ECSE 6961
Wireless Broadband: Introduction

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Slides based upon books by Tse/Viswanath, A.Goldsmith, Rappaport, J.Andrews etal

Objectives

- Where is wireless broadband today? Where has it come from in the last decade? What is its future potential?
- Why is wireless *channel* different from wired?
- How does wireless design overcome the challenges of the channels and interference?
  - What are key wireless communication *concepts*?
  - Rapid fire introduction to buzz words and why they matter: OFDM/CDMA/MIMO …
- How do they feature in modern/emerging wireless *systems* (Wifi: 802.11a/b/g/n, 3G, mobile WIMAX: 802.16e)?
- Note: Mobile ad-hoc and sensor networks are covered in the MONET course by Prof. Abouzeid (and another course by Prof. Art Sanderson)

- **Refs**: Chap 1 in Tse/Viswanath, and Chap 1 in Goldsmith.

Wireless Broadband: Potential

Why Wireless?

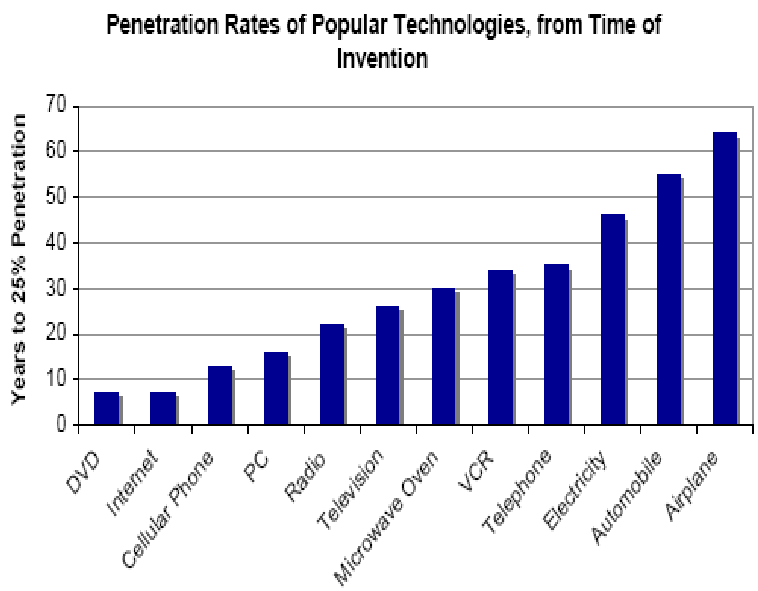
- Characteristics
  - Mostly radio transmission, new protocols for data transmission are needed
- Advantages
  - Spatial flexibility in radio reception range
  - Ad hoc networks without former planning
  - No problems with wiring (e.g. historical buildings, fire protection, esthetics)
  - Robust against disasters like earthquake, fire – and careless users which remove connectors!
- Disadvantages
  - Generally very low transmission rates for higher numbers of users
  - Often proprietary, more powerful approaches, standards are often restricted
  - Many national regulations, global regulations are evolving slowly
  - Restricted frequency range, interferences of frequencies
- Nevertheless, in the last 10-20 years, it has really been a wireless revolution…

The Wireless Revolution

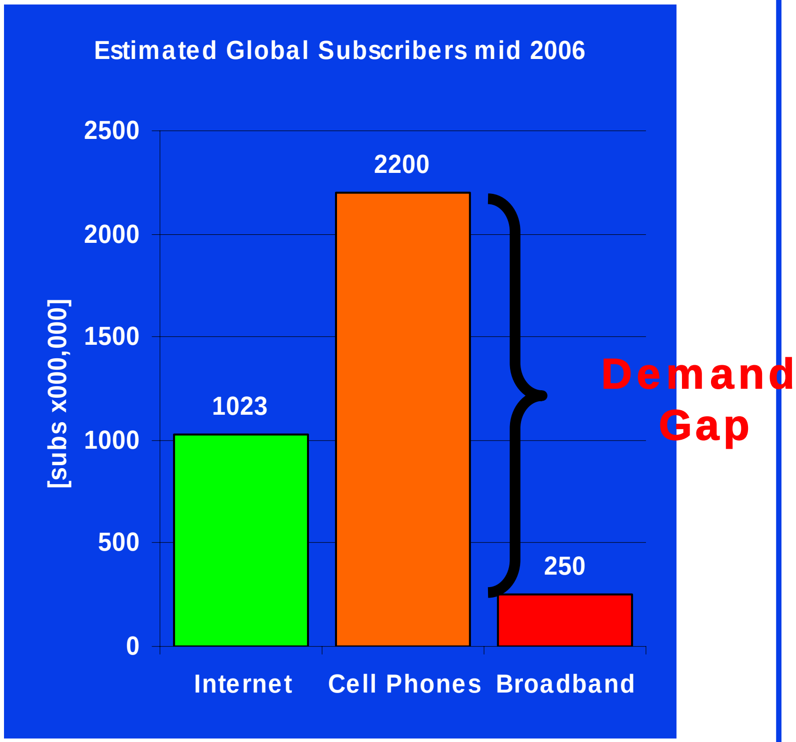
- Cellular is the fastest growing sector of communication industry (exponential growth since 1982, with over 2 billion users worldwide today)
- Three generations of wireless
  - First Generation (1G): Analog 25 or 30 KHz FM, voice only, mostly vehicular communication
  - Second Generation (2G): Narrowband TDMA and CDMA, voice and low bit-rate data, portable units.

    2.5G increased data transmission capabilities
  - Third Generation (3G): Wideband TDMA and CDMA, voice and high bit-rate data, portable units
  - <u>Fourth Generation (in progress):</u> true broadband wireless: WIMAX, 3G LTE, 802.11 a/b/g/n, UWB{<u>**THIS COURSE's FOCUS**</u>}

The Wireless Broadband Opportunity

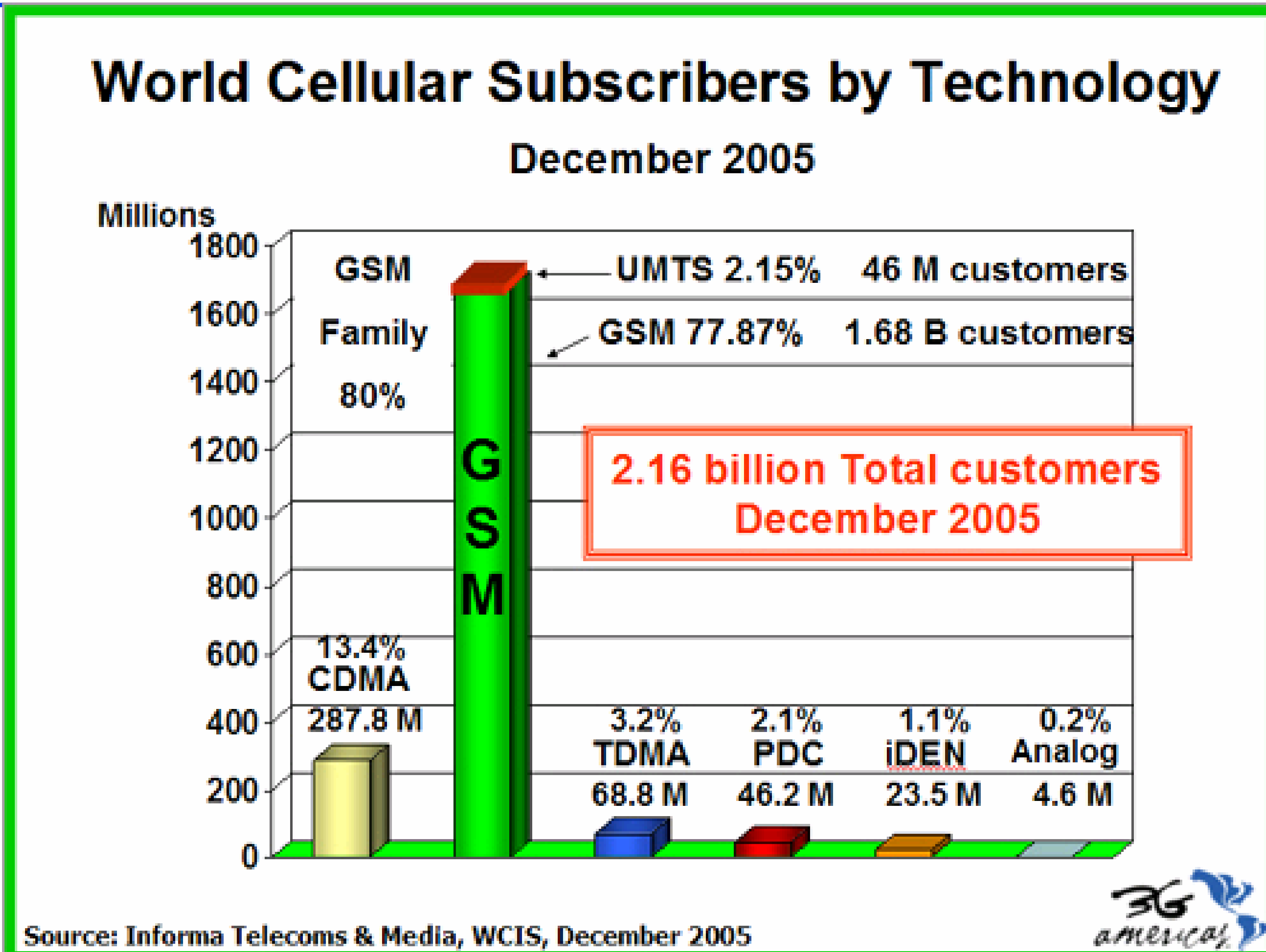


Source: Federal Reserve Bank of Dallas, Consumer Electronics Association



Wireless mobile services grew from 11 million subscribers worldwide in 1990 to over 2 billion in 2005.

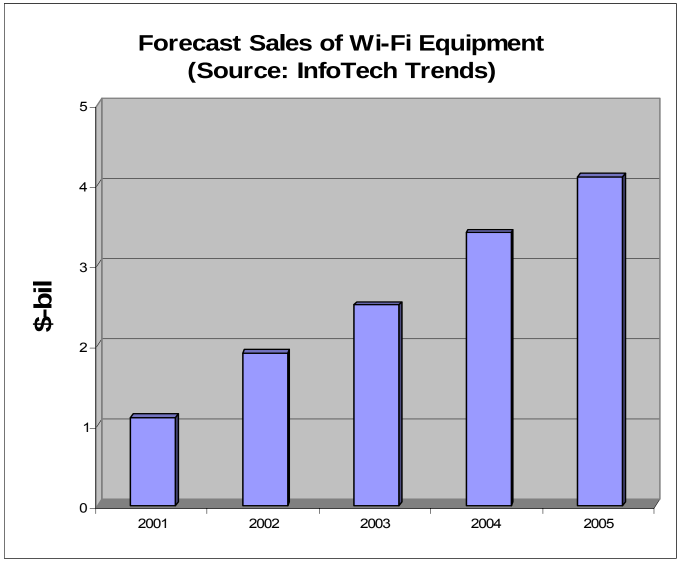
In the same period, the Internet grew from being a curious academic tool to about 1 billion users. Broadband internet access is also growing rapidly

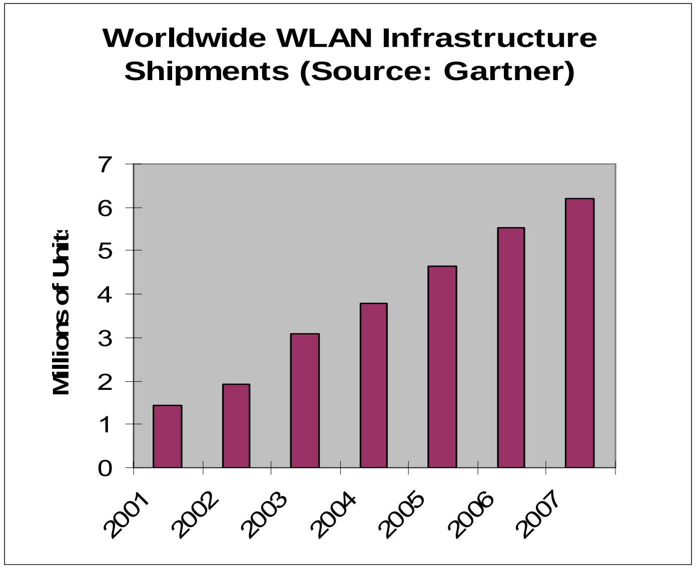


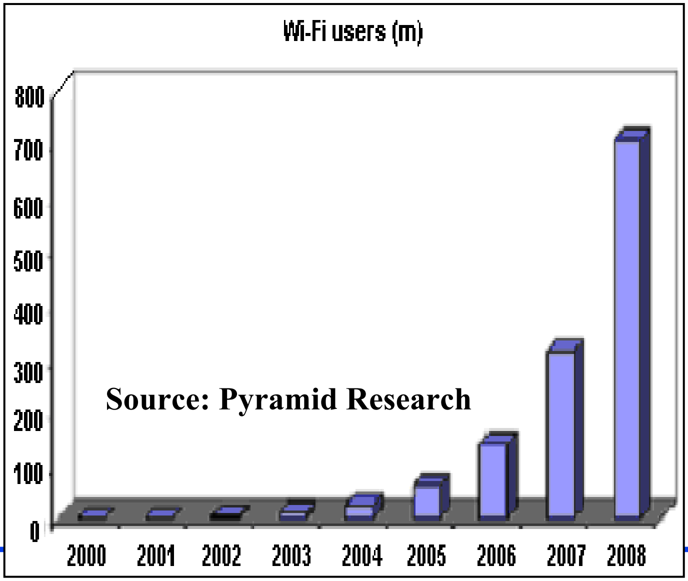
- **Sept 2006 figures**: 2.53 Billion total; 2.02 B (GSM), 320 M (CDMA), 81.2M UMTS

Source: http://www.3gamericas.org/English/Statistics/

WLAN Market: WiFi







WLAN Growth Drivers

- Convenience & Flexibility
- Productivity Gains
- Low Cost
- Embedded WLAN

Source: AirTight Networks

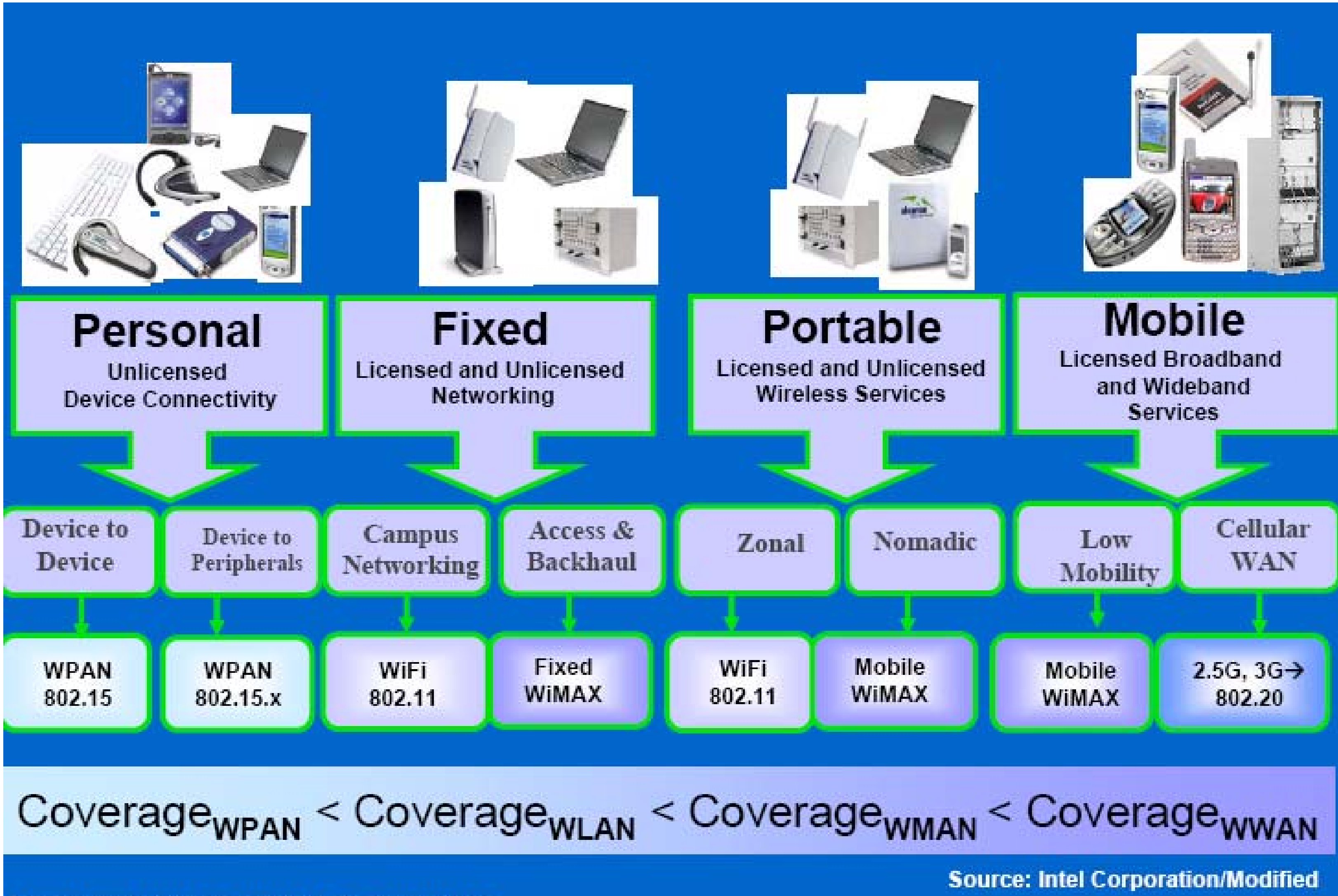
Internet Trends today…

Global Internet Data Points…

Google →	7.6B global searches (+74% Y/Y, 5/05); 384MM global unique visitors (+36%, 5/05) per comScore
Broadband →	179MM global subscribers (+45% Y/Y, CQ2); 57MM in Asia; 45MM in N. America
Yahoo! →	917MM streaming video (music…) sessions (+119% Y/Y, CQ4)
Digital Music →	695MM cumulative iTunes as of 9/05; 6MM iPods sold in CQ2:05 (+295% Y/Y)
Personalization →	40MM+ estimated My Yahoo! users
Blogging →	27% of US Internet users read blogs, 11/04
Tencent →	16MM peak simultaneous Instant Message users, China, CQ2
Ringtones →	$3B annualized ringtone sales (Informa 5/05) - vs. $495MM cumulative iTunes sales (7/05)

- Source: Morgan Stanley, Oct 2005

Wireless: The Big Picture…



Wireless: Understanding the Big Picture…

- **Wireless (vs wired)…** communication *medium*
- **Cellular (vs meshed vs MANETs)…** *architectures* for coverage, capacity, QoS, mobility, auto-configuration, infrastructure support
- **Mobile (vs fixed vs portable)…** implications for *devices*: phone vs PSP vs PDA vs laptop vs ultramobile
- **WAN (vs WLAN vs WMAN)…** *network scope*, coverage, mobility
- **Market segments:** Home networks, SOHO, SME, enterprise, Hotspots, WISPs, cellular …
- **Technologies/Standards/Marketing Alliances:** 802.11, UWB, Bluetooth, Zigbee, 3G, GSM, CDMA, OFDM, MIMO, Wimax…

Mobile Computing/Entertainment/Commns

iPoD: impact of disk size/cost

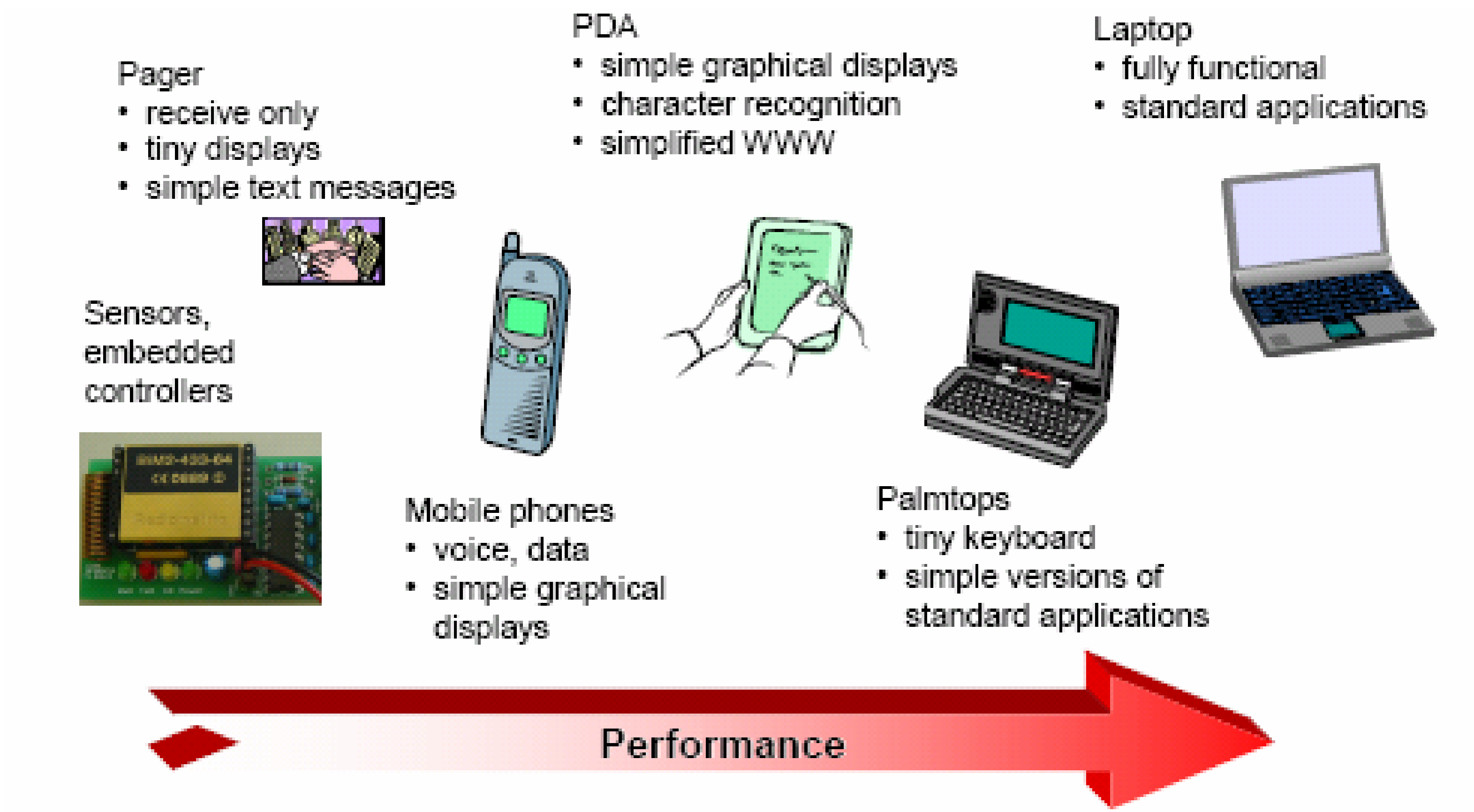
Samsung Cameraphone
w/ camcorder

Blackberry: phone + PDA

SONY PSP: mobile gaming

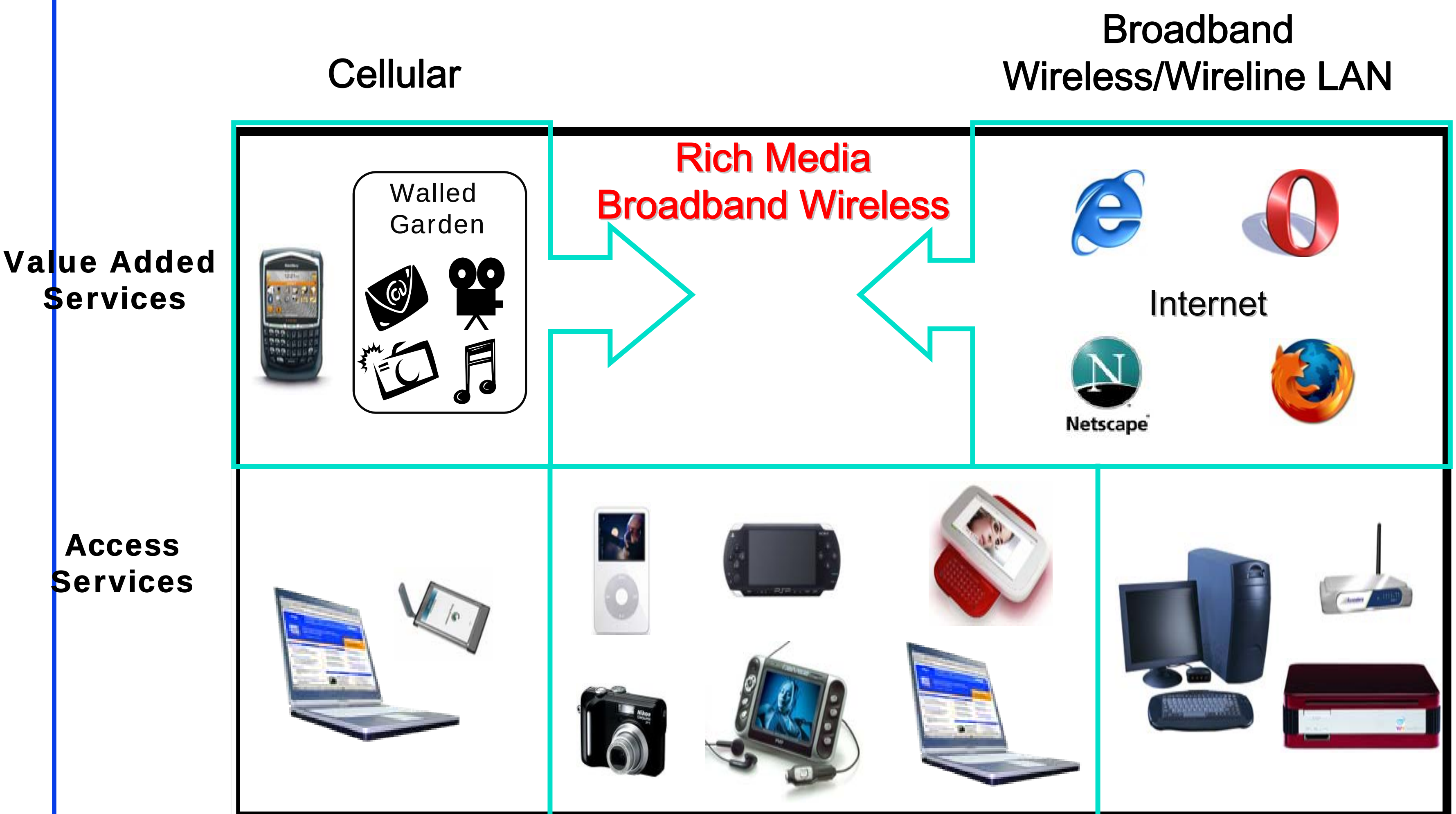
- Computing: smaller, faster
- Disks: larger size, small form
- Communications: wireless voice, data
- Multimedia integration: voice, data, video, games

Variety of Wireless-Capable Devices



2006 Thanksgiving sales: < $1000 Plasma 42” TVs.
These will soon be wireless-broadband enabled and can play home movies/videos from the Internet

Emerging Rich Media Broadband Wireless



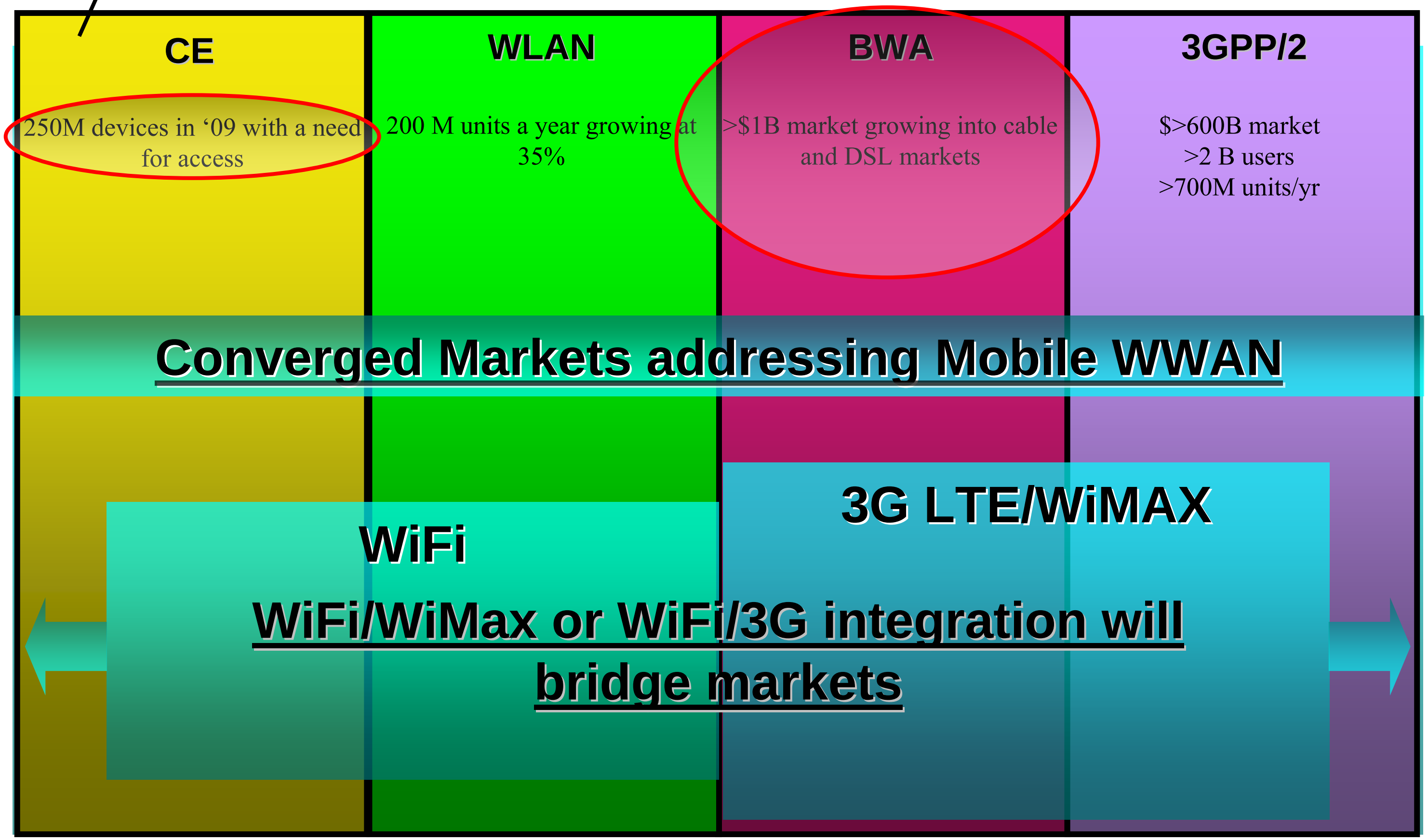
*Other brands and names are the property of their respective owners.

Converging Markets Drive Economies of Scale

CE devices will require low cost WLAN/WWAN access

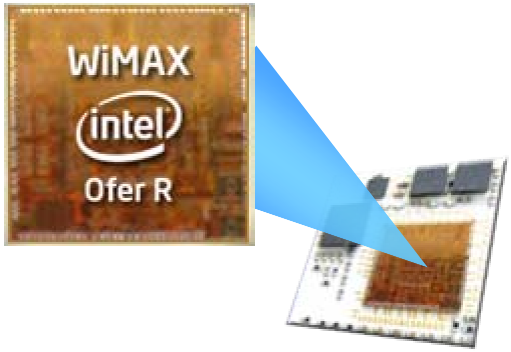
~220M BB users (CBL+DSL+other)

Market demand is >1B



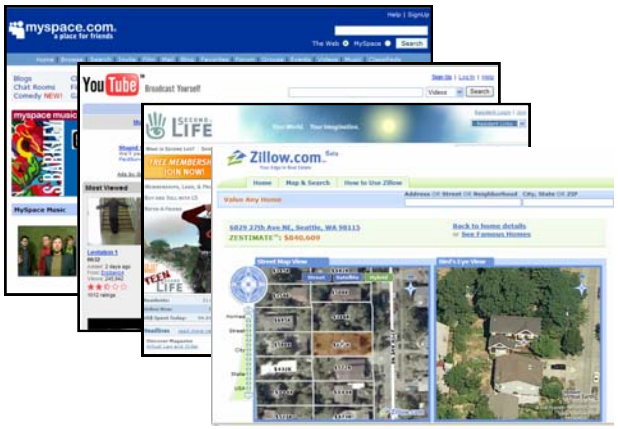
Source: Intel Estimates, IDC,

Mainstream Mobile Broadband Internet Will Also Require:



Innovation in Distribution:

Single Chip WiFi + WiMAX/3G
for Mass Market



Innovation in Services:

Web 2.0, AJAX, Mashups,
Personal Internet

Innovation in Billing:

Pay as You Go, Pre-paid,
or Monthly Subscription

Wireless History (Brief)

Wireless History

1901: First radio reception across the Atlantic Ocean

1924: First Mobile Radio Telephone

Early Cellular Systems

- 1940s-50s: cellular concept discovered (AT&T)
- **1st Generation:** Analog:
  - AMPS: FDMA with 30 KHz FM-modulated voice channels.
  - **1983**: The first analog cellular system deployed in Chicago: saturated by 1984,
  - FCC increased the cellular spectral allocation from 40 MHz to 50 MHz.
    - Two 25MHz channels: DL and UL (FDD)
  - AT&T moved on to fiber optics in '80s.

