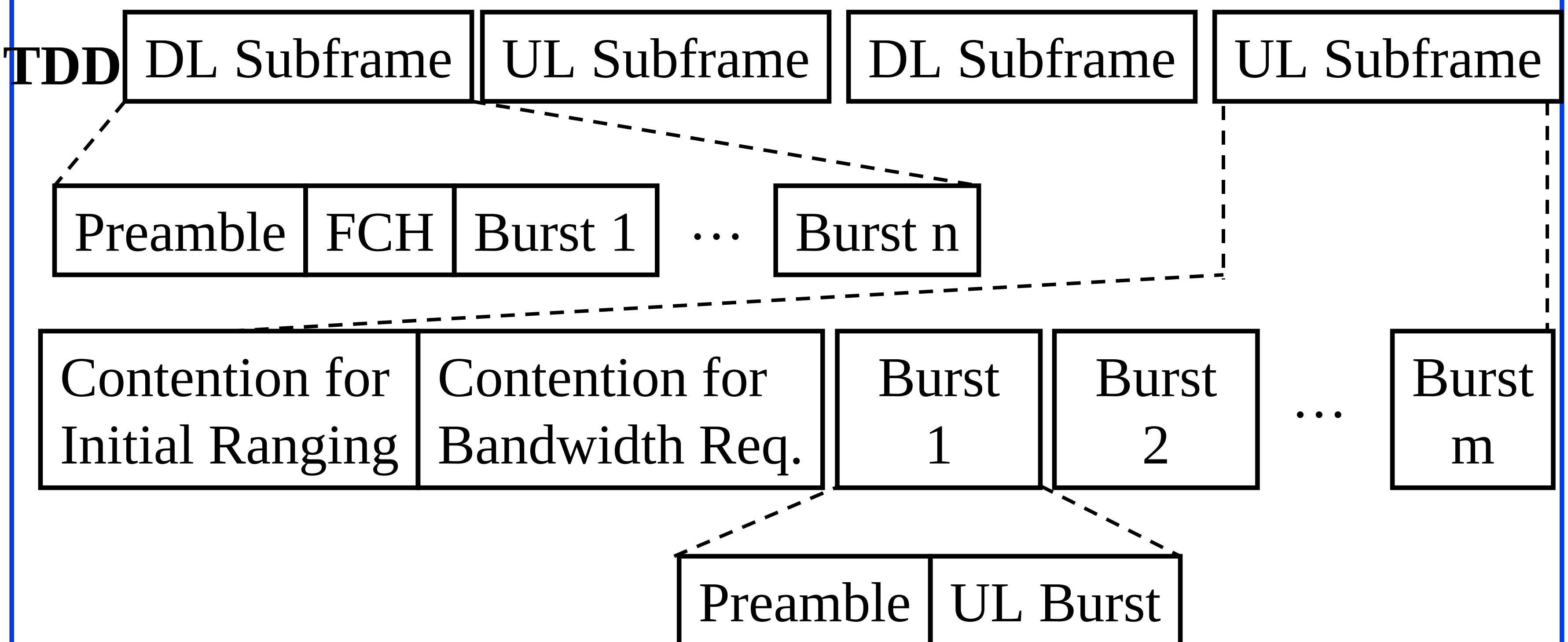


- Contiguous
  $\Rightarrow$ Subchannels allocated based on use's SINR
  $\Rightarrow$ AMC $\Rightarrow$ Not suitable for mobile applications

Subcarrier Permutations

- 1024 subcarriers for 10 MHz
  $\Rightarrow$ 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

