White Spaces Regulations and Standards

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Introducing TV White Spaces

- Allocated spectrum under 3 GHz has significant unused capacity at any given space and time
  - Shared Spectrum Company, NSF funded measurements, http://www.sharedspectrum.com/measurements
- The economic potential for the TV white spaces was estimated at $100 billion
  - R. Thanki, “The economic value generated by current and future allocations of unlicensed spectrum,” http://www.ingeniousmedia.co.uk/websitefiles/Value_of_unlicensed_-_website_-_FINAL.pdf
- Modern technology allows effective sharing of sparsely used TV broadcast spectrum
- In 2004, the FCC started investigating the potential of allowing operation of unlicensed 2-way data communications in the TV broadcast VHF and UHF bands

TVBD
TV Band Device

History and Regulatory Landscape

- NPRM in May 2004
  - http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-113A1.pdf
- November 4, 2008 FCC approved Report & Order 08-260, allowing unlicensed use of TV band spectrum
  - http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-01-260A1.pdf
- On February 17, 2009, the FCC released the final rules for “Unlicensed Operation in the TV Broadcast Bands”
  - http://edocket.access.gpo.gov/2009/pdf/E9-3279.pdf
- Ofcom (UK) is in the process of making this Digital Dividend band available
  - https://mentor.ieee.org/802.18/dcn/09/18-09-0059-00-0000-ofcom-update-on-the-digital-dividend.ppt
- ECC of CEPT in Europe is conducting consultation on the band; first report due May 2010
- China TV band regulations expected in 2015

ECC = Electronic Communications Committee
CEPT = European Conference on Postal and Telecommunications
NPRM = Notice of Proposed Rule Making

Frequency Allocation of TV Channels

	Channel #	Frequency Band	
Fixed TVBDs only	2-4	54-72 MHz	VHF
	5-6	76-88 MHz	
	7-13	174-216 MHz	
	14-20	470-512 MHz**	UHF
	21-51*	512-692 MHz	

*Channel 37 (608-614 MHz) is reserved for radio astronomy
**Shared with public safety
http://www.fcc.gov/mb/engineering/usallochrt.pdf

Transition from NTSC to ATSC (analog to digital TV) in June 12, 2009 freed up channels 52-69 (above 692 MHz)

NTSC = National Television System Committee
ATSC = Advanced Television Systems Committee

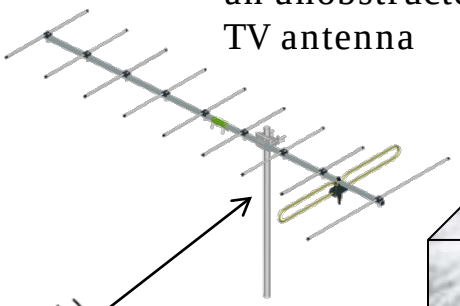
Operation in the TV Bands Final Rules

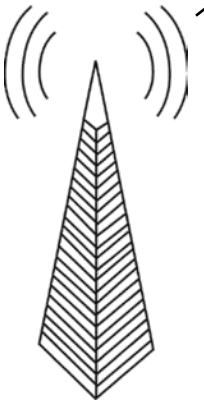
- Unlicensed Operation in the TV Broadcast Bands, Final Rules (http://edocket.access.gpo.gov/2009/pdf/E9-3279.pdf) states that …
- TVBDs are divided into two categories: Fixed and Personal/portable (PP)
- Fixed TVBDs
  - Operate from a known, fixed location and can use a transmit power of up to 4 W EIRP
  - Required to have a geolocation capability, capability to retrieve list of available channels from an authorized database and a spectrum sensing capability.
  - Can only operate on channels that are not adjacent to an incumbent TV signal in any channel between 2 and 51 except channels 3, 4, and 37
- Personal/portable devices
  - Restricted to channels 21 – 51 (except Channel 37)
  - Maximum EIRP of 100 mW on non-adjacent channels and 40 mW on adjacent channels
  - Divided into 2 types: Mode I and Mode II. Mode I devices do not need geolocation capability or access to a database but must have sensing capability. Mode II devices, like fixed devices, must have geolocation, database access and sensing.
- Fixed and personal portable (PP) devices must sense TV broadcasting and wireless microphone signals

Appears impractical

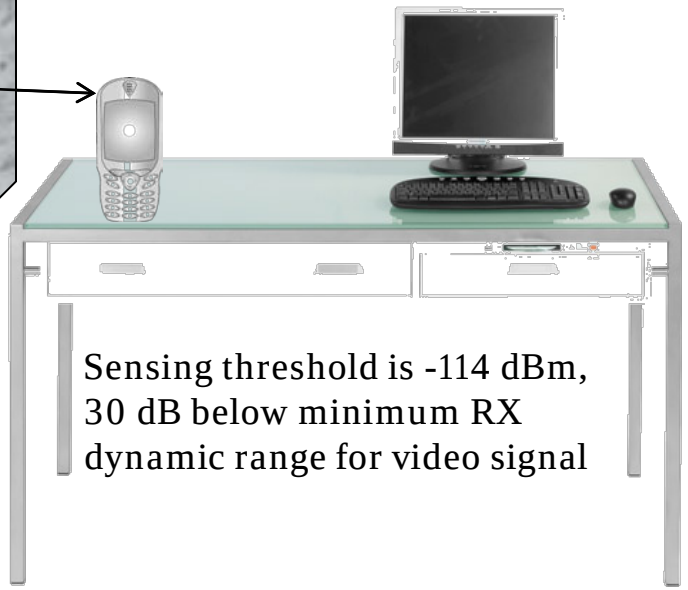
Hidden Node Scenario and Sensing

TV broadcast received by an unobstructed rooftop TV antenna





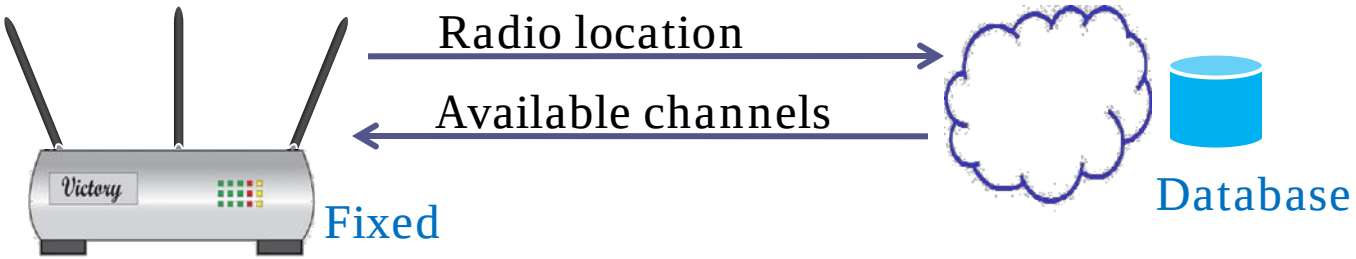
TV signal attenuated by an obstruction (wall) is undetectable by a TVBD. TVBD transmits, interfering with TV broadcast, which is received unobstructed by a rooftop antenna.



Sensing threshold is -114 dBm, 30 dB below minimum RX dynamic range for video signal

Database

- Fixed TVBDs require geolocation capability and Internet access to a database of protected radio services.
- *White Spaces Database Group* was started by Google and other companies to create and standardize the database.
- Database related proposals to the FCC:
  - http://fjallfoss.fcc.gov/ecfs/comment_search/execute?proceeding=04-186&applicant=&lawfirm=&author=&disseminated.minDate=&disseminated.maxDate=&recieved.minDate=1%2F6%2F09&recieved.maxDate=&address.city=&address.state.stateCd=&address.zip=&daNumber=&fileNumber=&submissionTypeId=&__checkbox_exParte=true



PP

www.showmywhitespace.com

Search Results For:

225 Cedar Hill Street, Marlborough, MA 01752

Available Channels

2	✓	12	✗	22	✓	32	✗	42	✗
3	✗	13	✗	23	✗	33	✓	43	✗
4	✗	14	✗	24	✓	34	✓	44	✗
5	✓	15	✗	25	✓	35	✗	45	✓
6	✓	16	✗	26	✗	36	✗	46	✓
7	✗	17	✗	27	✗	37	✗	47	✗
8	✓	18	✗	28	✓	38	✗	48	✓
9	✗	19	✗	29	✗	39	✗	49	✗
10	✗	20	✗	30	✗	40	✗	50	✓
11	✓	21	✗	31	✗	41	✗	51	✗

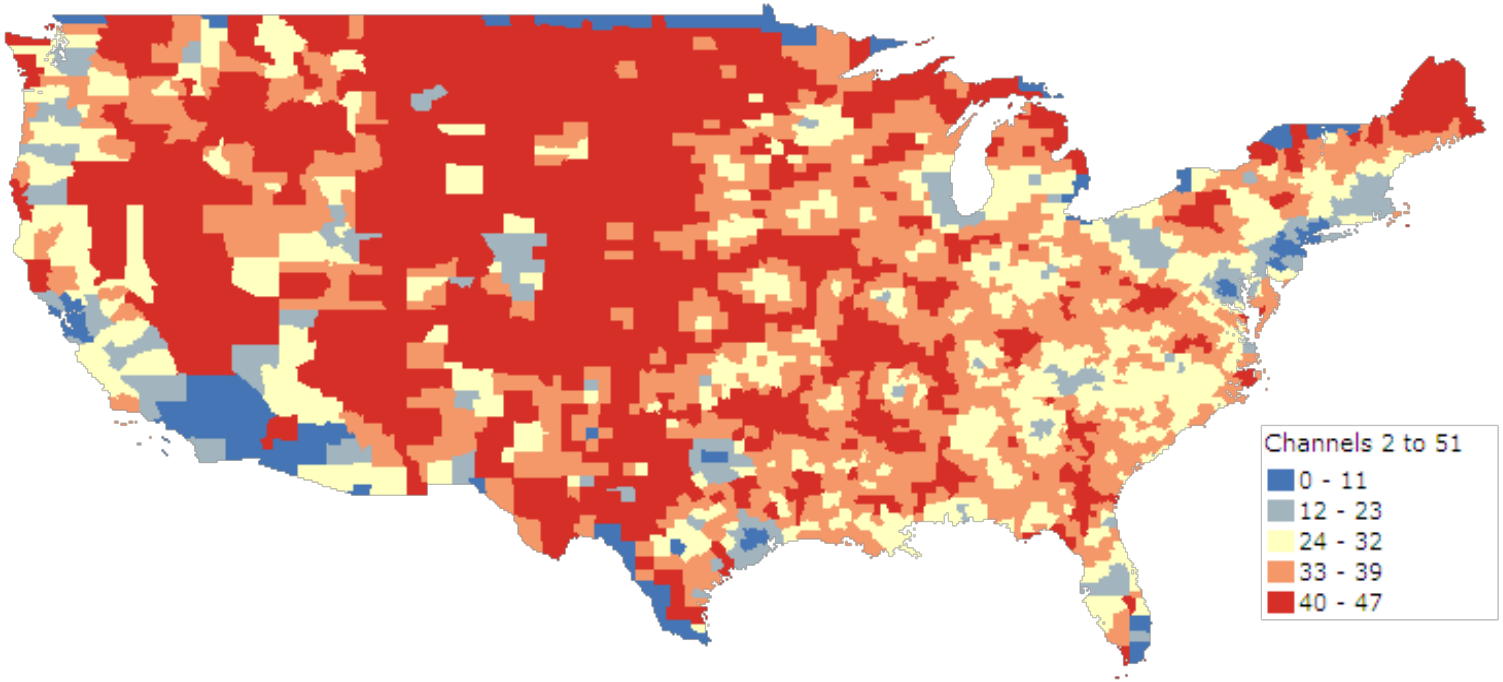
Maintained by Spectrum Bridge

Fixed TVBDs only

Fixed or PP TVBDs

Taking Advantage of TV White Spaces

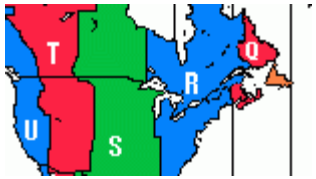
- Channel availability based on the geolocation query of TV band internet database



Source: Rick Tornado, Spectrum Bridge

Secondary Market for Licensed TV Band and other Bands?