- **2nd generation:** digital: **early 90s**
  - higher capacity, improved cost, speed, and power efficiency of digital hardware

Wireless Timeline (Partial)

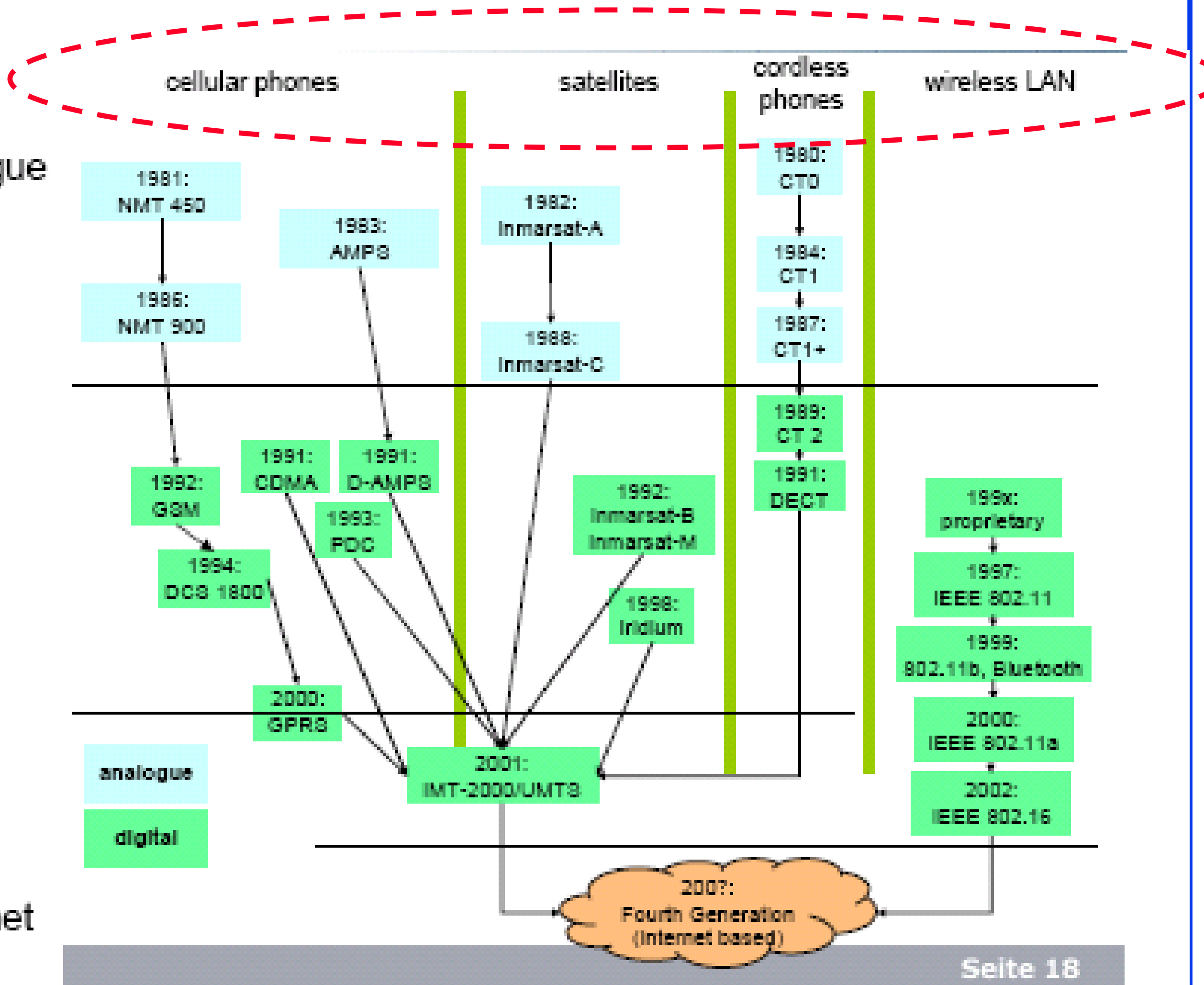
- **1991** - Specification of DECT (cordless phone)
  - Digital European Cordless Telephone (today: Digital Enhanced Cordless Telecommunications). Other cordless standards: PHS (Japan), CT-2 (Europe/Asia)
  - 1880-1900MHz, ~100-500m range, 120 duplex channels, 1.2Mbit/s data transmission, voice encryption, authentication, up to several 10000 user/km^2, used in more than 50 countries.
- **1992** - Start of GSM
  - In Germany as D1 and D2, fully digital, 900MHz, 124 channels
  - Automatic location, hand-over, cellular
  - Roaming in Europe - now worldwide in more than 170 countries
  - Services: data with 9.6kbit/s, FAX, voice, ...
- **1996** - HiperLAN (High Performance Radio Local Area Network)
  - ETSI, standardization of type 1: 5.15 - 5.30GHz, 23.5Mbit/s
  - Recommendations for type 2 and 3 (both 5GHz) and 4 (17GHz) as wireless ATM-networks (up to 155Mbit/s)
- **1997** - Wireless LAN – IEEE 802.11
  - IEEE standard, 2.4 - 2.5GHz and infrared, 2Mbit/s
  - Already many (proprietary) products available in the beginning
- **1998** - Specification of GSM successors
  - UMTS (Universal Mobile Telecommunication System) as European proposals for IMT-2000
  - Iridium: 66 satellites (+6 spare), 1.6GHz to the mobile phone

Wireless Timeline (Partial)

- **1999** - Standardization of additional wireless LANs
  - IEEE standard 802.11b, 2.4-2.5GHz, 11Mbit/s
  - Bluetooth for piconets, 2.4Ghz, <1Mbit/s
  - Decision about IMT-2000
    - Several "members" of a "family": UMTS, cdma2000, DECT, …
  - Start of WAP (Wireless Application Protocol) and i-mode
  - Access to many (Internet) services via the mobile phone
- **2000** - GSM with higher data rates
  - HSCSD offers up to 57,6kbit/s
  - First **GPRS** trials with up to 50 kbit/s (packet oriented!)
  - GSM Enhancements for data transmission pick up (EDGE, GPRS, HSCSD)
  - UMTS auctions/beauty contests
  - Hype followed by disillusionment (approx. 50 B$ payed in Germany for 6 UMTS licenses!)
- **2001** - Start of 3G systems
  - Cdma2000 in Korea, UMTS in Europe, Foma (almost UMTS) in Japan
- **2002** – Standardization of high-capacity wireless networks
  - IEEE 802.16 as Wireless MAN

Wireless Evolution Timeline

- 1st generation: analogue
- 2nd generation: digital
- 3rd generation (3G): integration of voice and data
- 4th generation (4G): integration with Internet (When and how?)



Broadband (Fixed) Wireless: History

- **Step 1:** ***wireless local loop*** (WLL): where a wired local loop did not exist (eg: developing countries such as China, India, Indonesia, Brazil and Russia). DECT/CDMA based.
  - February 1997: AT&T: wireless access system for the 1900 MHz PCS band that could deliver two voice lines and a 128 kbps data connection to subscribers. (Project Angel)
  - CDPD overlaid on cellular, Metricom/Ricochet (smaller cells).
- **Step 2:** ***Local Multipoint Distribution Systems*** (LMDS) supporting up to several hundreds of megabits per second were also developed in microwave frequency bands such as the 24 GHz and 39 GHz bands. Issues: rooftop access, short range
  - ***Multichannel Multipoint Distribution Services*** or MMDS band at 2.5 GHz. The MMDS band was historically used to provide broadcast video services called "wireless cable." Satellite TV killed this market.
  - 1998: FCC allowed spectrum MMDS holders to offer wireless pt-Mpt services
  - Issues: Outdoor antenna, LOS requirements
  - LOS deployments in 3.5 GHz and 5+ GHz also.

Broadband (Fixed) Wireless: History

- **Step 3:** Cellular architecture, NLOS coverage, more capacity. Initial use of OFDM, multiple-antennas etc. Proprietary technologies. Telecom bust period (early 2000s)

- **Step 4:** Standards-based Technology (IEEE 802.16): wireless MAN
  - Originally for 10-66 GHz band (LMDS like)
  - Modification 802.16a for 2-11 GHz, licensed/license-exempt
  - OFDM, OFDMA MAC, MIMO introduced soon: 802.16-2004 and 802.16e (mobile).
  - WIMAX: an industrial consortium that "shepherds" the 802.16 standards to guarantee interoperability & certifies products.
  - Other technologies: i-Burst technology from ArrayComm and Flash-OFDM technology from Flarion (now Qualcomm)

Broadband Wireless Milestones: Summary

Date	Event
February, 1997	AT&T announces development of fixed wireless technology code named "Project Angel"
February, 1997	FCC auctions 30 MHz spectrum in 2.3 GHz band for Wireless Communications Services (WCS)
September, 1997	American Telecasting (acquired later by Sprint) announced wireless Internet access services in the MMDS band offering 750 kbps downstream with telephone dial-up modem upstream
September, 1998	FCC relaxed rules for MMDS band to allow two-way communications
April, 1999	MCI and Sprint acquire several "Wireless Cable" operators to get access to MMDS spectrum
July, 1999	First working group meeting of IEEE 802.16 group
March, 2000	AT&T launches first commercial high-speed fixed wireless service after years of trial.
May, 2000	Sprint launches first MMDS deployment in Phoenix using first generation LOS technology.
June, 2001	WiMAX Forum established
October, 2001	Sprint halts MMDS deployments
December, 2001	AT&T discontinues fixed wireless services
December, 2001	IEEE 802.16 standards completed for > 11 GHz.
February, 2002	Korea allocates spectrum in the 2.3 GHz band for Wireless Broadband (WiBro)
January, 2003	IEEE 802.16a standard completed
June, 2004	IEEE 802.16-2004 standard completed and approved
September, 2004	Intel begins shipping the first WiMAX chipset called "Rosedale"
December, 2005	IEEE 802.16e standard completed and approved
January 2006	First WiMAX Forum certified product announced for fixed applications
June 2006	WiBro commercial services launched in Korea
August 2006	Sprint Nextel announces plans to deploy Mobile WiMAX in the US

Source: J.Andrews, A. Ghosh, R. Muhamed, Fundamentals of WIMAX

Wireless Systems: From Narrowband to Broadband

What do service providers need?

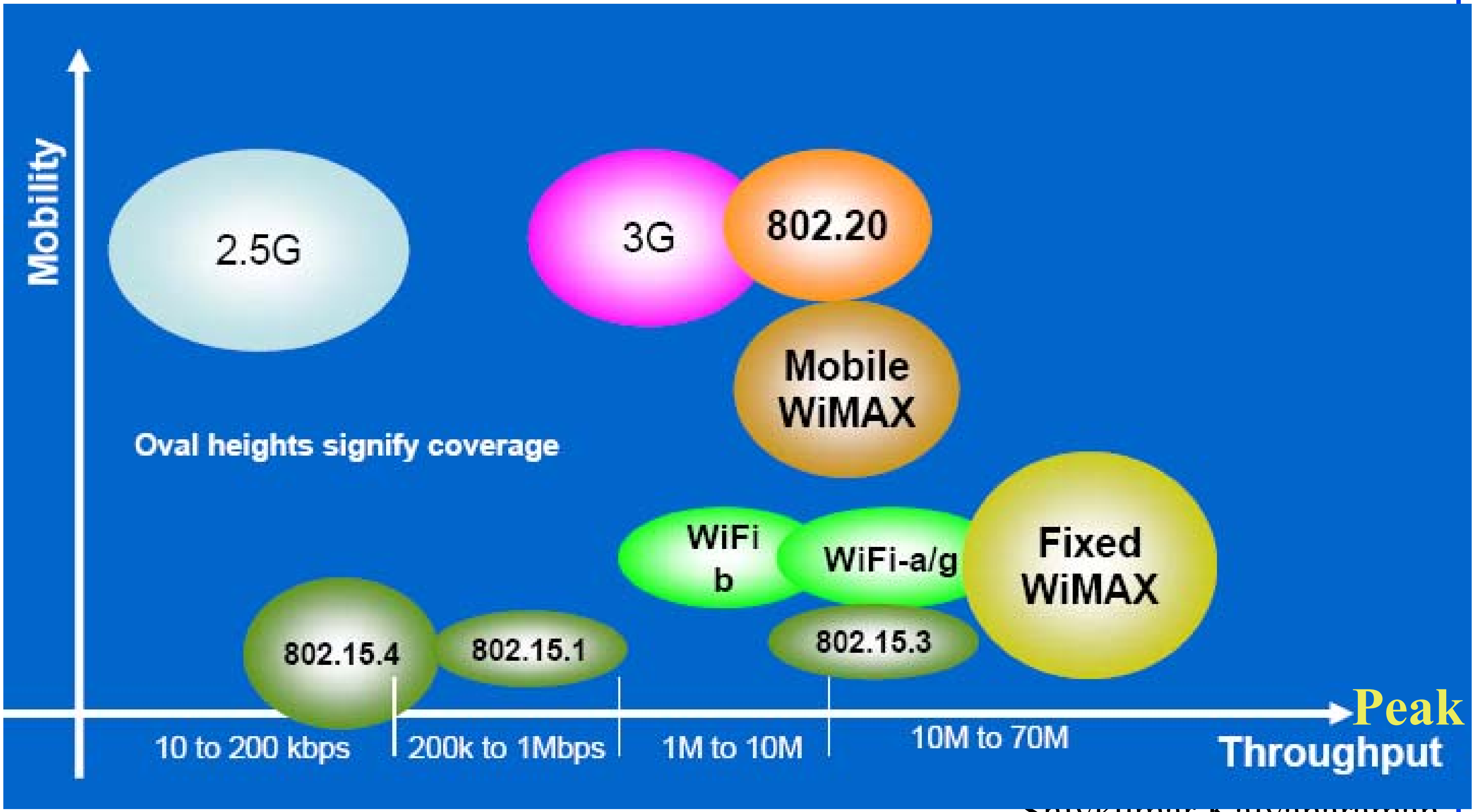
- Highest possible consumer satisfaction…
  - *consumers will blame the Service Provider*
  - *Want lots of sticky customers paying higher ARPU*
- QoS is primary requirement – video and high throughput (mobile) data sessions
- Management capability to the devices: easy service provisioning, billing.
- Secure mobility support: Handoff & Mesh
  - Avoid theft-of-service
- New services…

What do Home users want?

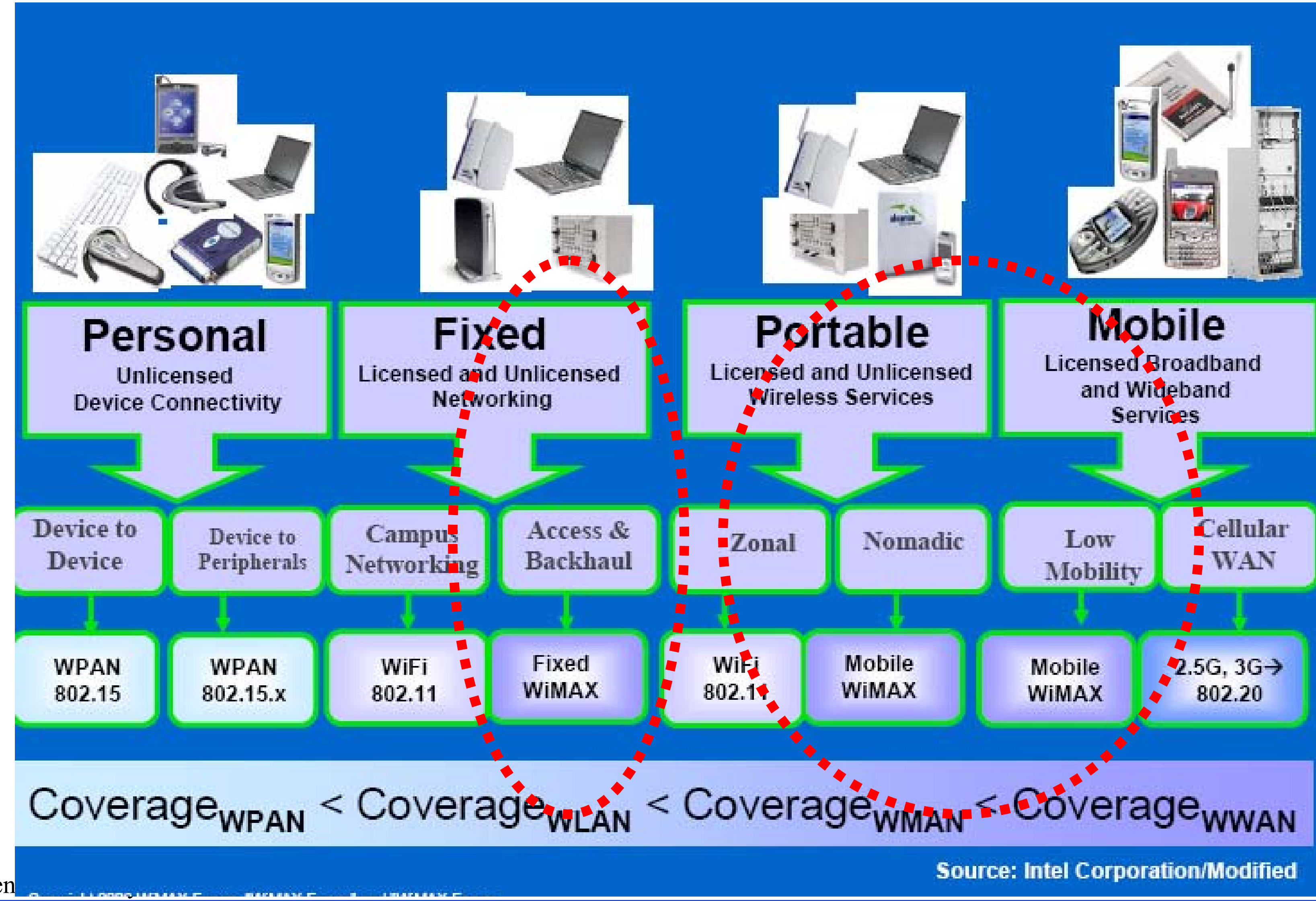
- Range: reliable wireless networking throughout the home
- High fidelity A/V: good Quality of Service for high quality audio and video

- Throughput!
  - HDTV-720 in the US @ 16 Mbps (MPEG2)
  - HDTV-1080 in Japan @ 20 Mbps (MPEG2)
  - Next generation Media Center will support 2 concurrent video streaming, and by .11n ratification 4 concurrent streaming
  - For 3 streams in the home, with picture-in-picture, and Internet access, 100Mbps UDP level throughput is easily consumed

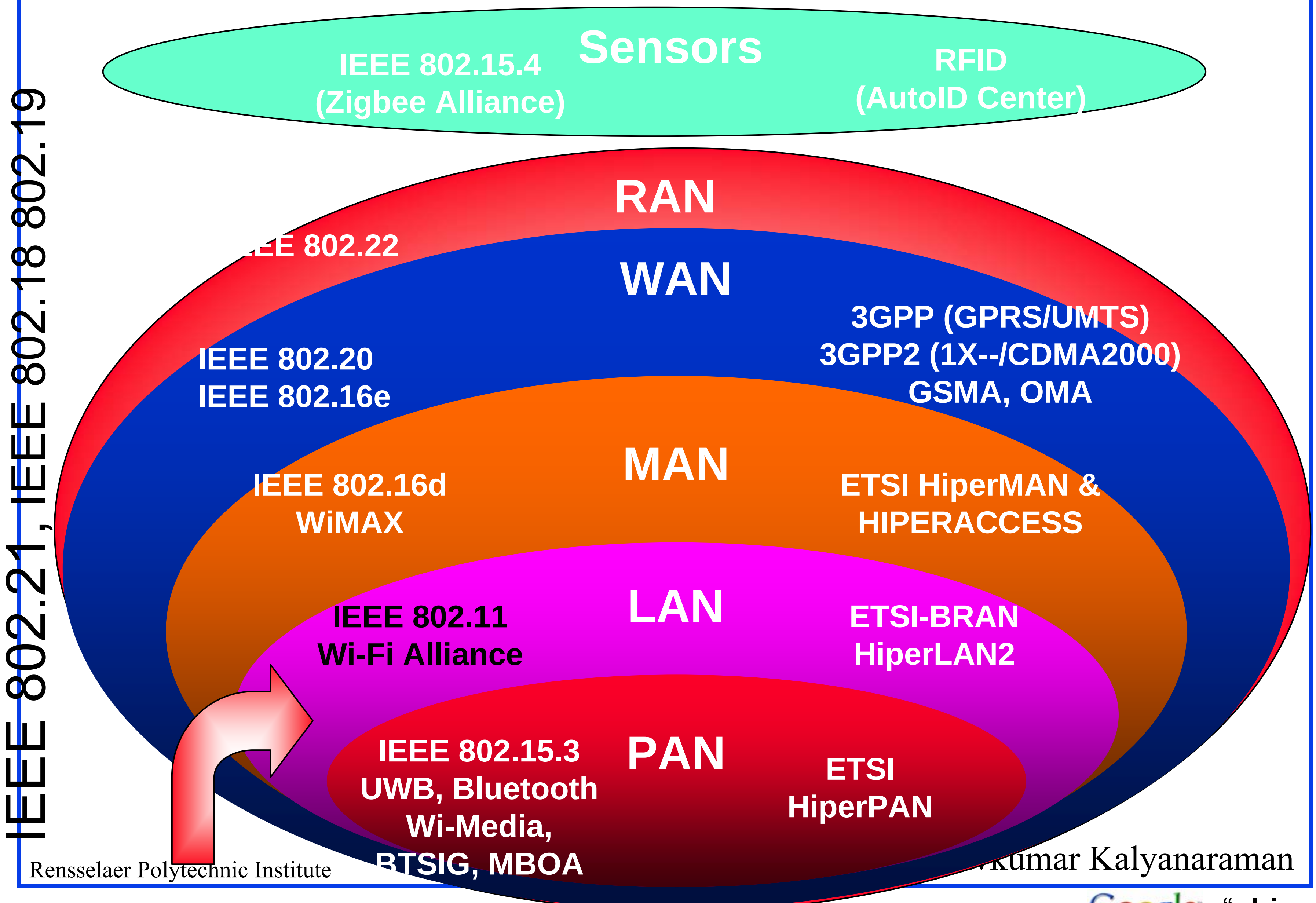
Modern Wireless Systems



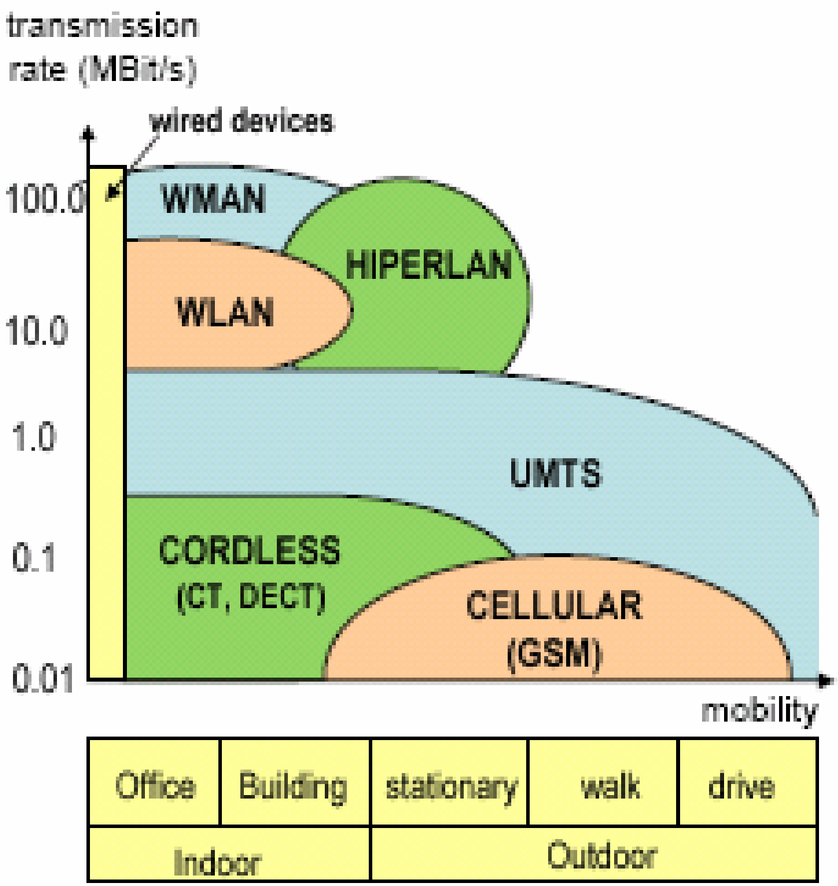
Modern Wireless Systems (by Segment)



IEEE Wireless Standards



Tradeoffs: Mobility/Coverage/BitRate



- CT - Cordless Telephony (analogous predecessor of DECT)
- DECT - Digital Enhanced Cordless Telecommuni-cations (Standard for wireless phones in a local range)
- **GSM** - *Global System for Mobile Communication (cellular phone system)*
- **UMTS** - *Universal Mobile Telecommunications System (universal system, comprising several different access systems)*
- **WLAN** - *Wireless Local Area Network (Standard for wireless networking of (portable) computer)*
- **HIPERLAN** – alternative LAN to WLAN, „wireless ATM enhancement"
- **WMAN** – Wireless MAN (Bridging the last mile between a fixed network and the end user, wireless alternative to DSL)
- And furthermore: **Satellite systems**, **Bluetooth/IrDA** in very short range

Wireless LANs: WiFi/802.11

- Based on the IEEE 802.11a/b/g/n family of standards, and is primarily a local area networking technology designed to provide *in-building* or *campus* broadband coverage.
  - IEEE 802.11a/g peak physical layer data rate of ***54 Mbps*** and indoor coverage over a distance of ***100 feet.***
  - Beyond buildings: *municipal WiFi, Neighborhood Area Networks (NaN), hotspots*
- Much higher peak data rates than 3G systems, primarily since it operates over a larger bandwidth (20 MHz).
  - Its MAC scheme CSMA (Carrier Sense Multiple Access) is **inefficient** for **large** numbers of users
  - The interference constraints of operating in the license-exempt band is likely to significantly reduce the actual capacity of *outdoor* Wi-Fi systems.
  - Wi-Fi systems are not designed to support high-speed mobility.
  - Wide availability of terminal devices
- **802.11n:** MIMO techniques for range extension and higher bit rates

Wireless LAN Standards

- 802.11b (Current Generation)
  - Standard for 2.4GHz ISM band (80 MHz)
  - Frequency hopped spread spectrum
  - 1.6-10 Mbps, 500 ft range
- 802.11a (Emerging Generation)
  - Standard for 5GHz NII band (300 MHz)
  - OFDM with time division
  - 20-70 Mbps, variable range
  - Similar to HiperLAN in Europe
- 802.11g (New Standard)
  - Standard in 2.4 GHz and 5 GHz bands
  - OFDM
  - Speeds up to 54 Mbps

In 2006, WLAN cards have all 3 standards

IEEE 802.11n

- Over-the-air (OTA): 200 Mbps; MAC layer (MC-SAP): 100Mbps
- Rich content distribution- 3 HDTV quality streams and simultaneous broadband access; VoIP over WLAN supporting many simultaneous clients
- Service providers: microcells, neighborhood area networks (NANs)
- PHY
  - MIMO/multiple antenna techniques
  - Advanced FEC, (forward error correctio
  - 10, 20 & 40Mhz channels widths
  - Higher order modulation/coding
- MAC
  - Flexible & efficient packet aggregation
  - Legacy and channel width coexistence
  - Power saving mechanisms
  - Novel data flow techniques

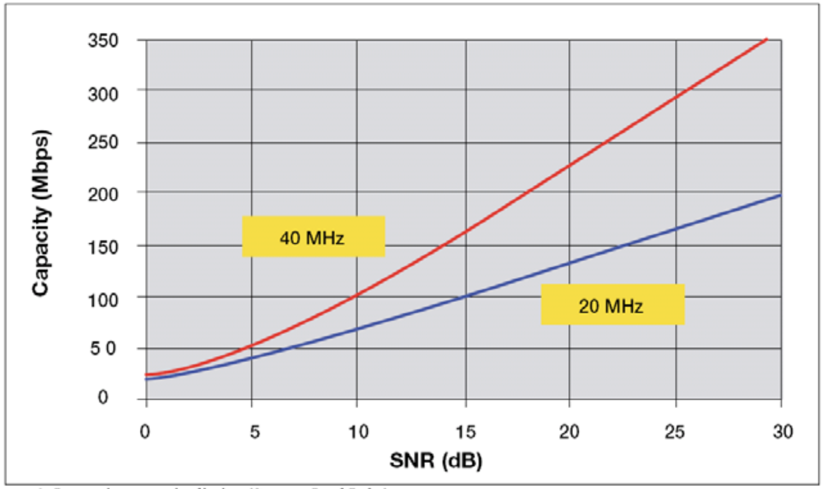


Figure 2. Increasing capacity limits. (Source: Intel Labs)

Wireless LAN Throughput by IEEE Standard

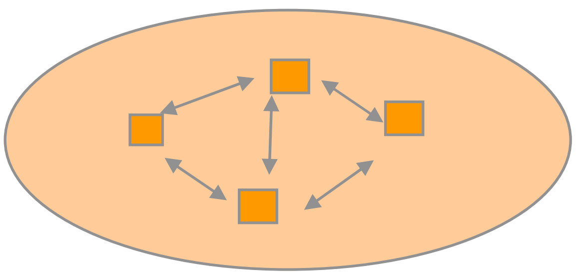
IEEE WLAN Standard	Over-the-Air (OTA) Estimates	*Media Access Control Layer, Service Access Point (MAC SAP) Estimates
802.11b	11 Mbps	5 Mbps
802.11g	54 Mbps	25 Mbps (when .11b is not present)
802.11a	54 Mbps	25 Mbps
802.11n	200+ Mbps	100 Mbps

Table 1. Comparison of different 802.11 transfer rates (Source: Intel Labs).

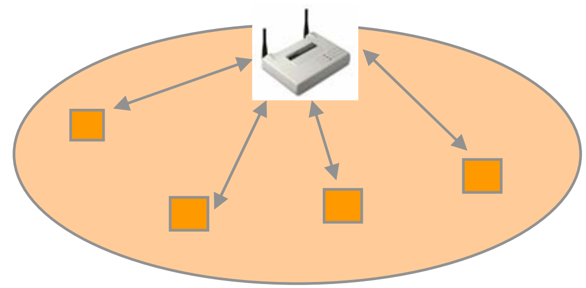
WLAN Network Architecture

Basic Service Set (BSS): a set of stations which communicate with one another

Ad hoc network



Infrastructure Mode



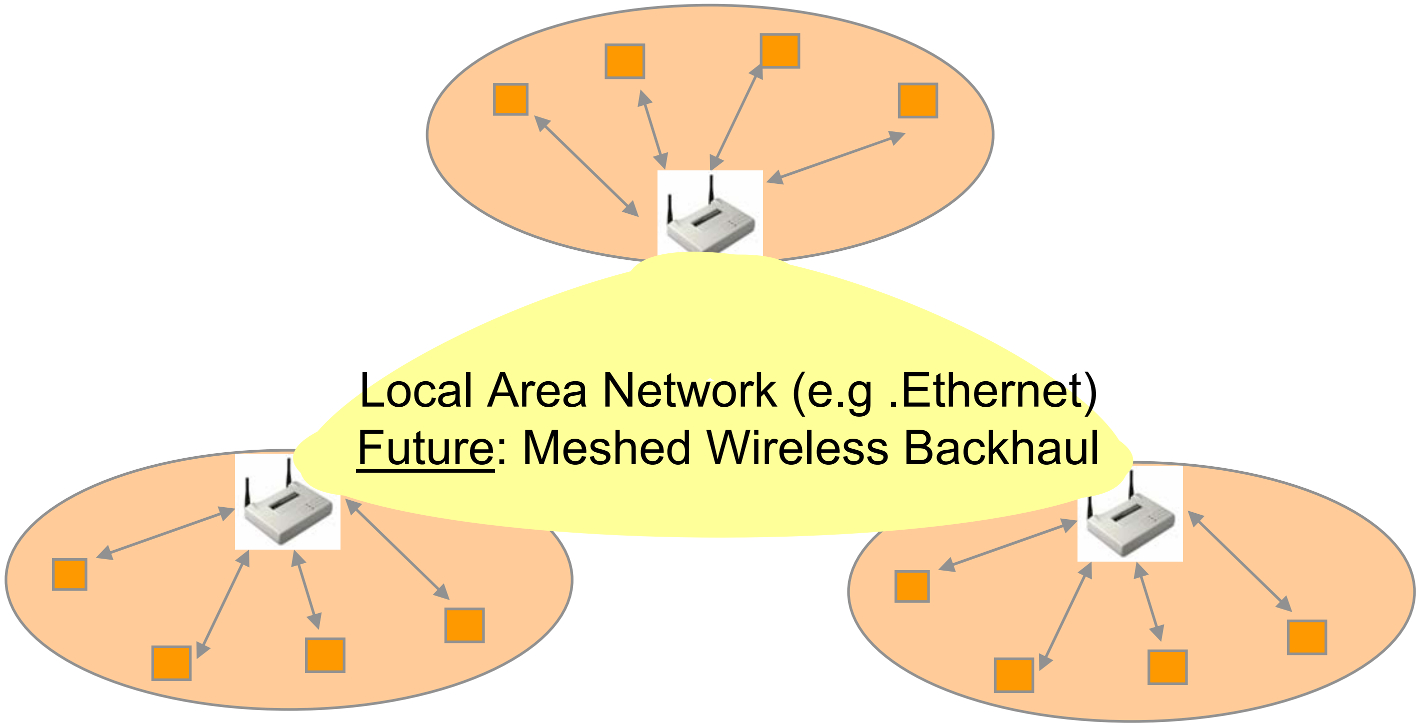
- Only direct communication possible
- No relay function

- Stations communicate with AP
- AP provides connection to wired network (e.g. Ethernet)
- Stations not allowed to communicate directly
- Some similarities with cellular (covered later)

Source: AirTight Networks

WLAN Network Architecture (2)

ESS: a set of BSSs interconnected by a distribution system (DS)

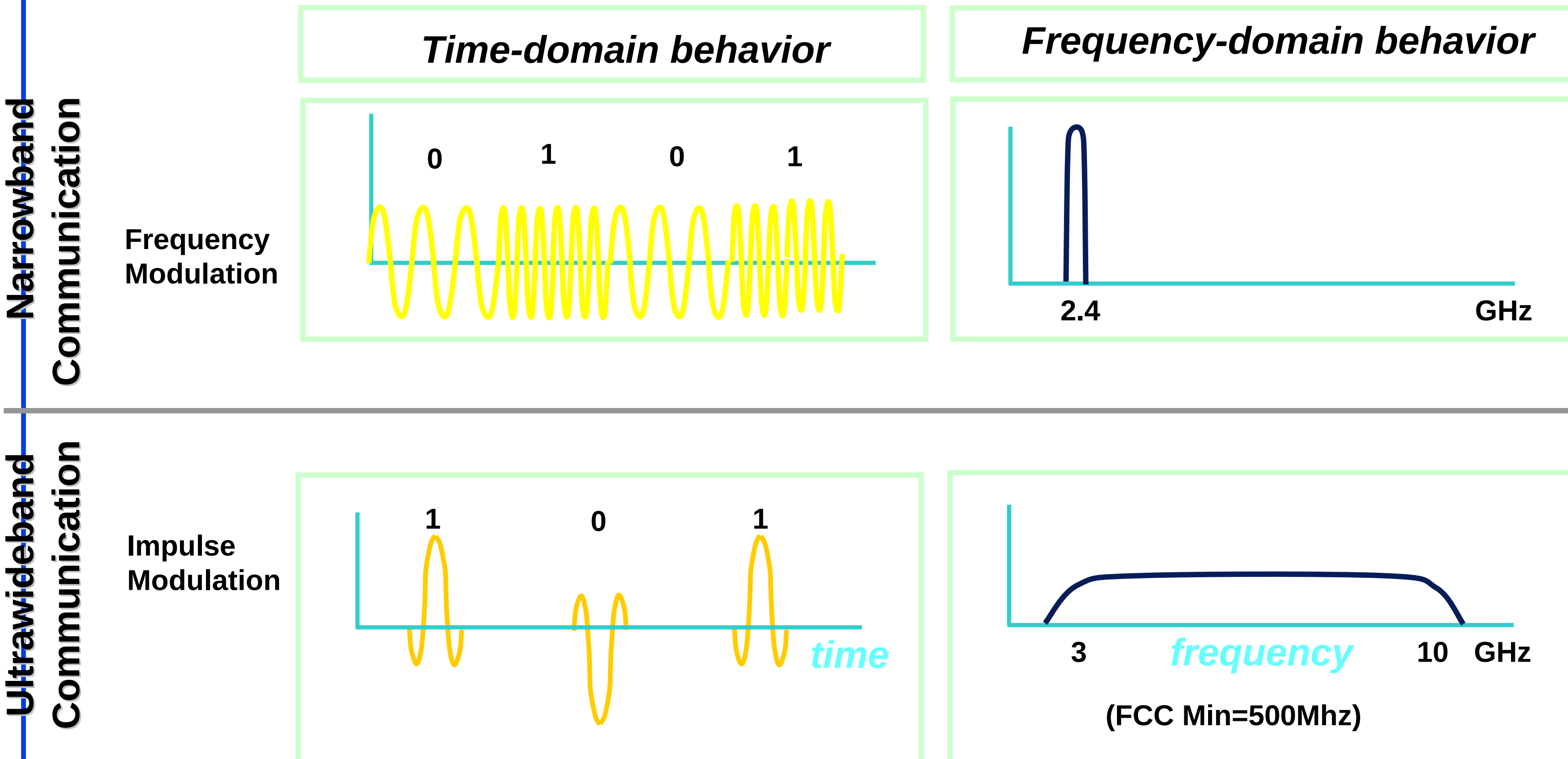


Source: AirTight Networks

Bluetooth: WPAN

- Cable replacement RF technology (low cost)
- Short range {10m (1mW), 100m (100 mW)}
  - Lower power than WiFi
- 2.4 GHz band (crowded)
- 1 Data (723.2 Kbps, reverse channel 57.6kbps: ACL)
- Or 3 synchronous voice channels (64kbps, SCO)
- Frequency-hopping for multiple access with a carrier spacing of 1 MHz for 8 devices per pico-net.
  - 80 carriers => 80MHz.
  - Collisions when multiple piconets nearby.
- Widely supported by telecommunications, PC, and consumer electronics companies.
  - Hands free phone (ear set) for cars, internet chat/VoIP
  - Intra-car networking announced by some car manufacturers in Europe.