802.16 Frame Structure

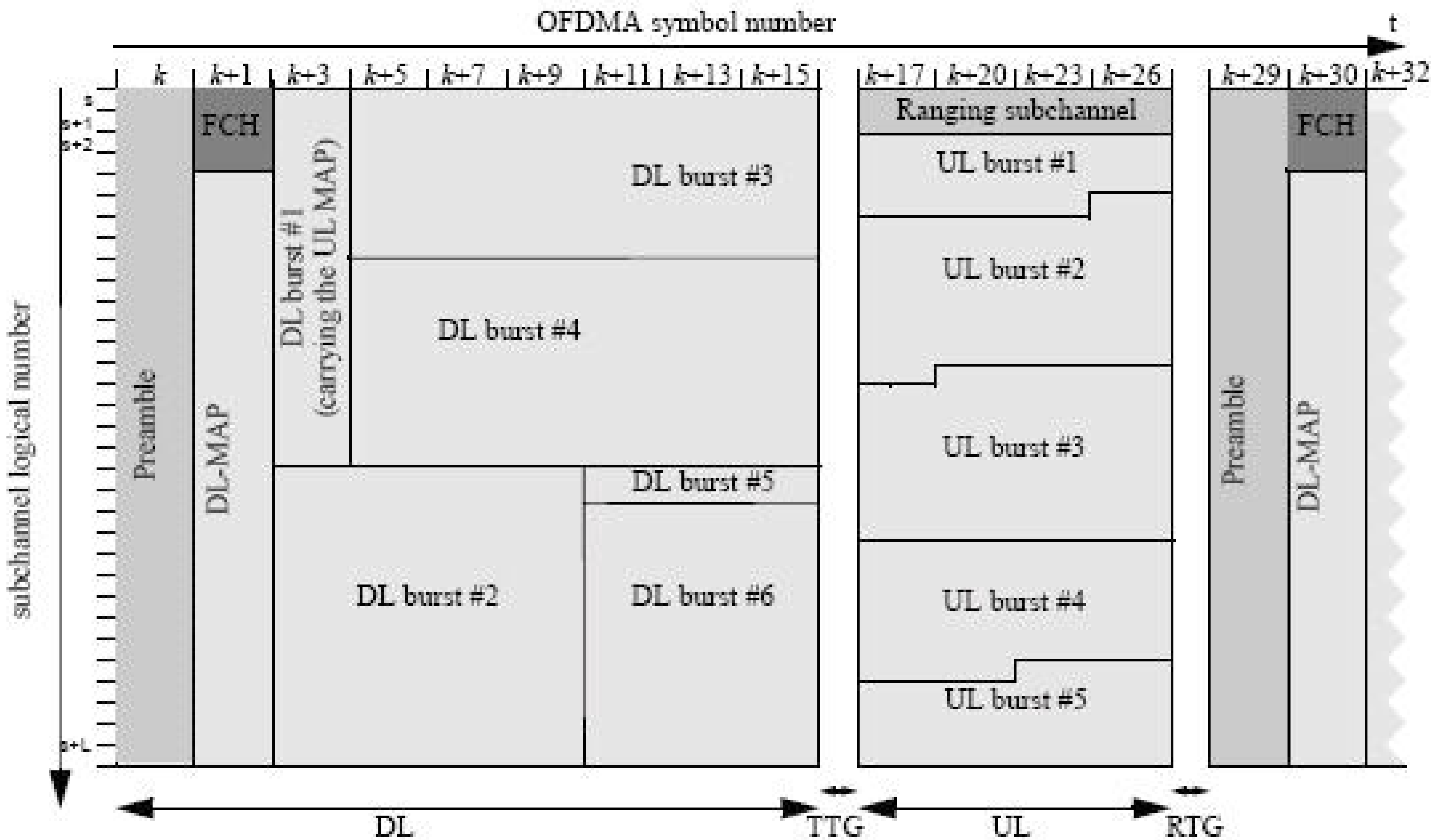


TDD = Time Division Duplexing
DL = Downlink (Base to subscriber)
FCH = Frame control header:

FDD = Freq Div Duplexing
UL = Uplink

Burst Profile, Down-link map, Uplink map, DL channel descriptor, etc.

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.

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)

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

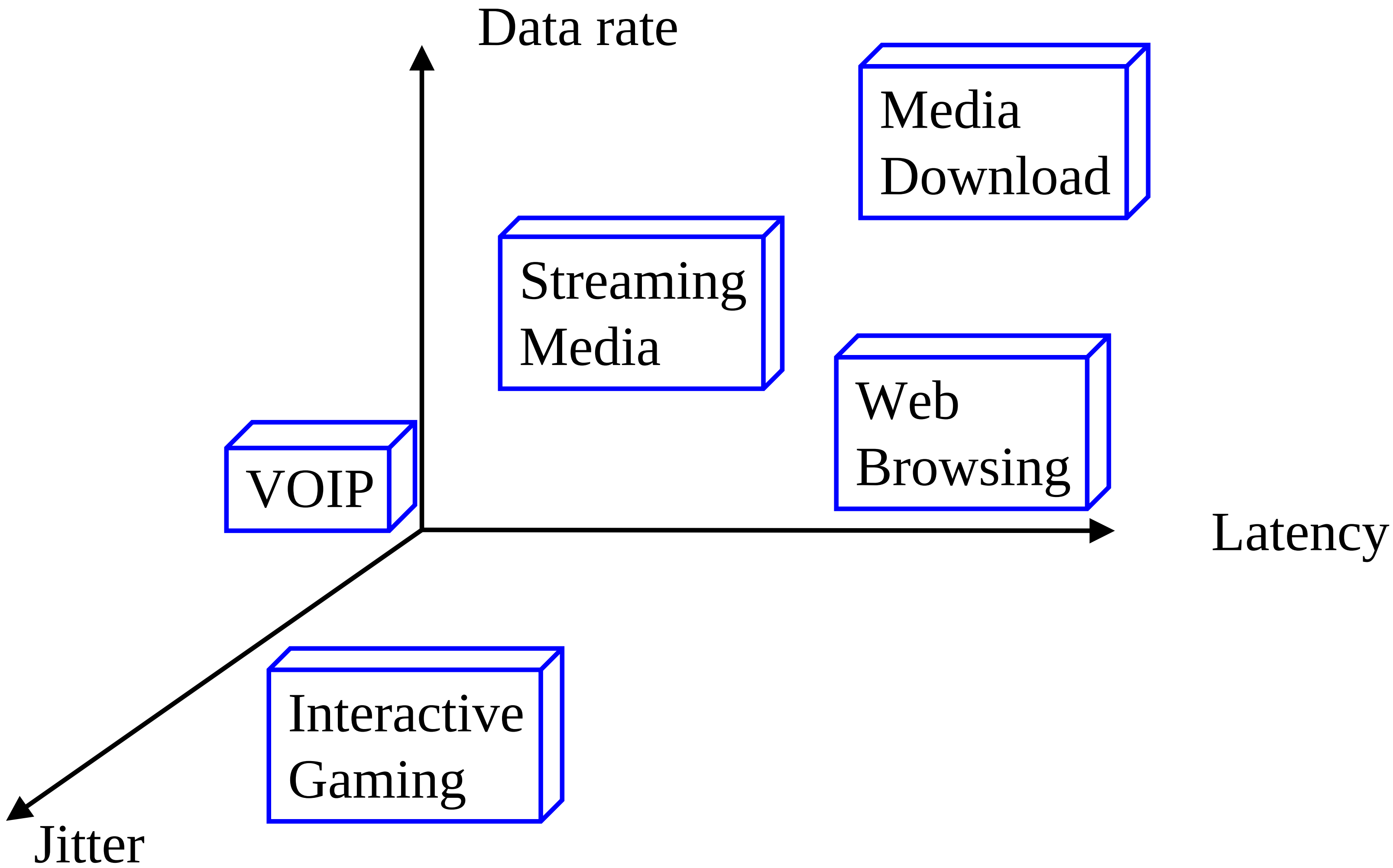
Band Index	Frequency Band	Channel Width	OFDM FFT	Duplexing	Notes
1	2-3-2.4	5	512	TDD	2
		10	1024	TDD	2
		8.75	1024	TDD	
2	2.305-2.320	3.5	512	TDD	
		5	512	TDD	
		10	1024	TDD	
3	2.496-2.690	5	512	TDD	2
		10	1024	TDD	2
4	3.3-3.4	5	512	TDD	
		7	1024	TDD	
		10	1024	TDD	
5	3.4-3.8	5	512	TDD	
	3.4-3.6	7	1024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

