octoScope

NEW YORK // OCTOBER 3-7, 2011 // JAVITS CENTER INTEROP

4G Broadband

what you need to know about

LTE

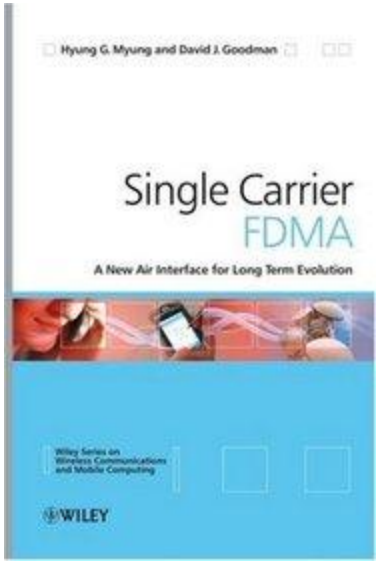
Fanny Mlinarsky
President
octoScope, Inc.

7-Oct-11

www.octoscope.com

Dr. Hyung G. Myung

- **Dr. Hyung G. Myung is currently with Qualcomm working on IP Strategy. He previously worked at ArrayComm, Samsung Advanced Institute of Technology, and InterDigital Communications in various wireless projects as a research and development engineer. He also served in the Republic of Korea Air Force as a lieutenant officer and he was with Department of Electronics Engineering at Republic of Korea Air Force Academy as a faculty member. He holds BS and MS degrees from Seoul National University, South Korea, MS degree from Santa Clara University, and PhD from Polytechnic University, Brooklyn, NY (now, Polytechnic Institute of NYU).**



Dr. Myung's book

(SC-FDMA is LTE uplink modulation)

Long Ago…

BBC broadcast 1935

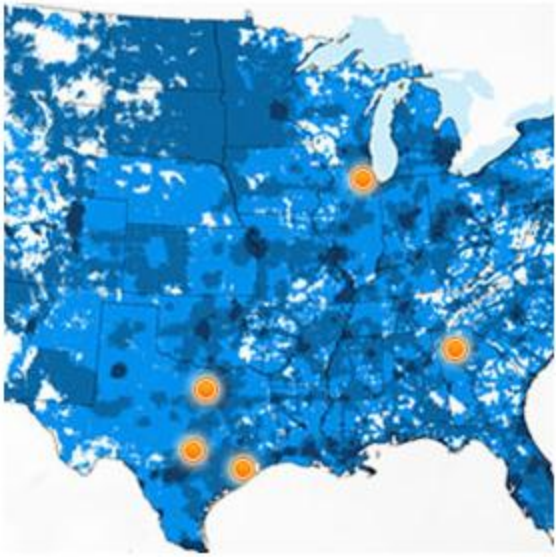
Over the last 5 years wireless bandwidth deployed in the US has increased 553-fold.

George Gilder

G	The G's	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
4	LTE-Advanced	1000 Mbps	500 Mbps

AT&T Test

- **AT&T launched its LTE network in 5 cities on 9/18/11**
- **PC Magazine article: AT&T vs. Verizon: LTE, Head-to-Head**
  - http://www.pcmag.com/article2/0,2817,2393182,00.asp#fbid=fD0LlOUpHzx
  - Unable to roam between AT&T and Verizon LTE networks
  - AT&T has put coverage maps on its site advocating merger with T-Mobile