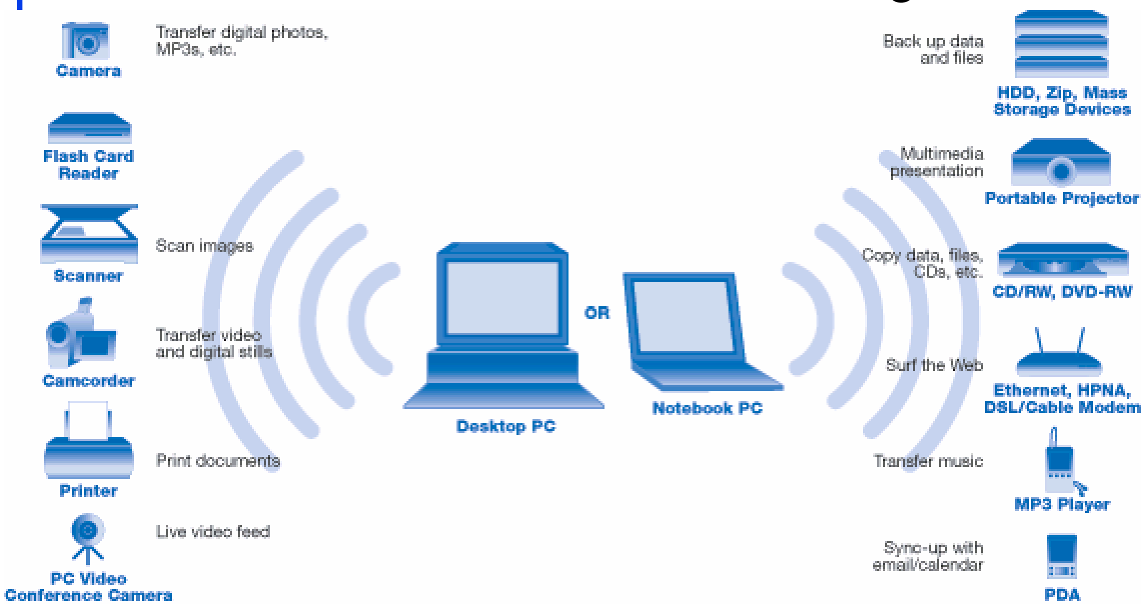
What is UltraWideBand?



Communication occupies more than 500 MHz of spectrum: baseband or 3.6-10.1 GHz range. (7 GHz!). Strict power limits.

Ultrawideband Radio (UWB)

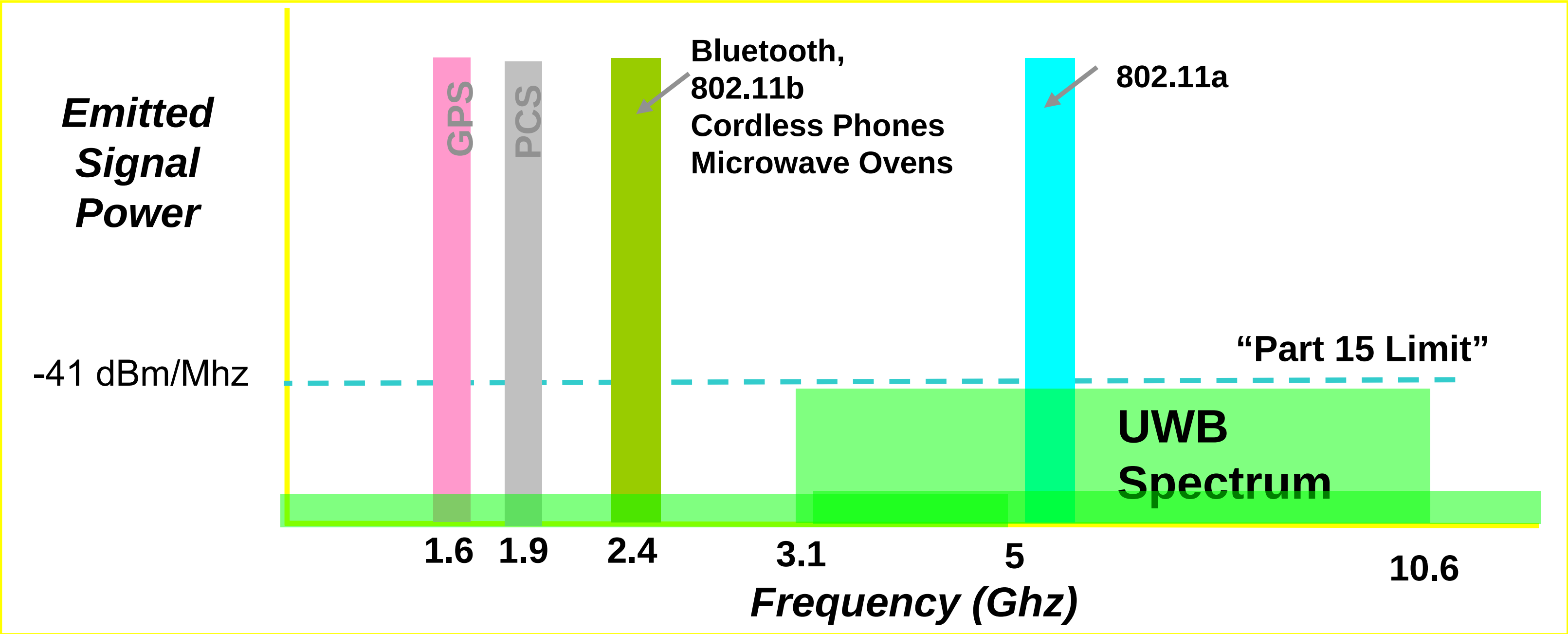
- UWB is an impulse radio: sends pulses of tens of picoseconds(10^{-12}) to nanoseconds (10^{-9})
- Duty cycle of only a fraction of a percent; carrier is not necessarily needed
- Uses a lot of bandwidth (GHz); Low probability of detection
- Excellent ranging capability; Synchronization (accurate/rapid) an issue.
- Multipath highly resolvable: good and bad
  - Can use OFDM or Rake receiver to get around multipath problem.



Standards: WiMedia, IEEE 802.15.3a

Apps: Wireless USB, 480 Mbps, 10m, Wireless 1394 (firewire)

UWB Spectrum



- FCC ruling issued 2/14/2002 after ~4 years of study & public debate
- FCC believes current ruling is conservative
- Worldwide regulations differ – Japan, EU, Asia…

Why is UWB Interesting?

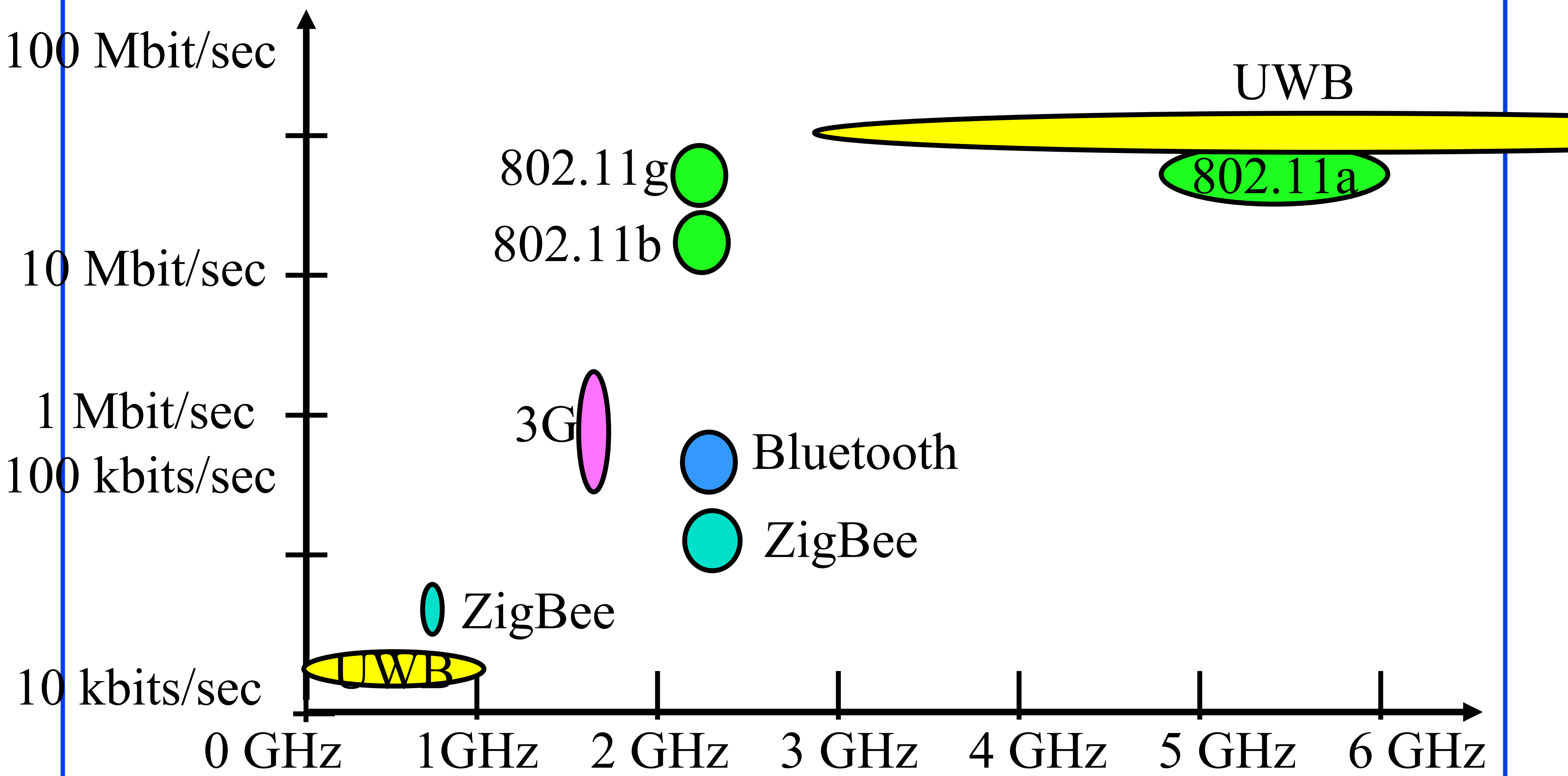
- Unique Location and Positioning properties
  - 1 cm accuracy possible
- Low Power CMOS transmitters
  - 100 times lower than Bluetooth for same range/data rate
- Very high data rates possible
  - 500 Mbps at ~10 feet under current regulations
- 7.5 Ghz of "free spectrum" in the U.S.
  - FCC recently legalized UWB for commercial use
  - Spectrum allocation overlays existing users, but its allowed power level is very low to minimize interference
- "Moore's Law Radio"
  - Data rate scales with the shorter pulse widths made possible with ever faster CMOS circuits

IEEE 802.15.4 / ZigBee Radios

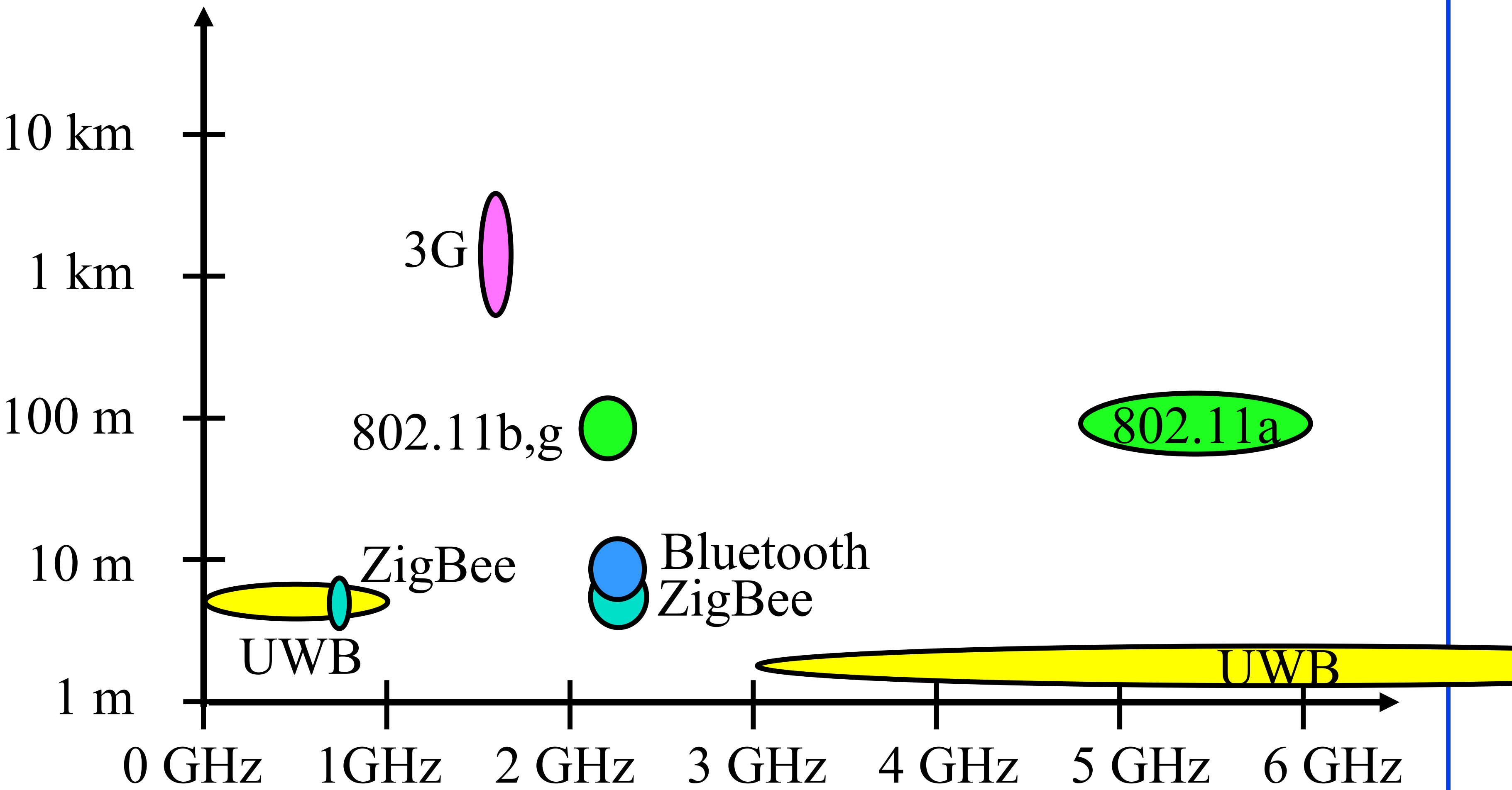
- Low-Rate WPAN, Very low power consumption (no recharge for *months* or years!), up to 255 devices
- Data rates of 20, 40, 250 kbps
- Star clusters or peer-to-peer operation
- Support for low latency devices
- CSMA-CA channel access
- Frequency of operation in ISM bands
- Home automation, consumer electronics applications, RFID/tagging applications (supply-chain)

Feature(s)	IEEE 802.11b	Bluetooth	ZigBee
Power Profile	Hours	Days	Years
Complexity	Very Complex	Complex	Simple
Nodes/Master	32	7	64000
Latency	Enumeration upto 3 seconds	Enumeration upto 10 seconds	Enumeration 30ms
Range	100 m	10m	70m-300m
Extendability	Roaming possible	No	YES
Data Rate	11Mbps	1Mbps	250Kbps
Security	Authentication Service Set ID (SSID)	64 bit, 128 bit	128 bit AES and Application Layer user defined

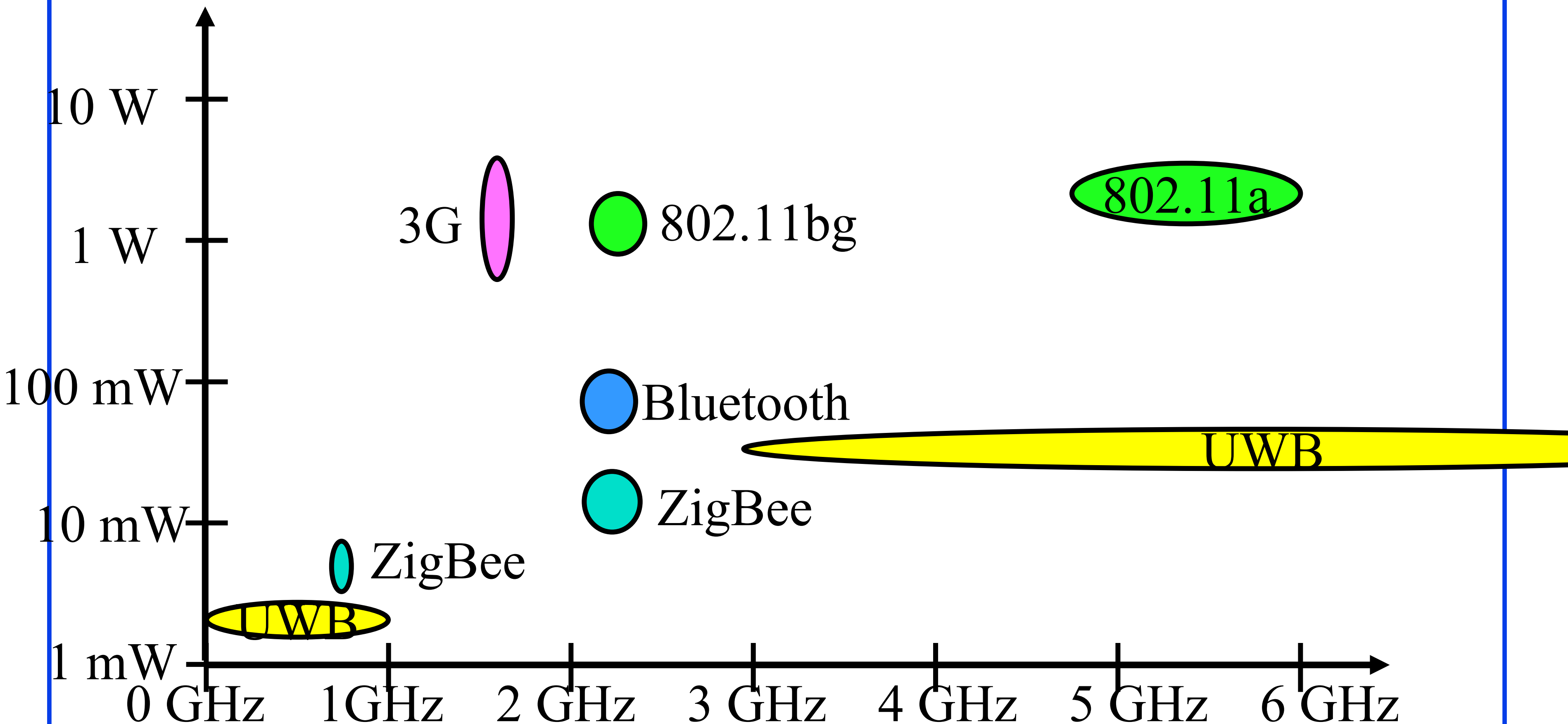
Data rate


100 Mbit/sec
10 Mbit/sec
1 Mbit/sec
100 kbits/sec
10 kbits/sec
UWB
802.11g
802.11b
802.11a
3G
Bluetooth
ZigBee
ZigBee
UWB
0 GHz
1GHz
2 GHz
3 GHz
4 GHz
5 GHz
6 GHz

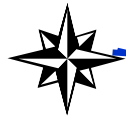
Range

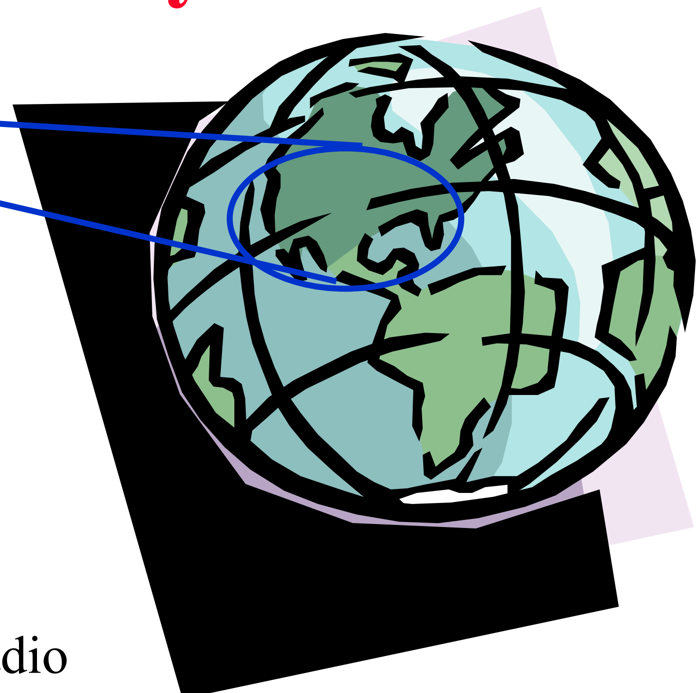

10 km
1 km
100 m
10 m
1 m
3G
802.11b,g
802.11a
Bluetooth
ZigBee
ZigBee
UWB
UWB
0 GHz
1GHz
2 GHz
3 GHz
4 GHz
5 GHz
6 GHz

Power Dissipation



Wide Area: Satellite Systems



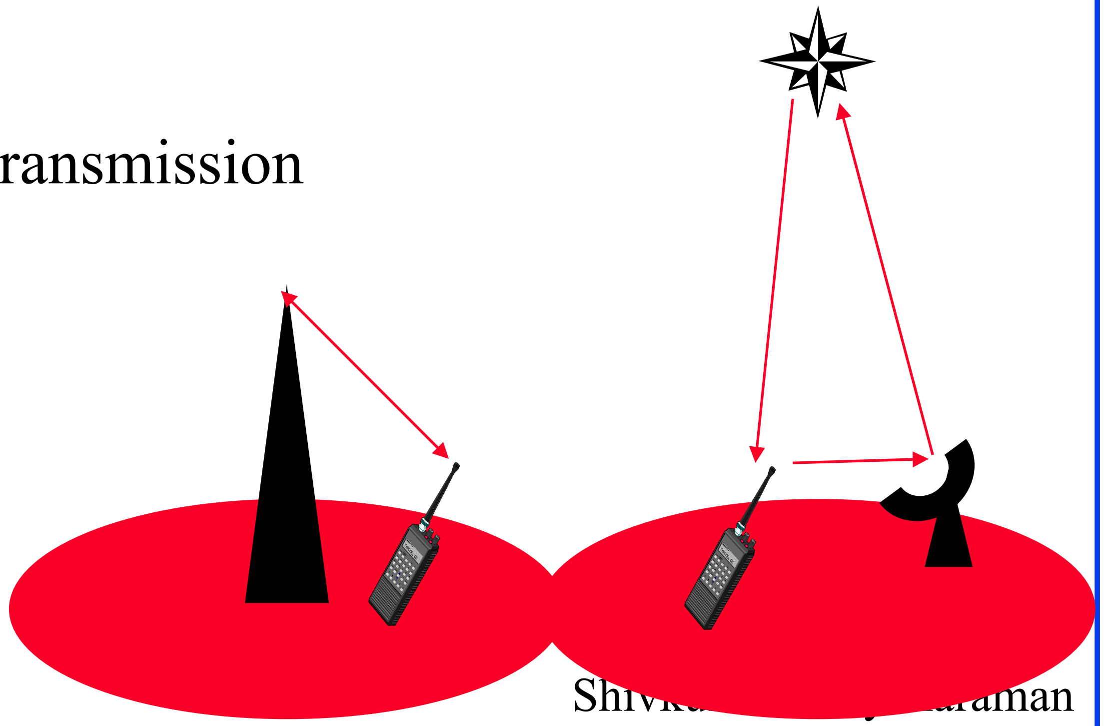


- Cover very large areas
- Different orbit heights
  - GEOs (39000 Km), LEOs (2000 Km), MEOs (9000km)
- Dish antennas, or bulky handsets
- Optimized for one-way transmission,

location positioning, GPS systems, Satellite Radio
  - Radio (XM, DAB) and movie (SatTV) broadcasting
  - Killed MMDS wireless TV offerings.
  - Future: satTV (eg: directTV) in your car
- Most two-way systems struggling or bankrupt
  - Expensive alternative to terrestrial cellular system (2G)
- Trucking fleets, journalists in wild areas, Oil rigs

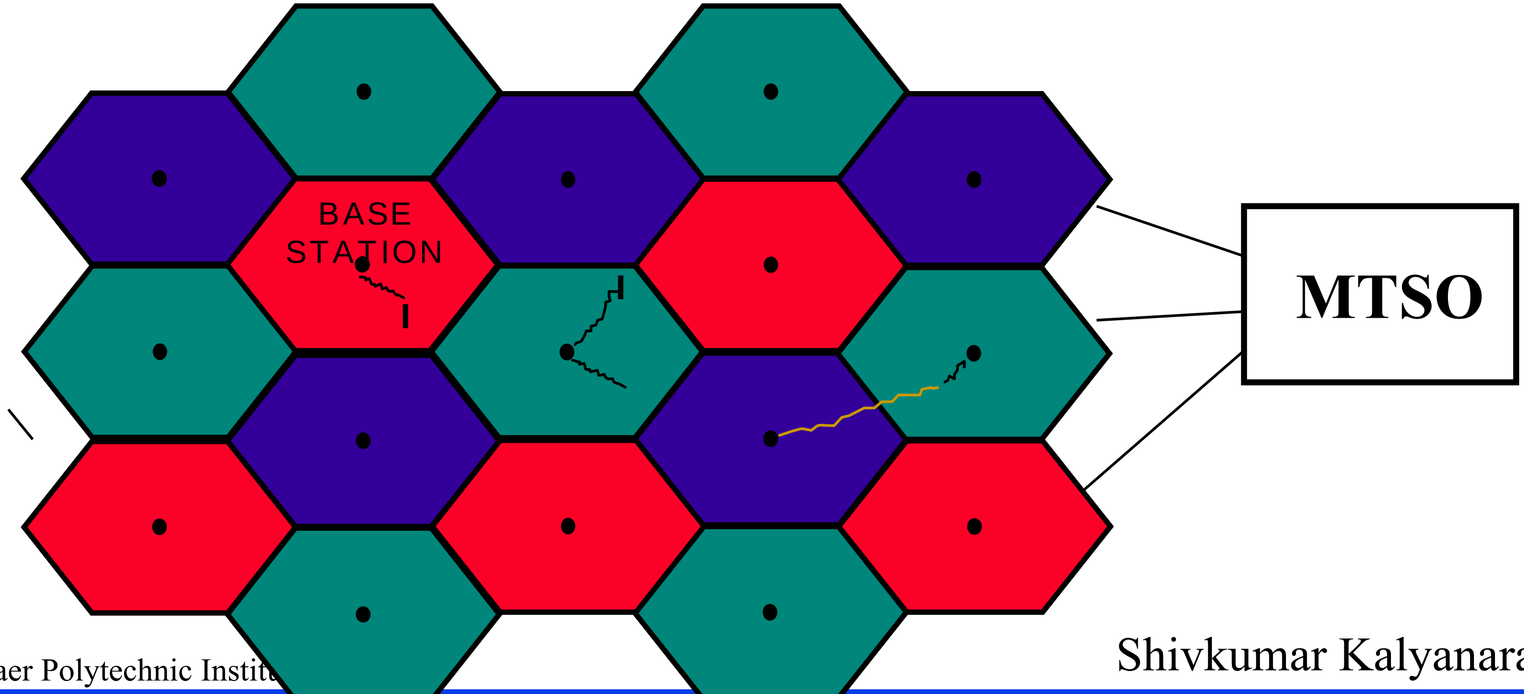
Paging Systems: Coverage, 1-way

- Broad coverage for short messaging
- Message broadcast from all base stations
- High Tx power (hundreds of watts to kilowatts), low power pagers
- Simple terminals
- Optimized for 1-way transmission
- Answer-back hard
- Overtaken by cellular

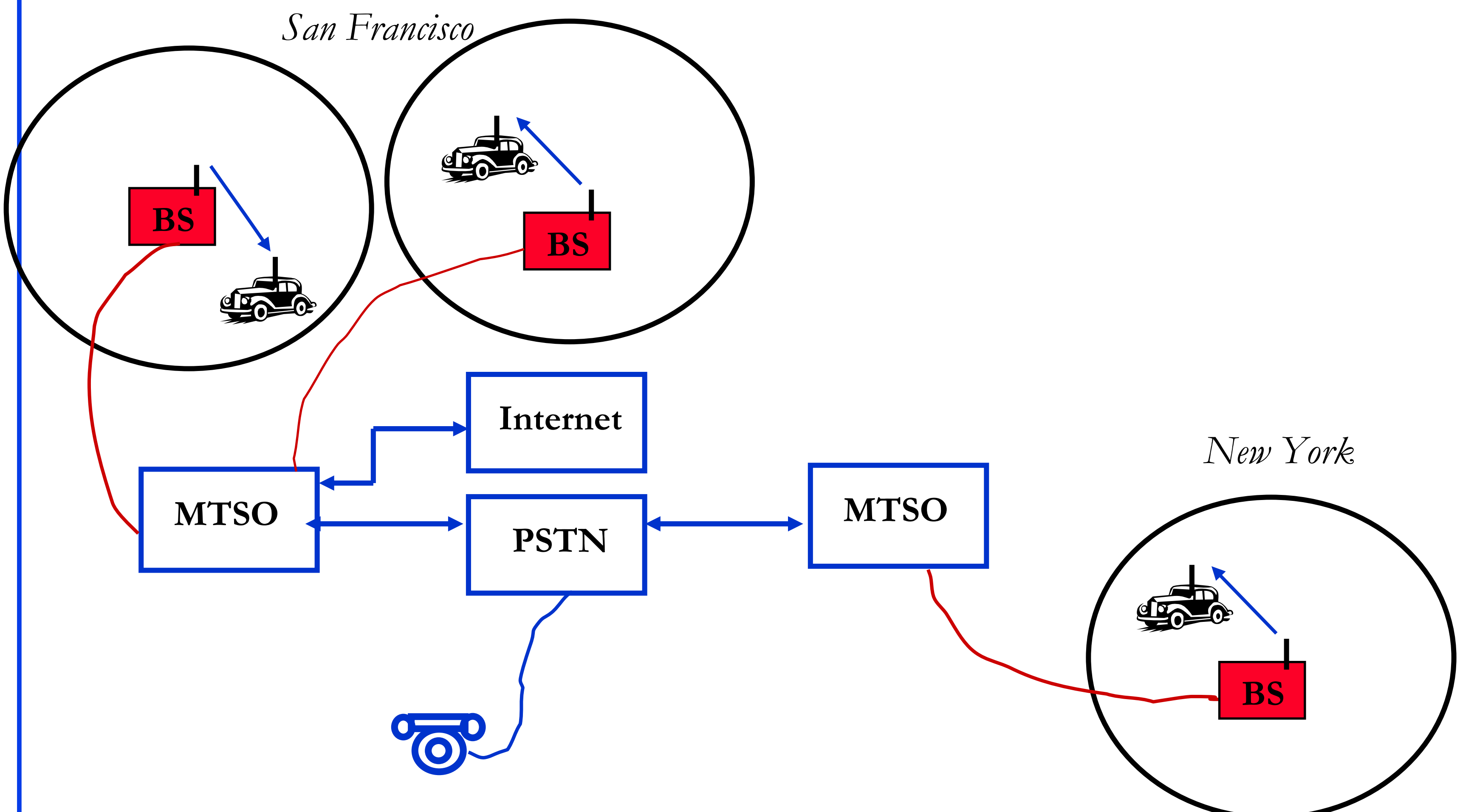


Cellular Systems:
(coverage, 2-way, reuse channels for capacity)