- FCC has been petitioned by Spectrum Bridge and other companies to allow dynamic bandwidth allocation – short term leases of TV bands or ‘owned spectrum’ (references on next slide)
  - Database driven auction for spectrum
- Dynamic allocation per
  - Geographic region
  - Frequency channels
  - Time



US TV Band Proposals to FCC

- Comsearch
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355190
- Key Bridge Global
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020356596
- WSdb
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355170
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355171
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- Spectrum Bridge
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355177
- NeuStar
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355229
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355230
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355231
- Key Bridge Enterprises
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355219
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- Google
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355207
- Frequency Finder
  - http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355224

IEEE TV Band Related Standards

- **802.11af** – formed in January 2010 to adapt 802.11 to TV band operation
- **802.16h** – originally organized to adapt 802.16 to the 3650-3700 MHz contention band (see next slide), now also working on TV band operation of 802.16
- **802.22** – cognitive radio approach
  - Regional Area Networks group that guided the FCC in the recent TV band regulations
  - Uses spectrum sensing and location information to determine whether given transmit frequencies and power levels will cause harmful interference to licensed services.
- **802.19** TAG – defines coexistence among dissimilar networks that will operate in the TV band
- **SCC 41** – defines layers above the MAC and PHY for dynamic spectrum access networks

TAG = technical advisory group

Lightly Regulated Band

- March 2005 FCC offered 50 MHz 3650 to 3700 MHz for *contention-based protocol*
- 802.11y and 802.16h are expected to share this band
- 21st century regulation geared for digital communications
  - multiple services to share the band in an orderly way

- **300 Million licenses one for every person or company**
- **$300 per license for 10 years**
- **Registered stations (base stations): 1 W/MHz, ~15 km**
- **Unregistered stations (handsets, laptops): 40 mW/MHz, 1-1.5 km**

802.11af – TVBD Amendment

- The goal is to keep new amendment as simple as possible – a few changes to make .11 work in TV bands; capitalize on work already done in 802.11y
- About 15 pages / 2 years to approval

  Use the OFDM PHYs with 5-, 10- and 20-MHz channel widths to specify the basis for a system that the regulators can approve for operation in the TV white spaces bands.

- Focus engineering effort on well defined regulatory domains (Canada, US, EU,...)

802.11af Focus

- Re-banding of the popular 802.11 systems
- FCC EIRP: 4 W, 100 mW, 50 mW
- Possible deployment scenarios
  - Indoor (< 100 m): like present WLAN
  - Outdoor (< 5 Km): comparable to the range of typical urban model
- Database is considered out of scope of 802.11af
  - 802.18 will generate output documents for FCC Database Managers public notice and Ofcom Geolocation for Cognitive Access consultation on Thursday
  - Joint effort involving 802.11/19/22

Ecma and CogNeA TV Band Standard

- Ecma International TC48-TG1 is developing PHY-MAC and coexistence protocols for wireless networks in the TV band http://www.ecma-international.org/memento/TC48-TG1.htm
- Sponsor Organization: Ecma International (http://www.ecma-international.org) and CogNeA (http://www.cognea.org)
- CogNeA and Ecma TC48-TG1 standard
  - CogNeA is an industry alliance formed in 2008 to develop a specification for white spaces.
  - In March 2009 the draft/early specification developed by CogNeA was transferred to the Technical Committee 48 – Task Group 1 (TC48-TG1) within Ecma-International
  - http://www.ecma-international.org/publications/files/drafts/tc48-tg1-2009-132.pdf
- Expected adoption by ISO/IEC: Oct. 2010

CogNeA = Cognitive Networking Alliance

Ecma Link Parameters

	Lowest	Highest
Data Rate	4.75 Mbps	23.74 Mbps
Average transmit power	20 dBm	20 dBm
Total path loss (600 MHz)	88 dB (at 1000 m)	68 dB (at 100 m)
Received power/bit	-68 dBm	-48 dBm
Total noise power/bit (with 6 dB Noise Figure)	-101.20 dBm	-94.25 dBm
Required E_b/N_o (BER of 1.0e-6)	3.1 dB	12.52
Fading margin	10 dB	10 dB
Implementation & other losses	14 dB	14 dB
Link Margin	6.09 dB	9.74 dB

- Expected link parameters based on the Ecma standard
  - Source: Ecma white paper, "First Cognitive Radio Networking Standard for Personal/Portable Devices in TV White Spaces", http://www.ecma-international.org/publications/files/drafts/tc48-tg1-2009-132.pdf

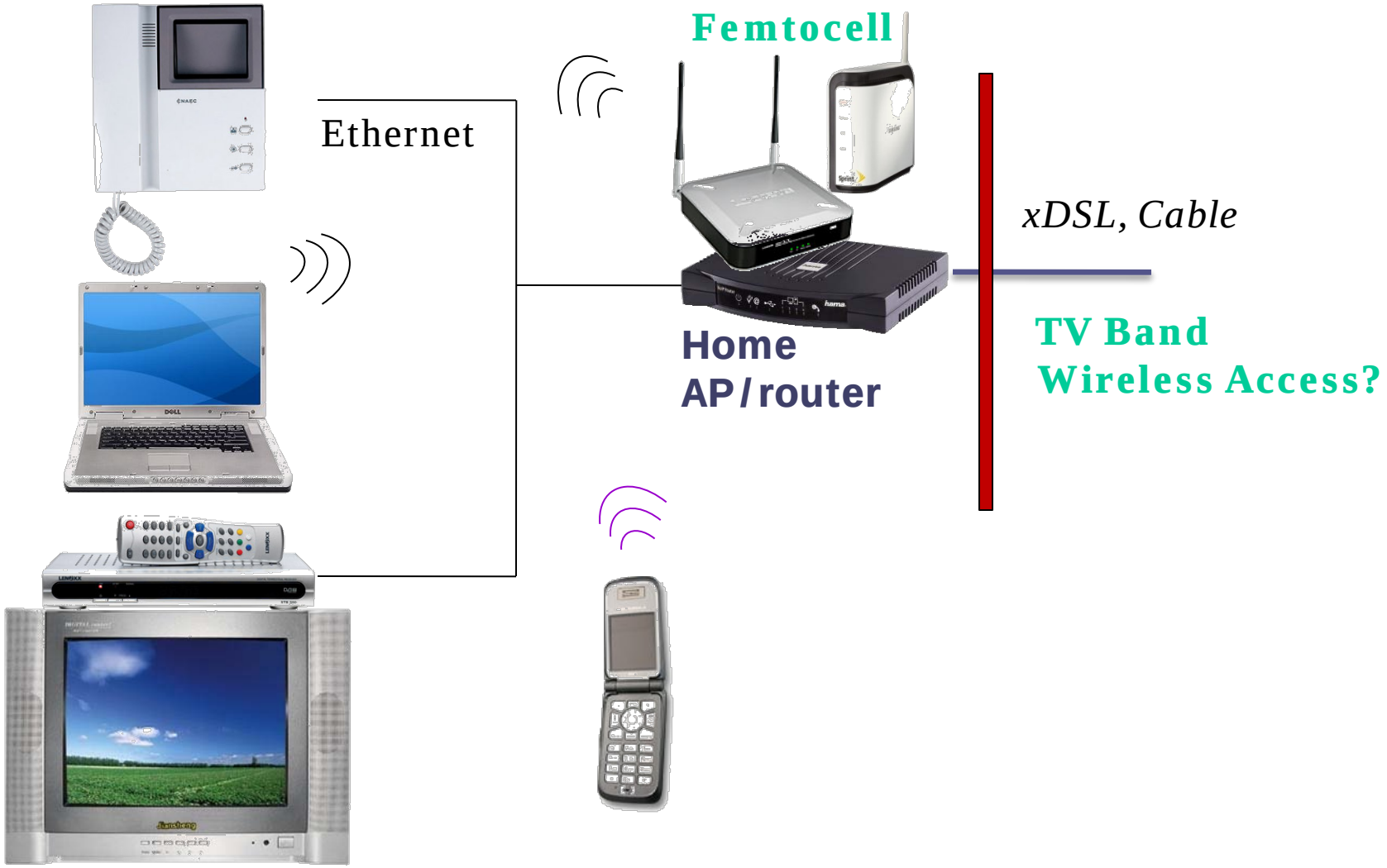
SDR Forum Efforts

- In Home Networking
- WhiteFi (rural ISP service)
- Wireless Control/Sensors (e.g. Smart Grid)
- Secondary Broadcast
- Microcell Broadcast
- Military Equipment
- Public Safety Equipment
- Wi-Fi on Steroids
- Body Area Networks
- Sensor Networks
- TVBD to WiFi Gateway
- Low Data Rate devices with intermittent use

SDR Forum is working with the FCC on test and measurement methodology for white spaces

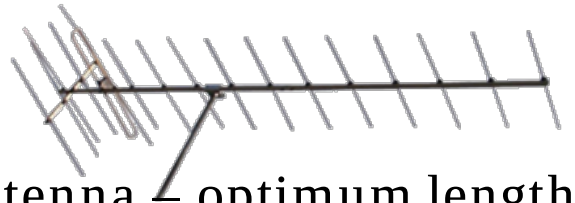
← Use case scenarios the SDR Forum is currently studying

Wireless Use Cases in the Home



VHF/UHF Beach-front Property?

- Lower frequencies experience lower attenuation in free space and through obstructions, e.g. buildings
- However, when propagating through metal frames in modern buildings, Fresnel zone gets constricted and attenuation is introduced