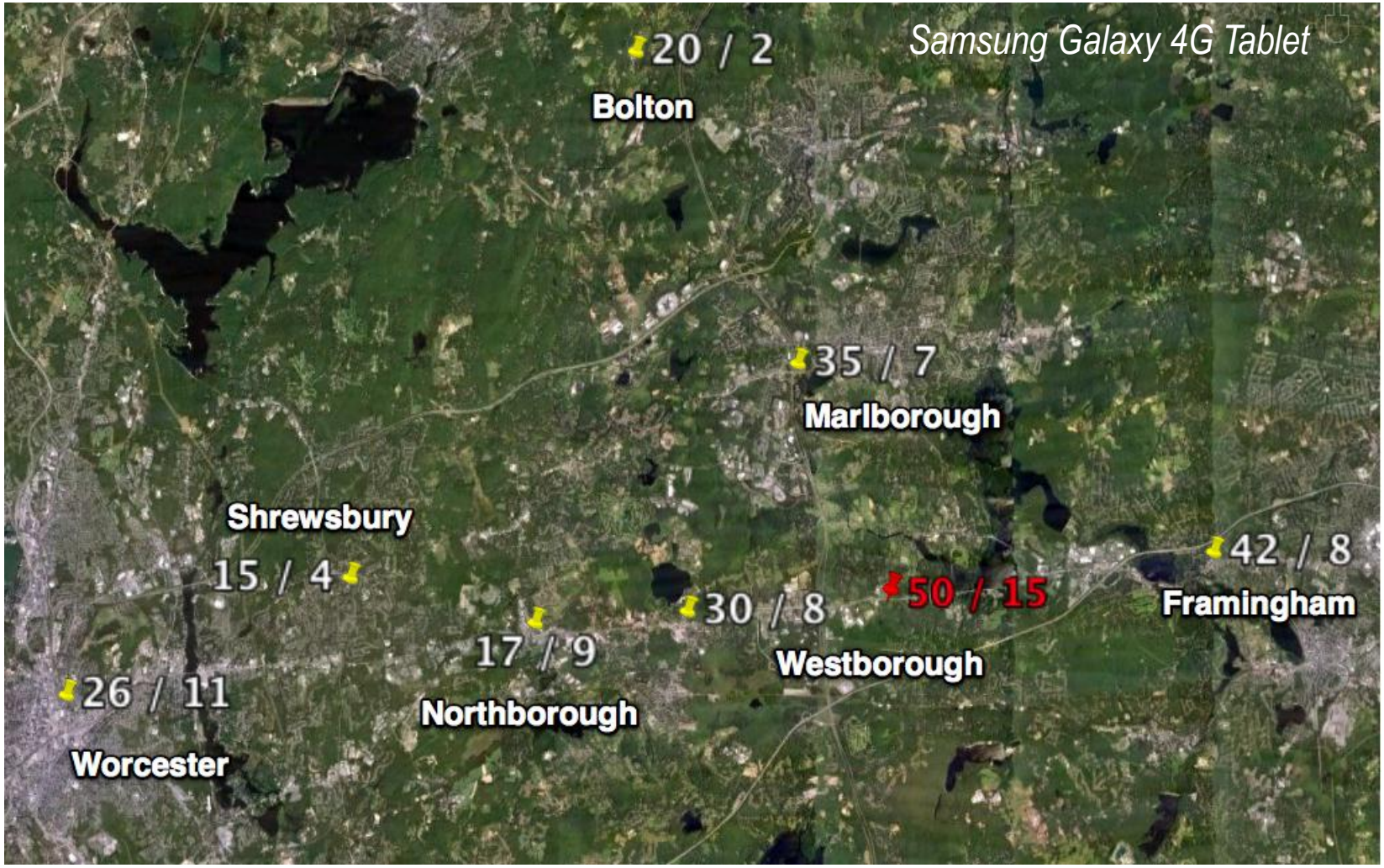


AT&T LTE vs. Verizon Wireless: PCMAG.com results in Houston, TX						
Device	Speedtest.net avg download (Mbps)	Speedtest.net max download (Mbps)	Speedtest.net avg upload (Mbps)	Average ping (ms)	Web time to first byte (sec)	Average Web page load speed (Mbps)
AT&T USBConnect Momentum 4G (modem)	24.65	42.85	11.44	45.00	0.30	0.27
AT&T USBConnect Elevate 4G (hotspot)	24.63	39.09	11.53	50.00	0.32	0.24
Pantech UML290 for Verizon Wireless	16.70	23.81	4.01	51.00	0.27	0.25