- Geographic region divided into cells
- Frequencies/timeslots/codes reused at spatially-separated locations.
- Co-channel interference between same color cells.
- Base stations/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well as networking burden

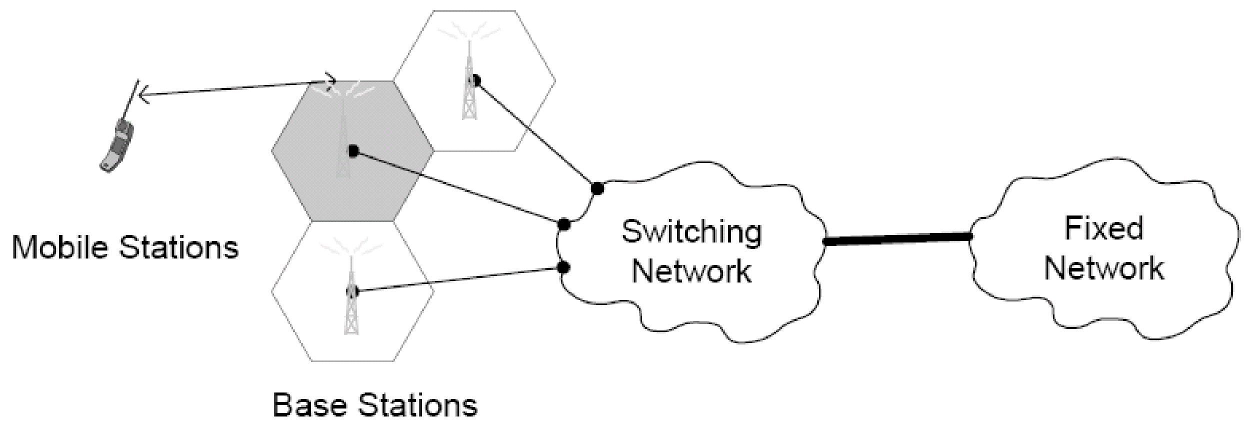


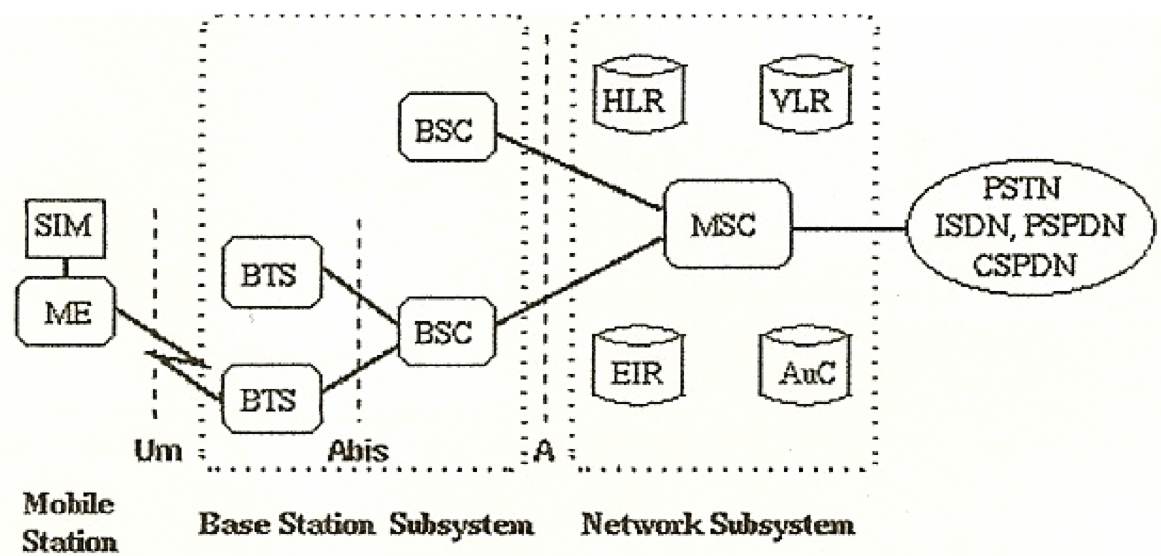
Cellular Phone Networks



Inside the BS & MTSO:

GSM System Buzzwords Bonanza!



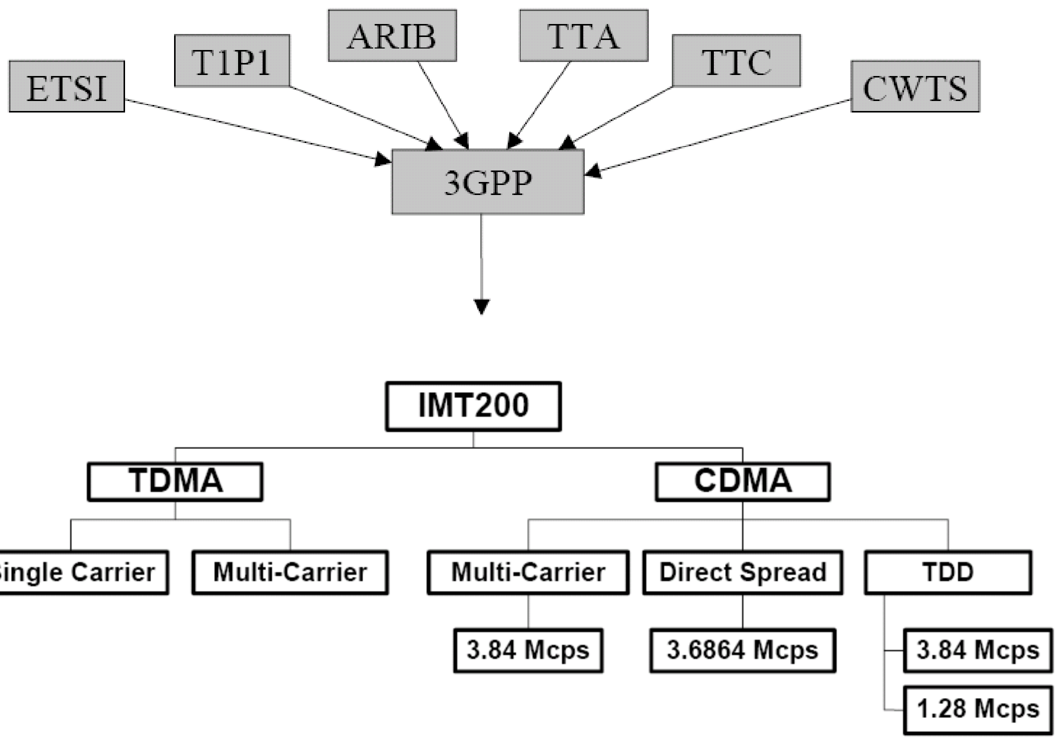


SIM Subscriber Identity Module
ME Mobile Equipment
BTS Base Transceiver Station
BSC Base Station Controller
HLR Home Location Register
VLR Visitor Location Register
MSC Mobile services Switching Center
EIR Equipment Identity Register
AuC Authentication Center

3GPP, UMTS, IMT-2000

3GPP is a "umbrella" aiming to form compromised standards by taking into account, political, industrial, and commercial pressures from local specification bodies:

ETSI	European Telecommunication Standard Institute /Europe
ARIB	Association of Radio Industries and Business /Japan
CWTS	China Wireless Telecommunication Standard group /China
T1	Standardisation Committee T1 Telecommunications /US
TTA	Telecommunication Technology Association /Korea
TTC	Telecommunication Technology Committee /Japan



1G, 2G and 3G

1G Systems: NMT, AMPS, TACS.

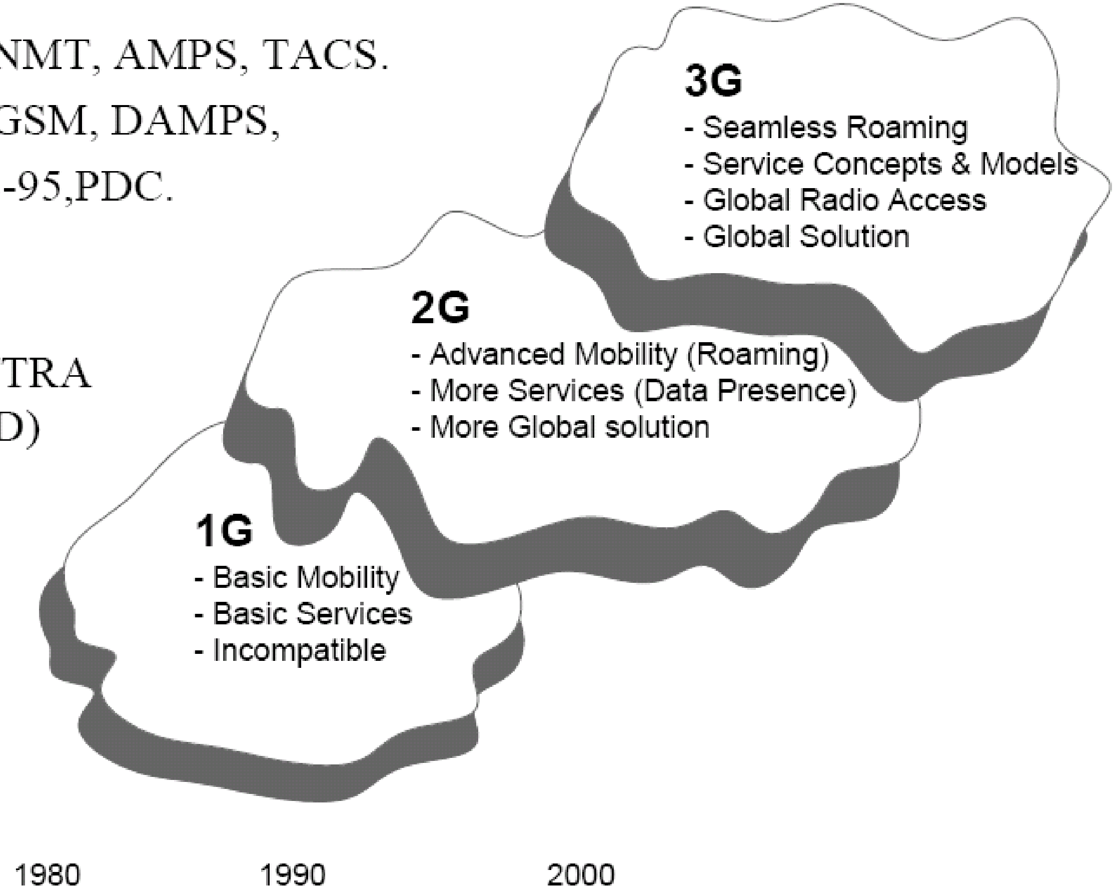
2G Systems: GSM, DAMPS,
IS-136, IS-95,PDC.

3G Systems:

WCDMA
(UMTS,UTRA
FDD+TDD)

cdma2000

EDGE

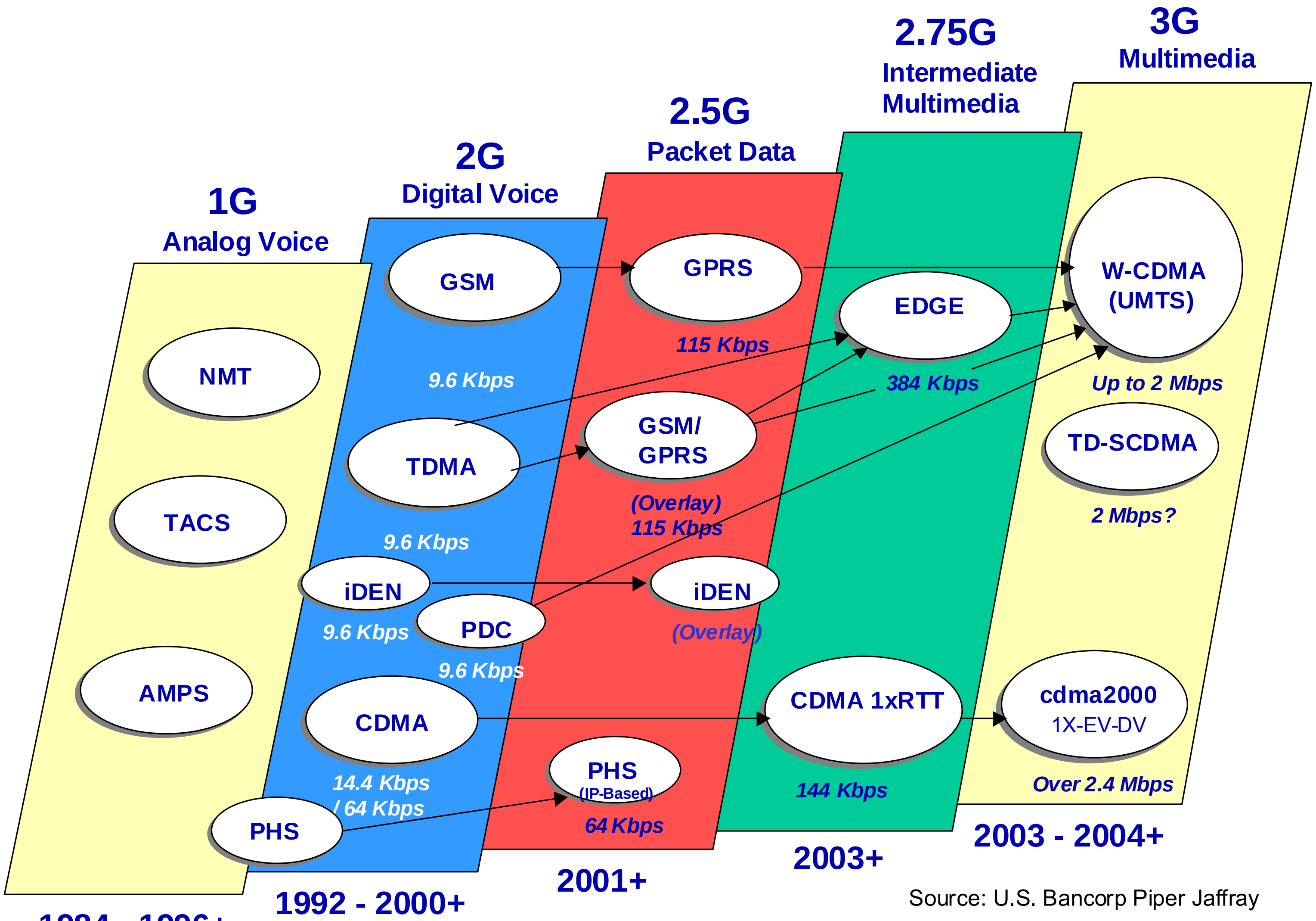


2G (GSM) vs 3G (WCDMA)

	WCDMA	GSM
Carrier spacing	5 MHz	200 kHz
Frequency reuse factor	1	1-18
Power control frequency	1500 Hz	2 Hz or lower
Quality control	Radio resource management algorithms	Network planning (Frequency planning)
Frequency diversity	5 MHz bandwidth gives multipath diversity with RAKE receiver	Frequency hopping
Packet data	Load based packet scheduling	Time slot based scheduling with GPRS
Dowlink transmit diversity.	Supported for improving downlink capacity.	Not supported by the standard but can be applied.

- 3G speeds: 384 Kbps (pedestrian); 144 Kbps (vehicular); 2 Mbps (indoor office).
- 3G appeared earlier in Japan: spectrum allocated by "beauty contests", not expensive auctions.

2.5G, 2.75G …
(yes, 3.5G, 3.75G too!)



Source: U.S. Bancorp Piper Jaffray

Sampling of Technical Differences (2G vs 2.5G)

- **2G**: 900 MHz cellular frequency band standards:
  - **IS-54**, which uses a combination of TDMA and FDMA and phase-shift keyed modulation,
  - **IS-95**, which uses direct-sequence CDMA with binary modulation and coding.
  - **IS-136** (which is basically the same as IS-54 at a higher frequency (2GHz)),
  - European **GSM** standard (also for 2Ghz digital cellular).
  - Proliferation of standards => roaming very tough/impossible!
- **2.5G: GPRS, EDGE, HDR (CDMA 2000 1x EV-DO)**
  - GSM systems provide data rates of up to 100 Kbps by aggregating all timeslots together for a single user: enhancement is called GPRS.
  - A more fundamental enhancement, Enhanced Data Services for GSM Evolution (EDGE), further increases data rates using a high-level modulation format combined with FEC coding.
    - This modulation is more sensitive to fading effects
    - EDGE uses SNR feedback-based adaptive modulation/coding techniques to mitigate.
  - The IS-54 and IS-136 systems currently provide data rates of 40-60 Kbps by aggregating time slots and using high-level modulation.
    - This evolution of the IS-136 standard is called IS-136HS (high-speed).
    - IS-95 systems: higher data w/ a time-division technique called high data rate (HDR)

Cellular Wireless Data Networks (3G)

- 2G Wireless:
  - GSM or CDMA based mobile phone service. 2 Billion users!
- 3G evolution: (from voice to voice+data)
  - GSM operators → **UMTS** (Universal Mobile Telephone System) and **HSDPA** (High Speed Downlink Packet Access)
  - CDMA operators → **1x EV-DO**
  - China etc: ***TD-SCDMA*** (Time Division - Synchronous CDMA)

HSDPA/HSUPA

- **HSDPA**: ***downlink-only*** air interface defined in 3GPP UMTS Release 5 specifications.
  - Peak user data rate (Layer 2 throughput) of 14.4 Mbps using a 5 MHz channel.
  - Realizing this data rate, however, requires the use of all 15 codes, which is unlikely to be implemented in mobile terminals.
  - Using 5 and 10 codes, HSDPA supports peak data rates of 3.6 Mbps and 7.2 Mbps respectively.
  - Typical average rates that users obtain are in the range of 250-750 kbps.
  - Enhancements such as spatial processing, diversity reception in mobiles, and multi-user detection can provide significantly higher performance over basic HSDPA systems that are currently being deployed.

- Until an ***uplink complement*** of HSDPA is implemented, the peak data rates achievable on the uplink will be less than 384 kbps, in most cases averaging 40-100 kbps.
  - **HSUPA** (uplink version) that supports peak data rates up to 5.8 Mbps is standardized as part of the 3GPP Release 6 specifications, and deployments are expected in 2007.

- HSDPA and HSUPA together is referred to as HSPA.

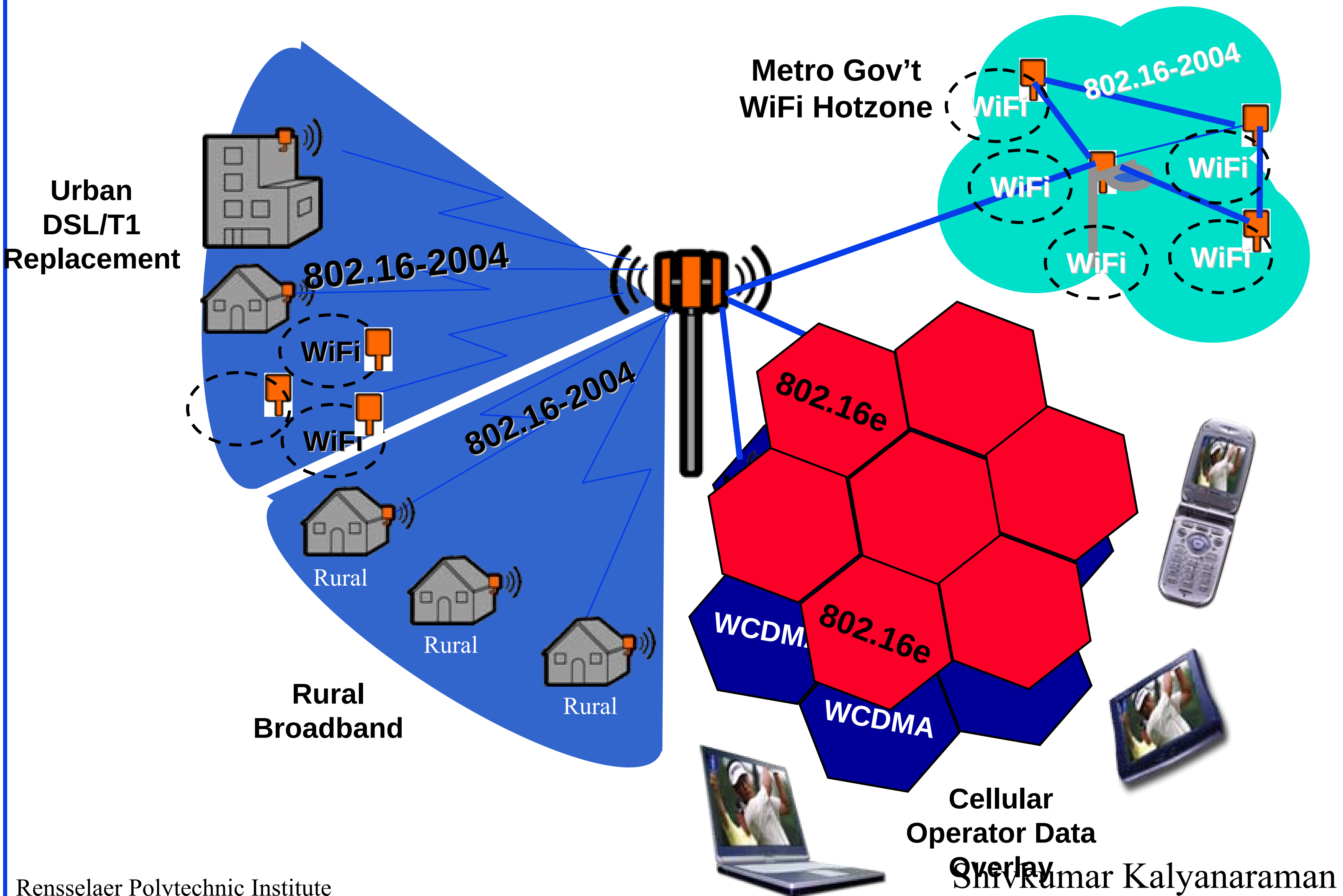
CDMA Broadband: 1xEVDO

- 1x EV-DO is a high-speed data standard defined as an evolution to second generation IS-95 CDMA systems by 3GPP2
- Bit Rates:
  - Peak downlink data rate of 2.4 Mbps in a 1.25 MHz channel.
  - Typical user experienced data rates are in the order of a 100-300 kbps.
  - **Revision A** of 1x EV-DO supports a ***peak*** rate of 3.1 Mbps to a mobile user, and Revision B will support 4.9 Mbps.
  - These versions can also support uplink data rates of up to 1.8 Mbps.
  - Revision B also has options to operate using higher channel bandwidths (upto 20 MHz) offering potentially up to 73 Mbps in the downlink and up to 27 Mbps in the uplink.
- Multimedia services: 1x EV-DO Rev A standard enables voice and video telephony over IP.
  - 1xEV-DO Rev A reduces air-link latency to almost 30 ms, introduces intra-user QoS and fast inter-sector handoffs.
  - Multicast and broadcast services are also supported in 1x EV-DO.
  - Similarly, development efforts are underway to support IP voice, video and gaming, as well as multicast and broadcast services over UMTS/HSPA networks.

3G LTE: Long-Term Evolution

- Goals: Peak data rate of 100 Mbps in the downlink and 50 Mbps in the uplink, with an average spectral efficiency that is 3-4 times that of Release 6 HSPA.
  - Based upon OFDM, OFDMA, MIMO (like Wimax)
- 3GPP2 has longer term plans to offer higher data rates by moving to higher bandwidth operation.
  - The objective is to support up to 70-200 Mbps in the downlink and up to 30-45 Mbps in the uplink in EV-DO Revision C using up to 20 MHz of bandwidth.
- Neither LTE nor EV-DO Rev C systems are expected to be available until about 2010.

WiMAX: markets



WiMAX Fixed and Mobile

- WiMAX Fixed / Nomadic
  - 802.16d or 802.16-2004
  - Usage: Backhaul, Wireless DSL
  - Devices: outdoor and indoor installed CPE
  - Frequencies: 2.5GHz, 3.5GHz and 5.8GHz (Licensed and LE)
  - Description: wireless connections to homes, businesses, and other WiMAX or cellular network towers
- WiMAX Mobile
  - 802.16e
  - Usage: Long-distance mobile wireless broadband
  - Devices: PC Cards, Notebooks and future handsets
  - Frequencies: 2.5GHz
  - Description: Wireless connections to laptops, PDAs and handsets when outside of Wi-Fi hotspot coverage

IEEE 802.16 standards

	802.16	802.16-2004	802.16e-2005
Status	Completed December 2001	Completed June 2004	Completed December 2005
Frequency Band	10-66 GHz	2-11 GHz	2-11 GHz for fixed; 2-6 GHz for mobile applications
Application	Fixed Line-of-Sight (LOS)	Fixed Non-Line-of-sight	Fixed and Mobile Non-LOS
MAC Architecture	Point to Multi-Point, Mesh	Point to Multi-Point, Mesh	Point to Multi-Point, Mesh
Transmission Scheme	Single carrier only	Single carrier, 256 OFDM or 2048 OFDM	Single carrier, 256 OFDM or scalable OFDM with 128, 512, 1024 or 2048 subcarriers
Modulation	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64 QAM	QPSK, 16QAM, 64QAM
Gross Data Rate	32 - 134.4 Mbps	1 - 75 Mbps	1 - 75 Mbps
Multiplexing	Burst TDM/TDMA	Burst TDM/TDMA/ OFDMA	Burst TDM/TDMA/OFDMA
Duplexing	TDD and FDD	TDD and FDD	TDD and FDD
Channel Band-widths	20, 25, 28 MHz	1.75, 3.5, 7, 14, 1.25, 5, 10,15, 8.75 MHz	1.75, 3.5, 7, 14, 1.25, 5, 10,15, 8.75 MHz

IEEE 802.16 vs WIMAX

- IEEE 802.16 specification allows many frequencies and channel bandwidths
  - Anywhere from 2 – 66 GHz
  - Licensed or unlicensed bands
  - 3 – 20 Mhz channel bandwidth
- Specification allows 4 PHYs
  - SC, SCa, OFDM, OFDMA
- Interoperability requires options match between equipment

- **WiMax** is an industry group that defined *compatibility profiles*
  - Only OFDM PHY
  - 3.5 Ghz Licensed in Europe
  - 2.3 GHz Licensed MMDS band in USA
  - 2.4 GHz Unlicensed, Worldwide
  - 5.8 Upper Unlicensed Upper UNII band in USA and Europe

Wimax Certification Profiles

Table 2.2. Fixed and Mobile WiMAX Initial Certification Profiles

Band Index	Frequency Band	Channel Bandwidth	OFDM FFT Size	Duplexing	Notes
Fixed WiMAX Profiles					
1	3.5 GHz	3.5 MHz	256	FDD	Products already certified
		3.5 MHz	256	TDD	
		7 MHz	256	FDD	
		7 MHz	256	TDD	
2	5.8 GHz	10 MHz	256	TDD	
Mobile WiMAX Profiles					
1	2.3 - 2.4 GHz	5 MHz	512	TDD	Both bandwidths must be supported by the MS
		10 MHz	1024	TDD	
		8.75 MHz	1024	TDD	
2	2.305 - 2.320, 2.345 - 2.360 GHz	3.5 MHz	512	TDD	
		5 MHz	512	TDD	
		10 MHz	1024	TDD	
3	2.496 - 2.69 GHz	5 MHz	512	TDD	Both bandwidths must be supported by the MS
		10 MHz	1024	TDD	
4	3.3 - 3.4 GHz	5 MHz	512	TDD	
		7 MHz	1024	TDD	
		10 MHz	1024	TDD	
5	3.4 - 3.8 GHz, 3.4 - 3.6 GHz, 3.6 - 3.8 GHz	5 MHz	512	TDD	
		7 MHz	1024	TDD	
		10 MHz	1024	TDD	

WIMAX vs 3G etc

- **Flexibility**: Unlike 3G systems, which have a fixed channel bandwidth, WiMAX defines a selectable channel bandwidth *from 1.25 to 20 MHz*, which allows for a very flexible deployment ("*scalable*" OFDMA)
- **Peak Data Rates**: With 10 MHz TDD channel, assuming a 3:1 downlink to uplink split and 2 X 2 MIMO/OFDM, WiMAX offers 46 Mbps peak downlink throughput and 7 Mbps uplink.
- **System Capacity**: WiMAX can achieve *spectral efficiencies* higher than what is typically achieved in 3G systems. (MIMO etc incorporated from the start, and TDD allows reciprocity-based feedback)
  - OFDM physical layer used by WiMAX is more amenable to MIMO implementations than CDMA systems
- Efficiently supports **symmetric** links (eg: T1 replacement); flexible/dynamic adjustment of DL/UL ratios

C O M P A R I S O N

Table 1.2. Comparison of WiMAX with other broadband wireless technologies

Parameter	Fixed WiMAX	Mobile WiMAX	HSPA	1x EV-DO Rev A	Wi-Fi
Standards	IEEE 802.16-2004	IEEE 802.16e-2005	3GPP Release 6	3GPP2	IEEE 802.11a/g/n
Peak Down-link Data Rate	9.4 Mbps in 3.5 MHz with 3:1 DL to UL ratio TDD; 6.1 Mbps with 1:1	46 Mbps[a] with 3:1 DL to UL ratio TDD; 32 Mbps with 1:1	14.4 Mbps using all 15 codes; 7.2 Mbps with 10 codes	3.1 Mbps; Rev. B will support 4.9 Mbps	54 Mbps[b] shared using 802.11a/g; over 100 Mbps peak layer 2 throughput using 802.11n
Peak Uplink Data Rate	3.3 Mbps i 3.5 MHz using 3:1 DL to UL ratio; 6.5 Mbps with 1:1	7 Mbps in 10 MHz using 3:1 DL to UL ratio; 4 Mbps using 1:1	1.4 Mbps initially; 5.8 Mbps later	1.8 Mbps	
Bandwidth	3.5 and 7 MHz in 3.5 GHz band; 10 MHz in 5.8 GHz band	3.5, 7, 5, 10 and 8.75 MHz initially	5 MHz	1.25 MHz	20 MHz for 802.11a/g; 20/40 MHz for 802.11n
Modulation	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM	QPSK, 8PSK, 16 QAM	BPSK, QPSK, 16 QAM, 64 QAM
Multiplexing	TDM	TDM/OFDMA	TDM/CDMA	TDM/CDMA	CSMA
Duplexing	TDD, FDD	TDD initially	FDD	FDD	TDD
Frequency	3.5 and 5.8 GHz initially.	2.3, 2.5, and 3.5 GHz initially.	800/900/1800/1900/2100 MHz	800/900/1800/1900 MHz	2.4 GHz, 5 GHz
Coverage (typical)	3-5 miles;	< 2 miles	1-3 miles	1-3 miles	< 100 ft. indoor; < 1000 ft. outdoor
Mobility	Not applicable	Mid	High	High	Low

a. assumes 2 x 2 MIMO and a 10 MHz channel
b. due to inefficient CSMA MAC this typically only translates to~20-25 Mbps Layer 2 throughput

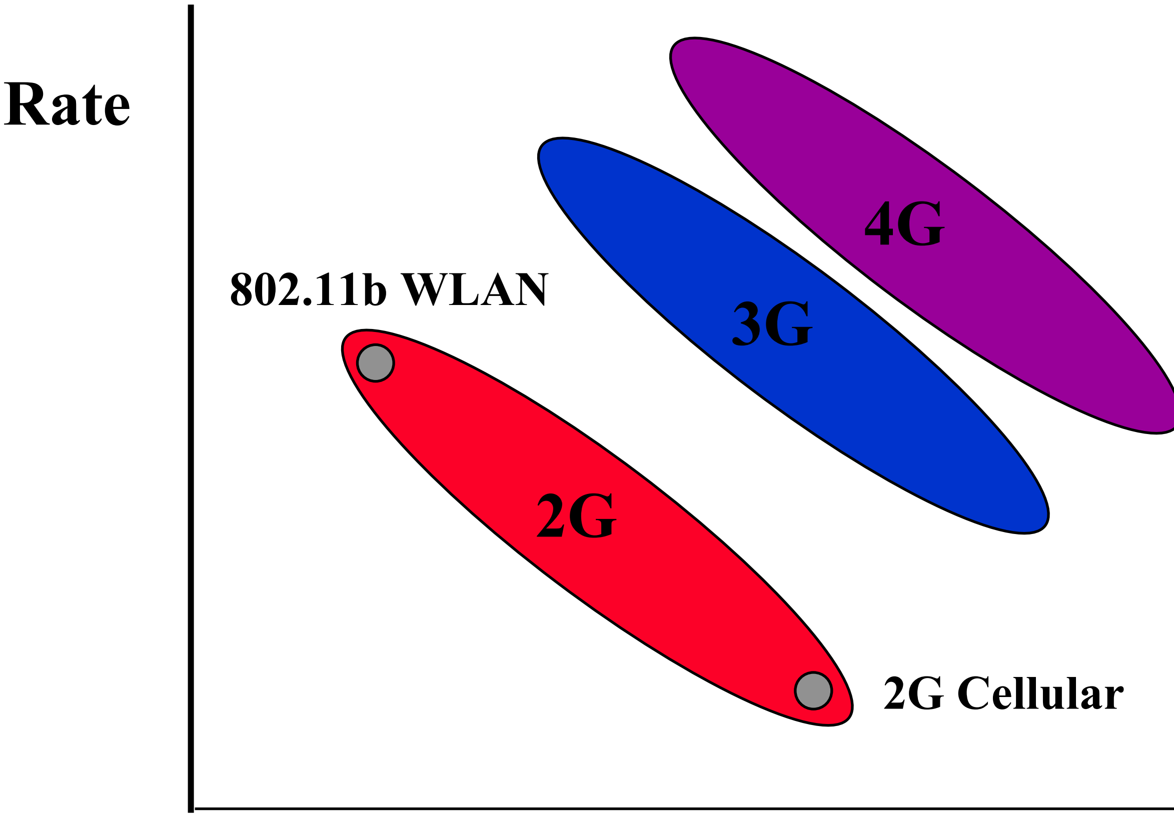
Caution: Peak vs Average Data Rates

Technology	*Peak Data Rate*		*Spectrum*
	Downlink	*Uplink*	
ADSL	8 Mbps (per user)	1 Mbps (per user)	N/A
DOCSIS 1.0	38 Mbps (shared)	9 Mbps (shared)	N/A
1X-EVDO Rev A 2.5 MHz	3.1 Mbps (shared)	1.8 Mbps (shared)	licensed
HSPA 10 MHz	14 Mbps (shared)	6 Mbps (shared)	licensed
WiFi (802.11a/b/g) 20 MHz	54 Mbps combined (shared)		unlicensed
Mobile WiMAX (2x2 MIMO) 10 MHZ	72 Mbps combined (shared)		licensed

Interesting rule of thumb: the actual capacity (Mbps per channel per sector) in a multi-cell environment for most wireless technologies is about 20% to 30% of the peak theoretical data rate.