2. Both bandwidths must be supported by mobile station.

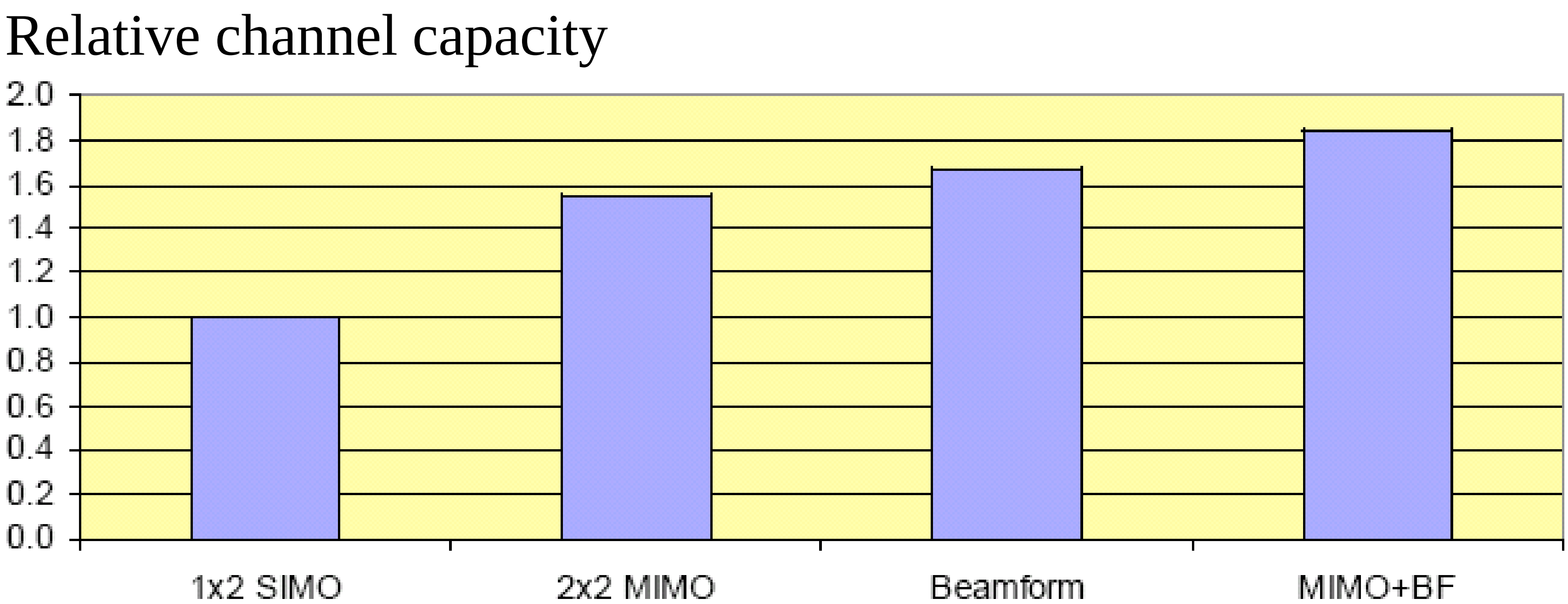
WiMAX AWG Application Classes

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				

WiMAX AWG Classes (Cont)