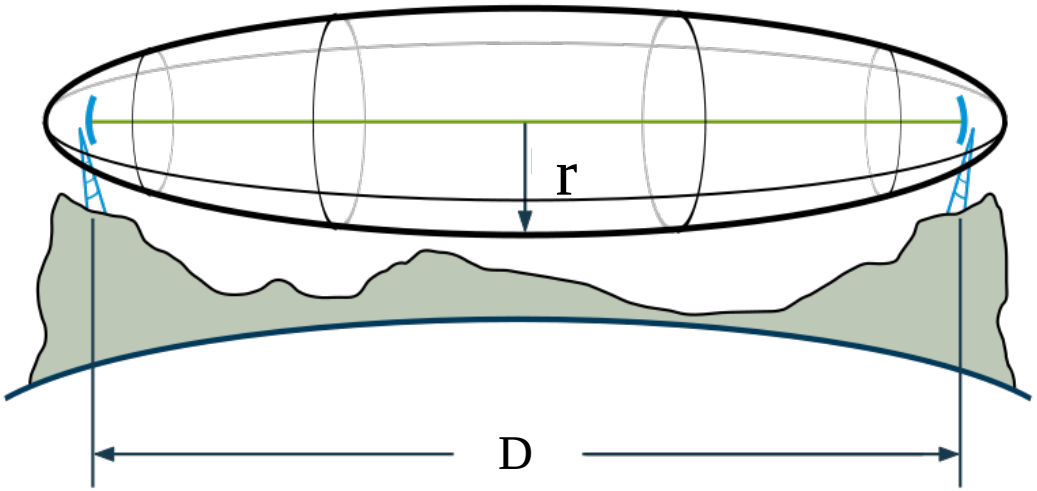


Antenna – optimum length is a multiple of ¼ wavelength

3.3 feet for 70 MHz
4” for 700 MHz
1” for 2.4 GHz

Longer antennas required for UHF may be problematic for handheld devices

Antenna Fresnel Zone



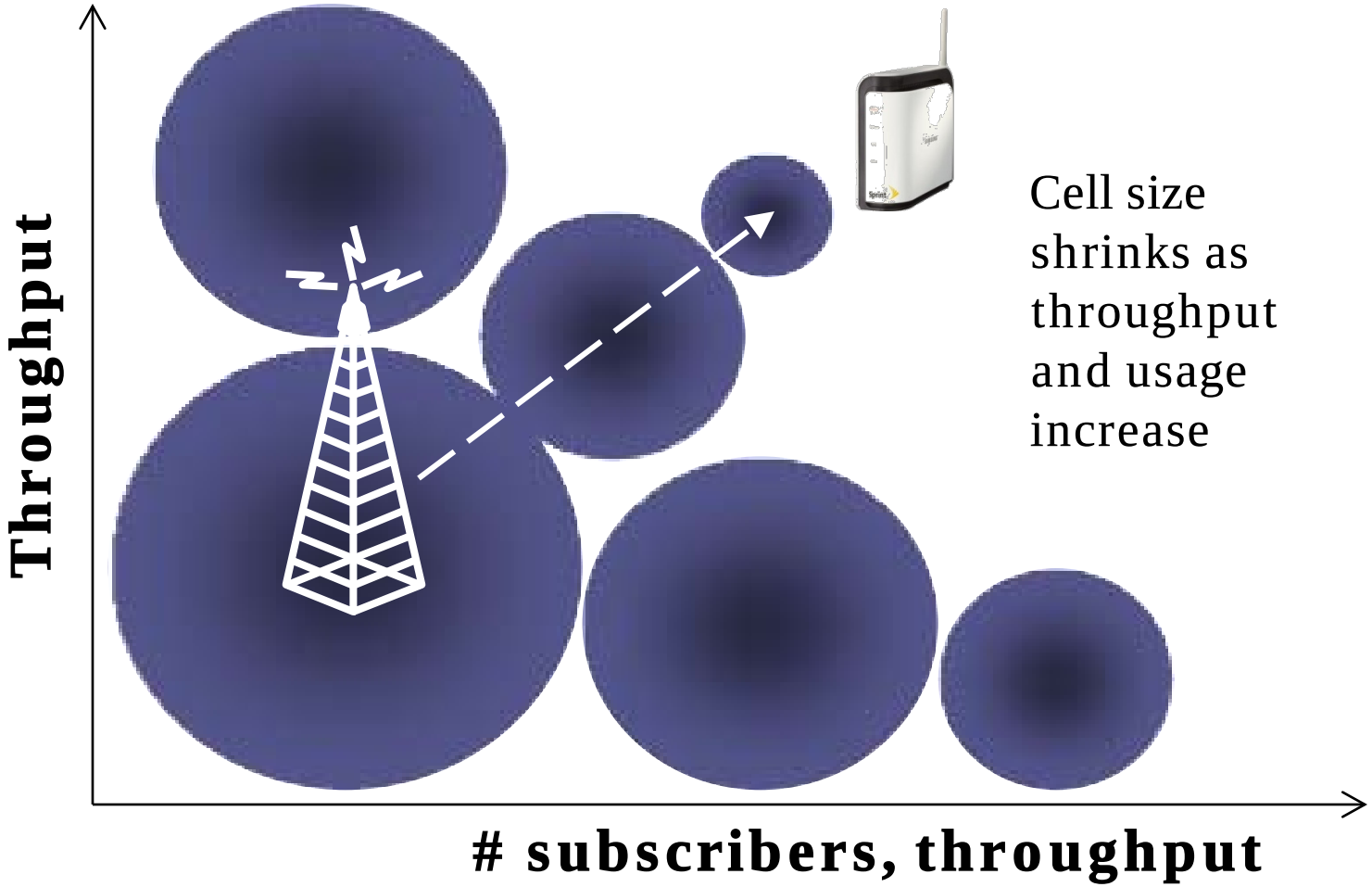
$$r = 72.05\sqrt{\frac{D}{4f}}$$

r = radius in feet
D = distance in miles
f = frequency in GHz

- **Fresnel zone** is the shape of electromagnetic signal and is a function of frequency
- Constricting the Fresnel zone introduces attenuation and signal distortion

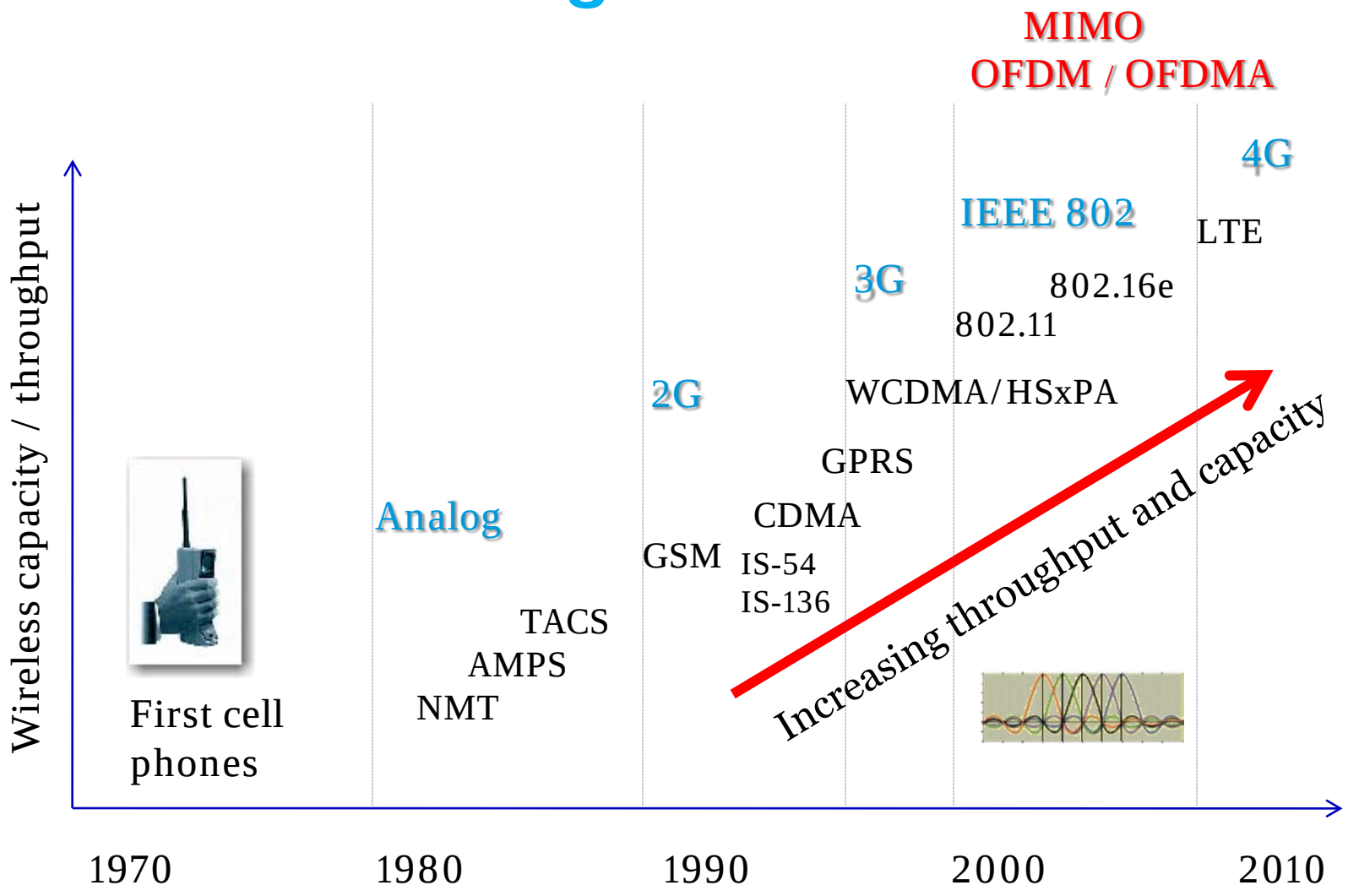
Example: D = 0.5 mile
r = 30 feet for 700 MHz
r = 16 feet for 2.4 GHz
r = 10 feet for 5.8 GHz

Trend is Toward Smaller Cells



Background on Wireless Evolution

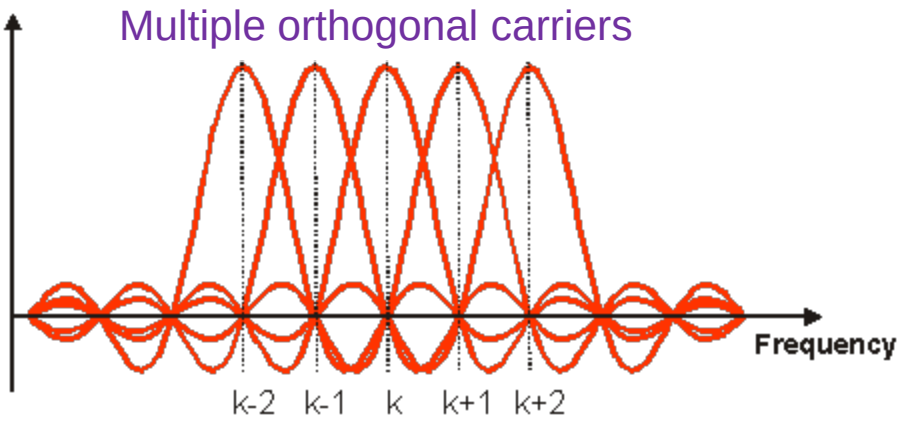
Wireless Technologies



OFDM/OFDMA = orthogonal frequency domain multiplexing / multiple access
MIMO = multiple input multiple output

OFDM (Orthogonal Frequency Division Multiplexing)

ADSL, VDSL
DVB, DAB
MediaFLO
Wi-Fi
WiMAX
LTE

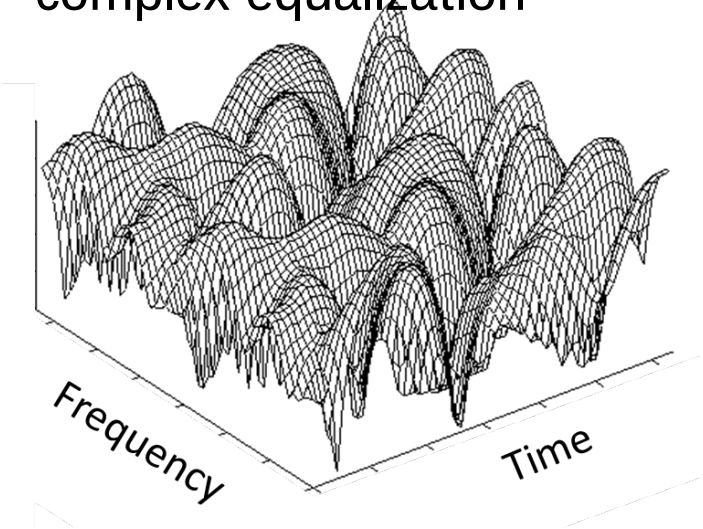


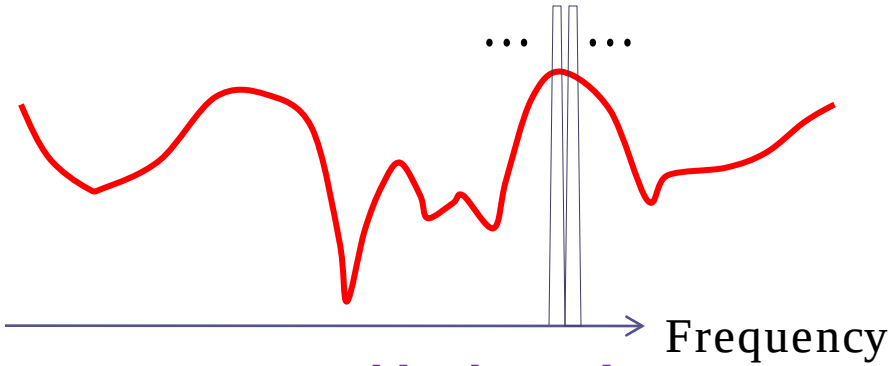
- OFDM is the most robust signaling scheme for a hostile wireless channel
  - Works well in the presence of multipath thanks to multi-tone signaling and cyclic prefix (aka guard interval)
- OFDM is used in all new wireless standards, including
  - 802.11a, g and draft 802.11ac, ad
  - 802.16d,e; 802.22
  - DVB-T, DVB-H, DAD
- LTE is the first 3GPP standard to adopt OFDM

MediaFLO = Media Forward Link Only

OFDM for Frequency- and Time-Variable Channel

- OFDM transforms a frequency- and time-variable fading channel into parallel correlated flat-fading channels, eliminating the need for complex equalization





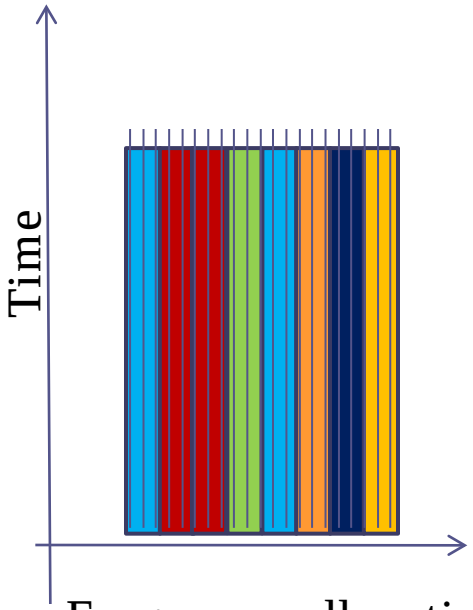
Frequency-variable channel appears flat over the narrow band of an OFDM subcarrier.