Quick check: Wimax capacity = 0.2 * 72 ~= 14 Mbps DL.
(+ 6.7 Mbps UL => 30% of peak)

Future Generations



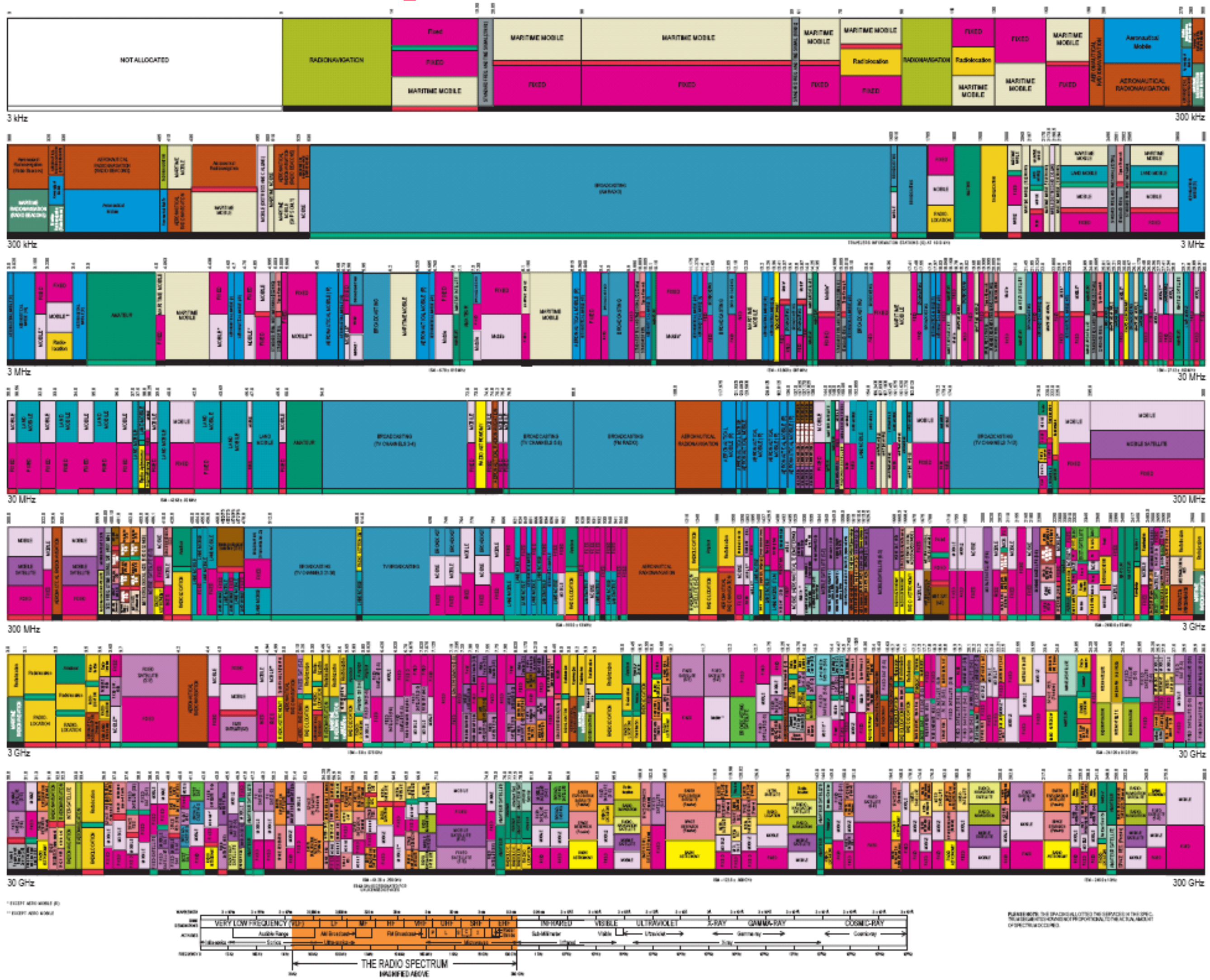
Other Tradeoffs:

- Rate vs. Coverage
- Rate vs. Delay
- Rate vs. Cost
- Rate vs. Energy

Fundamental Design Breakthroughs Needed

Wireless Broadband: Technical Challenges & Basic Concepts

Crowded Spectrum: FCC Chart



http://www.ntia.doc.gov/osmhome/allochrt.pdf

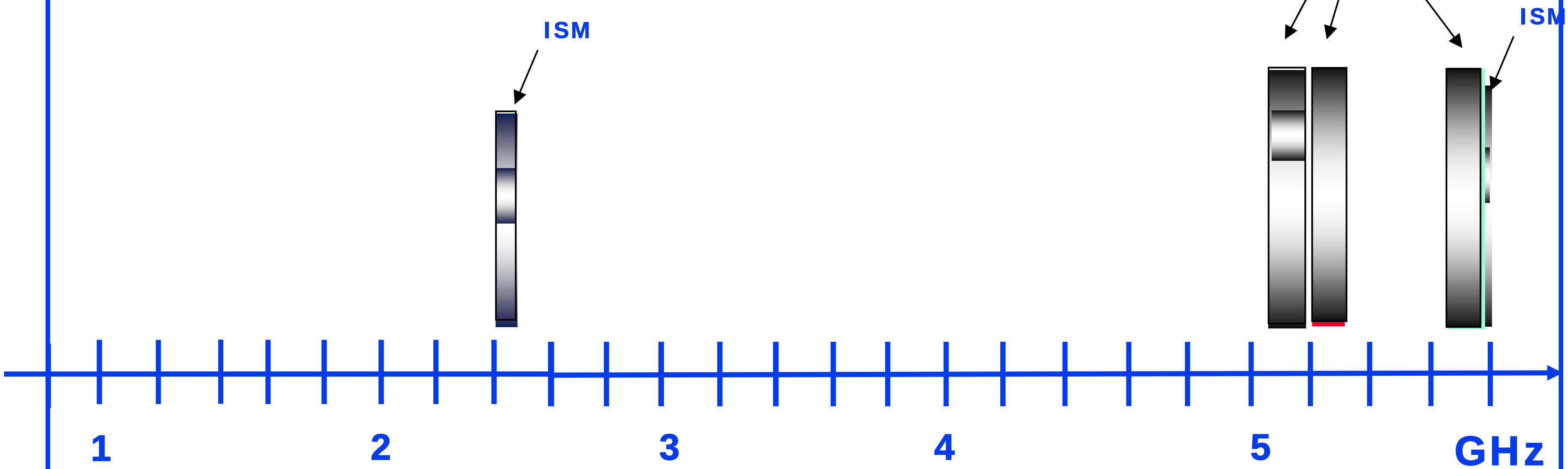
Radio/TV/Wireless Allocations: *30 MHz-30 GHz*

AM Radio	535-1605 KHz
FM Radio	88-108 MHz
Broadcast TV (Channels 2-6)	54-88 MHz
Broadcast TV (Channels 7-13)	174-216 MHz
Broadcast TV (UHF)	470-806 MHz
3G Broadband Wireless	746-764 MHz, 776-794 MHz
3G Broadband Wireless	1.7-1.85 MHz, 2.5-2.69 MHz
1G and 2G Digital Cellular Phones	806-902 MHz
Personal Communications Service (2G Cell Phones)	1.85-1.99 GHz
Wireless Communications Service	2.305-2.32 GHz, 2.345-2.36 GHz
Satellite Digital Radio	2.32-2.325 GHz
Multichannel Multipoint Distribution Service (MMDS)	2.15-2.68 GHz
Digital Broadcast Satellite (Satellite TV)	12.2-12.7 GHz
Local Multipoint Distribution Service (LMDS)	27.5-29.5 GHz, 31-31.3 GHz
Fixed Wireless Services	38.6-40 GHz

Open Spectrum: ISM and UNII Bands

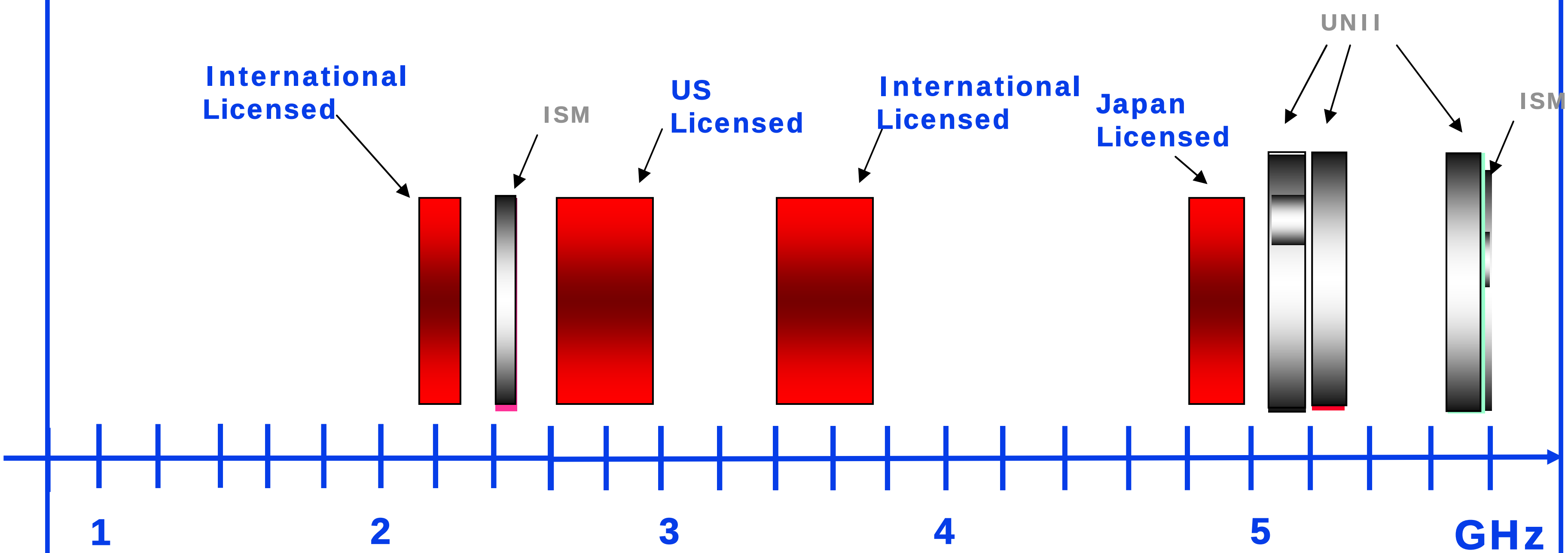
ISM: Industrial, Scientific & Medical Band

UNII: Unlicensed National Information Infrastructure band



ISM Band I (Cordless phones, 1G WLANs)	902-928 MHz
ISM Band II (Bluetooth, 802.11b WLANs)	2.4-2.4835 GHz
ISM Band III (Wireless PBX)	5.725-5.85 GHz
NII Band I (Indoor systems, 802.11a WLANs)	5.15-5.25 GHz
NII Band II (short outdoor and campus applications)	5.25-5.35 GHz
NII Band III (long outdoor and point-to-point links)	5.725-5.825 GHz

802.11/802.16 Spectrum

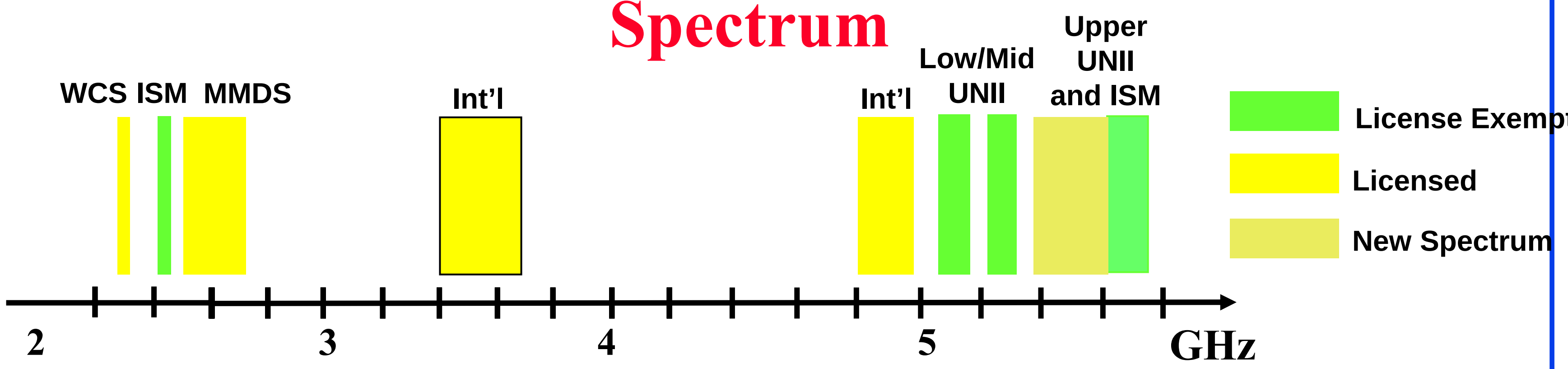


802.16a has both licensed and license-exempt options

ISM: Industrial, Scientific & Medical Band – Unlicensed band

UNII: Unlicensed National Information Infrastructure band – Unlicensed band

Summary: Key Pieces of Licensed and Unlicensed Spectrum

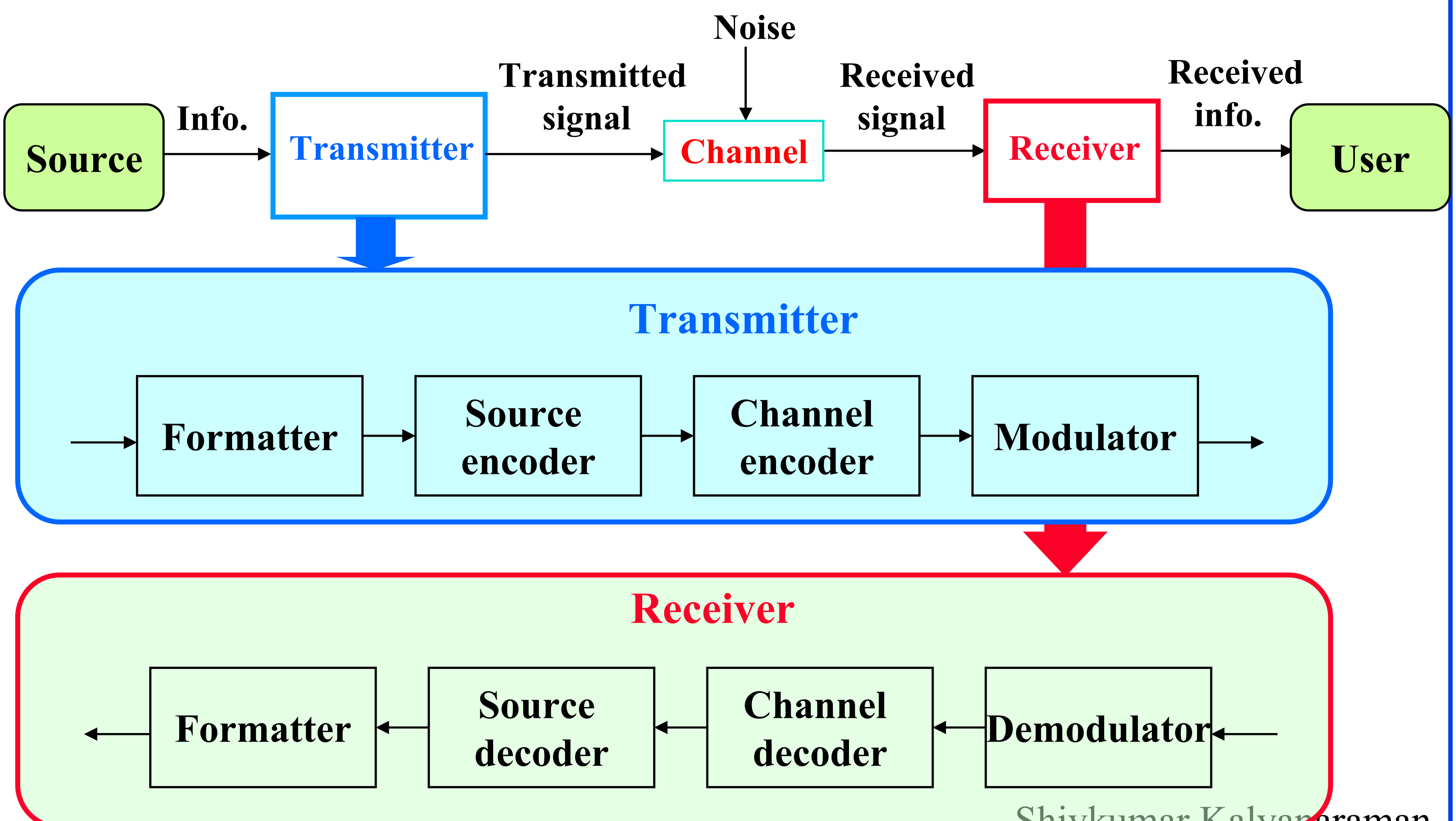


UHF	0.75 - 0.8	Channels 60-69, called the upper 700 MHz, are by congressional statute to be reclaimed for new services (broadband wireless).
ISM	0.9 - 0.93	Industrial, Scientific & Medical Band – License exempt band
UPCS	1.91 - 1.93	License exempt Personal Communications Services
WCS	2.3	Wireless Communications Service
ISM	2.4 - 2.48	Industrial, Scientific and Medical Band
MMDS	2.5 - 2.7	Multi-channel Multipoint Distribution Service.
Int'l	3.4 - 3.7 4.8 – 5.0	Licensed Bands- Europe, Latin America, Asia Licensed Bands-Japan
UNII	5.15 - 5.35 5.725 - 5.85	License exempt National Information Infrastructure band
New Spectrum	5.470- 5.725	FCC NPRM 03-110 Part 15

Spectrum Allocation Methods

- **Auctions**: raise revenue, market-based, but may shut out smaller players; upfront cost stifles innovation (lower equipment budget).
- **Beauty contest:** best technology wins. (Japan) Faster deployments, monopolies/oligopolies.
- **Unlicensed**: power limits, equipment. (WiFi, some Wimax)
- **Underlay**: primary vs secondary users. Stricter power limits for secondary: hide in a wider band under the noise floor (UWB)
- **Cognitive radio:** primary user has priority. Secondary user can use greater power, but has to detect and vacate the spectrum when primary users come up. {*future*}

Digital Communication System: Structure



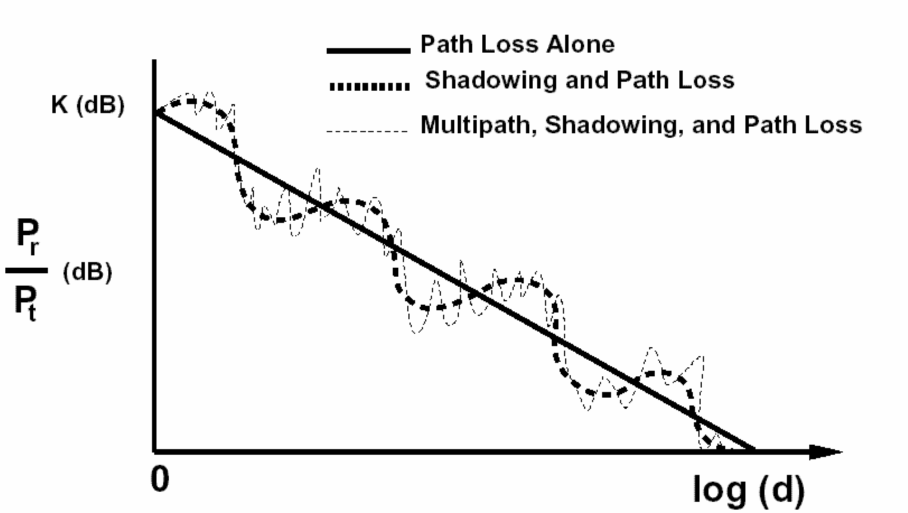
Wireless Channel is Very Different!

- Wireless channel "feels" very different from a wired channel.
  - Not a point-to-point link: EM signal propagates in patterns determined by the antenna gains and environment
  - Noise adds on to the signal (AWGN)
  - Signal strength falls off rapidly with distance (especially in cluttered environments): *large-scale* fading.
  - Shadowing effects make this large-scale signal strength drop-off non-isotropic.
  - Fast fading leads to *huge* variations in signal strength over short distance, times, or in the frequency domain.
  - Interference due to superimposition of signals, leakage of energy can raise the noise-floor and fundamentally limit performance:
    - Self-interference (inter-symbol, inter-carrier), Co-channel interference (in a cellular system with high frequency reuse), Cross-system (microwave ovens vs WiFi vs bluetooth)

- Results:
  - Variable capacity
  - Unreliable channel: errors, outages
  - Variable delays.
  - Capacity is shared with interferers.

Path Loss, Shadowing, Fading

- Variable & rapid decay of signal due to environment, multi-paths, mobility



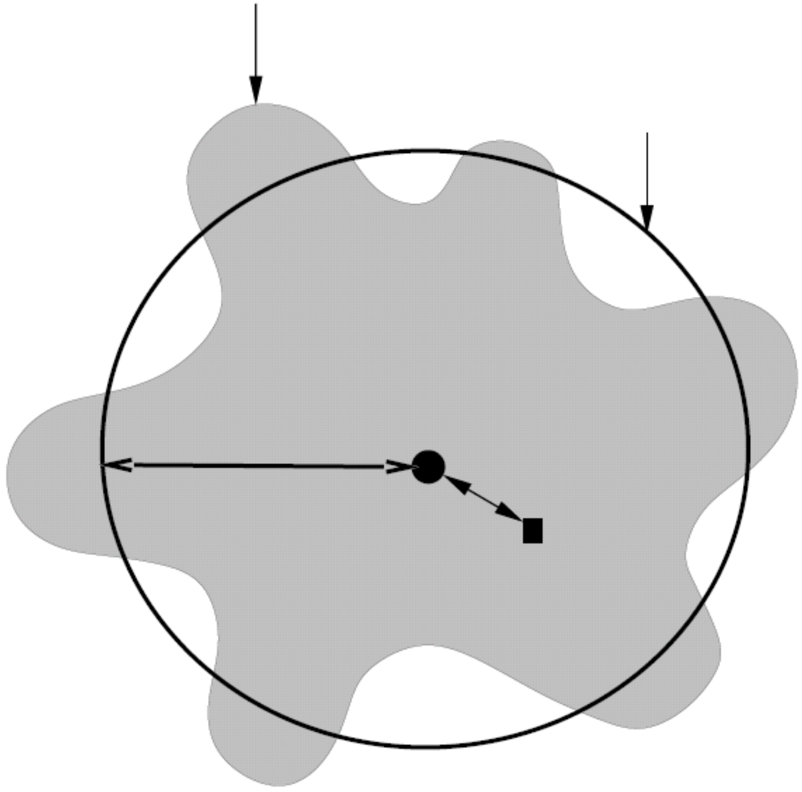
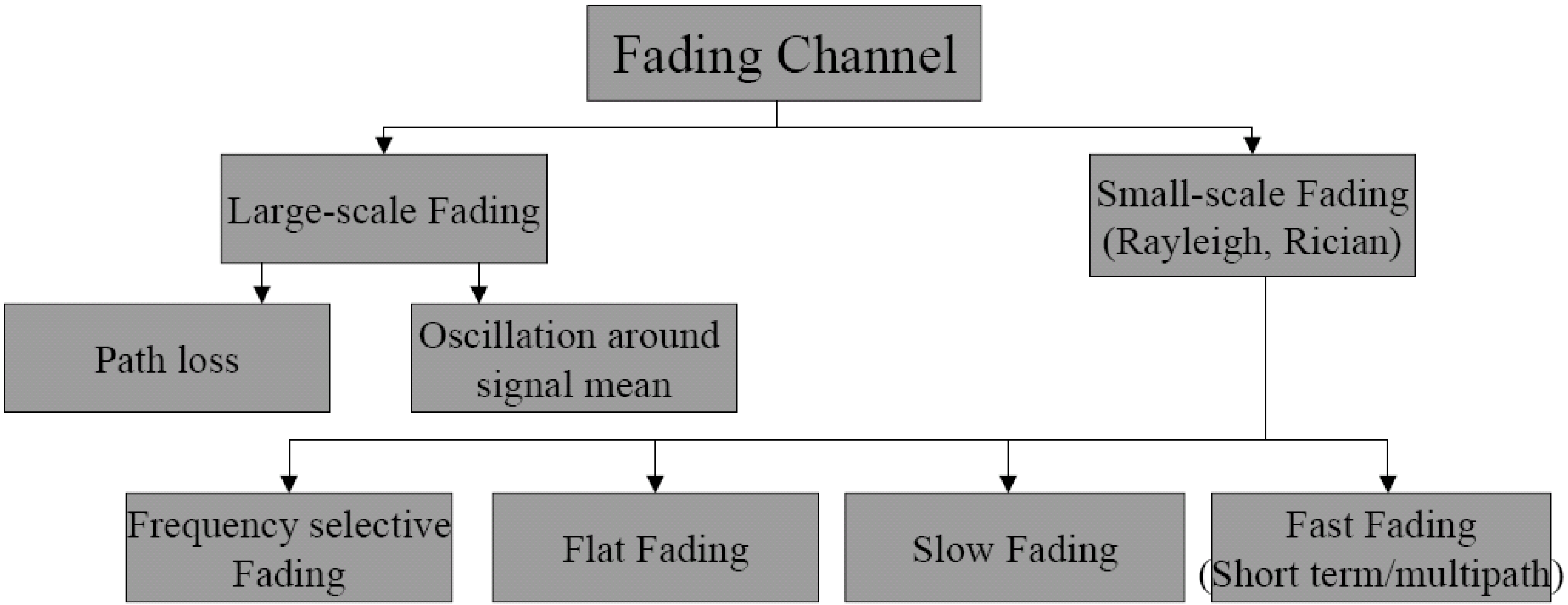


Figure 2.10: Contours of Constant Received Power.

<u>Slow fading:</u> outage in uncovered areas. A coding scheme that achieves the outage capacity is said to be universal since it communicates reliably over all slow fading channels that are not in outage.

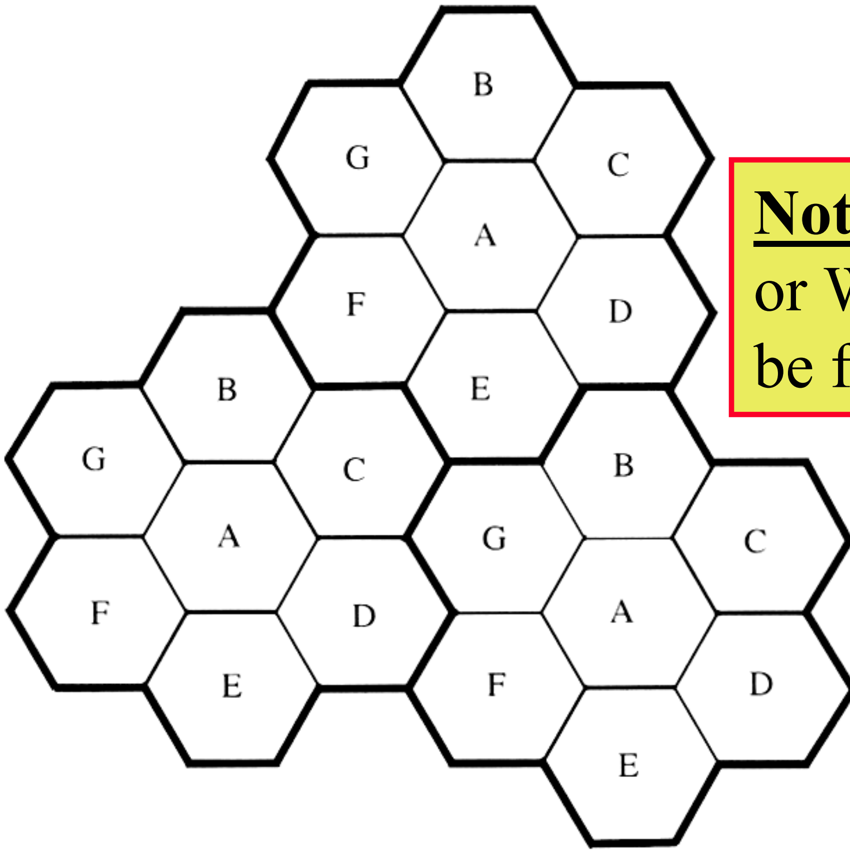
Fading Channel



Counter-attacking the Challenges!

- Turn disadvantages into advantages!
- Resources associated with a fading channel: 1) diversity; 2) number of degrees of freedom; 3) received power.
- Cellular concept: *reuse* frequency and capacity by taking advantage of the fact that signal fades with distance. Cost: cells, interference management
- *Multiple access* technologies: CDMA, OFDMA, CSMA, TDMA: share the spectrum amongst variable number of users within a cell
- Leverage *diversity* i.e. use performance variability as an ally by having access to multiple modes (time, frequency, codes, space/antennas, users) and combining the signal from all these modes
  - Directional/Smart/Multiple Antenna Techniques (MIMO): use spatial diversity, spatial multiplexing.
  - Adaptive modulation/coding/power control per-user within a frame (time-diversity, multi-user diversity, water-filling in low-SNR regime)
  - Cooperative diversity (eg: cooperative/virtual MIMO)
- *Multi-hop/Meshed* wireless networks with micro-cells
- *Interference*: still the biggest challenge.
  - Interference estimation and *cancellation* techniques (eg: multi-user) may be key in the future.
  - CDMA: interference averaging.
  - <u>Opportunistic beamforming</u>: *increase* the *fluctuations of the interference* imparted on adjacent cells

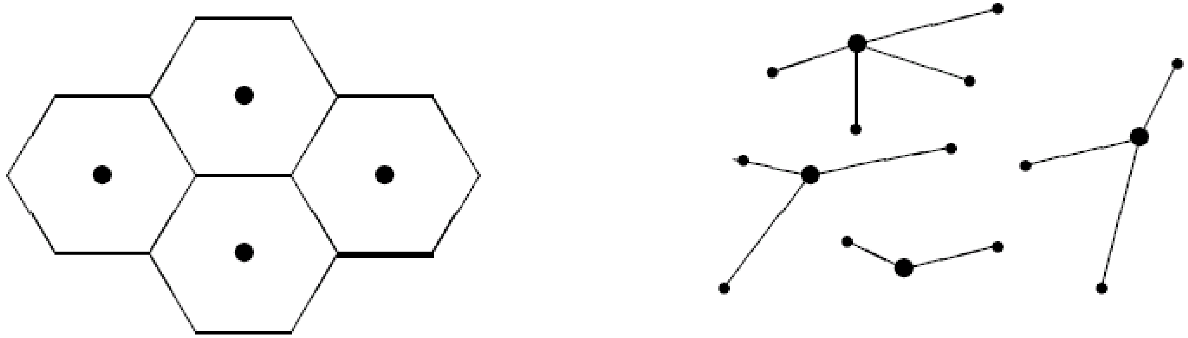
The Cellular Concept: Spatial Reuse



<u>Note:</u> today w/ CDMA or WIMAX there can be frequency reuse of 1

Cells In Reality

- Cellular model vs reality: shadowing and variable large-scale propagation due to environment



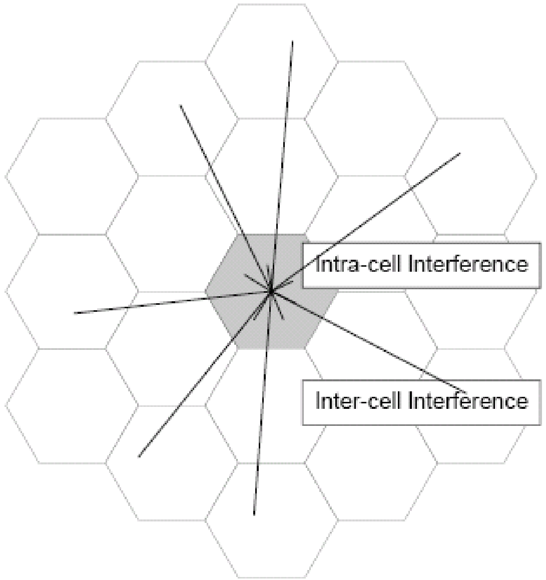
(a) (b)

Part (a): an oversimplified view in which each cell is hexagonal.