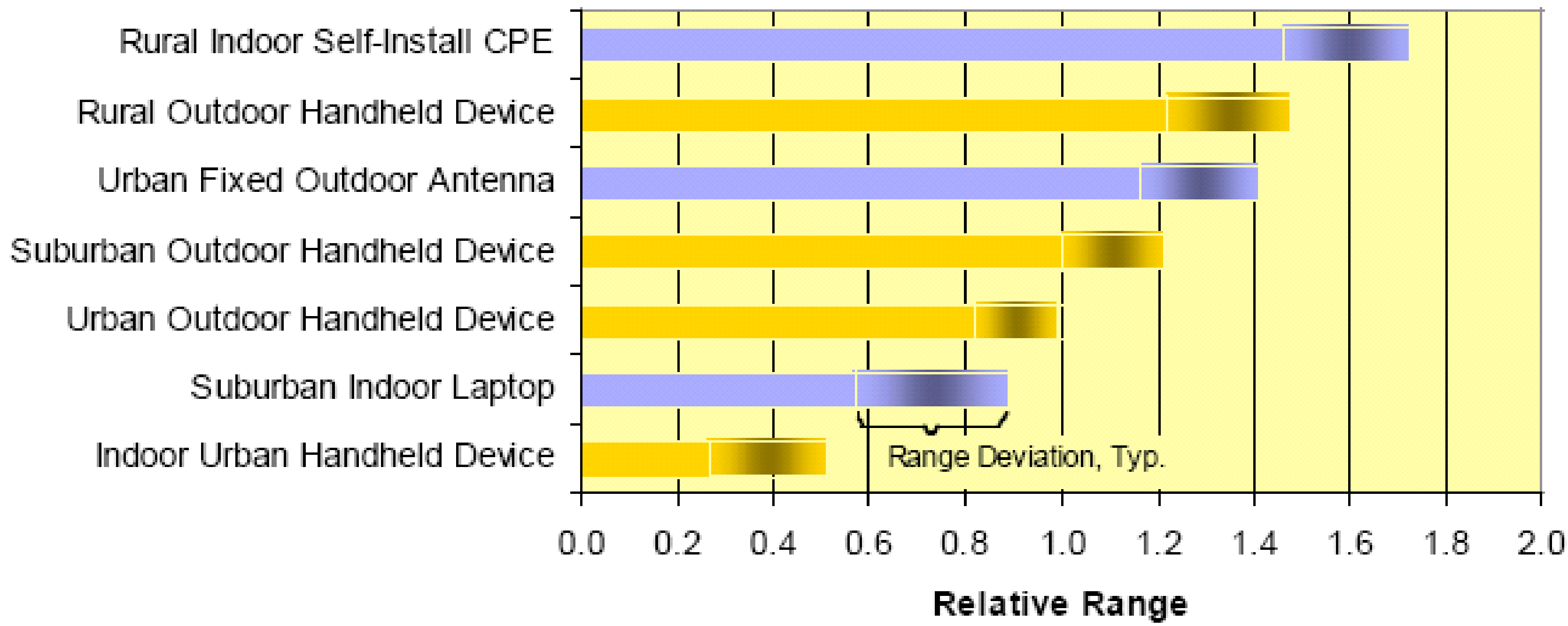


Effect of MIMO on Capacity



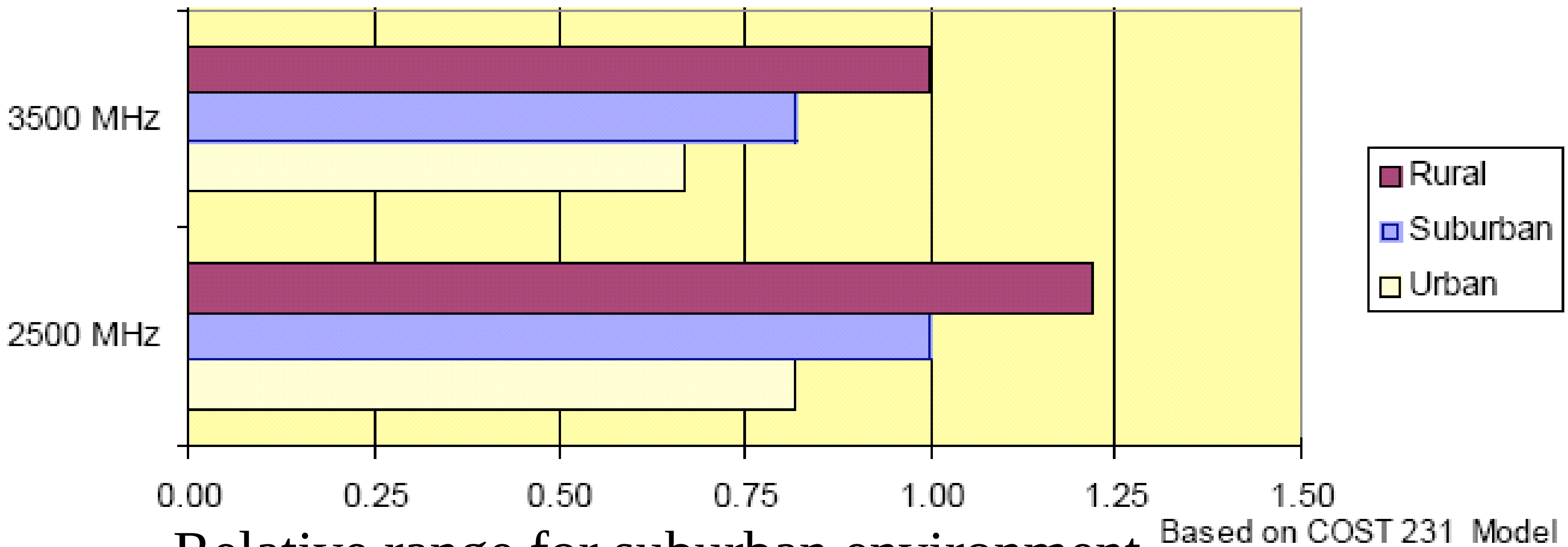
- Ref: WiMAX Forum, “A Comparative Analysis of Mobile WiMAX Deployment Alternatives in the Access Network,” White paper, May 2007.