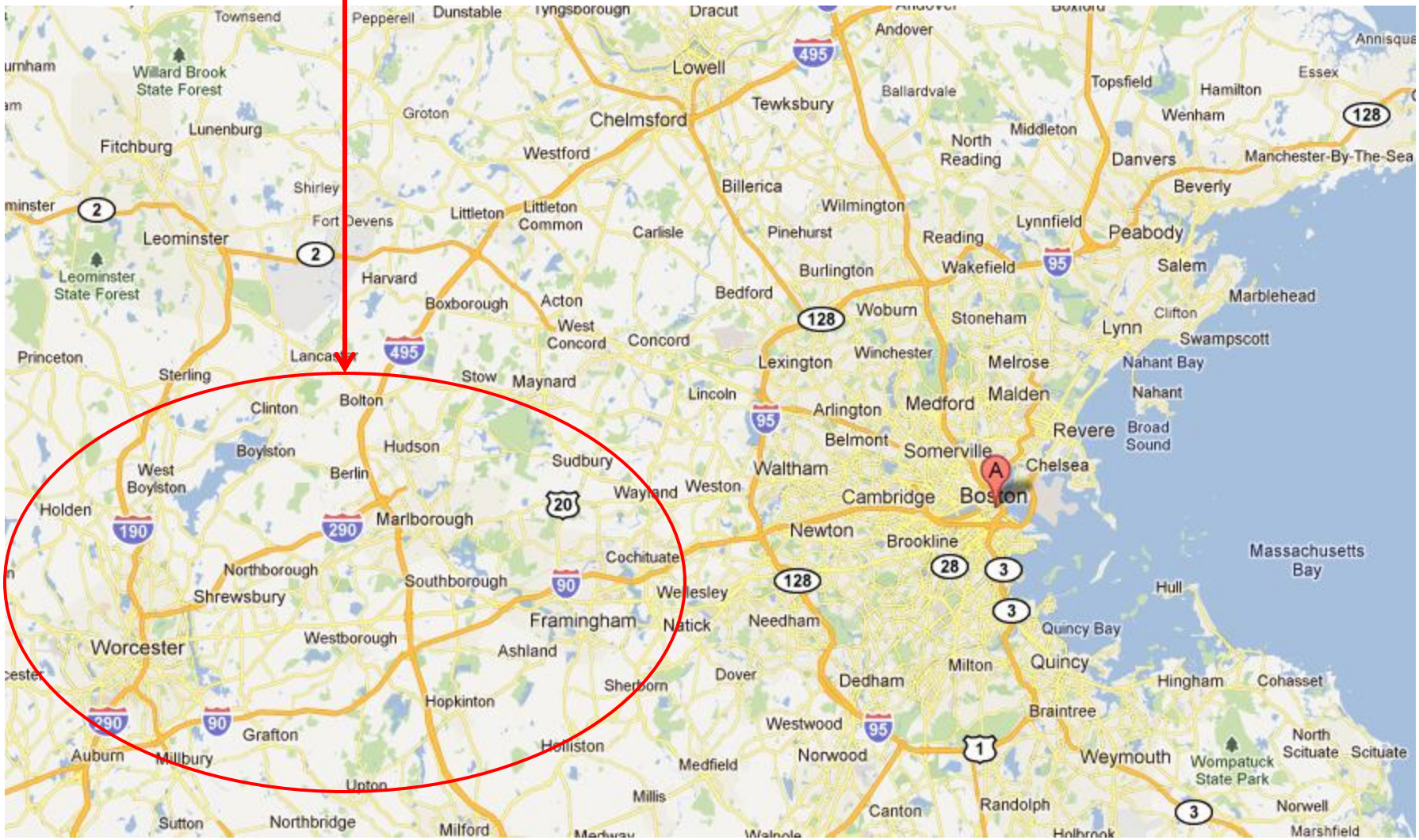
Dallas-Fort Worth
San Antonio
Houston
Atlanta
Chicago