OFDM combined with multiple antenna techniques combats time- and frequency-variability of the wireless channel

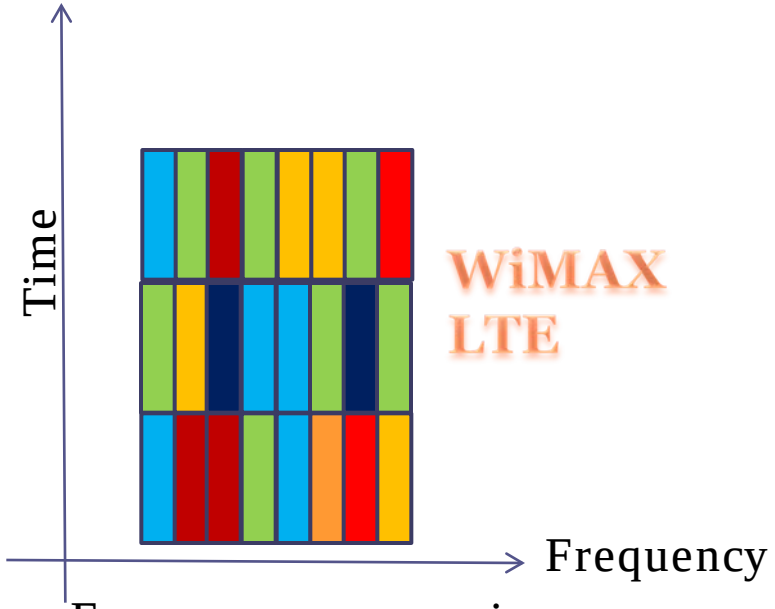
OFDMA (Orthogonal Frequency Division Multiple Access)

OFDM is a modulation scheme

OFDMA is a modulation and access scheme



Frequency allocation per user is continuous vs. time



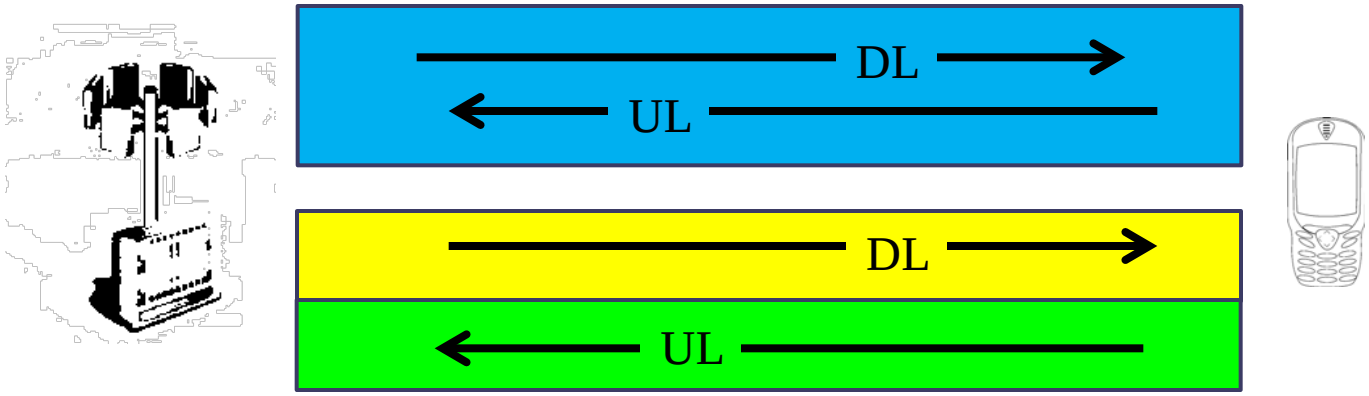
WiMAX
LTE

Frequency per user is dynamically allocated vs. time slots

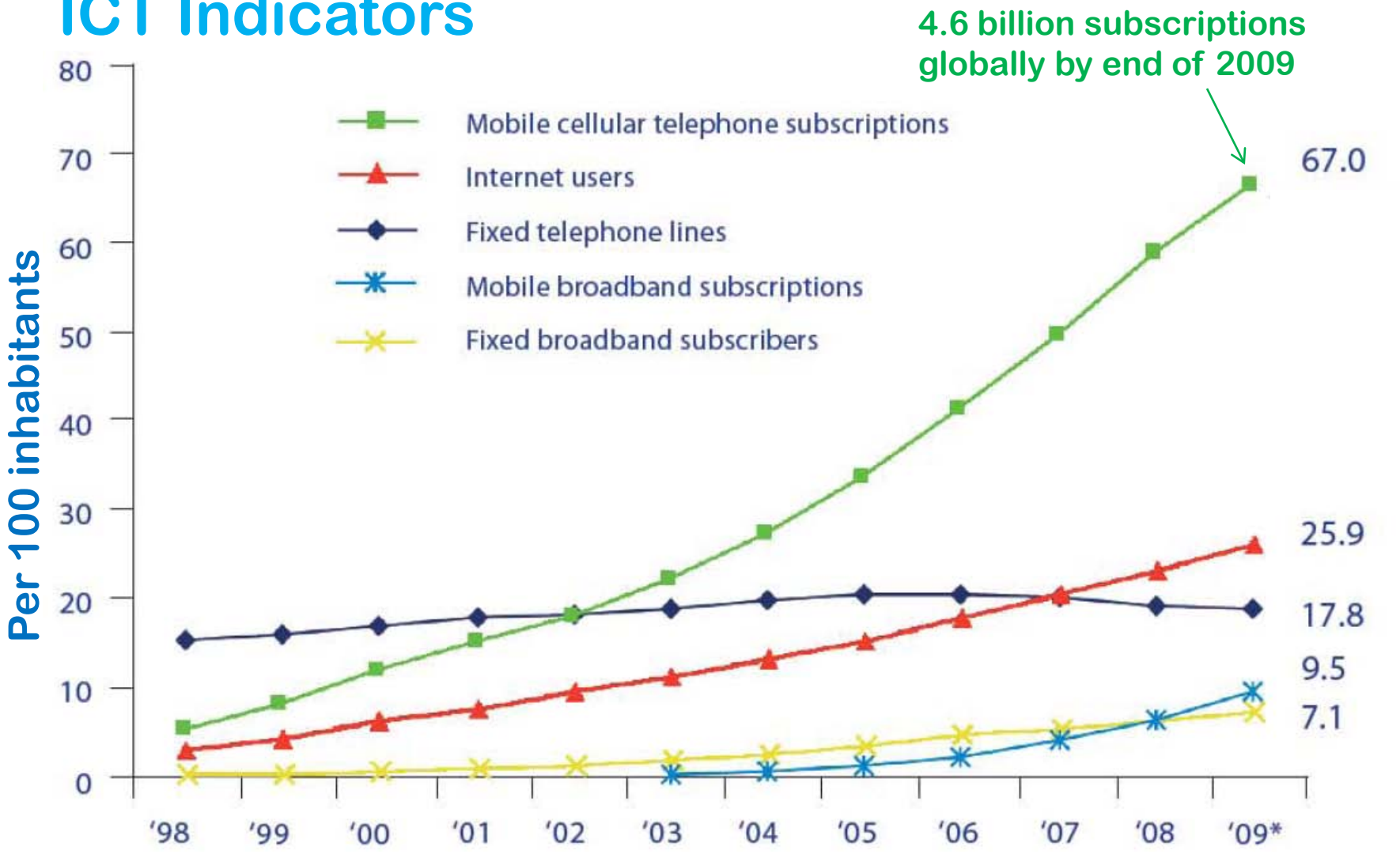
User 1	User 2	User 3	User 4	User 5

FDD and TDD Support

- FDD (frequency division duplex)
  - Paired channels
- TDD (time division duplex)
  - Single frequency channel for uplink an downlink
  - Is more flexible than FDD in its proportioning of uplink vs. downlink bandwidth utilization
  - Can ease spectrum allocation issues



ITU World Telecommunications ICT Indicators



ICT = information and communications technology

ITU International Mobile Telecommunications

- **IMT-2000**
  - Global standard for third generation (3G) wireless communications
  - Provides a framework for worldwide wireless access by linking the diverse systems of terrestrial and satellite based networks.
  - Data rate limit is approximately 30 Mbps
  - Detailed specifications contributed by 3GPP, 3GPP2, ETSI and others

- **IMT-Advanced**
  - New generation framework for mobile communication systems beyond IMT-2000 with deployment around 2010 to 2015
  - Data rates to reach around 100 Mbps for high mobility and 1 Gbps for nomadic networks (i.e. WLANs)
  - IEEE 802.11ac and 802.11ad VHT (very high throughput) working to define the nomadic interface
  - 3GPP working to define LTE and LTE-Advanced high mobility interface and so is IEEE 802.16m

3GPP (3rd Generation Partnership Project)

- Partnership of 6 regional standards groups that translate 3GPP specifications to regional standards
- Defines standards for mobile broadband, including UMTS and LTE

The G's

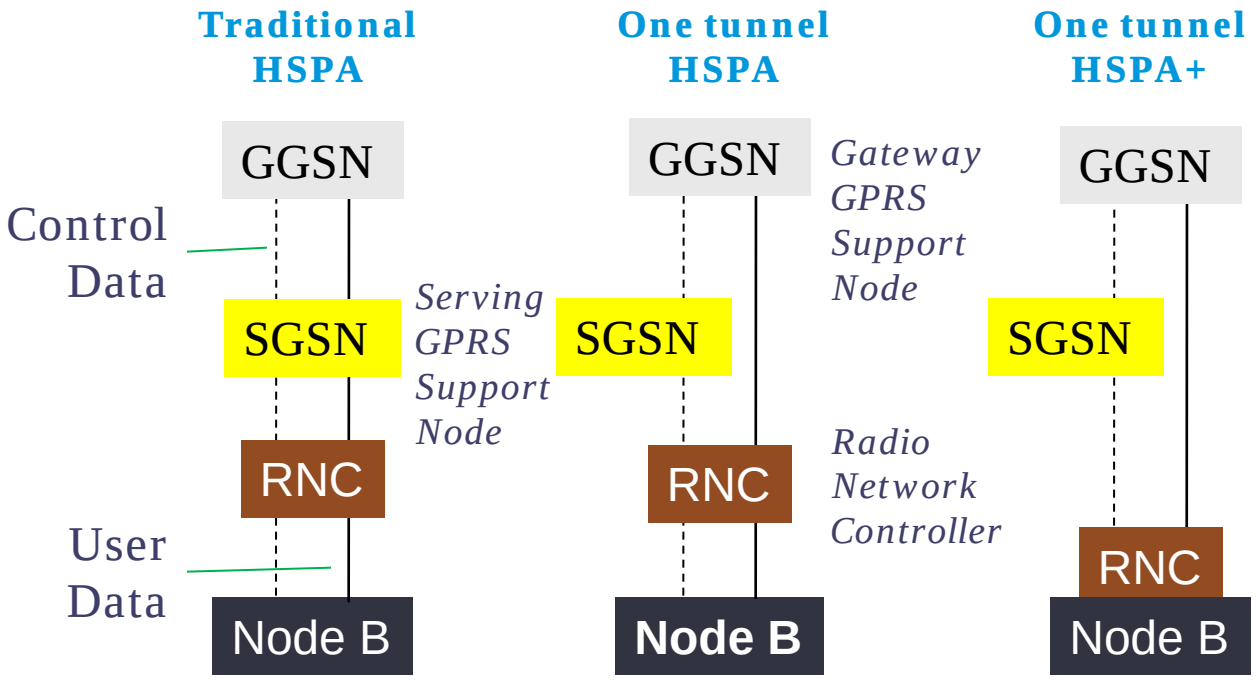
G		Peak Data Rate (Mbps)	
		Downlink	Uplink
1	Analog	19.2 kbps	
2	Digital – TDMA, CDMA	14.4 kbps	
3	Improved CDMA variants (WCDMA, CDMA2000)	144 kbps (1xRTT); 384 kbps (UMTS); 2.4 Mbps (EVDO)	
3.5	HSPA (today)	14 Mbps	2 Mbps
3.75	HSPA (Release 7) DL 64QAM or 2x2 MIMO; UL 16QAM	28 Mbps	11.5 Mbps
	HSPA (Release 8) DL 64QAM and 2x2 MIMO	42 Mbps	11.5 Mbps
3.9	WiMAX Release 1.0 TDD (2:1 UL/DL ratio), 10 MHz channel	40 Mbps	10 Mbps
	LTE, FDD 5 MHz UL/DL, 2 Layers DL	43.2 Mbps	21.6 Mbps
	LTE CAT-3	100 Mbps	50 Mbps

OFDM

Maximum LTE data rates in the 20 MHz channel are 326 Mbps DL (4 streams), 172 Mbps UL (2 streams)