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



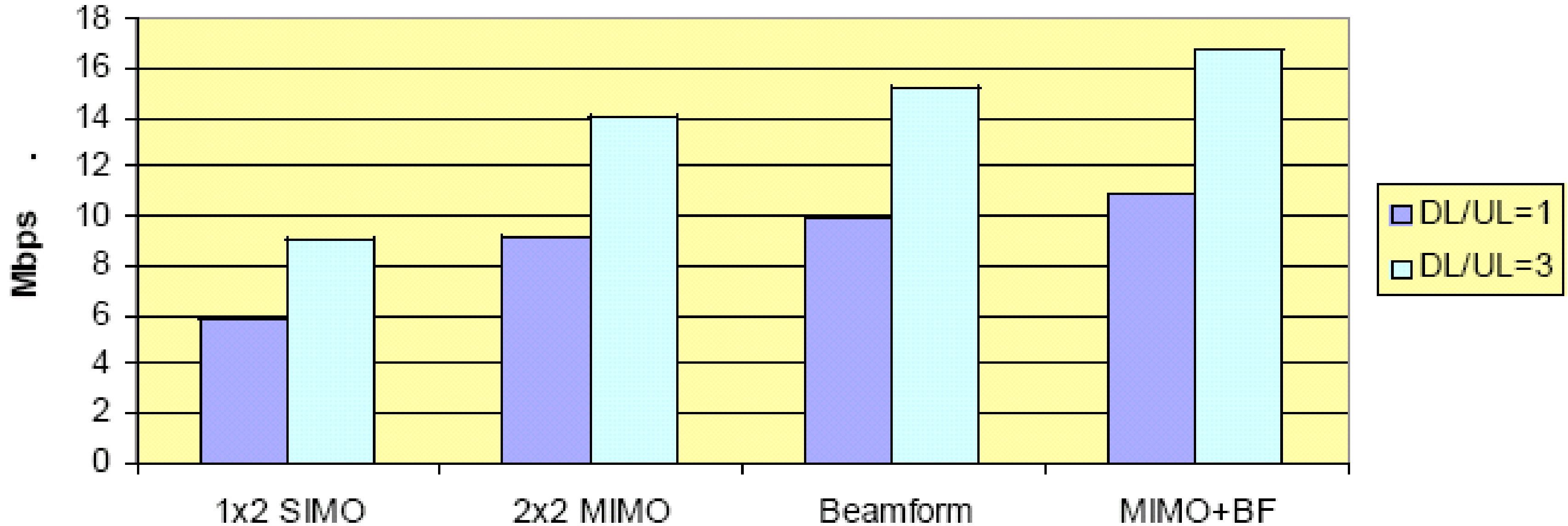
Relative range for suburban environment

- 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)