octoScope's LTE Throughput Measurements in MA

DL/UL, Mbps



Measurements Performed Here



Output Captured by speedtest.com

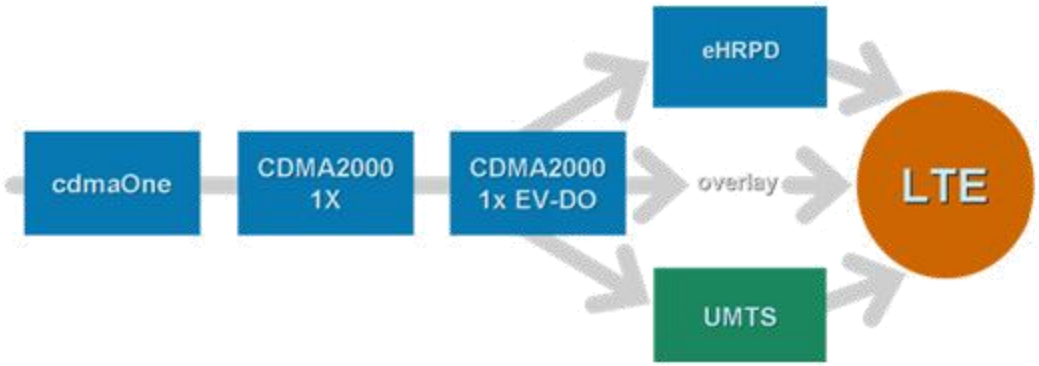
kbps — msec

Date	ConnType	Lat	Lon	Download	Upload	Latency	ServerName	Internal IP	External IP
10/2/2011 11:10	Lte	42.41827	-71.6034	19518	4920	98	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 11:10	Lte	42.41827	-71.6034	19518	3983	106	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 11:09	Lte	42.41827	-71.6034	17300	2772	96	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 11:05	Ehrpd	42.28415	-71.6087	1917	1000	194	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 11:00	Ehrpd	42.28415	-71.6087	742	1000	148	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:57	Ehrpd	42.28415	-71.6087	1373	842	150	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:56	Ehrpd	42.28415	-71.6087	1910	901	180	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:55	Lte	42.28415	-71.6087	11467	309	98	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:55	Lte	42.28415	-71.6087	35694	6542	96	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:54	Lte	42.28415	-71.6087	31827	7324	97	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:53	Lte	42.28415	-71.6087	21281	7423	90	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:53	Lte	42.28415	-71.6087	9455	6937	90	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:52	Lte	42.28415	-71.6087	18291	4633	94	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:39	Ehrpd	42.28415	-71.6087	2341	954	179	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:37	Lte	42.28415	-71.6087	14298	989	94	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:36	Lte	42.28415	-71.6087	41880	7882	92	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:36	Lte	42.28415	-71.6087	34324	7346	92	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:36	Lte	42.28415	-71.6087	42962	8904	90	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:35	Lte	42.28415	-71.6087	44814	7583	94	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:35	Lte	42.28415	-71.6087	22561	9205	100	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:35	Lte	42.28415	-71.6087	14173	3284	104	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:32	Ehrpd	42.28415	-71.6087	1593	830	192	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:29	Lte	42.28415	-71.6087	8507	262	92	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:29	Lte	42.28415	-71.6087	12333	1002	97	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:28	Lte	42.28415	-71.6087	34996	10387	88	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:28	Lte	42.28415	-71.6087	49833	14801	85	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:25	Lte	42.28415	-71.6087	29931	8027	90	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:25	Lte	42.28415	-71.6087	20394	8460	100	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123
10/2/2011 10:25	Lte	42.28415	-71.6087	17250	5815	99	Boston, MA	10.133.86.195, 10.165.70.146	166.248.1.123

↑ Geolocation recorded by speedtest.com is incorrect

What's eHRPD?