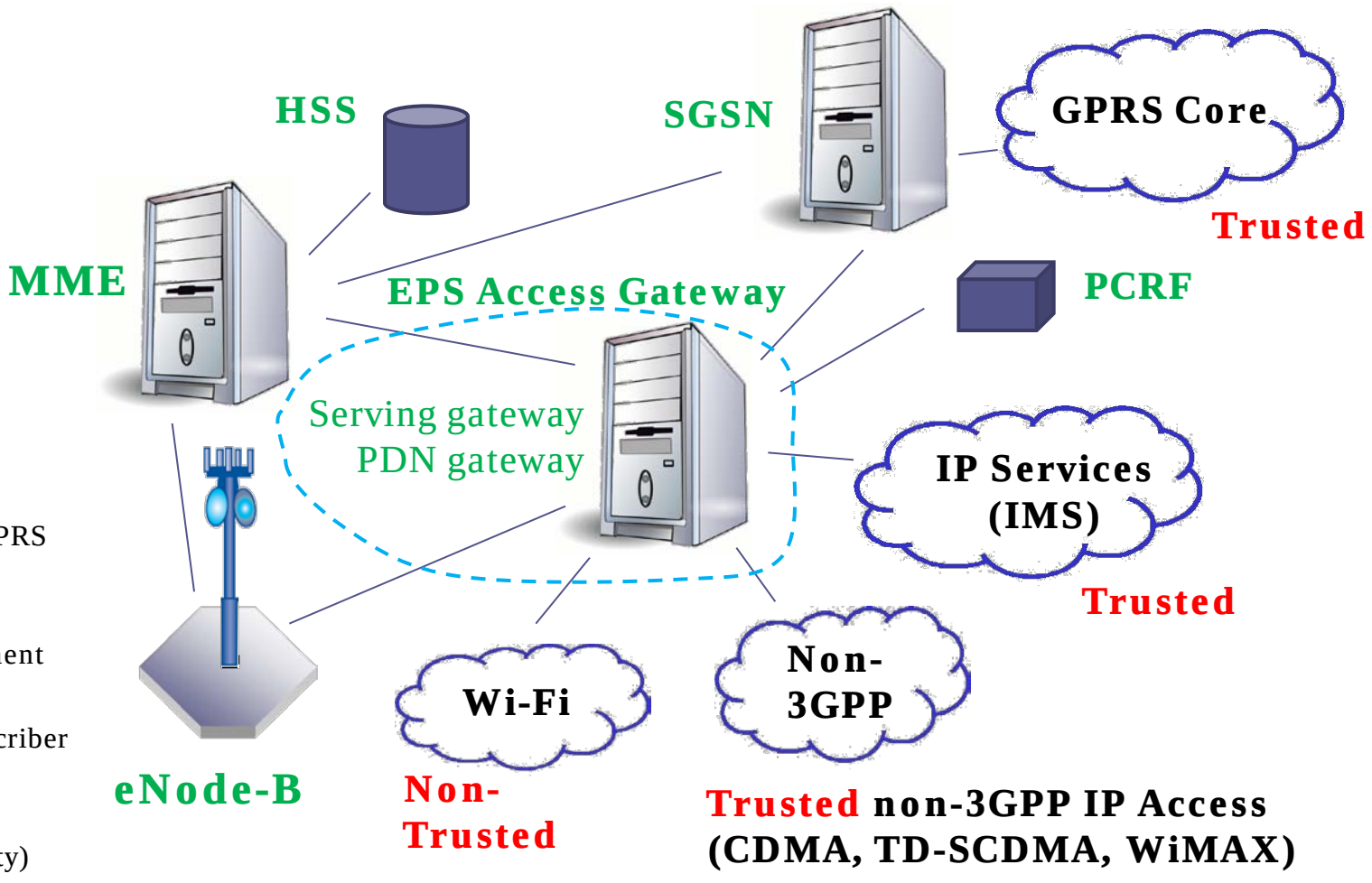
HSPA and HSPA+

- HSPA+ is aimed at extending operators' investment in HSPA
  - 2x2 MIMO, 64 QAM in the downlink, 16 QAM in the uplink
  - Data rates up to 42 MB in the downlink and 11.5 MB in the uplink.
- HSPA+ is CDMA-based and lacks the efficiency of OFDM



One-tunnel architecture flattens the network by enabling a direct transport path for user data between RNC and the GGSN, thus minimizing delays and set-up time

LTE EPS (Evolved Packet System)



SGSN (Serving GPRS Support Node)

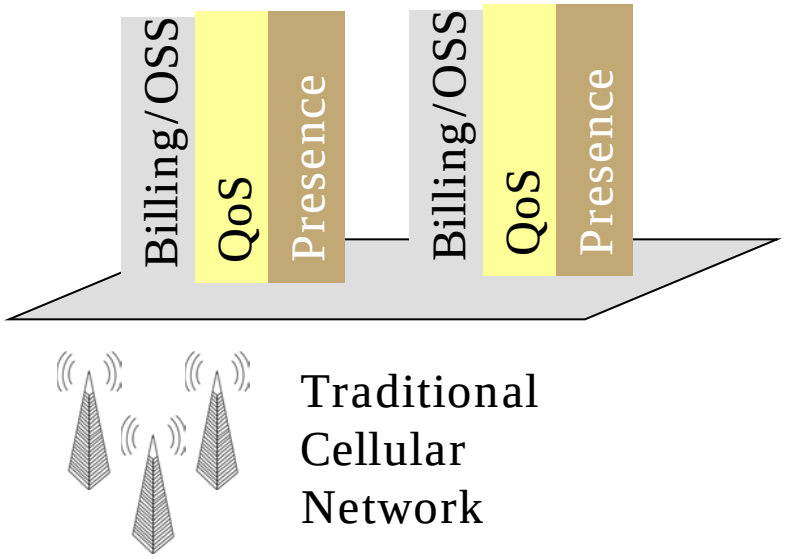
PCRF (policy and charging enforcement function)

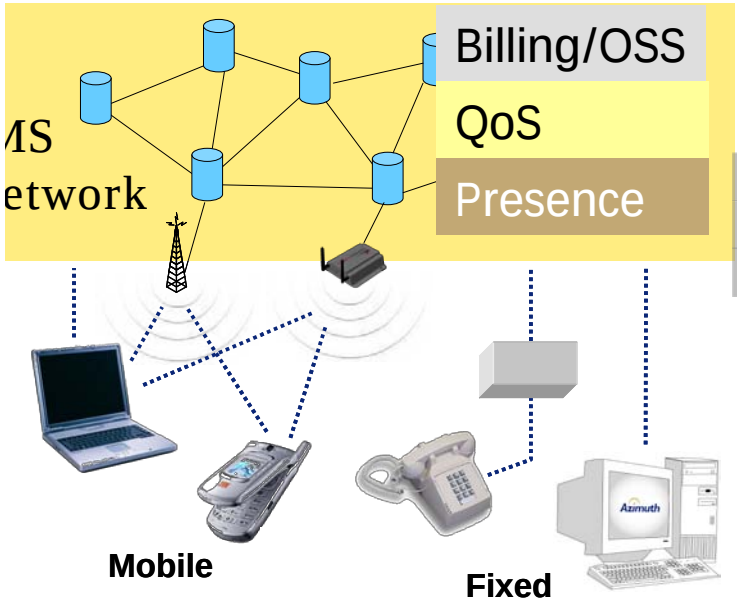
HSS (Home Subscriber Server)

MME (Mobility Management Entity)

PDN (Public Data Network)

Flat, low-latency architecture


Billing/OSS
QoS
Presence
Billing/OSS
QoS
Presence
Traditional
Cellular
Network


Billing/OSS
QoS
Presence
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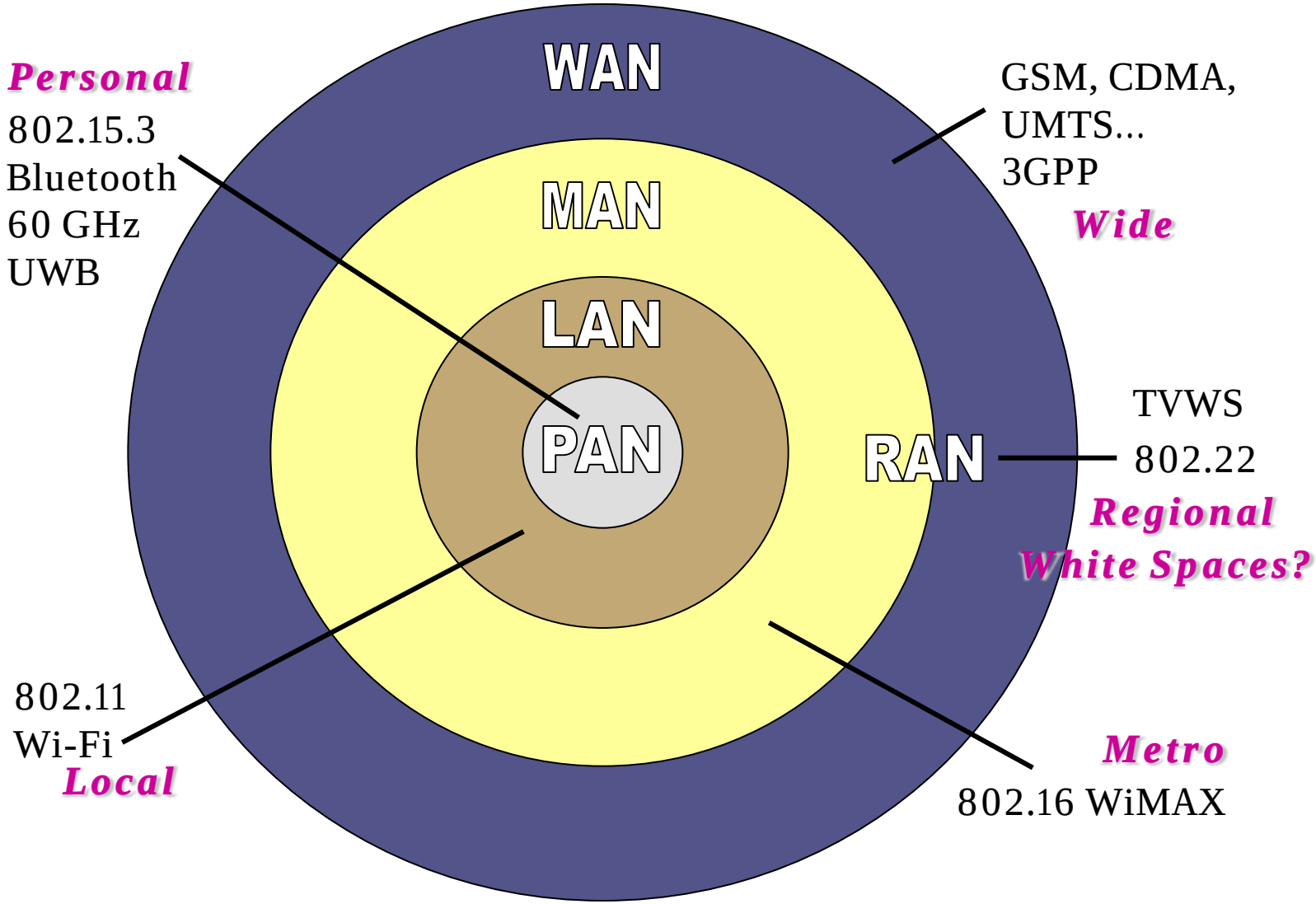
The IEEE 802 Wireless Technologies



Wireless standards dominate the work of IEEE 802

IEEE 802 LAN/MAN Standards Committee (LMSC)

- **802.1** Higher Layer LAN Protocols
- **802.3** Ethernet
- **802.11** Wireless LAN
- **802.15** Wireless Personal Area Network
- **802.16** Broadband Wireless Access
- **802.17** Resilient Packet Ring
- **802.18** Radio Regulatory *TAG (t*echnical advisory group)
- **802.19** Coexistence TAG
- **802.21** Media Independent Handoff
- **802.22** Wireless Regional Area Networks

History of IEEE 802.11

- **1989**: FCC authorizes ISM bands (Industrial, Scientific and Medical)
  - 900 MHz, 2.4 GHz, 5 GHz
- **1990**: IEEE begins work on 802.11
- **1994**: 2.4 GHz products begin shipping
- **1997**: 802.11 standard approved
- **1998**: FCC authorizes the UNII (Unlicensed National Information Infrastructure) Band - 5 GHz
- **1999**: 802.11a, b ratified
- **2003:** 802.11g ratified
- **2006:** 802.11n draft 2 certification by the Wi-Fi Alliance begins
- **2009:** 802.11n certification

20??: 802.11 ac/ad: 1 Gbps Wi-Fi

802.11 has pioneered commercial deployment of OFDM and MIMO – key wireless signaling technologies today

History of IEEE 802.16

From OFDM to OFDMA

orthogonal frequency division multiplexing
orthogonal frequency division multiple access