Part (b): a more realistic case where base stations are irregularly placed and cell phones choose the best base station

Interference In Cellular Networks

- Assume the asynchronous users sharing the same bandwidth and using the same radio base station in each coverage area or cell.
  - Intra-cell/co-channel interference due to the signal from the other users in the home cell.
  - Inter-cell/adjacent channel interference due to the signal from the users in the other cell.
  - Interference due to the thermal noise.



Inter-cell and intra-cell interference in a cellular system

- Methods for reducing interference:
  - **<u>Frequency reuse:</u>** in each cell of cluster pattern different frequency is used
    - By optimizing reuse pattern the problems of interference can be reduced significantly, resulting in increased capacity.
  - **<u>Reducing cell size</u>**: in smaller cells the frequency is used more efficiently: cell sectoring, splitting
  - **<u>Multilayer network design (overlays):</u>** macro-, micro-, pico-cells

Cell Splitting increases capacity

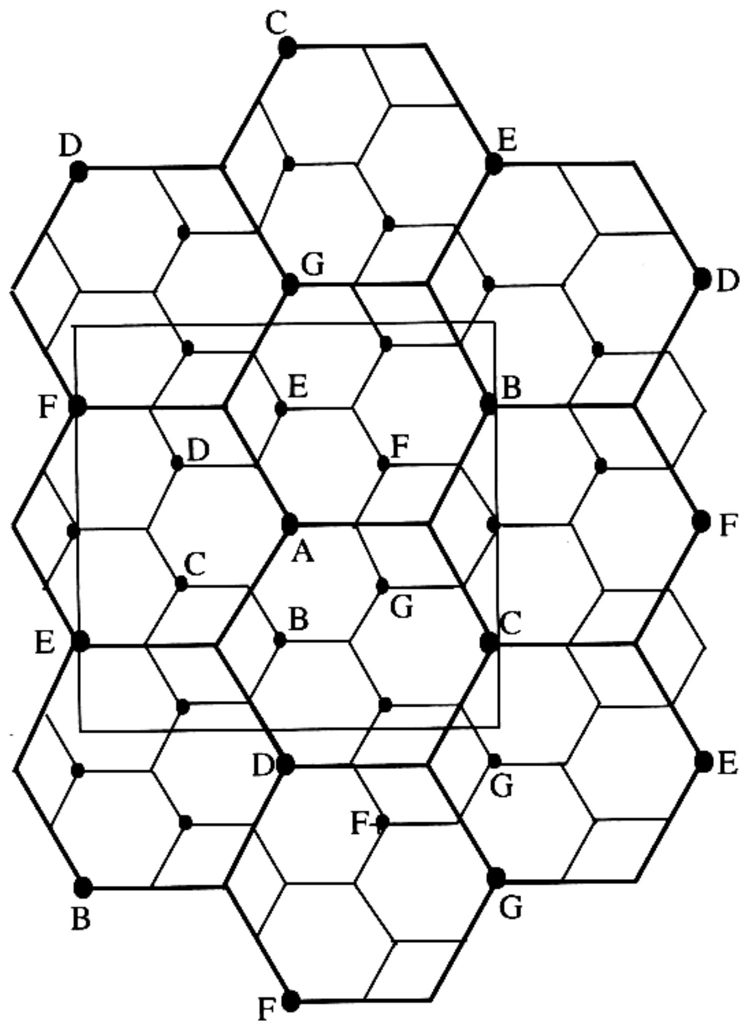


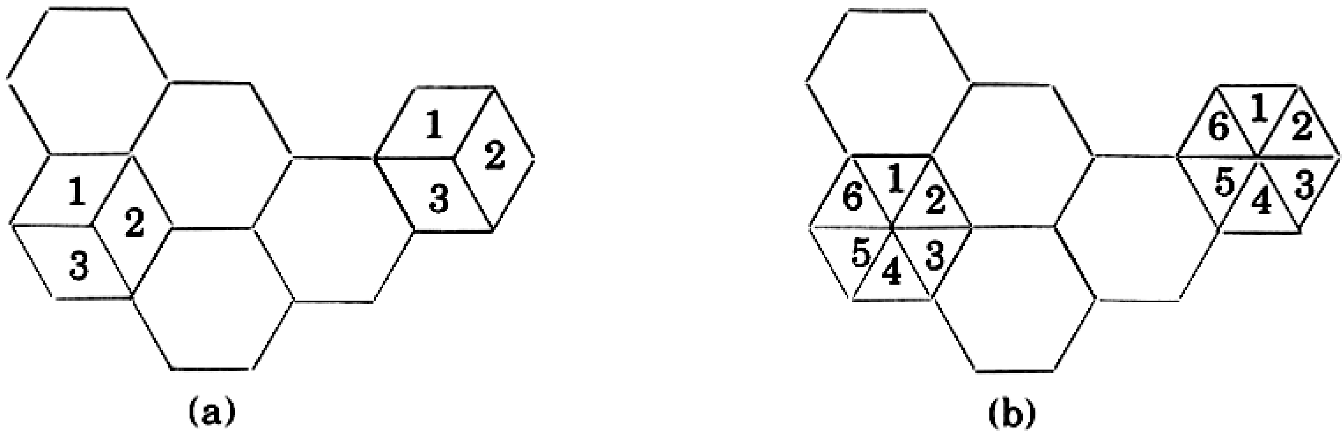
Figure 3.9 Illustration of cell splitting within a 3 km by 3 km square centered around base station A.

Trend towards Smaller Cells

- Drivers:
  - Need for higher capacity in areas with high user density
  - Reduced size and cost of base station electronics.
    - [Large cells required $1 million base stations]
  - Lower height/power, closer to street.

- Issues:
  - Mobiles traverse a small cell more quickly than a large cell.
    - **Handoffs** must be processed more quickly.
  - **Location management** becomes more complicated, since there are more cells within a given area where a mobile may be located.
  - May need wireless backhaul (NLOS backhaul hops may be required also)
  - Wireless propagation models don't work for small cells.
    - Microcellular systems are often designed using square or triangular cell shapes, but these shapes have a large margin of error

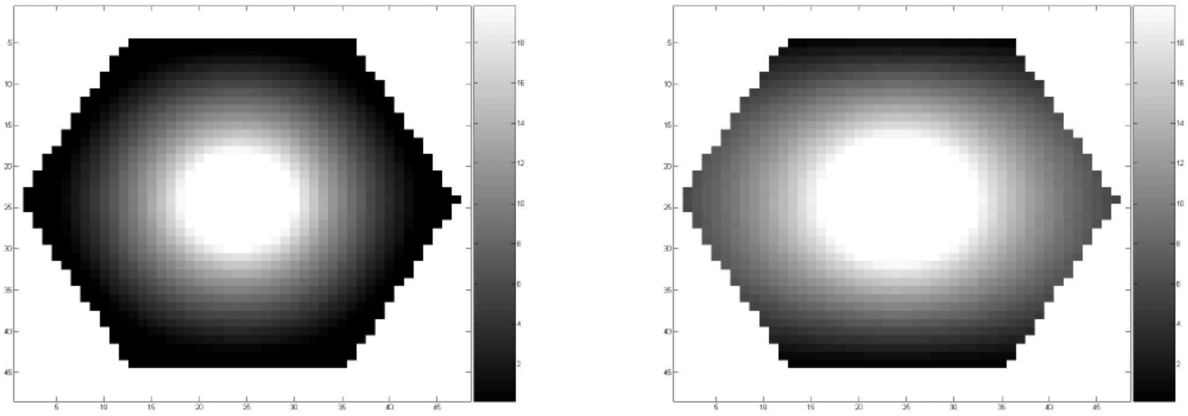
Sectoring improves S/I



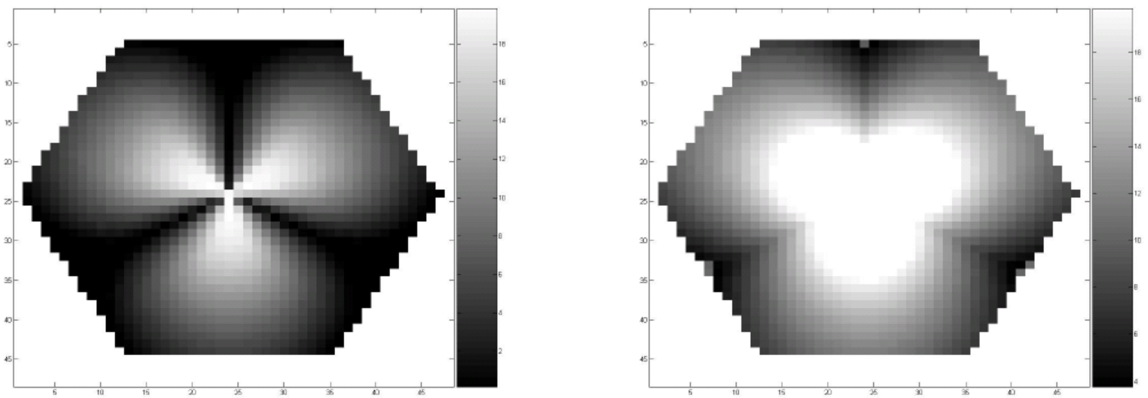
(a) 120° sectoring; (b) 60° sectoring.

- Capacity increase > 3X.
- Each sector can reuse time and code slots.
- Interference is reduced by sectoring, since users only experience interference from the sectors at their frequency.

SIR w/ and w/o 3 Sectors



(a) Universal frequency reuse, $f = 1$ (b) Frequency reuse ($f = 1/3$



(a) Universal frequency reuse(1:1) (b) Frequency reuse(1:3)

The received SIR in a cell with path-loss exponent $\alpha = 3.5$. The scale on the right indicates the SINR bins, i.e. darker indicates lower SIR.

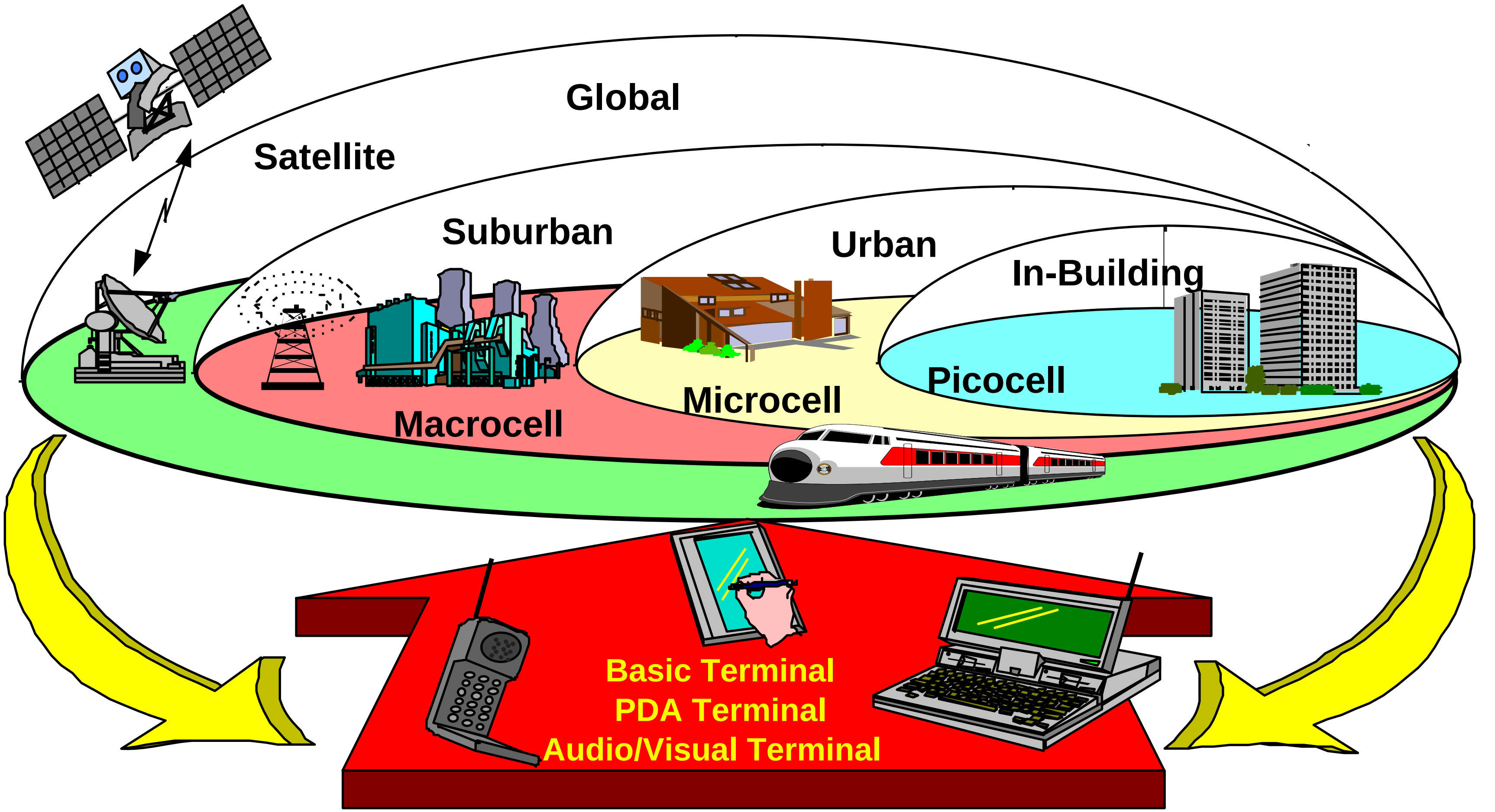
Source: J. Andrews et al, Fundamentals of Wimax

Google: "shiv rpi"

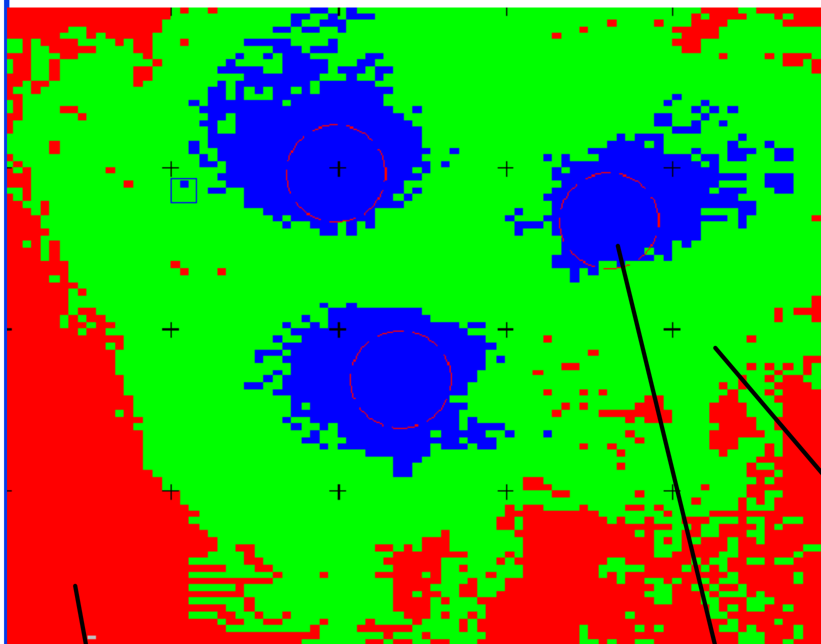
Sectoring: Tradeoffs

- More antennas.
- Reduces trunking efficiency.
- Even though intersector handoff is simpler compared to intercell handoff, sectoring also increases the overhead due to the increased number of inter-sector handoffs.
- In channels with heavy scattering, desired power can be lost into other sectors, which can cause inter-sector interference as well as power loss

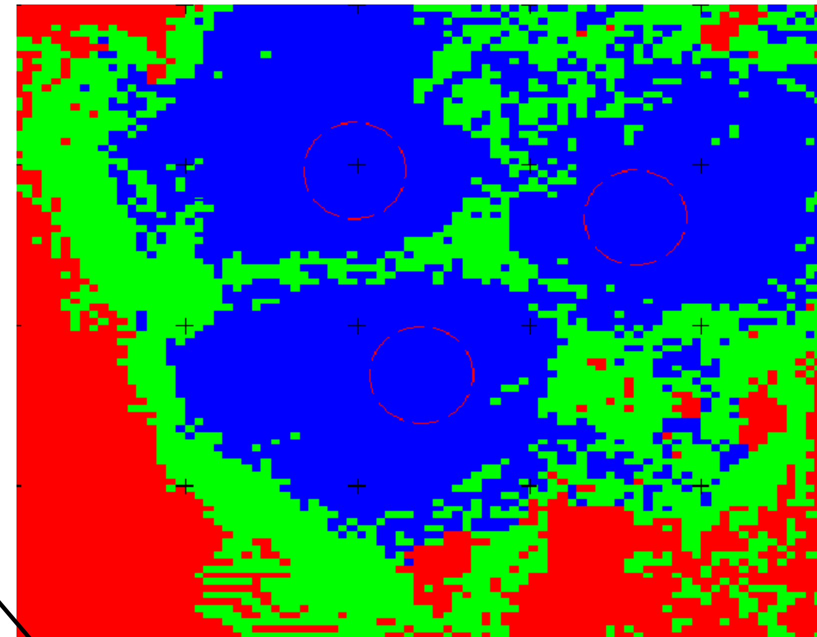
Cell Sizes…: Multiple Layers



Cell Breathing: CDMA networks



Case 1: 20 users



Case 2: 10 users

-10 < C/I < -5 dB

-15 < C/I < -10 dB

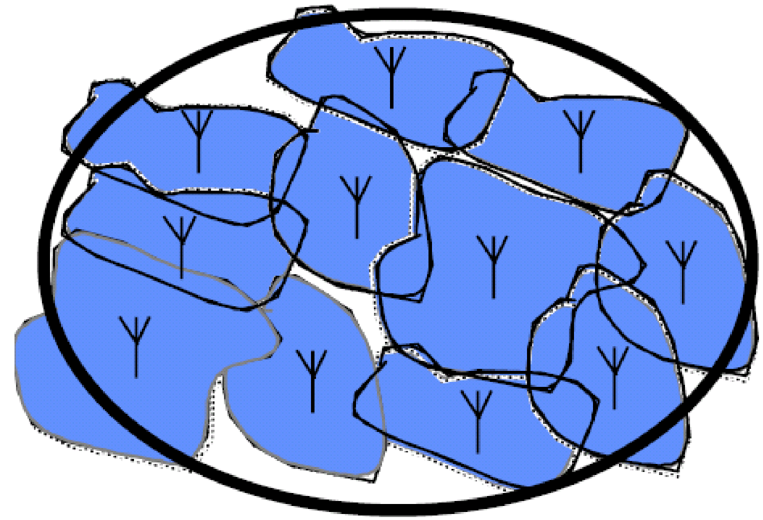
-15 < C/I < -50 dB

Dynamic cell range: f(# users)

○ cells

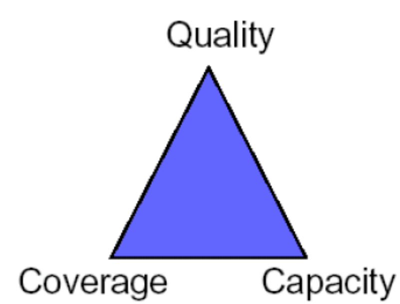
Capacity Planning: Multi-Cell Issues, Coverage-Capacity-Quality Tradeoffs

- Coverage and Range
  - Required site-to-site distance in [m]
- Capacity:
  - kbps/cell/MHz for data
- Quality
  - Service dependent



- Delay and packet loss rate important for data services

- Interference due to spectrum reuse in nearby cells.



“Mobility”

- Two aspects of mobility:
  - *User mobility*: a user communicates (wireless) „anytime, anywhere, with anyone“
  - *Device portability*: A device can connect to the network anytime and anywhere
- **Wireless vs. Mobile** — **Example**

Wireless	Mobile	Example
✗	✗	stationary computer
✗	✓	notebook in a hotel
✓	✗	Wireless LAN in buildings
✓	✓	Personal Digital Assistants (PDA)

- The demand for mobile communication creates the need for integration of wireless networks into existing fixed networks:
  - In the local range: standardization of IEEE 802.11, ETSI HIPERLAN
  - In the Internet: Mobile IP as enhancement of „normal“ IP
  - In wide area range: e.g. internetworking of GSM and ISDN

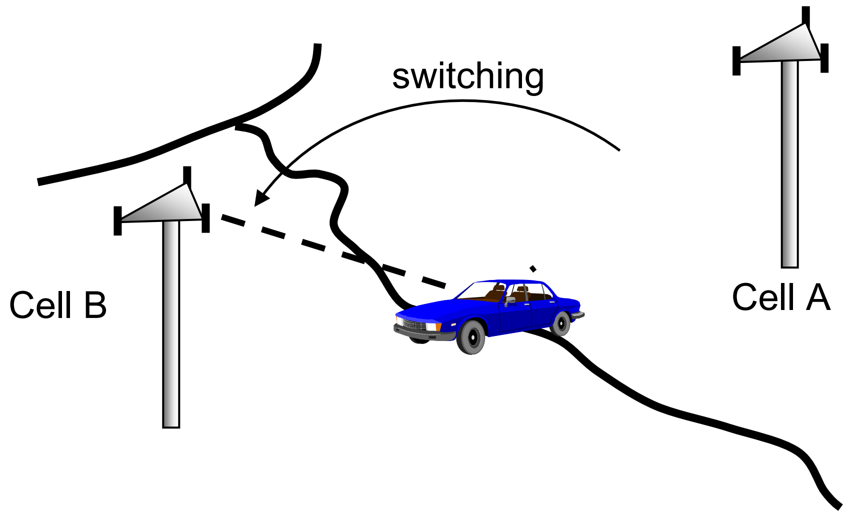
Handoff (1/2)

Handoff :

- Cellular system tracks mobile stations in order to maintain their communication links.
- When mobile station goes to neighbor cell, communication link switches from current cell to the neighbor cell.

Hard Handoff :

- In FDMA or TDMA cellular system, new communication establishes after breaking current communication at the moment doing handoff. Communication between MS and BS breaks at the moment switching frequency or time slot.

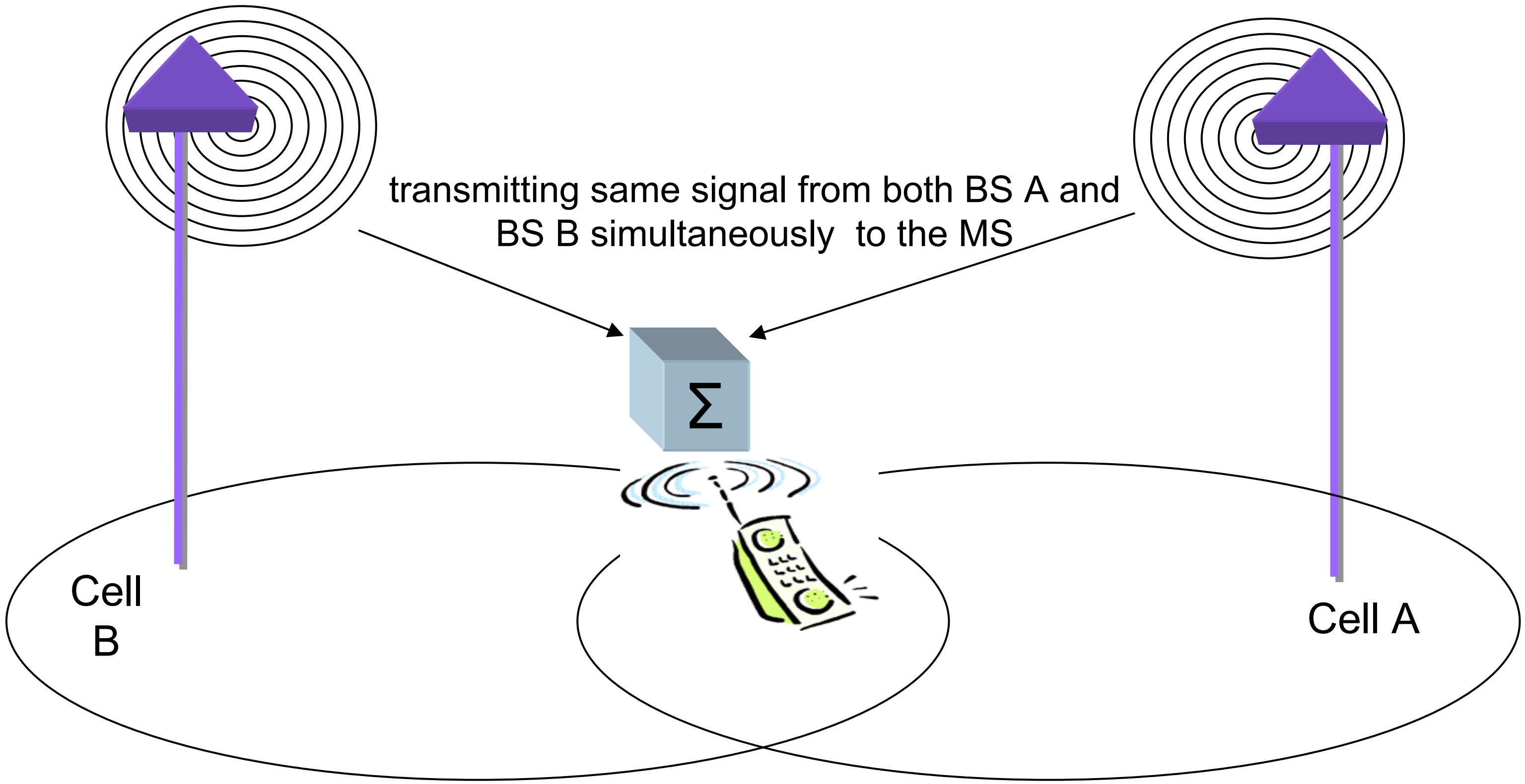


Hard handoff : connect (new cell B) after break (old cell A)

Soft Handoff (2/2)

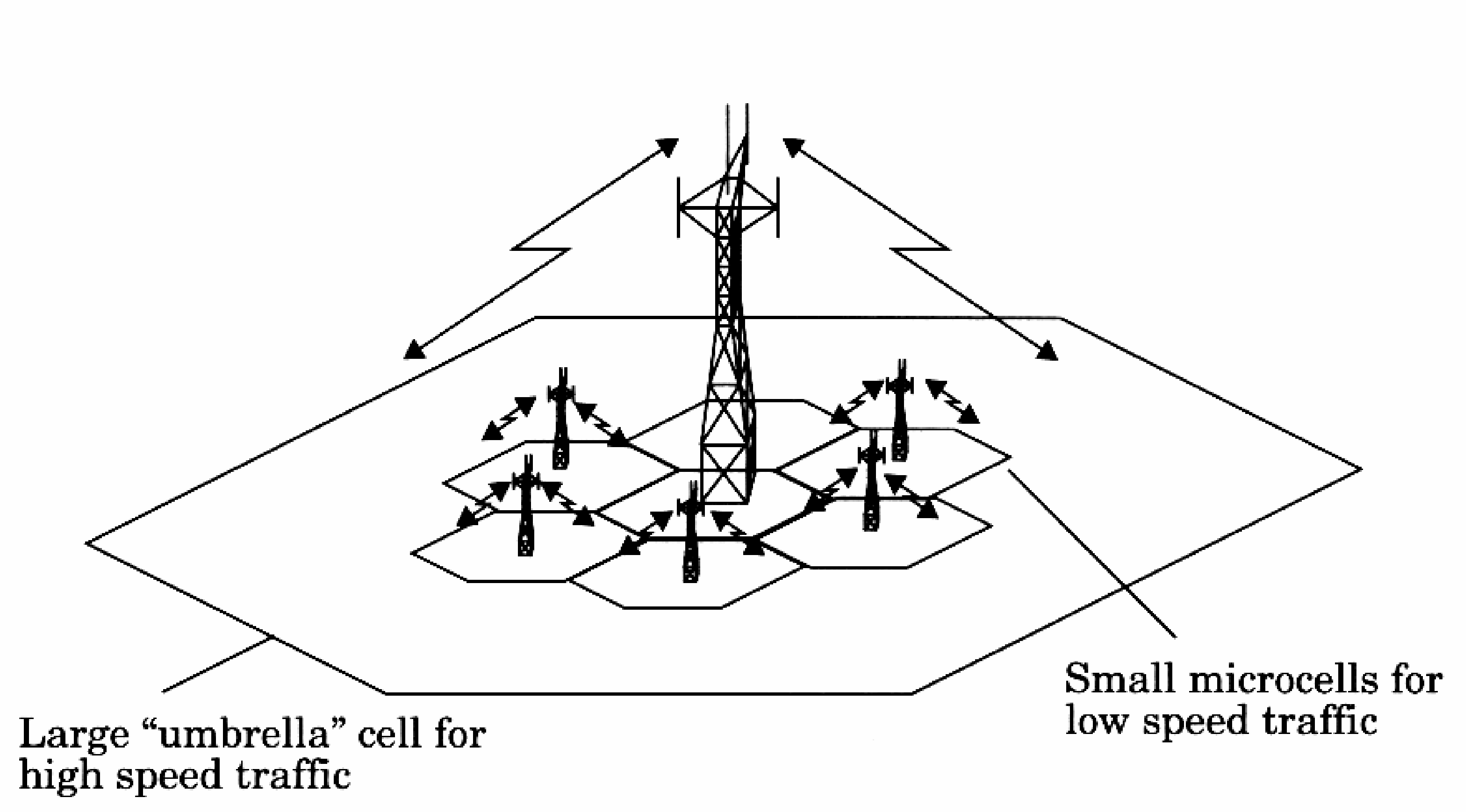
Soft Handoff :

- In CDMA cellular system, communication does not break even at the moment doing handoff, because switching frequency or time slot is not required.



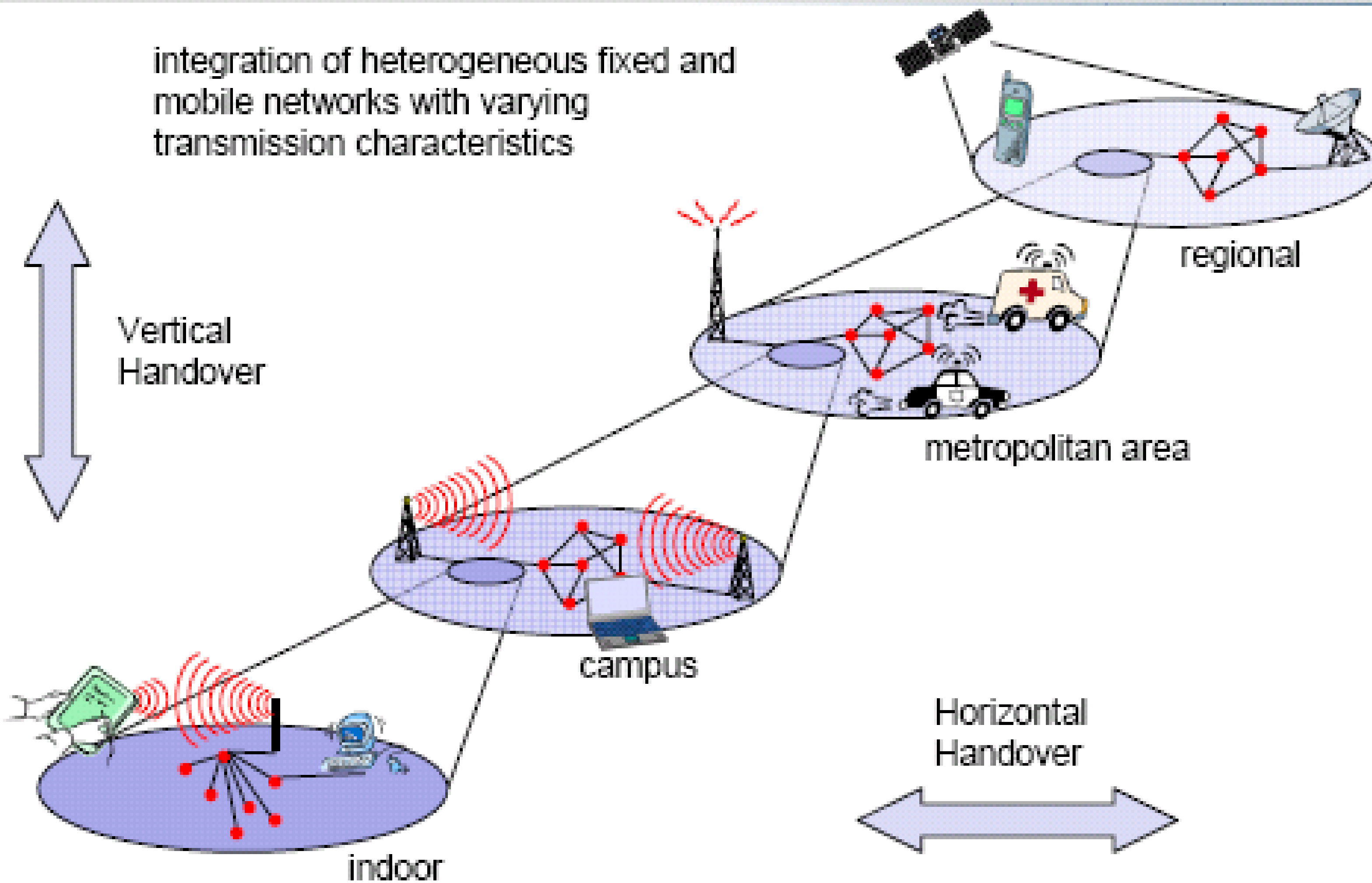
Soft handoff : break (old cell A) after connect (new cell B)

Mobility/Handoff in Umbrella Cells



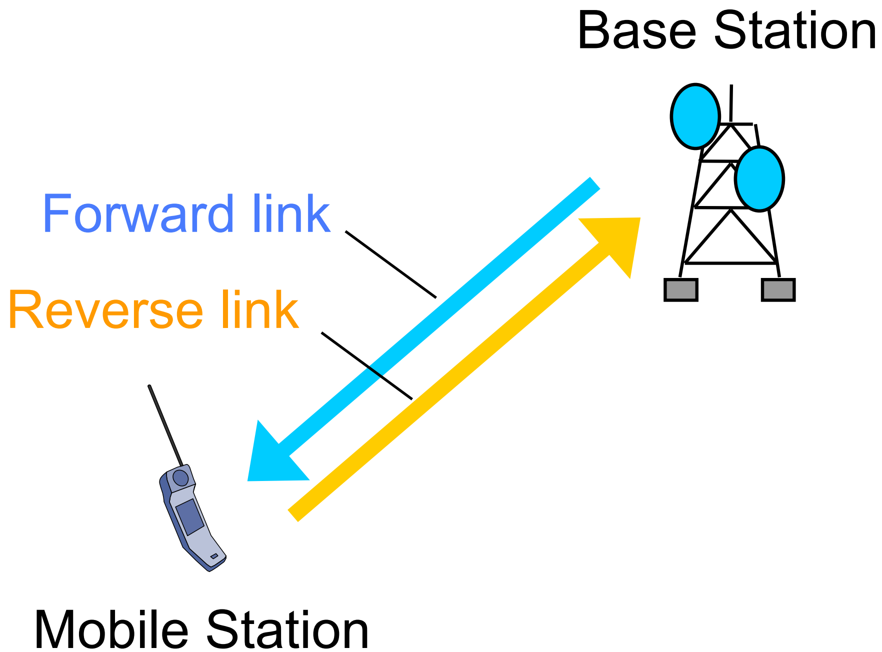
Avoids multiple handoffs.