- **eHRPD is Verizon's 3G; upgrade path to LTE**
  - CDMA based; enhanced HRPD (EVDO)
  - Maintains the same private IP when handset moves from tower to tower
  - Reduces dropped sessions and decreases the handover latency
- **eHRPD will be used by Verizon for VOIP calls until 2020**

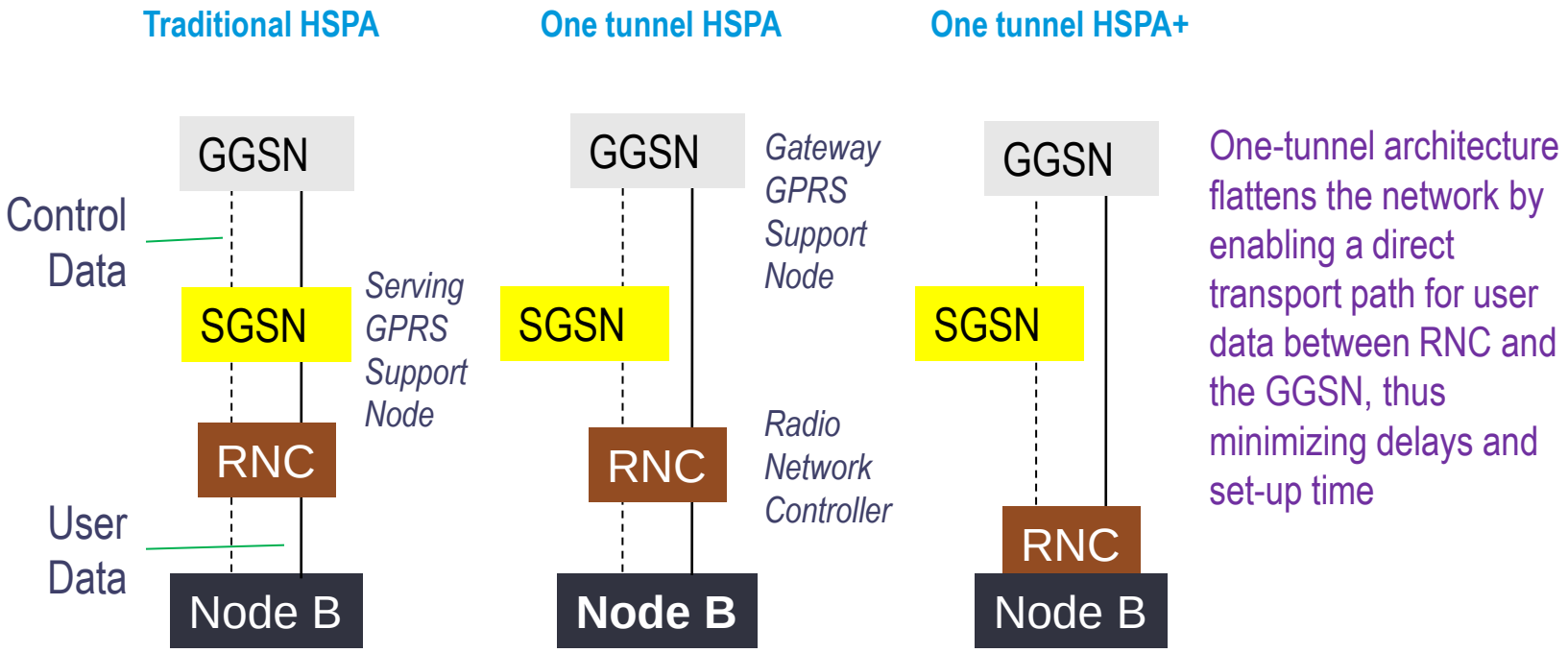


CDMA upgrade paths to LTE

eHRPD = enhanced high rate packet data