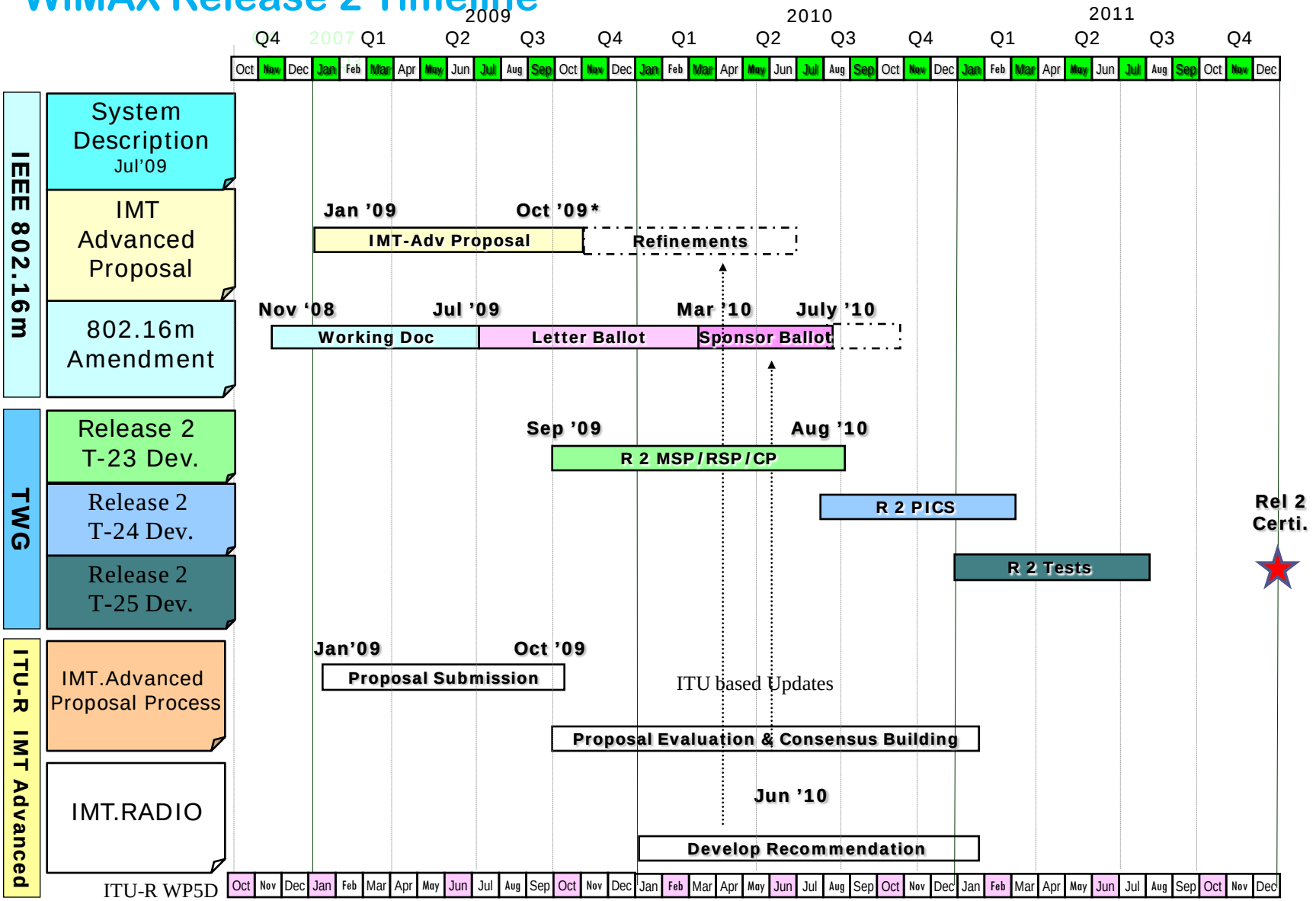
- **1998**: IEEE formed 802.16 WG
  - Started with 10–66 GHz band; later modified to work in 2–11GHz to enable NLOS (non-line of site)
- **2004:** IEEE 802.16-2004d
  - Fixed operation standard ratified
- **2005:** 802.16-2005e
  - Mobility and scalability in 2–6 GHz
- **Latest:** P802.16-2009 (Rev2)
- **Future:** 802.16m – next generation

IEEE 802.16 Active Task Groups

- 802.16h, License-Exempt Task Group
  - Working with 802.11 TGy and 802.19 Coexistence TAG
- 802.16m, IMT Advanced Air Interface
- GRIDMAN study group – new effort to adapt WiMAX to smart grid applications
- Maintenance
  - Completed 802.16 Rev2
  - Working with the WiMAX Forum

http://grouper.ieee.org/groups/802/16

WiMAX Release 2 Timeline

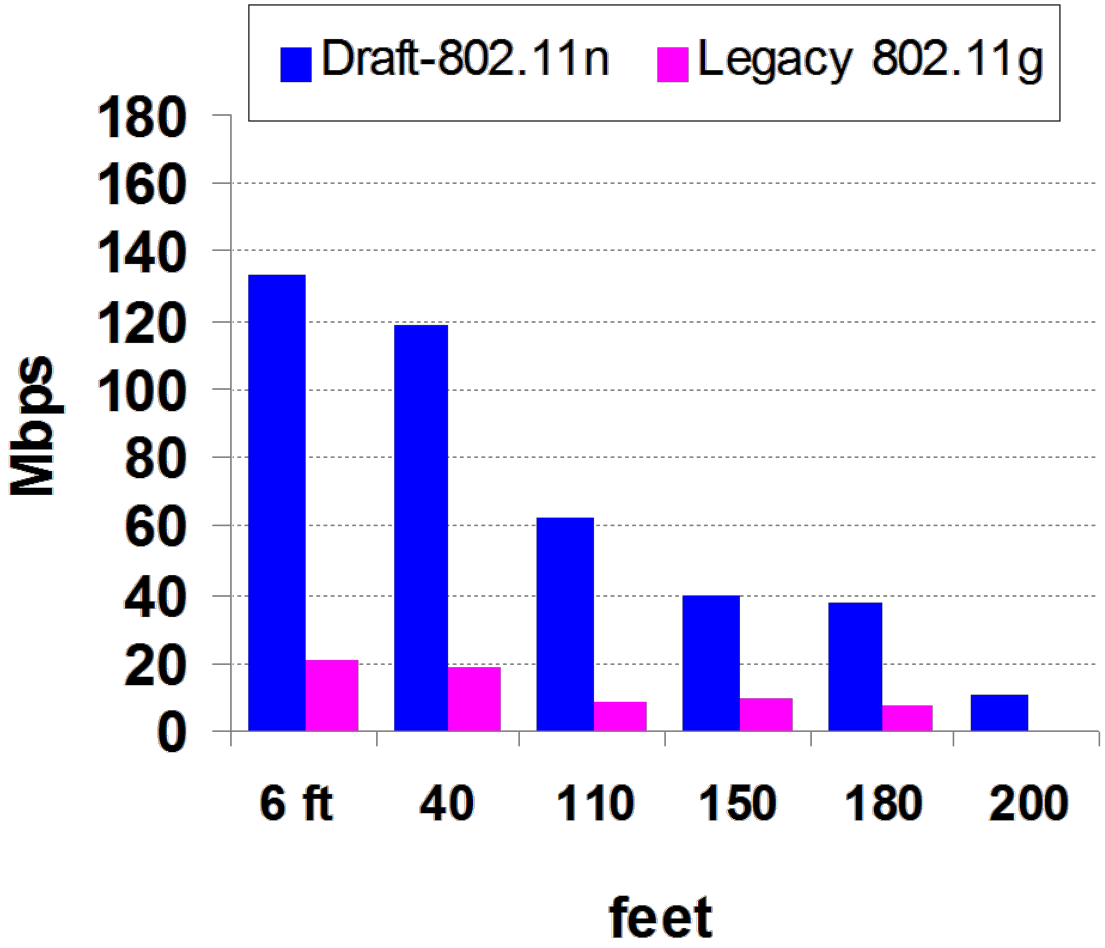


IEEE 802.11 Active Task Groups

- **TGp** – Wireless Access Vehicular Environment (WAVE/DSRC)
- **TGs** – ESS Mesh Networking
- **TGu** – InterWorking with External Networks
- **TGv** – Wireless Network Management
- **TGz** – Direct Link Setup
- **TGaa** – Robust streaming of AV Transport Streams
- **TGac** – VHTL6 (very high throughput < 6 GHz)
- **TGad** – VHT 60 GHz
- **TGae** – Prioritization of Management Frames
- **TGaf** – TV Band Operation

http://grouper.ieee.org/groups/802/11

Draft 802.11n vs. Legacy Throughput Performance



IEEE 802.11a,b,g,n Data Rates

	20 MHz Channel				40 MHz Channel			
	1 stream	2 streams	3 streams	4 streams	1 stream	2 streams	3 streams	4 streams
	Data Rate, in Mbps							
802.11b 2.4 GHz	1, 2, 5.5, 11							
802.11a 5 GHz	6, 9, 12, 18, 24, 36, 48, 54							
802.11g 2.4 GHz	1, 2, 6, 9, 12, 18, 24, 36, 48, 54							
802.11n 2.4 and 5 GHz	6.5, 13, 19.5, 26, 39, 52, 58.5, 65	13, 26, 39, 52, 78, 104, 117, 130	19.5, 39, 58.5, 78, 117, 156, 175.5, 195	26, 52, 78, 104, 156, 208, 234, 260	13.5, 27, 40.5, 54, 81, 108, 121.5, 135	27, 54, 81, 108, 162, 216, 243, 270	40.5, 81, 121.5, 162, 243, 324, 364.5, 405	54, 108, 162, 216, 324, 432, 486, 540
802.11n, SGI enabled 2.4 and 5 GHz	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	14.4, 28.9, 43.3, 57.8, 86.7, 115.6, 130, 144.4	21.7, 43.3, 65, 86.7, 130, 173.3, 195, 216.7	28.9, 57.8, 86.7, 115.6, 173.3, 231.1, 260, 288.9	15, 30, 45, 60, 90, 120, 135, 150	30, 60, 90, 120, 180, 240, 270, 300	45, 90, 135, 180, 270, 360, 405, **450**	60, 120, 180, 240, 360, 480, 540, **600**

Top rate commercially available today

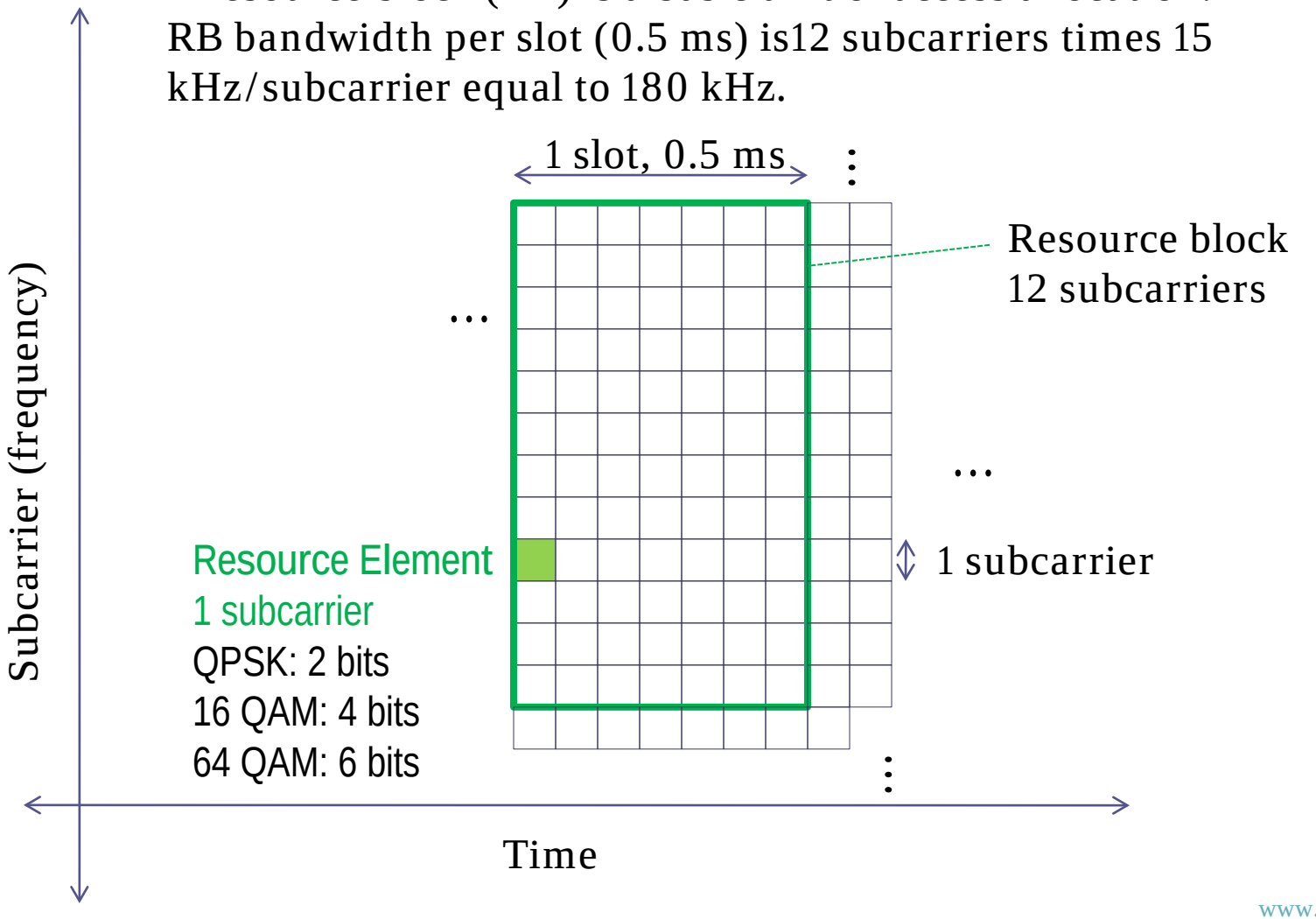
WiMAX/LTE Channel Scalability

	WiMAX						
Channel bandwidth (MHz)	1.25	5	10	20	3.5	7	8.75
Sample time (ns)	714.3	178.6	89.3	44.6	250	125	100
FFT size	128	512	1024	2048	512	1024	1024
Subcarrier spacing (kHz)	10.9				7.8		9.8
Symbol time (usec)	91.4				128		102.4