"Overlay" Wireless Networks: Mobility & Handover



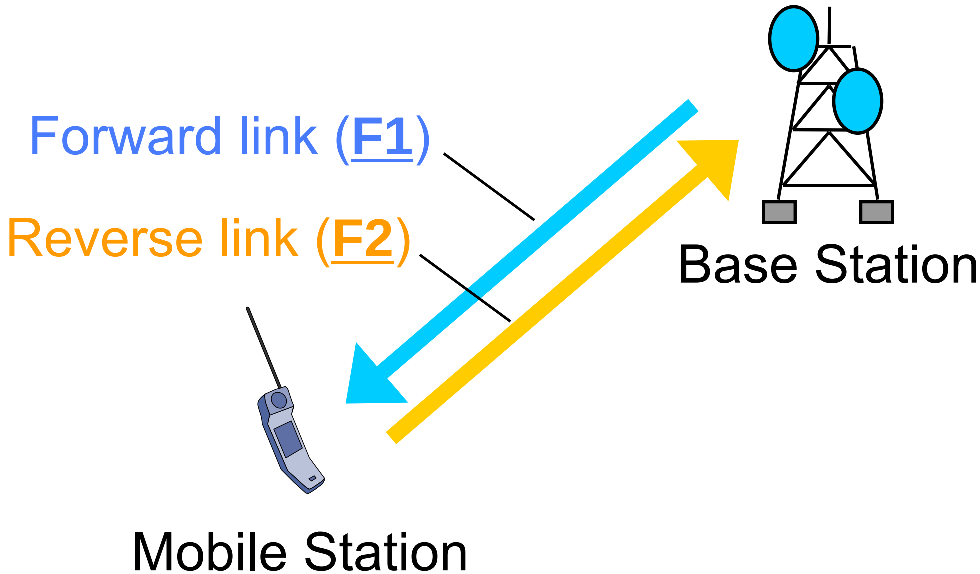
Duplexing, Multiplexing and Multiple Access Methods

Duplexing Methods for Radio Links

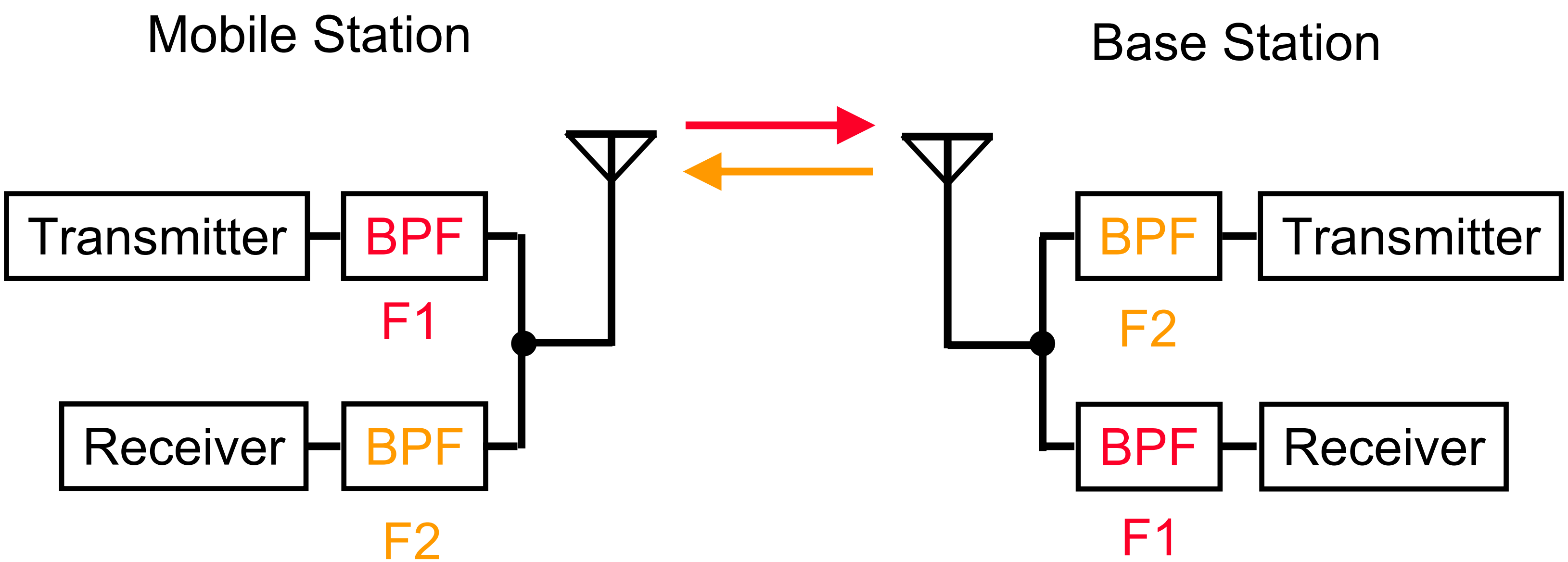


Frequency Division Duplex (FDD)

- Forward link frequency and reverse link frequency is different
- In each link, signals are continuously transmitted in parallel.



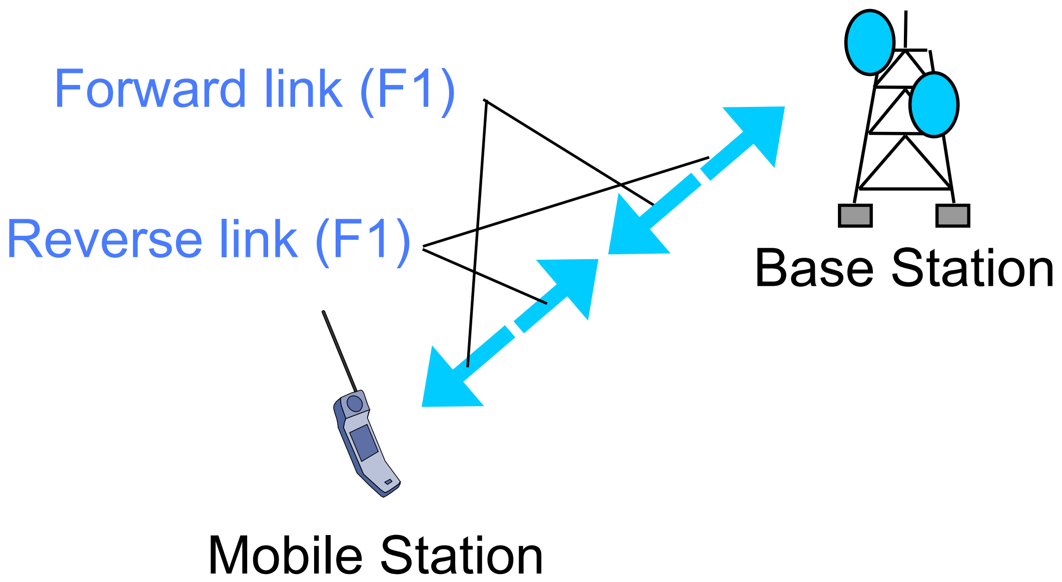
Example of FDD systems



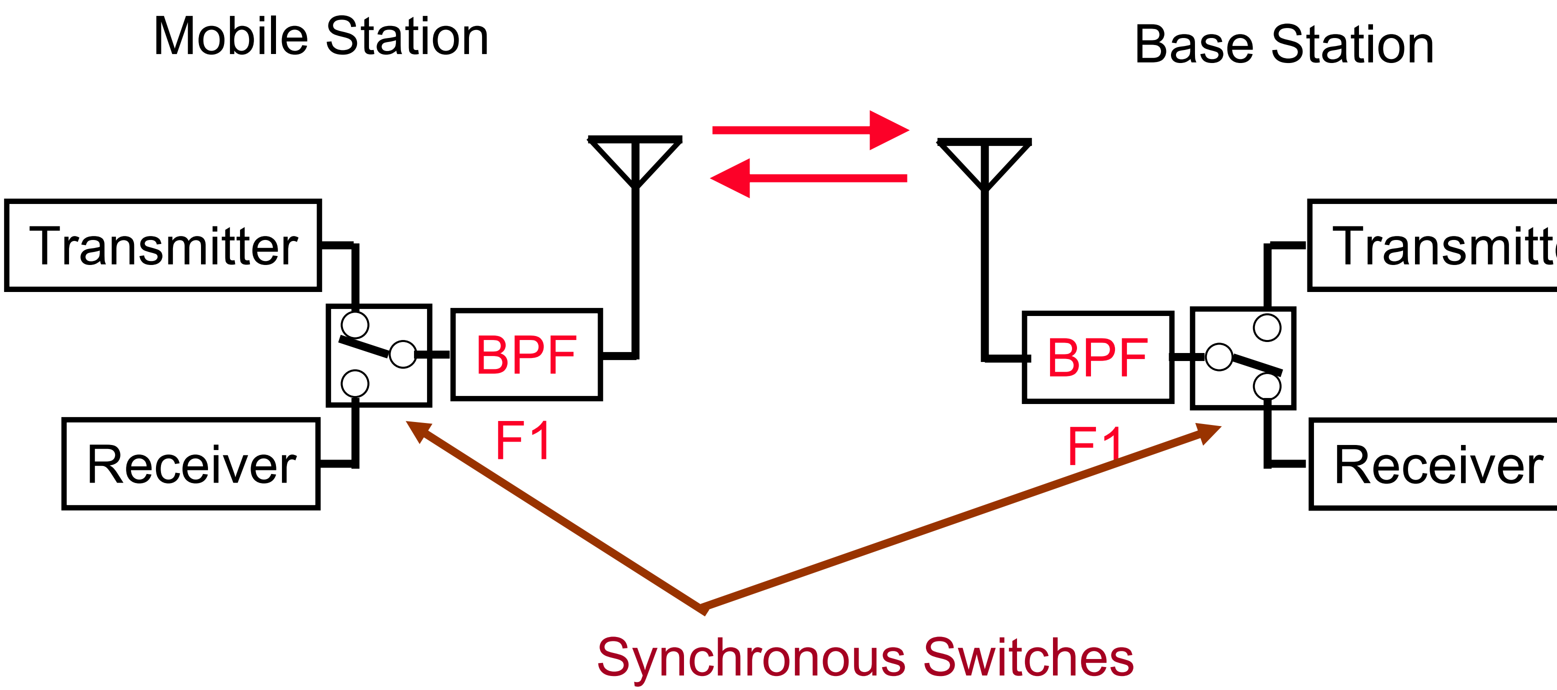
BPF: Band Pass Filter

Time Division Duplex (TDD)

- Forward link frequency and reverse link frequency is the same.
- In each link, signals take turns just like a ping-pong game.



Example of TDD Systems

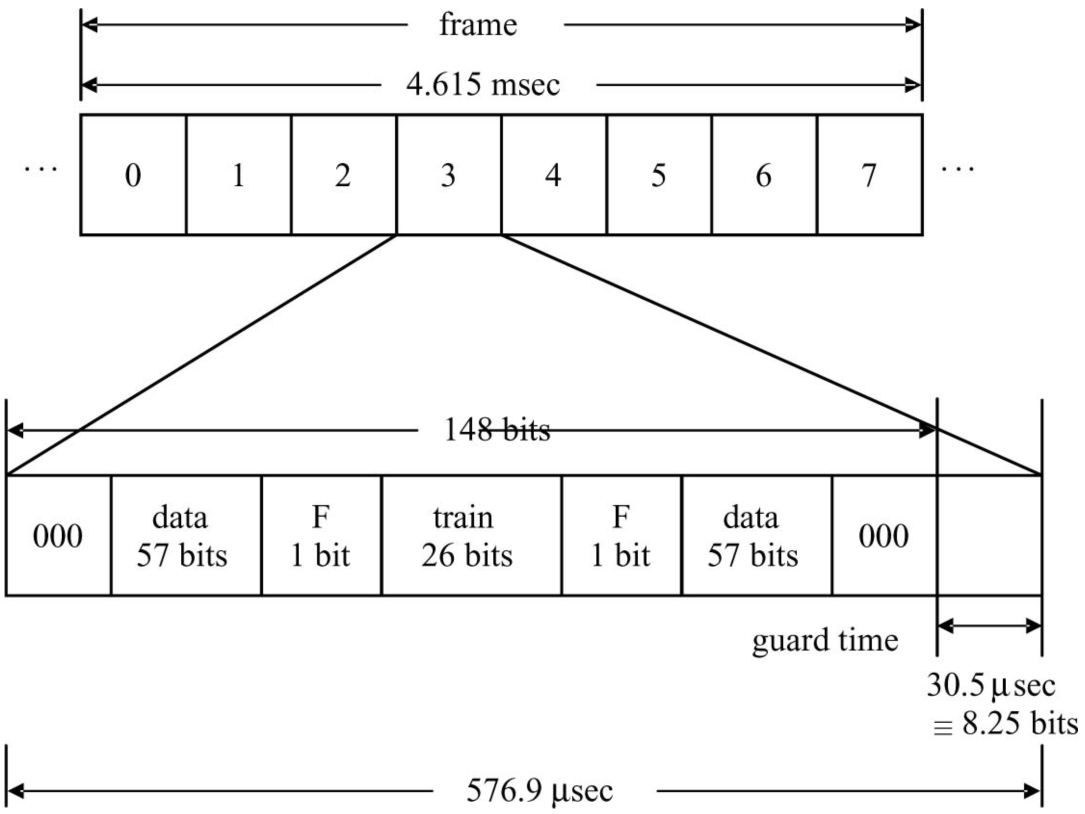


BPF: Band Pass Filter

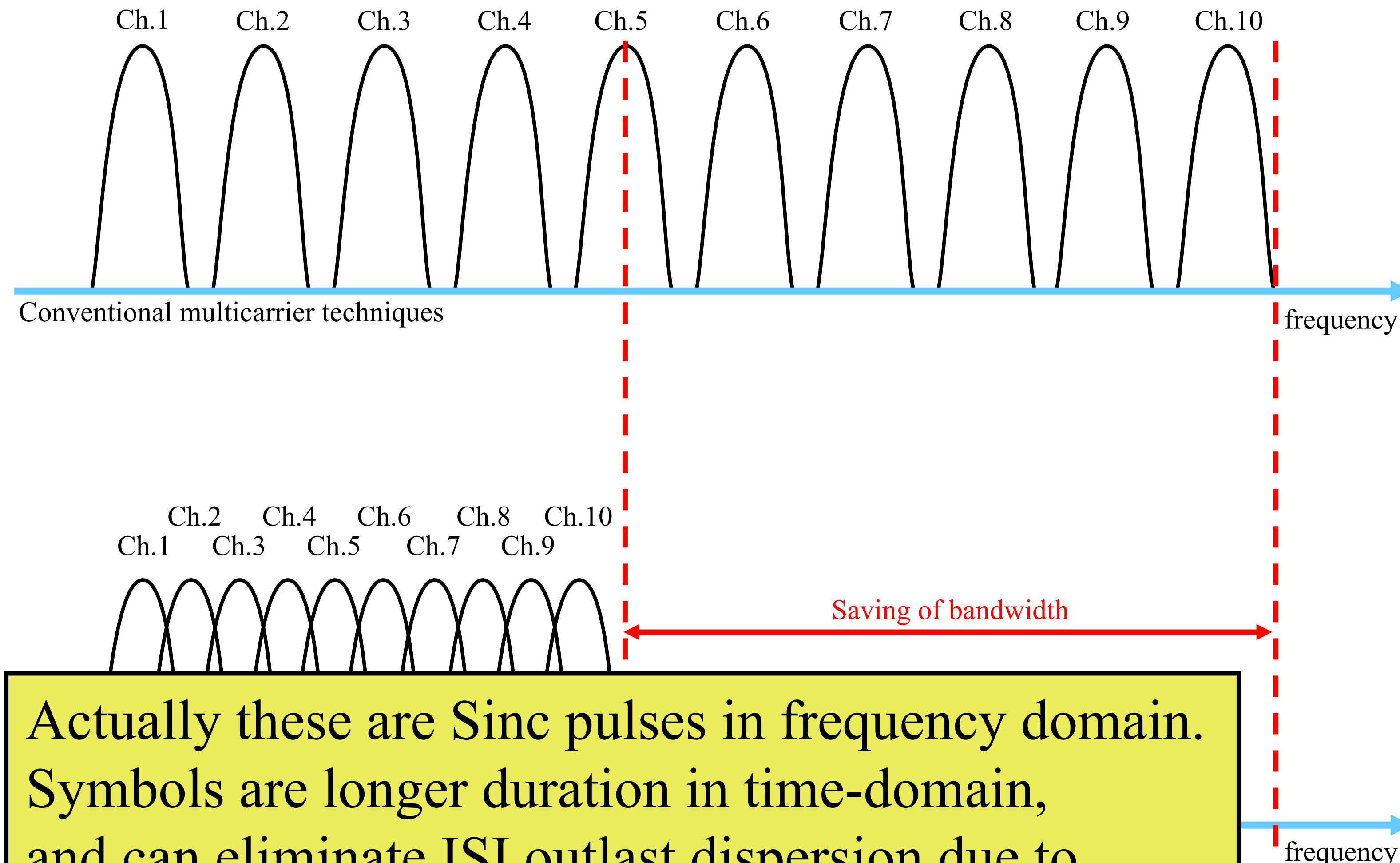
Multiplexing: Outline

- **Single link:**
  - Channel partitioning (TDM, FDM, WDM) vs Packets/Queuing/Scheduling
- **Series of links**:
  - Circuit switching vs packet switching
- **Statistical Multiplexing** (leverage *randomness*)
  - Stability, multiplexing gains, Amdahl's law
- **Distributed multiplexing** (MAC protocols)
  - Channel partitioning: TDMA, FDMA, CDMA
  - Randomized protocols: Aloha, Ethernet (CSMA/CD)
  - Taking turns: distributed round-robin: polling, tokens

Multiplexing: TDM



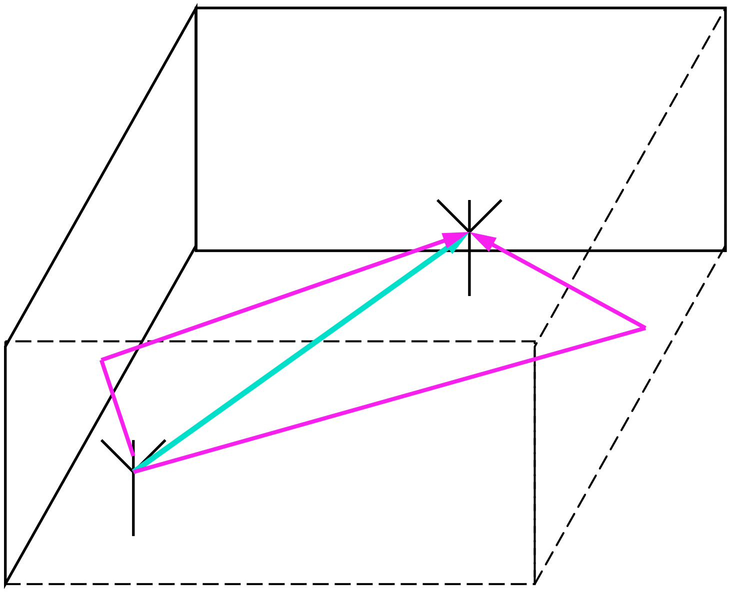
“Multi-carrier”: FDM and OFDM



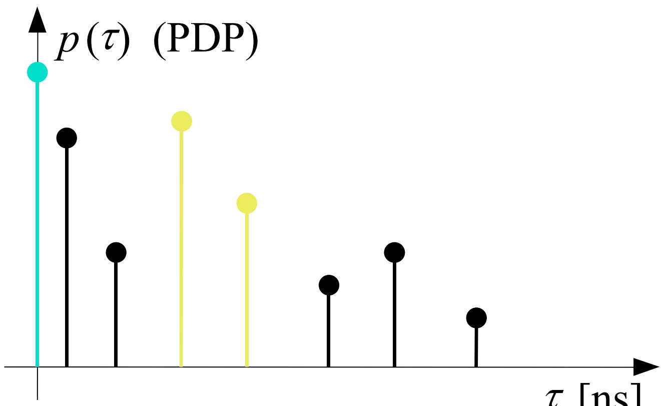
Actually these are Sinc pulses in frequency domain.
Symbols are longer duration in time-domain,
and can eliminate ISI outlast dispersion due to
multipaths (see next slide)…

Detour: Multipath Propagation & ISI

- Reflections from walls, etc.



- Time dispersive channel
  - Impulse response:



- Problem with high rate data transmission:
  - multi-path delay spread is of the order of symbol time
  - inter-symbol-interference (ISI)

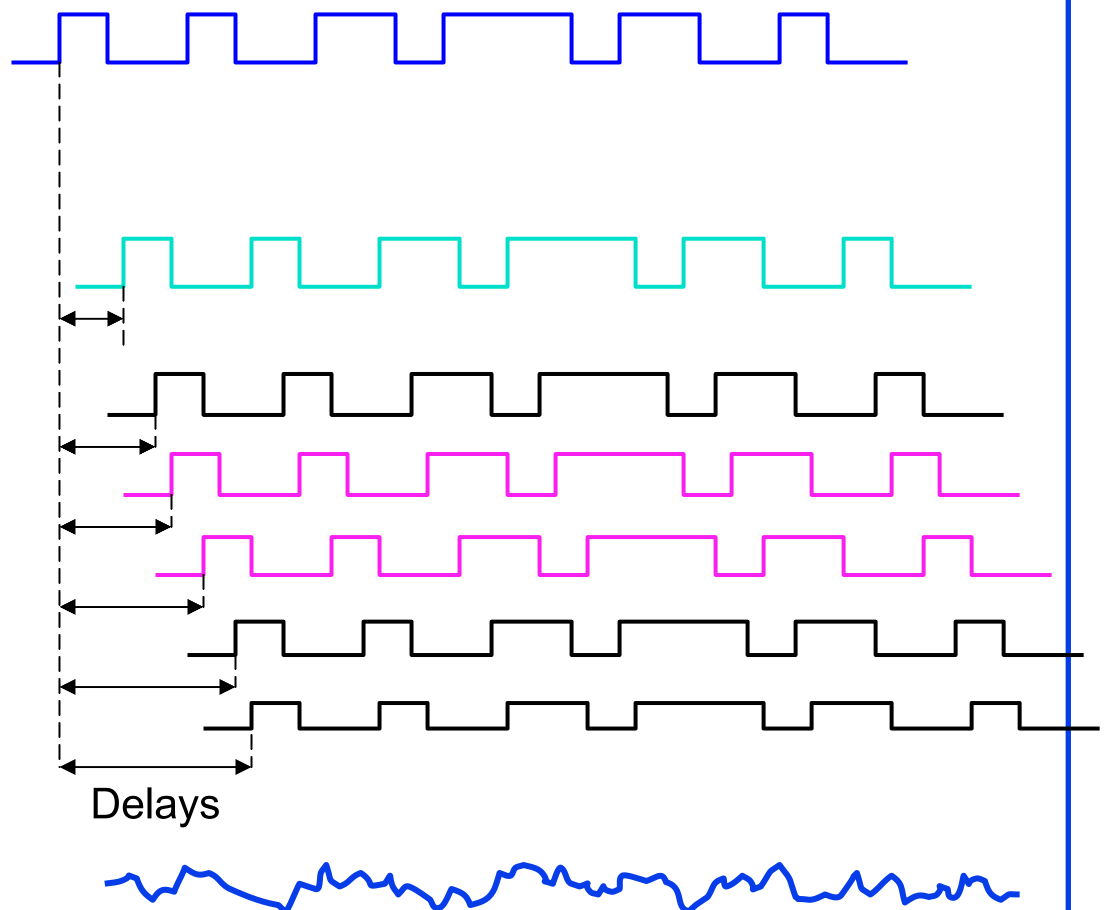
Detour: Inter-Symbol-Interference (ISI) due to Multi-Path Fading

Transmitted signal:

Received Signals:

Line-of-sight:

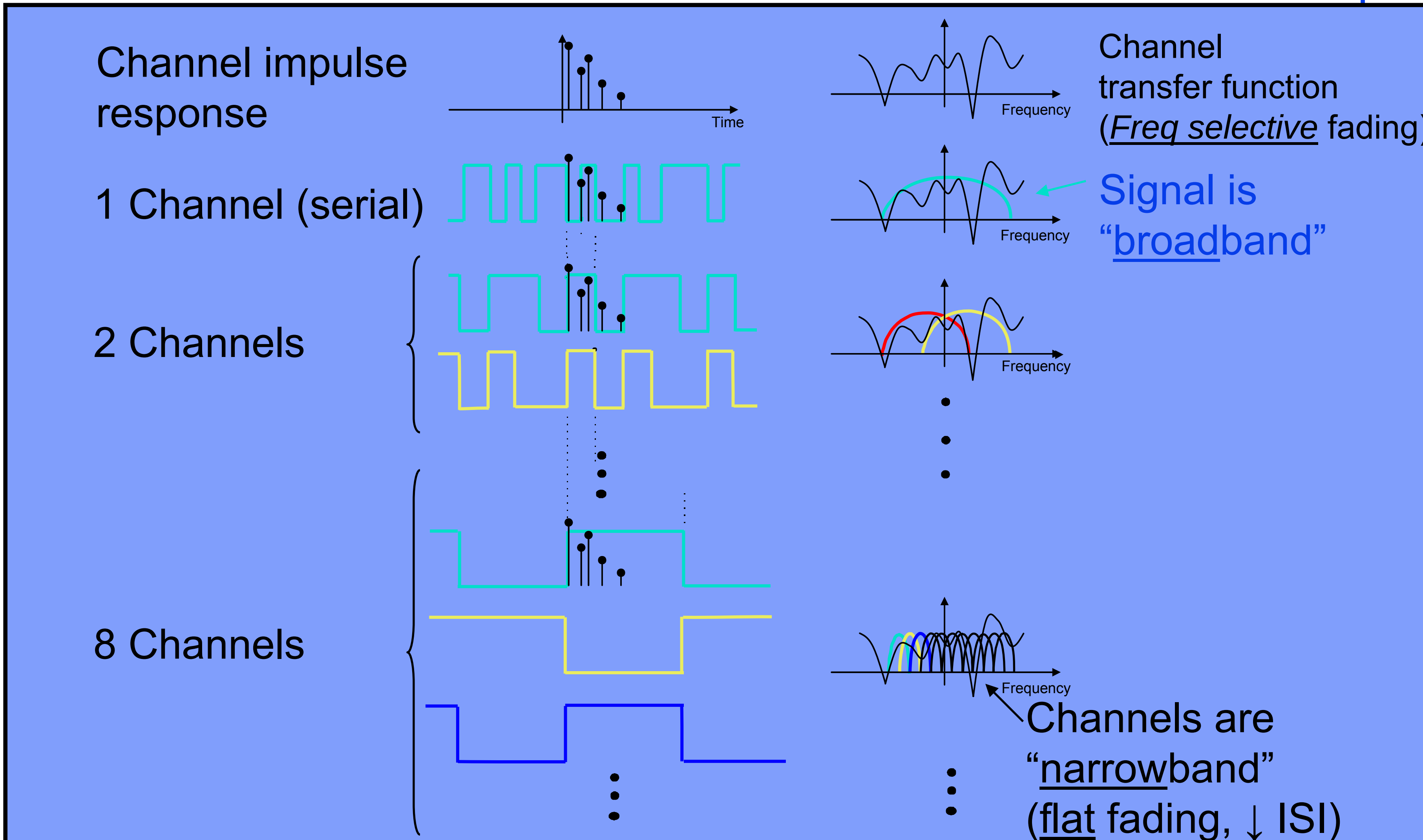
Reflected:



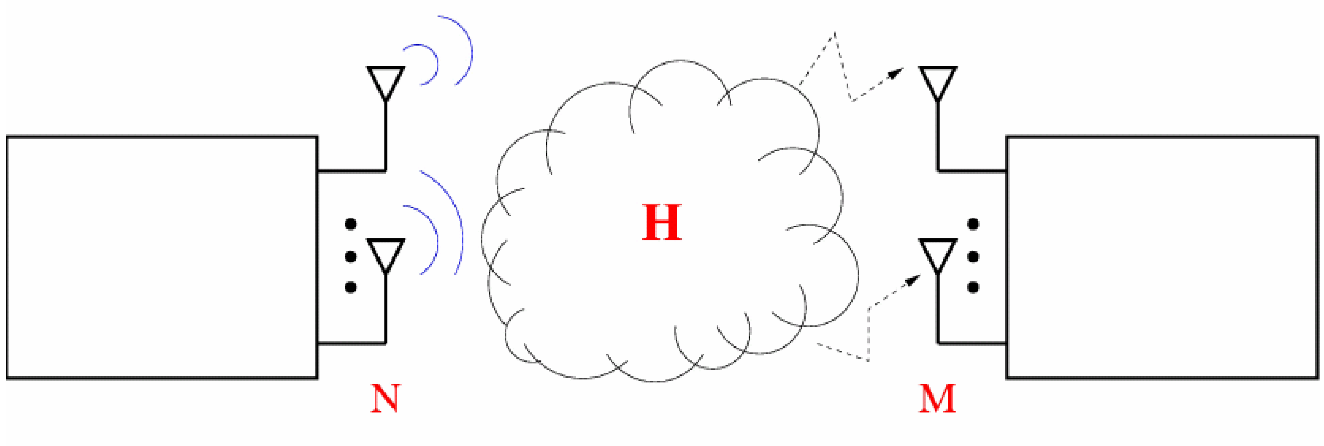
The **symbols add up** on the channel

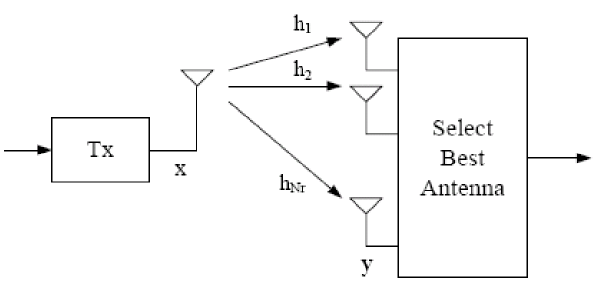
→ **Distortion!**

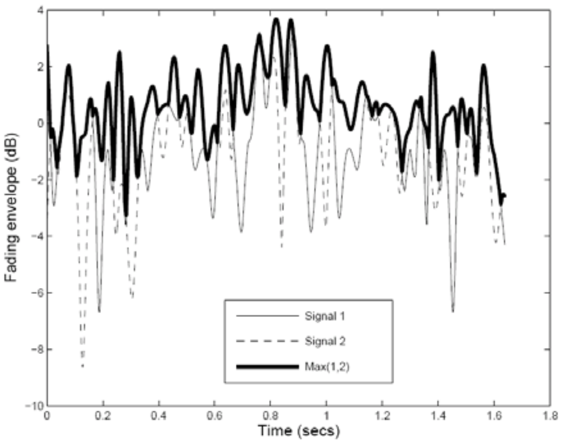
OFDM: Parallel Tx on Narrow Bands

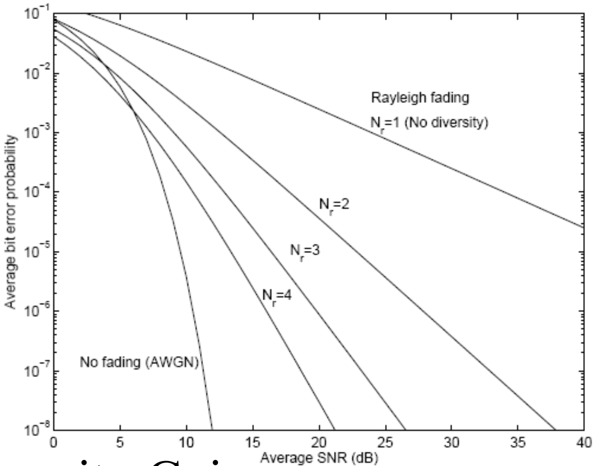


MIMO: Spatial Diversity, Spatial Multiplexing w/ Multiple Antennas



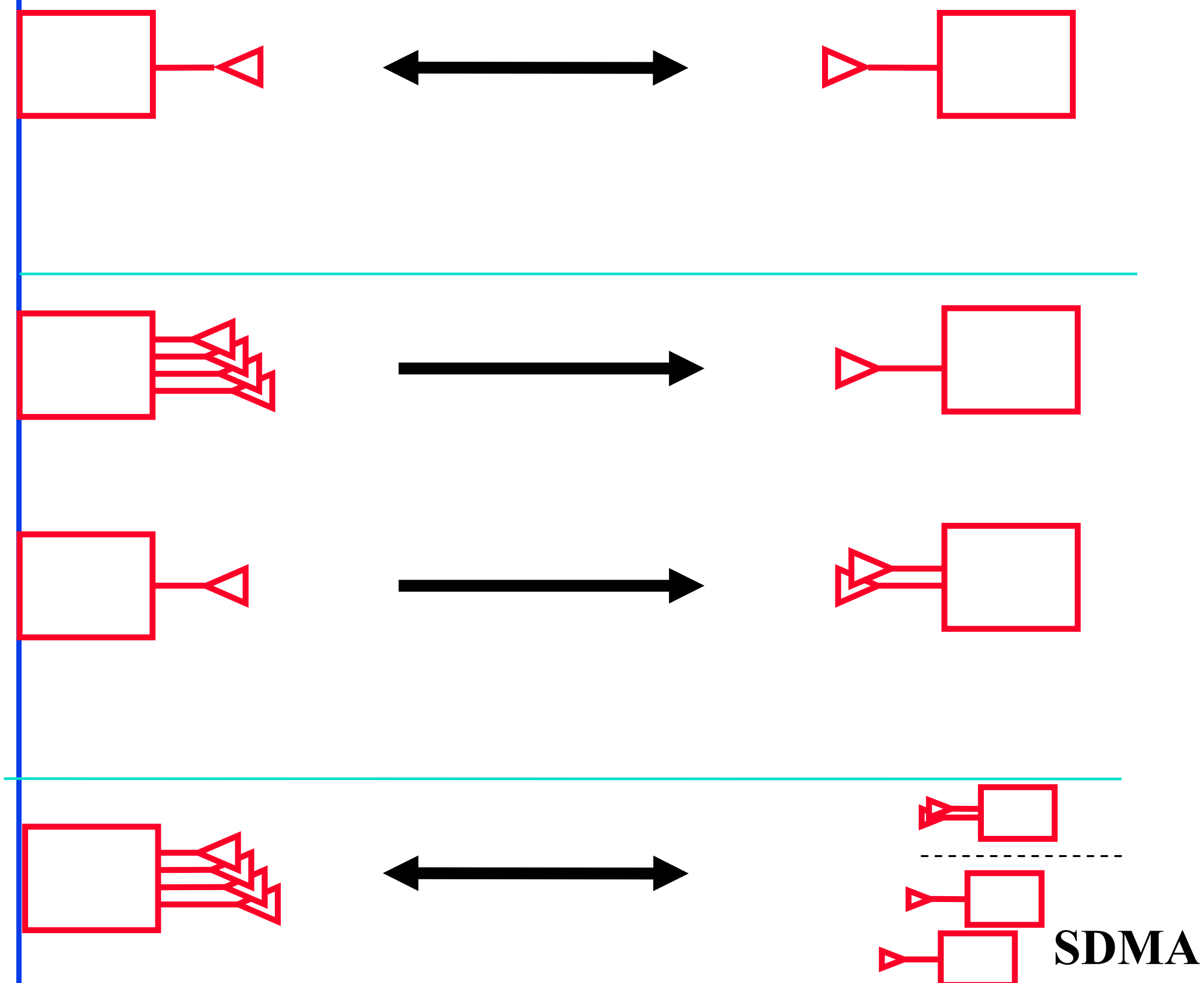






Example: Simple Selection Diversity (Rx only), Diversity Gains

SISO, MISO, SIMO, MIMO, SDMA…



SISO

- Single Input, Single Output

MISO

- Multiple Input, Single Output

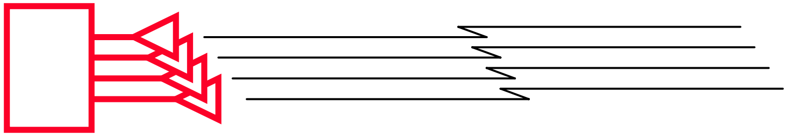
SIMO

- Single Input, Multiple Output

MIMO

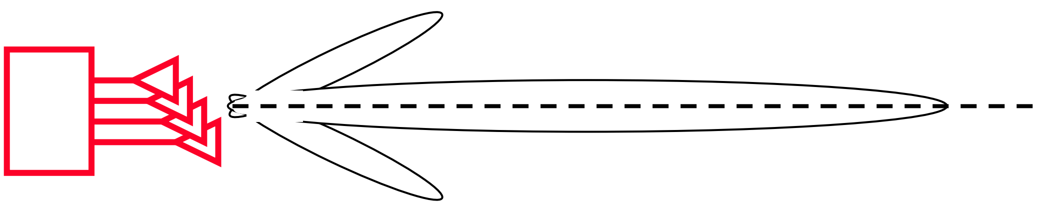
- Multiple Input, Multiple Output

Adaptive Antenna Gains (Tx or Rx)



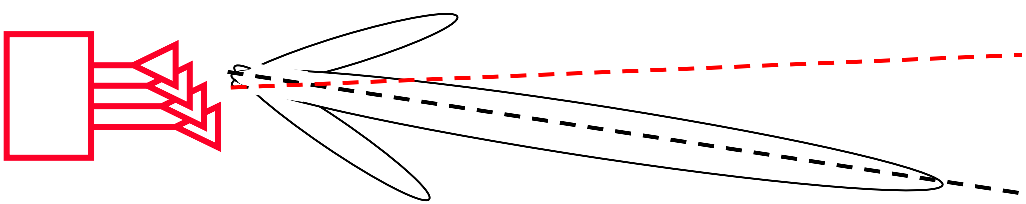
Diversity

- differently fading paths
- fading margin reduction
- no gain when noise-limited



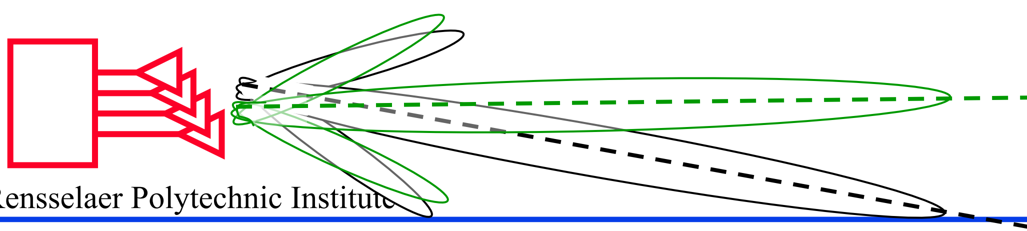
Coherent Gain

- energy focusing
- improved link budget
- reduced radiation



Interference Mitigation

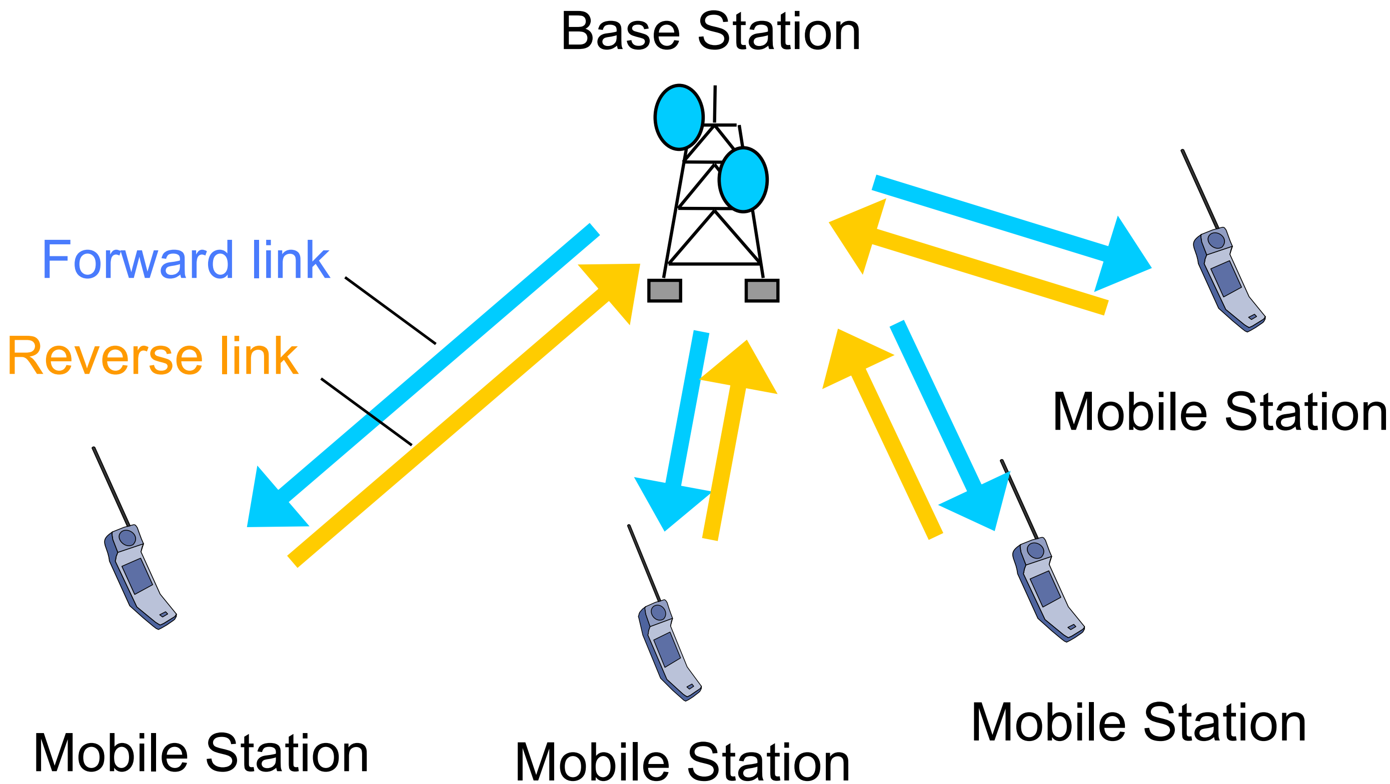
- energy reduction
- enhanced capacity
- improved link budget



Enhanced Rate/Throughput

- co-channel streams
- increased capacity
- increased data rate

Multiple Access Control (MAC)



MAC Protocols: a taxonomy

- **Channel <u>Partitioning:</u> TDMA, FDMA**
  - divide channel into "pieces" (time slots, frequency)
  - allocate piece to node for exclusive use

- **<u>Random</u> Access: Aloha, Ethernet CSMA/CD, WiFi CSMA/CA**
  - allow collisions
  - "recover" from collisions
  - Wireless: inefficiencies arise from hidden terminal problem, residual interference
    - Cannot support large numbers of users and at high loads

- **"Taking <u>turns</u>": Token ring, distributed <u>round-robin,</u> CDMA, polling**
  - Coordinate shared access using turns to avoid collisions.
  - Achieve statistical multiplexing gain & large user base, but ↑ complexity
  - CDMA can be loosely classified here (orthogonal code = token)
  - OFDMA w/ scheduling also in this category

MAC protocols taxonomy (contd)

Channel partitioning MAC protocols:

- share channel efficiently at high load
- inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!

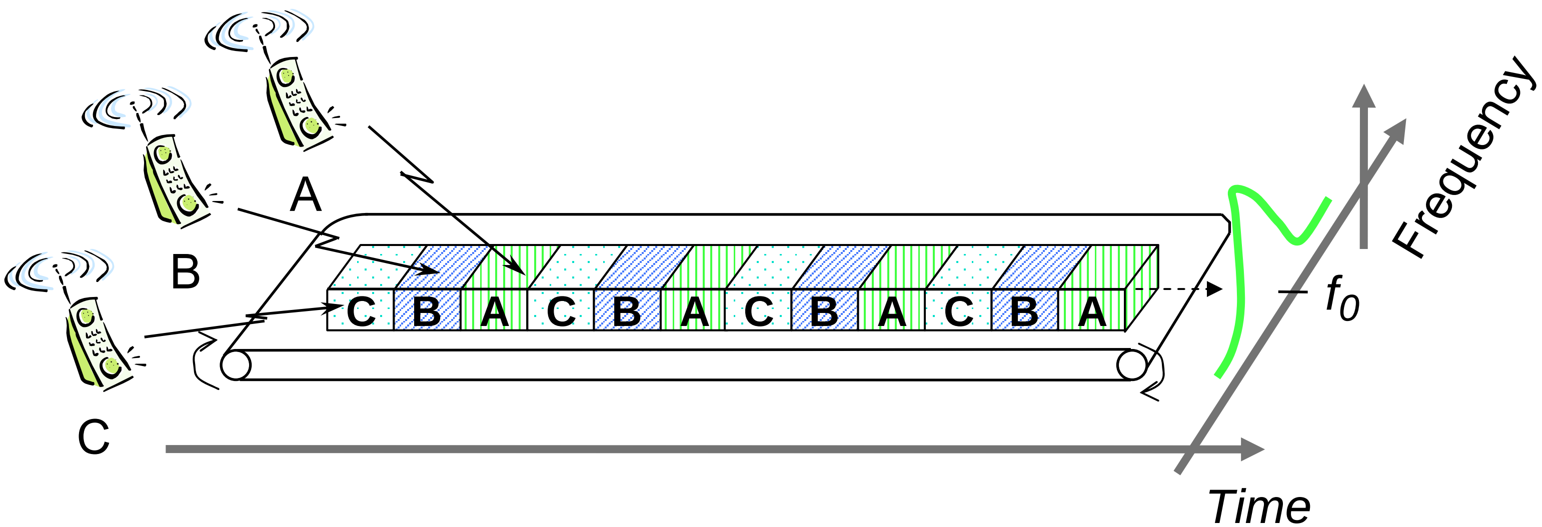
Random access MAC protocols

- efficient at low load: single node can fully utilize channel
- high load: collision overhead

"Taking turns" protocols

look for best of both worlds!

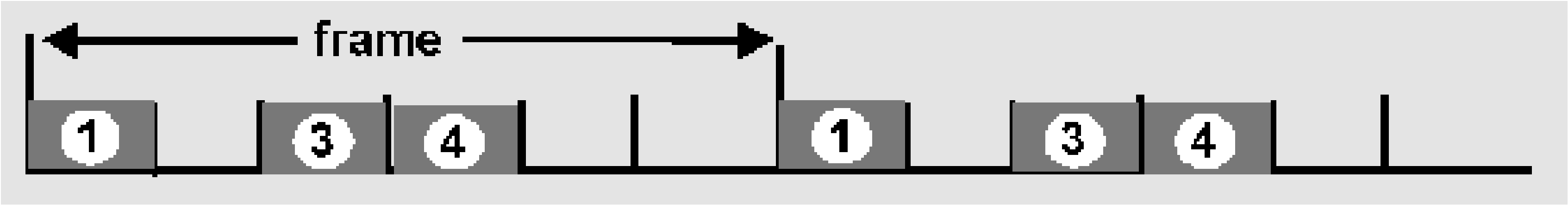
TDMA Overview



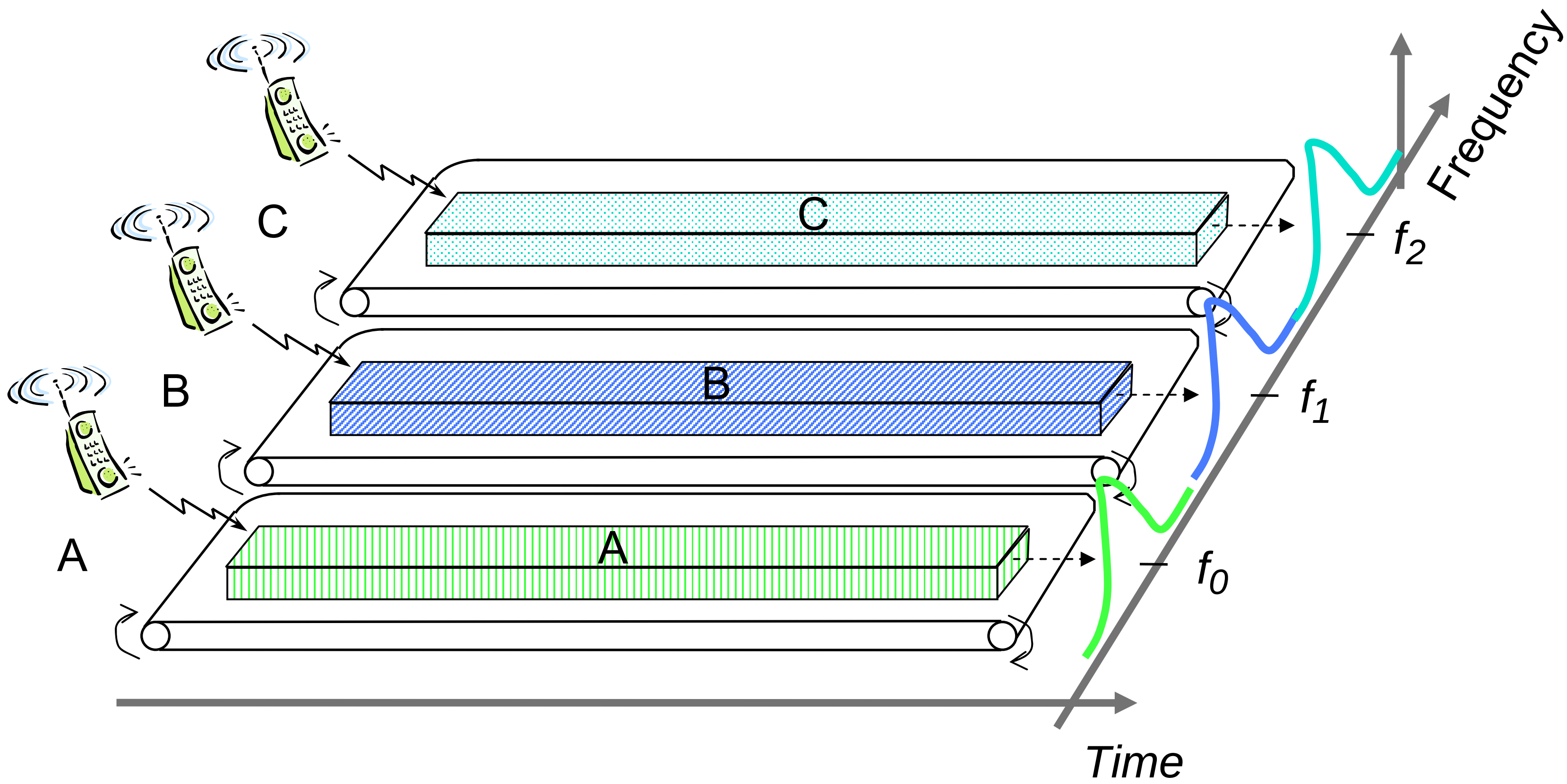
Channel Partitioning MAC protocols. Issues

TDMA: time division multiple access

- Access to channel in "rounds"
- Each station gets fixed length slot (length = pkt trans time) in each round
- *Unused slots go idle*
- Example: 6-station LAN, 1,3,4 have pkt, slots 2,5,6 idle
- Does not leverage *statistical* multiplexing gains here

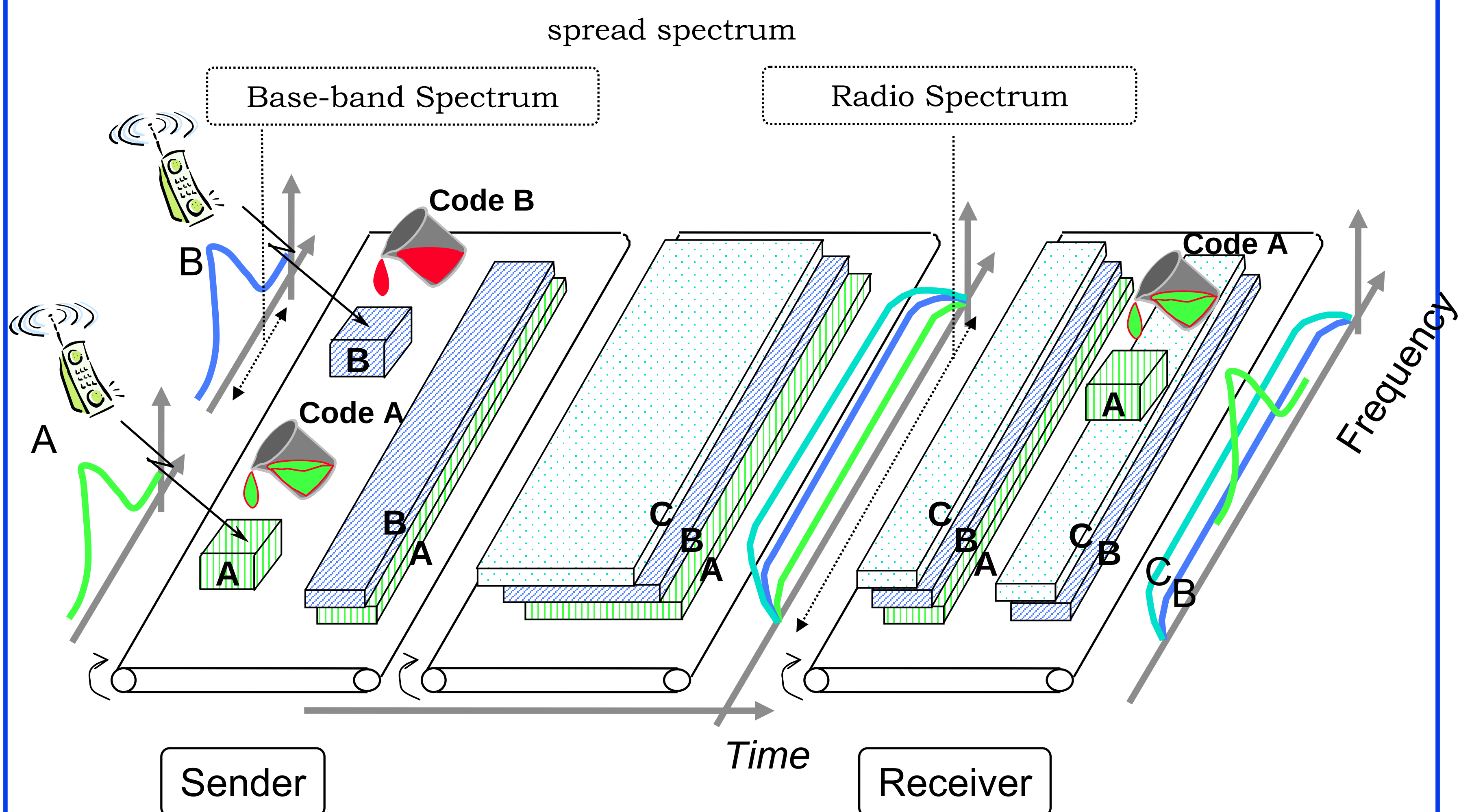


FDMA Overview

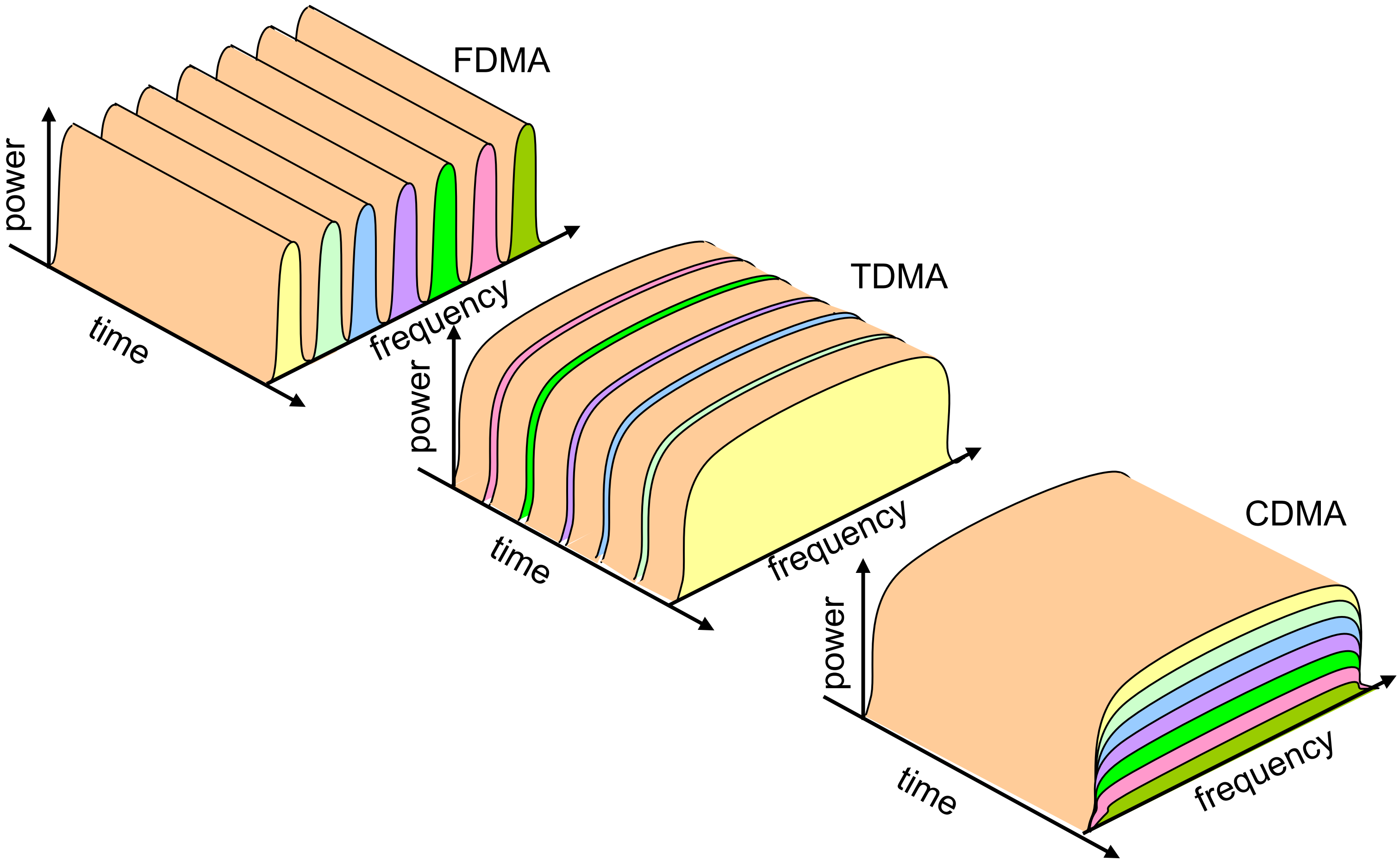


Need substantial guard bands: inefficient

CDMA


spread spectrum
Base-band Spectrum
Radio Spectrum
Code B
B
B
Code A
A
A
B
A
C
B
A
C
B
A
C
B
A
Code A
C
B
Frequency
Time
Sender
Receiver

Summary of Multiple Access



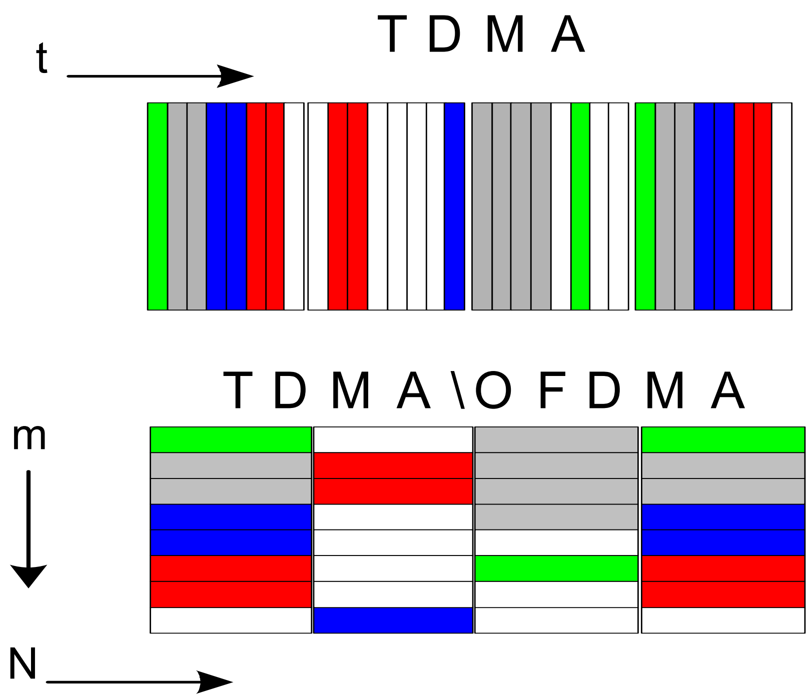
OFDMA

OFDMA: a mix of FDMA/TDMA: (OFDM modulation)

Sub Channels are allocated in the Frequency Domain,

OFDM Symbols allocated in the Time Domain.

Dynamic scheduling leverages statistical multiplexing gains, and allows adaptive modulation/coding/power control, user diversity



WLAN vs WMAN:

What's Really Different?
Comparison of Issues/Features

Scalability

802.11	802.16a
❑Wide, fixed (20MHz) frequency channels ❑MAC designed to support 10's of users	❑Channel bandwidths can be chosen by operator (e.g. for sectorization) ❑1.5 MHz to 20 MHz width channels. MAC designed for scalability independent of channel bandwidth ❑MAC designed to support thousands of users.

802.16a is designed for subscriber density

Bit Rate: Relative Performance

	Channel Bandwidth	Maximum Data Rate	Maximum bps/Hz
802.11a	20 MHz	54 Mbps	~2.7 bps/Hz
802.16a	10, 20 MHz; 1.75, 3.5, 7, 14 MHz; 3, 6 MHz	**63 Mbps***	~5.0 bps/Hz

* Assuming a 14 MHz channel

802.16a is designed for *metropolitan* performance

Interesting rule of thumb: the actual capacity (Mbps per channel per sector) in a multi-cell environment for most wireless technologies is about 20% to 30% of the peak theoretical data rate.

Adaptive Modulation/Coding

Modulation / Code Rate	QPSK 1/2	QPSK 3/4	16 QAM 1/2	16 QAM 3/4	64 QAM 2/3	64 QAM 3/4
1.75 MHz	1.04	2.18	2.91	4.36	5.94	6.55
3.5 MHz	2.08	4.37	5.82	8.73	11.88	13.09
7.0 MHz	4.15	8.73	11.64	17.45	23.75	26.18
10.0 MHz	8.31	12.47	16.63	24.94	33.25	37.40
20.0 MHz	16.62	24.94	33.25	49.87	66.49	74.81

Rate Calculator

Bandwidth (MHz)	Oversampling	Code Rate	Modulation Density	Guard Time	Bit Rate (Mbps)
5.00	**1 1/7**	**3/4**	**6**	**1/32**	**18.70**

Coverage

802.11	802.16a
❑ Optimized for indoor performance ❑ No mesh topology support within ratified standards	❑ Optimized for outdoor NLOS performance ❑ Standard supports mesh network topology ❑ Standard supports advanced antenna techniques

802.16a is designed for market coverage

Range

802.11	802.16a
❑ Optimized for ~100 *meters*	❑ Optimized for up to 50 Km
❑ No "near-far" compensation	❑ Designed to handle many users spread out over kilometers
❑ Designed to handle indoor multi-path (delay spread of 0.8μ seconds)	❑ Designed to tolerate greater multi-path delay spread (signal reflections) up to 10.0μ seconds
❑ Optimization centers around PHY and MAC layer for 100m range	❑ PHY and MAC designed with multi-mile range in mind
❑ Range can be extended by cranking up the power – but MAC may be non-standard	❑ Standard MAC; Sectoring/MIMO/AMC for Rate/Range dynamic tradeoff

802.16a is designed for distance

Quality of Service (QoS)

802.11	802.16a
❑ Contention-based MAC (CSMA/CA) => no guaranteed QoS	❑ Grant-request MAC
❑ Standard cannot currently guarantee latency for Voice, Video	❑ Designed to support Voice and Video from ground up
❑ Standard does not allow for differentiated levels of service on a per-user basis	❑ Supports differentiated service levels: e.g. T1 for business customers; best effort for residential.
❑ TDD only – asymmetric	❑ TDD/FDD/HFDD – symmetric or asymmetric
	❑ Centrally-enforced QoS
❑ 802.11e (proposed) QoS is prioritization only	

802.16a is designed for carrier class operation

QoS Requirements: Voice vs Data

- **Voice** systems have relatively low data rate requirements (around 20 Kbps) and can tolerate a fairly high probability of bit error (bit error rates, or BERs, of around 10^{-3}), but the total delay must be less than around 30 msec or it becomes noticeable to the end user.
- On the other hand, **data** systems typically require much higher data rates (1-100 Mbps) and very small BERs (the target BER is 10^{-8} and all bits received in error must be retransmitted) but do not have a fixed delay requirement.

Security

802.11	802.16a
❑ Existing standard is WPA + WEP ❑ 802.11i in process of addressing security	❑ Triple-DES (128-bit) and RSA (1024-bit)

802.16a maintains fixed wireless security

802.11 vs 802.16: *Summary*

802.11 and 802.16 both gain broader industry acceptance through conformance and interoperability by multiple vendors

802.16 *complements* 802.11 by creating a complete MAN-LAN solution

- **802.11 is optimized for license-exempt LAN operation**
- **802.16 is optimized for license-exempt *and licensed* MAN operation.**

Status of Wireless Broadband Today

- Despite many promising technologies, the reality of a ***wide-area network*** that …

  … services ***many users*** at ***high data rates*** …

  …. (***fixed and mobile***) …

  … with ***reasonable bandwidth and power resources***…

  … while maintaining ***high coverage*** and ***quality of service***

  ….. <u>has not yet been achieved</u>.

  – J. Andrews, A. Ghosh, R. Muhamed (Fundamentals of WIMAX, **<u>2007, to appear</u>**)