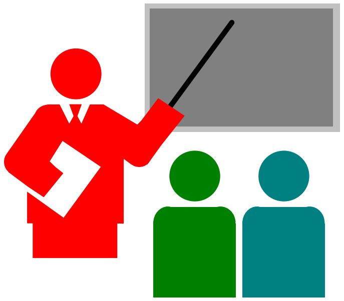
Downlink Throughput



TDD with 10 MHz

Ref: WiMAX Forum, Comparative Analysis whitepaper

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

Intentionally blank

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

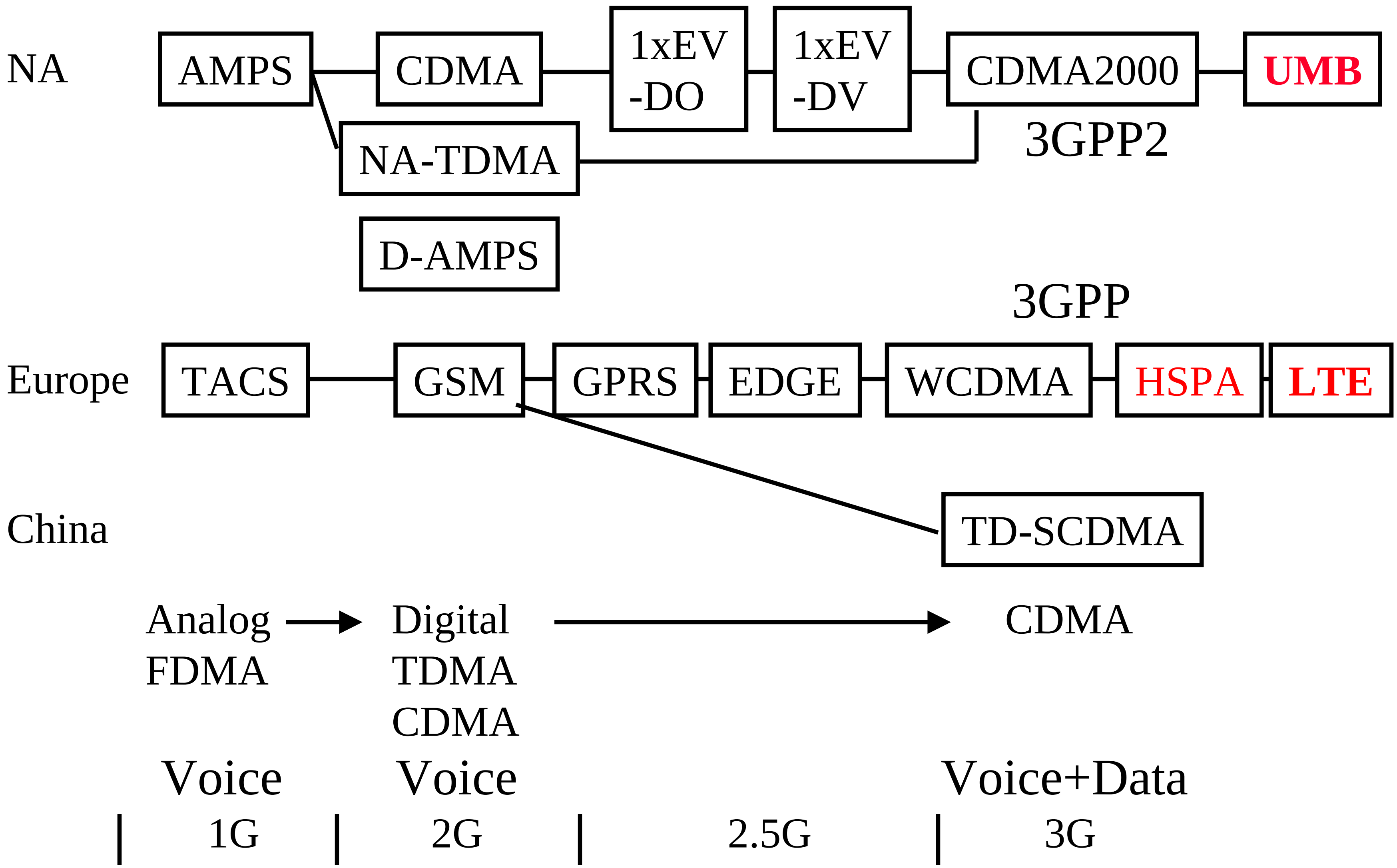
IEEE 802.11 vs. 802.16

	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.

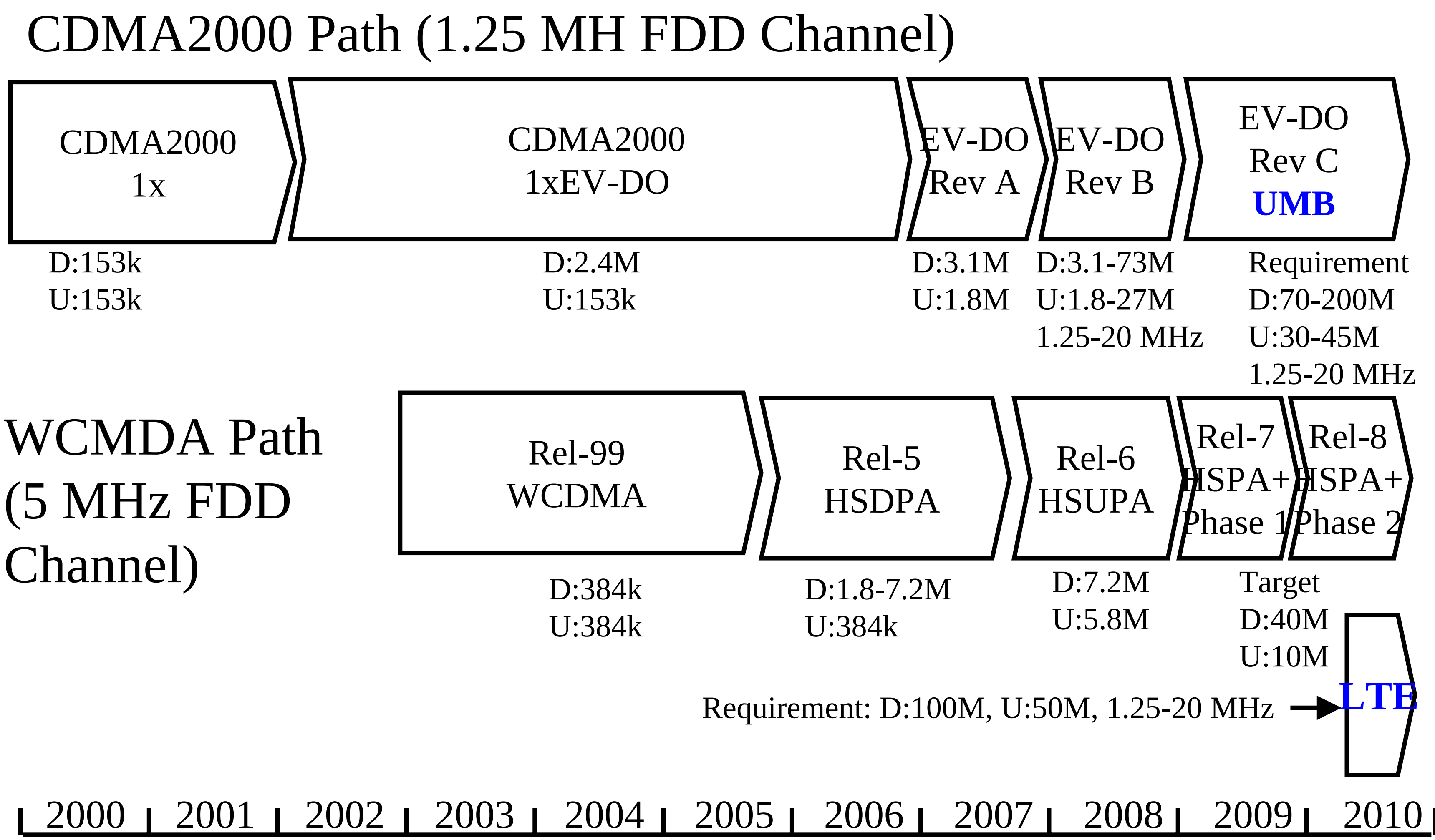
IEEE 802.11 vs. 802.16 (Cont)