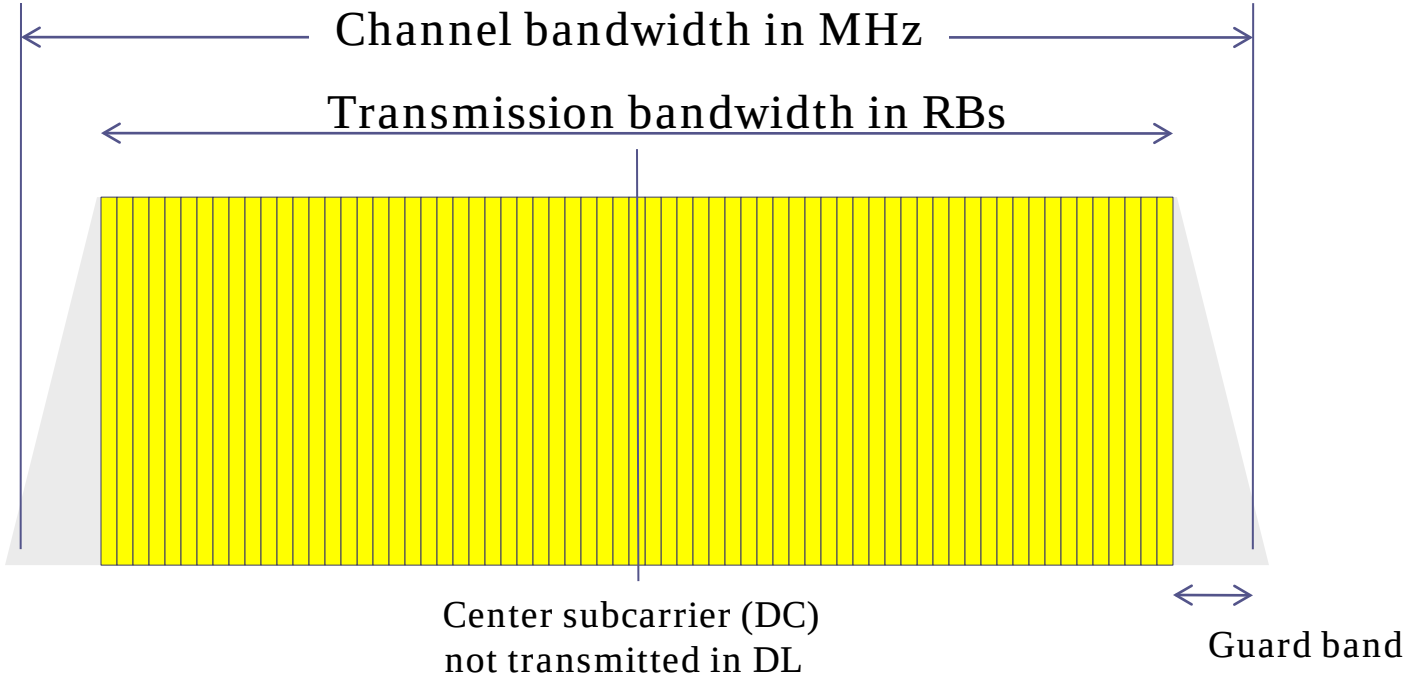
	LTE					
Channel bandwidth (MHz)	1.4	3	5	10	15	20
FFT size	128	258	512	1024	1536	2048
Subcarrier spacing	15 kHz					
Symbol time (usec)	71.4 (with normal CP)					

LTE Resource Block

A resource block (RB) is a basic unit of access allocation. RB bandwidth per slot (0.5 ms) is12 subcarriers times 15 kHz/subcarrier equal to 180 kHz.



LTE Scalable Channel Bandwidth



Channel bw	1.4	3	5	10	15	20	MHz
Transmission bw	1.08	2.7	4.5	9	13.5	18	
# RBs per slot	6	15	25	50	75	100	

WiMAX Frequency Bands - TDD

Band Class	(GHz) BW (MHZ)	Bandwidth Certification Group Code (BCG)
1	**2.3-2.4**	
	8.75	1.A
	5 AND 10	1.B
2	**2.305-2.320, 2.345-2.360**	
	3.5	2.A (Obsolete, replaced by 2.D)
	5	2.B (Obsolete, replaced by 2.D)
	10	2.C (Obsolete, replaced by 2.D)
	3.5 AND 5 AND 10	2.D
3	**2.496-2.69**	
	5 AND 10	3.A
4	**3.3-3.4**	
	5	4.A
	7	4.B
	10	4.C
5	**3.4-3.8**	
	5	5.A
	7	5.B
	10	5.C
7	**0.698-0.862**	
	5 AND 7 AND 10	7.A
	8 MHz	7.F

WiMAX Forum Mobile Certification Profile v1.1.0

A universal frequency step size of 250 KHz is recommended for all band classes, while 200 KHz step size is also recommended for band class 3 in Europe.

WiMAX Frequency Bands - FDD

Band Class	(GHz)BW (MHZ)	Duplexing Mode BS	Duplexing Mode MS	MS Transmit Band (MHz)	BS Transmit Band (MHz)	Bandwidth Certification Group Code (BCG)
2	2.305-2.320, 2.345-2.360					
	2x3.5 AND 2x5 AND 2x10	FDD	HFDD	2345-2360	2305-2320	2.E**
	5 UL, 10 DL	FDD	HFDD	2345-2360	2305-2320	2.F**
3	2.496-2.690					
	2x5 AND 2x10	FDD	HFDD	2496-2572	2614-2690	3.B
5	3.4-3.8					
	2x5 AND 2x7 AND 2x10	FDD	HFDD	3400-3500	3500-3600	5.D
6	1.710-2.170 FDD					
	2x5 AND 2x10	FDD	HFDD	1710-1770	2110-2170	6.A
	2x5 AND 2x10 AND Optional 2x20 MHz	FDD	HFDD	1920-1980	2110-2170	6.B
	2x5 AND 2x10 MHz	FDD	HFDD	1710-1785	1805-1880	6.C
7	0.698-0.960					
	2x5 AND 2x10	FDD	HFDD	776-787	746-757	7.B
	2x5	FDD	HFDD	788-793 AND 793-798	758-763 AND 763-768	7.C
	2x10	FDD	HFDD	788-798	758-768	7.D
	5 AND 7 AND 10 (TDD), 2x5 AND 2x7 AND 2x10 (H-FDD)	TDD or FDD	Dual Mode TDD/H-FDD	698-862	698-862	7.E*
	2x5 AND 2x10 MHz	FDD	HFDD	880-915	925-960	7.G
8	1.710-2.170 TDD					
	5 AND 10	TDD	TDD	1785-1805, 1880-1920, 1910-1930, 2010-2025	1785-1805, 1880-1920, 1910-1930, 2010-2025	8.A

LTE Frequency Bands - FDD

Band	Uplink (UL)	Downlink (DL)	Regions
1	1920 -1980 MHz	2110 - 2170 MHz	Europe, Asia
2	1850 -1910 MHz	1930 - 1990 MHz	Americas, Asia
3	1710 -1785 MHz	1805 -1880 MHz	Europe, Asia, Americas
4	1710 -1755 MHz	2110 - 2155 MHz	Americas
5	824-849 MHz	869 - 894 MHz	Americas
6	830 - 840 MHz	875 - 885 MHz	Japan
7	2500 - 2570 MHz	2620 - 2690 MHz	Europe, Asia
8	880 - 915 MHz	925 - 960 MHz	Europe, Asia
9	1749.9 - 1784.9 MHz	1844.9 - 1879.9 MHz	Japan
10	1710 -1770 MHz	2110 - 2170 MHz	Americas
11	1427.9 - 1452.9 MHz	1475.9 - 1500.9 MHz	Japan
12	698 - 716 MHz	728 - 746 MHz	Americas
13	777 - 787 MHz	746 - 756 MHz	Americas
14	788 - 798 MHz	758 - 768 MHz	Americas
17	704 - 716 MHz	734 - 746 MHz	

Source: 3GPP TS 36.104 V8.4.0 (2008-12)

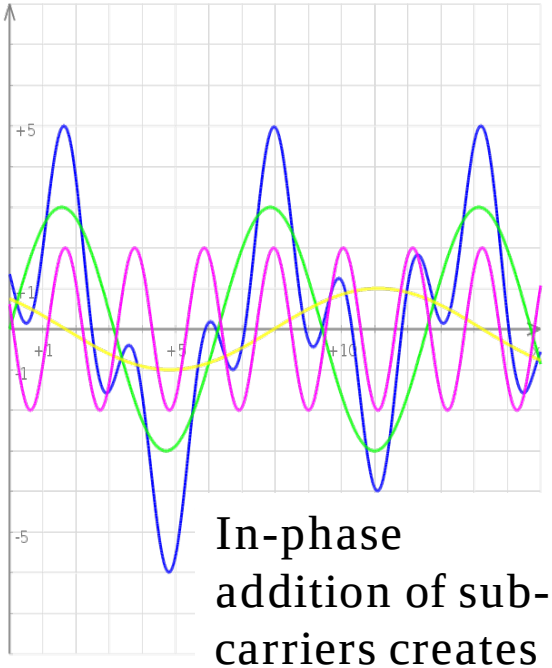
LTE Frequency Bands - TDD

Band	UL and DL	Regions
33	1900 - 1920 MHz	Europe, Asia (not Japan)
34	2010 - 2025 MHz	Europe, Asia
35	1850 - 1910 MHz	
36	1930 - 1990 MHz	
37	1910 - 1930 MHz	
38	2570 - 2620 MHz	Europe
39	1880 - 1920 MHz	China
40	2300 – 2400 MHz	Europe, Asia

Source: 3GPP TS 36.104 V8.4.0 (2008-12)

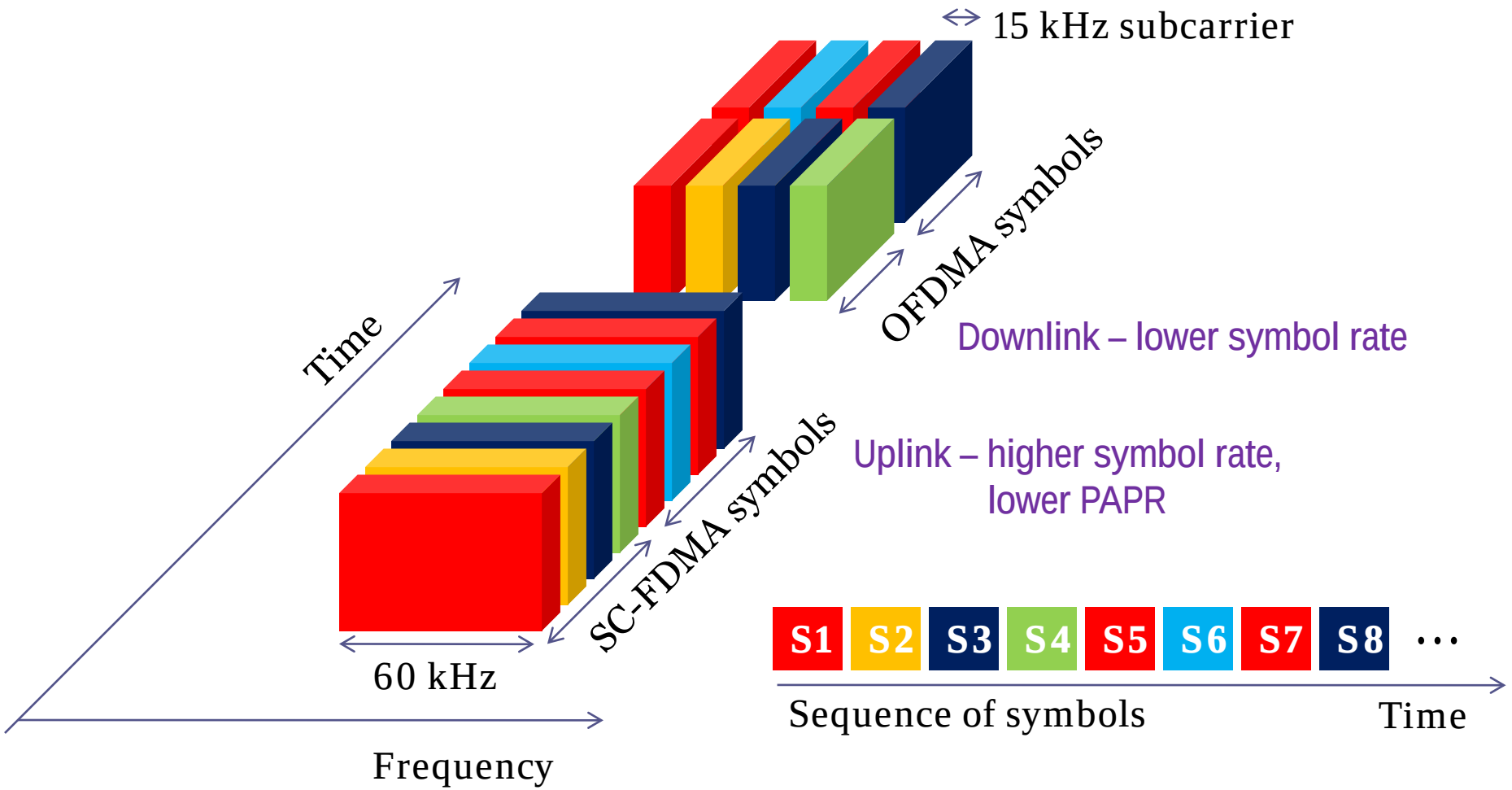
OFDMA vs. SC-FDMA (LTE Uplink)