EVDO = Evolution-Data Optimized

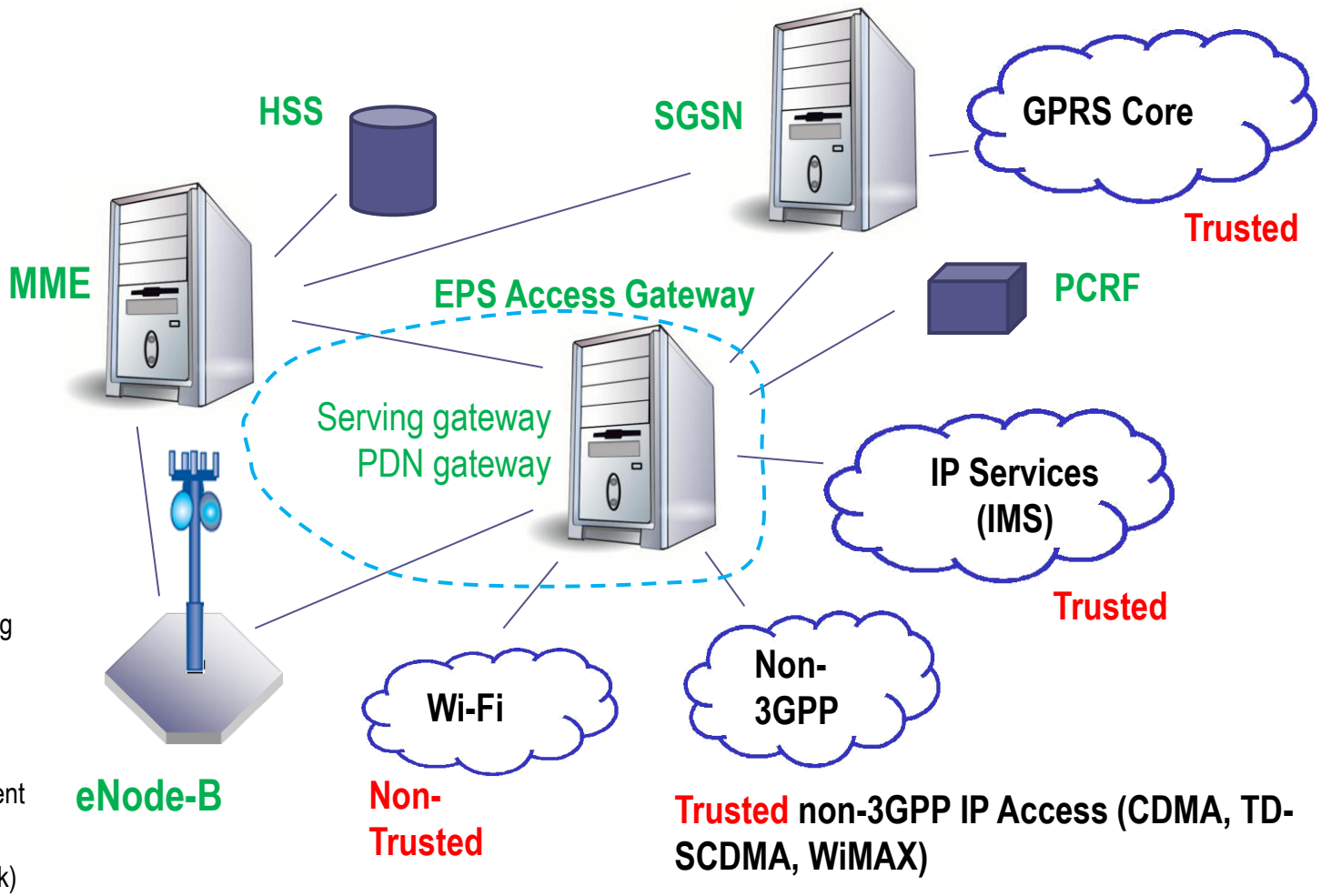
3G Network Latency

- **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.



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 EPC (Evolved Packet Core)



SGSN (Serving GPRS Support Node)

PCRF (policy and charging rules function)

HSS (Home Subscriber Server)

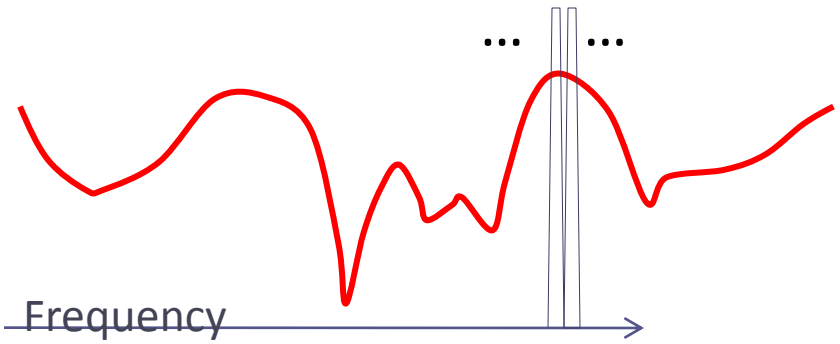
MME (Mobility Management Entity)