	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 Differentiation	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



3G Technologies: Bit Rates

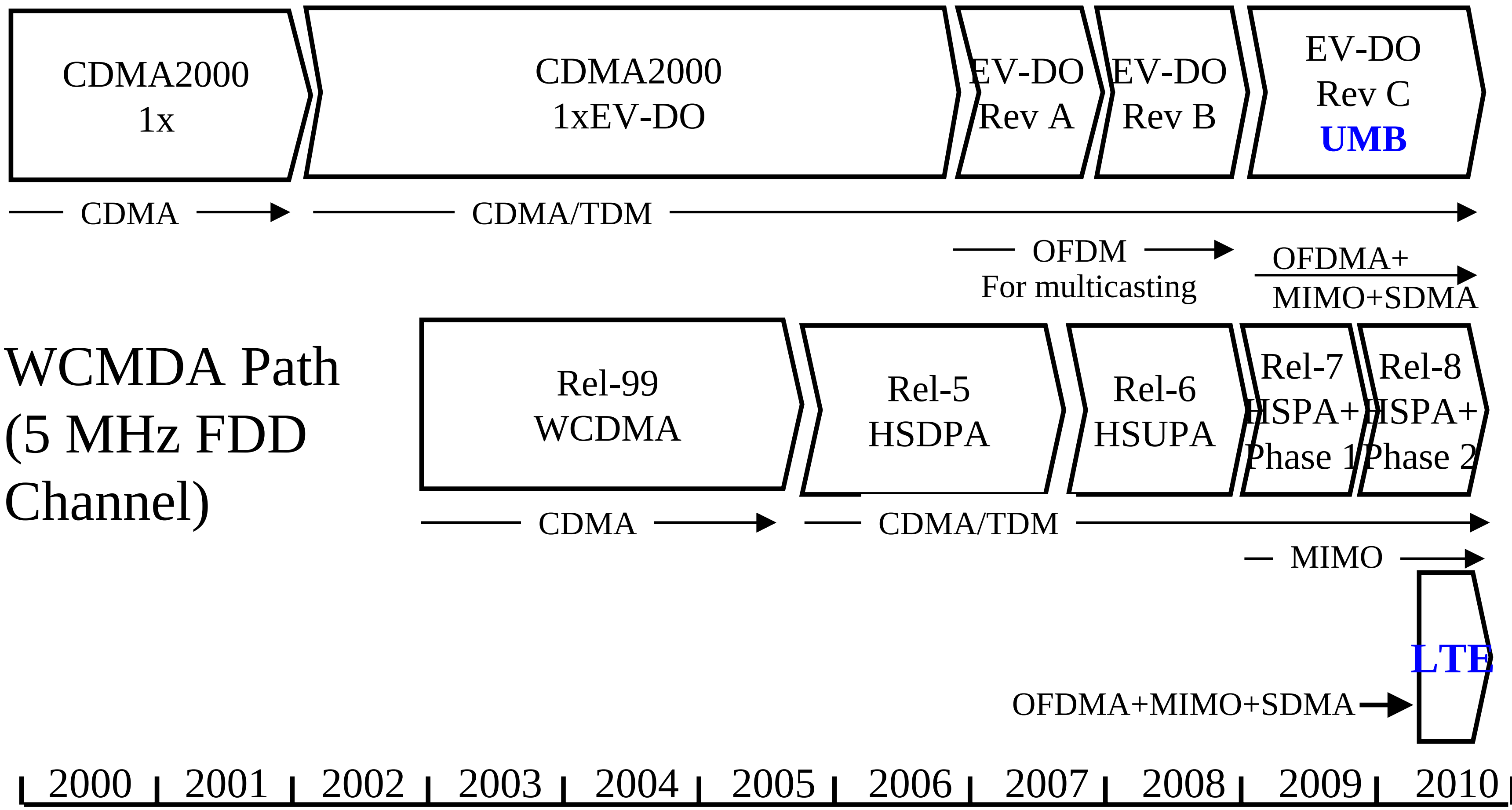


Note: WiMAX is also a 3G Technology now.