- Multi-carrier OFDM signal exhibits high PAPR (Peak to Average Power Ratio) due to in-phase addition of subcarriers.
- Power Amplifiers (PAs) must accommodate occasional peaks and this results low efficiency of PAs, typically only 15-20% efficient. Low PA efficiency significantly shortens battery life.
- To minimize PAPR, LTE has adapted SC-FDMA (single carrier OFDM) in the uplink. **SC-FDMA exhibits 3-6 dB less PAPR than OFDMA.**



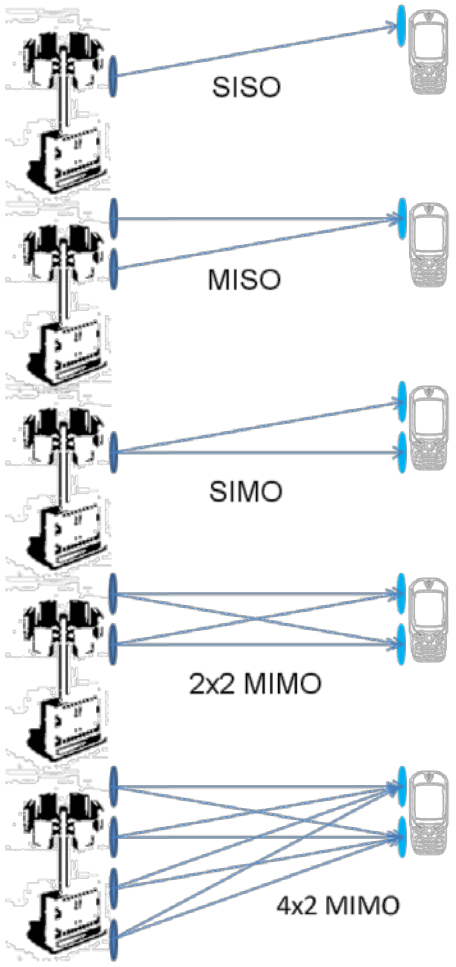
In-phase addition of sub-carriers creates peaks in the OFDM signal

SC-FDMA vs. OFDMA



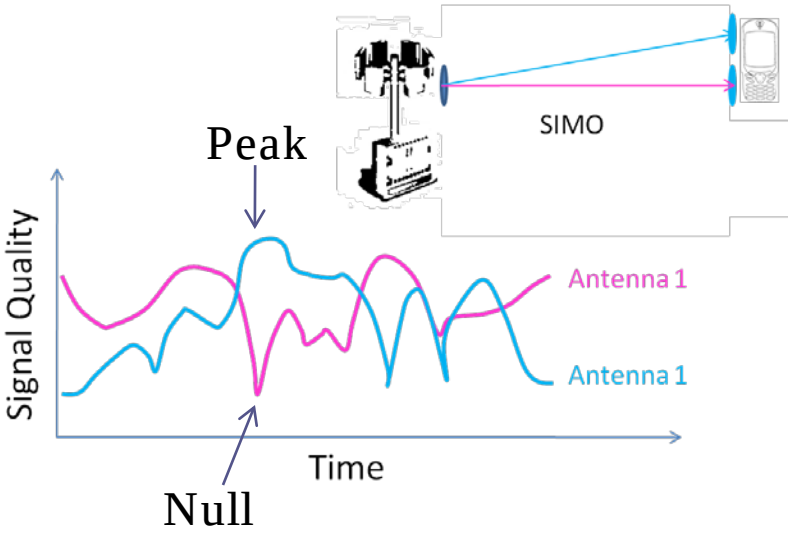
Multiple Antenna Techniques

- **SISO (Single Input Single Output)**
  - Traditional radio
- **MISO (Multiple Input Single Output)**
  - Transmit diversity
  - Space Frequency Block Coding (SFBC)
- **SIMO (Single Input Multiple Output)**
  - Receive diversity
  - Maximal Ratio Combining (MRC)
- **MIMO (Multiple Input Multiple Output)**
  - Spatial Multiplexing (SM) to transmit multiple streams simultaneously; can be used in conjunction with Cyclic Delay Diversity (CDD)
  - Works best in high SINR environments and channels de-correlated by multipath



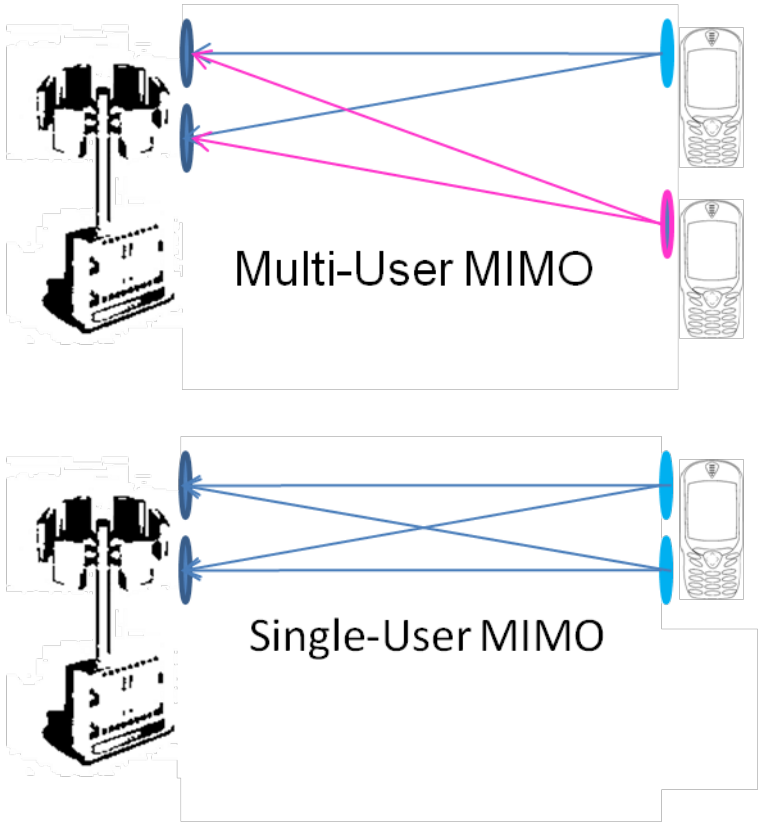
Receive and Transmit Diversity

- Receive diversity, MRC, makes use of the highest signal quality, combining signals from both antennas
- Transmit diversity techniques, CDD or SFBC, spread the signal so as to create artificial multipath to decorrelate signals from different antennas with the goal of delivering a peak on one receive antenna while there may be a null on another



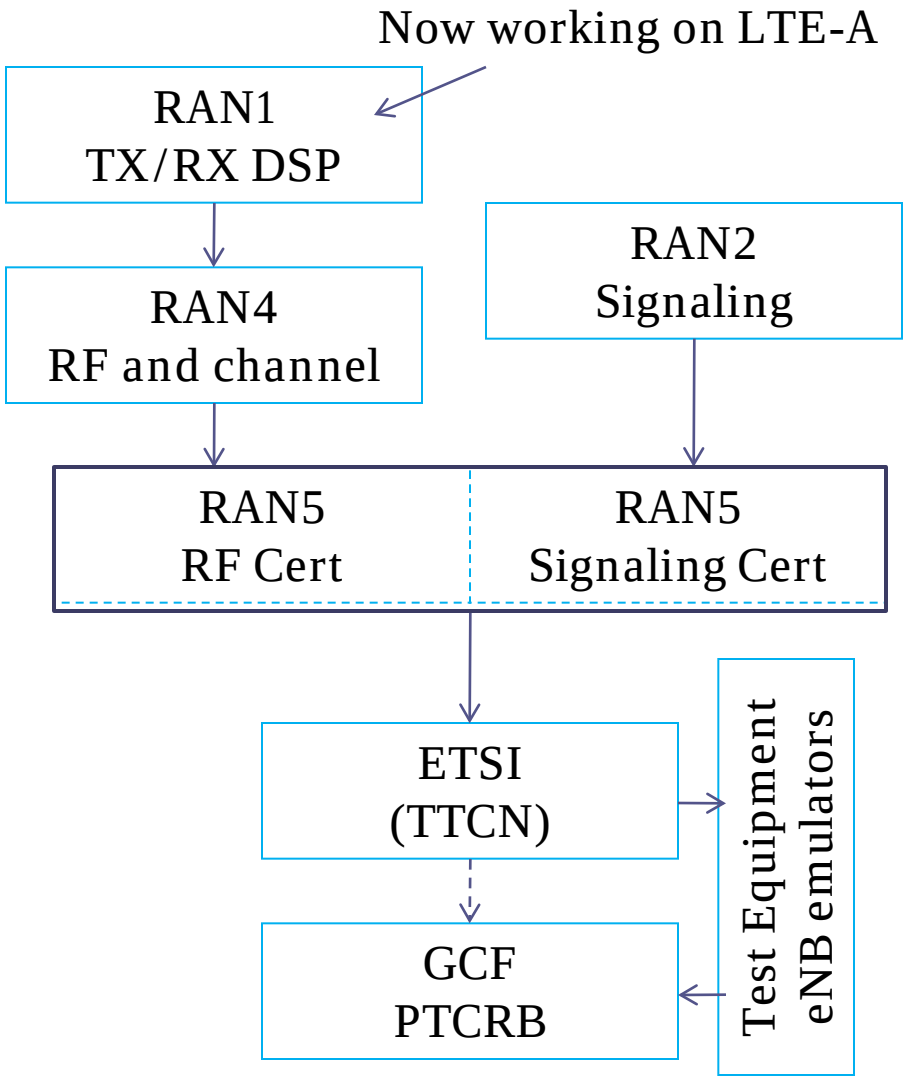
Single-, Multi-User MIMO

- MU-MIMO allows two mobile units to share RBs provided their channels to the base station are sufficiently decorrelated
- MU-MIMO increases uplink capacity
- SU-MIMO requires a mobile device to have two transmitters, which is detrimental to battery life and cost



3GPP Groups

- RAN1-4 develop the functionality standards
- RAN4 feeds RAN5 RF group with test requirements
- RAN1 feeds RAN5 RF group through RAN4
- RAN2 feeds RAN5 Signaling group with test requirements
- ETSI develops TTCN code per RAN5 standards and makes code available as open source
- Test equipment manufacturers are active contributors to the TTCN effort
- TTCN makes signaling certification uniform; RF certification is different among test equipment vendors



Concluding Thoughts

- White Spaces standards will capitalize on the OFDM and MIMO techniques developed by established wireless broadband services
  - Wi-Fi, WiMAX, LTE
- Wi-Fi may be the first protocol to produce commercial products using white spaces
  - Strong momentum
  - Economy of scale
  - Products expected in about 2 years
- Key use cases
  - In homes where propagation is poor at 2.4 and 5 GHz frequencies
  - Rural Internet access where the use of TV broadcast spectrum is sparse
- Regulations still evolving with most notable trend towards dynamic spectrum allocation
  - Based on space, time and region

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