PDN (Public Data Network)

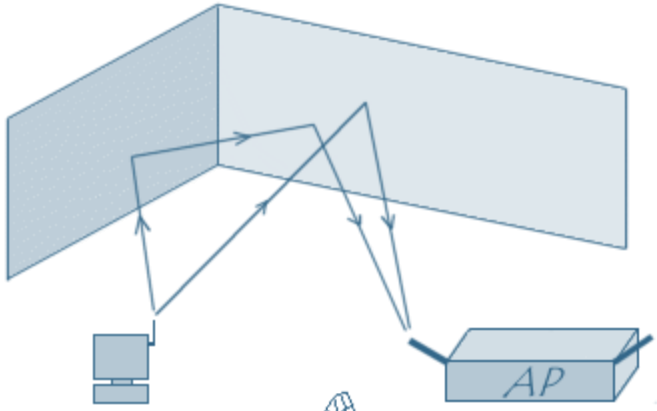
Flat, low-latency architecture

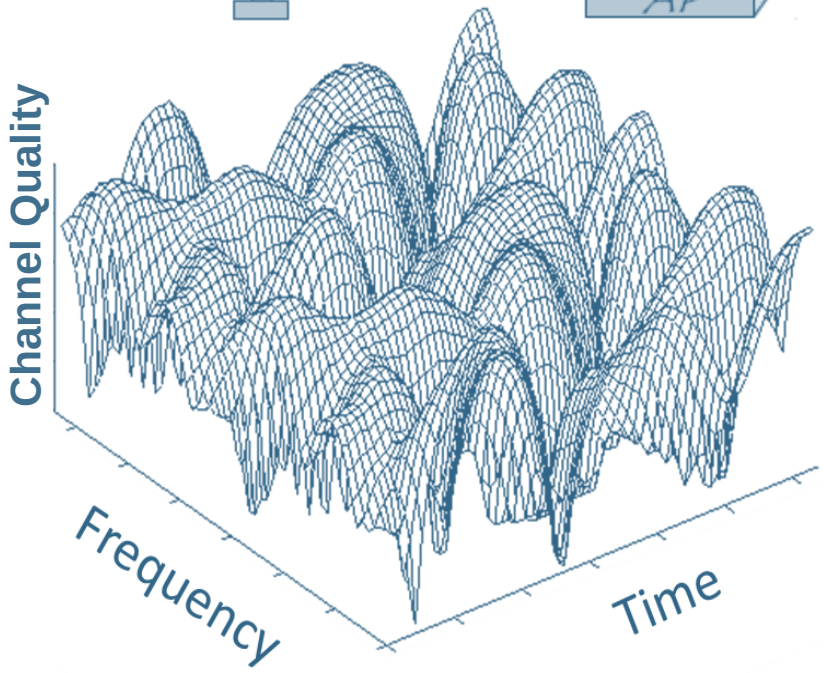
OFDM and MIMO

- **OFDM transforms a frequency- and time-variable fading channel into parallel correlated flat-fading channels, enabling wide bandwidth operation**