Source: www.cdg.org

3G Technologies: PHY

CDMA2000 Path (1.25 MH FDD Channel)



Source: www.cdg.org

3G Technologies (Cont)

- All data rates are for FDD
  $\Rightarrow$ 20MHz = 2×20 MHz
- On the downlink, LTE uses a modified version of OFDMA called DFT-Spread OFDMA, also known as single-carrier FDMA.
- UMB may utilize a combination of OFDMA and CDMA or OFDM and CDMA
- Data rates depend upon level of mobility

4G: IMT-Advanced

- International Mobile Telecommunications – Advanced or 4G
- Wireless broadband access to be standardized around 2010 and deployed around 2015
- 1 Gbps for nomadic/fixed and 100 Mbps for high mobility (150 km/h)
- Requirements will be set in 2008
- Set of 4G technologies will be selected by 2010

Ref: ITU-R M.1645, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000" (2003)

IEEE 802.16m

- Peak data rate:
  - Downlink (BS->MS) > 6.5 bps/Hz,
    Uplink (MS->BS) > 2.8 bps/Hz
    After PHY overhead
  - 20 MHz => 130 Mbps
- Mobility: Optimized for 0-15 km/h, marginal degradation 15-120 km/h, maintain connection 120-350 km/h
- 3 dB improvement in link budget over 16e
- Optimized for cell sizes of up to 5km. Graceful degradation in spectral efficiency for 5-30km. Functional for 30-100 km.

Ref: Draft IEEE 802.16m requirements, June 8, 2007,
http://ieee802.org/16/tgm/docs/80216m-07_002r2.pdf

700 MHz

- February 19, 2009: TV vacates 700-MHz
- FCC just approved 700 MHz for broadband access
- 108 MHz total available
  - 60 MHz available by Auction in January 16, 2008
  - 24 MHz for Public Safety
  - 24 MHz already owned by Access Spectrum, Aloa Partners, Pegasus Comm, Qualcomm,Verizon, DirecTV, Echostar, Google, Intel, Skype, and Yahoo!
- **Open Access**: Open applications, Open devices, Open services, and open networks
- **White spaces**: Unused spectrum between 54 and 698 MHz. (Channel 2 through 51)

Effect of Frequency

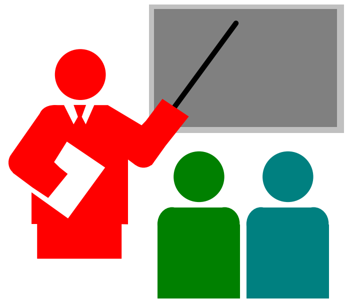
- Higher Frequencies have higher attenuation, e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need smaller antenna Antenna $\geq$ Wavelength/2, 800 MHz $\Rightarrow$ 6”
- Higher frequencies are affected more by weather Higher than 10 GHz affected by rainfall 60 GHz affected by absorption of oxygen molecules
- Higher frequencies have more bandwidth and higher data rate
- Higher frequencies allow more frequency reuse
- Mobility $\Rightarrow$ Below 10 GHz

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

Intentionally blank

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

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/fw07.htm

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

List of Acronyms

Raj Jain
Email: Jain@Acm.org

3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project II
4G	4th Generation
AM	Amplitude
AP	Access Point
APAC	Asia Pacific
ASPAC	Asia Pacific
AWG	Application Working Group at WiMAX Forum
BE	Best Effort
BPSK	Binary Phase Shift Keying
BS	Base Station
CDMA	Code Division Multiple Access
CQICH	Channel quality indicator channel
CSMA	Carrier Sense Multiple Access
DL	Downlink
DS	Direct sequence
DSP	Digital Signal Processing
DVB	Digital Video Broadcast
ECMA	European Computer Manufacturers Association
EV-DO	Evolution-Data Only
FCC	Federal Communications Commission
FDD	Frequency Duplexing
FEC	Forward Error Correction
GHz	Giga Hertz
GSM	Global System for Mobile Communications
HDMI	High-Definition Multimedia Interface
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
IDFT	Inverse Discrete Fourier Transform
IEEE	Institution of Electrical and Electronic Engineers
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISI	Inter-symbol interference
ITU	International Telecommunications Union
KISDI	Korea Information Society Development Institute
LAN	Local Area Network
LMDS	Local Multipoint Distribution System
LTE	Long Term Evolution

MHz	Mega Hertz
MIB	Management Information Base
MIMO	Multiple Input Multiple Output
MMDS	Multichannel Multipoint Distribution Service
MMR	Mobile Multihop Relay
MPEG	Motion Pictures Experts Group
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAN	Personal Area Network
PCMCIA	Personal Computer Memory Card International Association
PHY	Physical Layer
POTs	Plain Old Telephone Systems
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
S-OFDMA	Scalable Orthogonal Frequency Division Multiple Access
SDRs	Software Defined Radio
SINR	Signal to Interference and Noise Ratio
SSs	Subscriber Stations
STBC	Space Time Block Codes
TDD	Time Division Duplex
TV	Television
UGS	Unsolicited Grant Service
UL	Uplink (subscriber to Base station)
USB	Universal Serial Bus
UWB	Ultra Wideband
VOIP	Voice over IP
WLAN	Wireless LAN