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





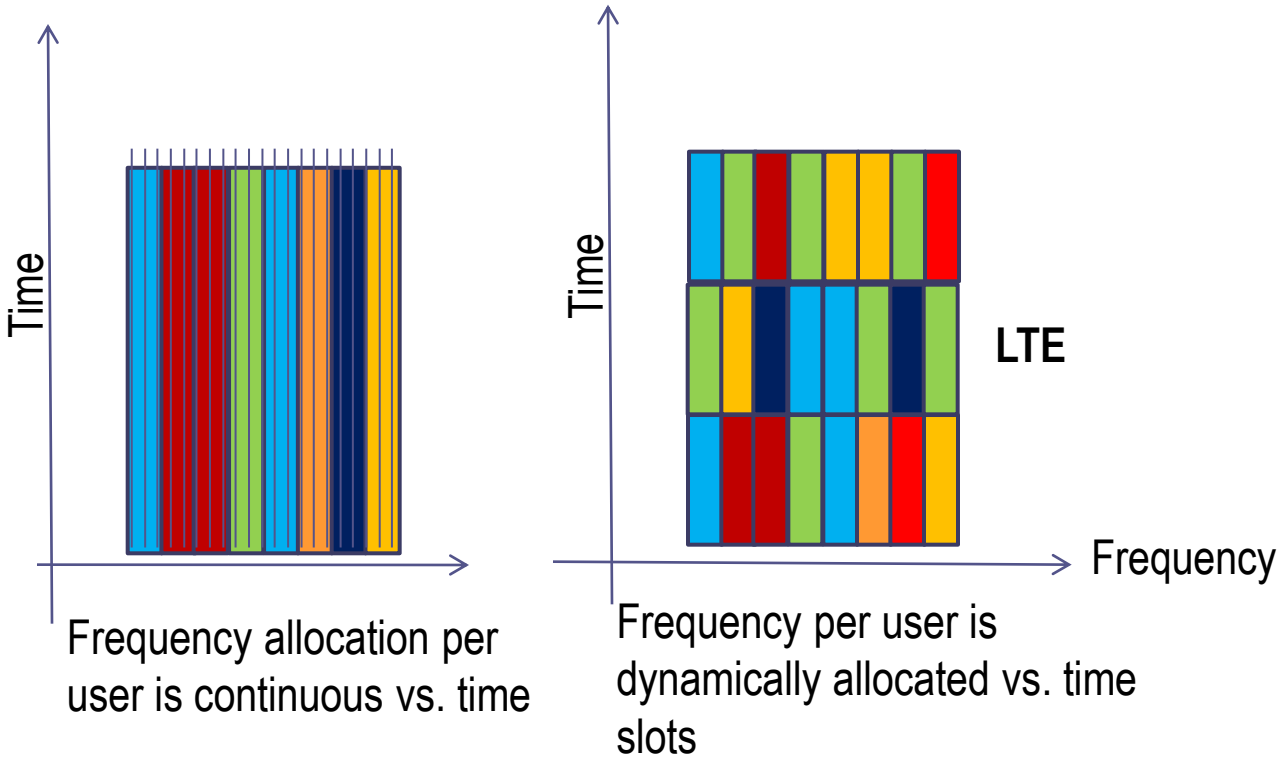
OFDM = orthogonal frequency division multiplexing
MIMO = multiple input multiple output

OFDMA

OFDM is a modulation scheme

OFDMA is a modulation and access scheme

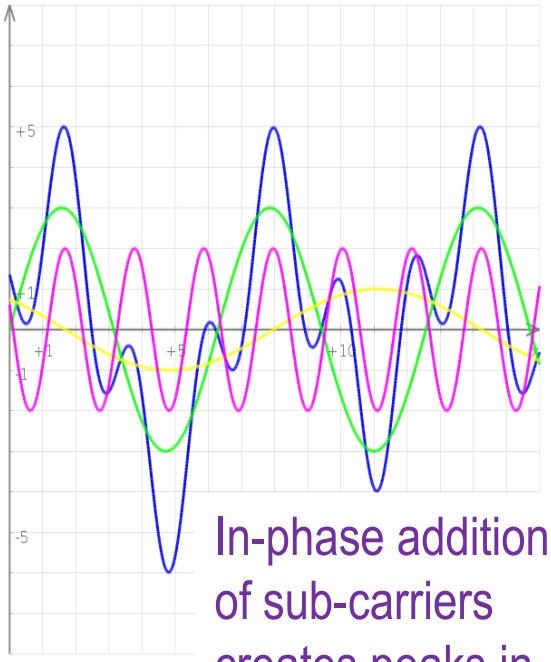
Multiple Access



OFDM = orthogonal frequency division multiplexing
OFDMA = orthogonal frequency division multiple access

OFDMA vs. SC-FDMA (LTE Uplink)

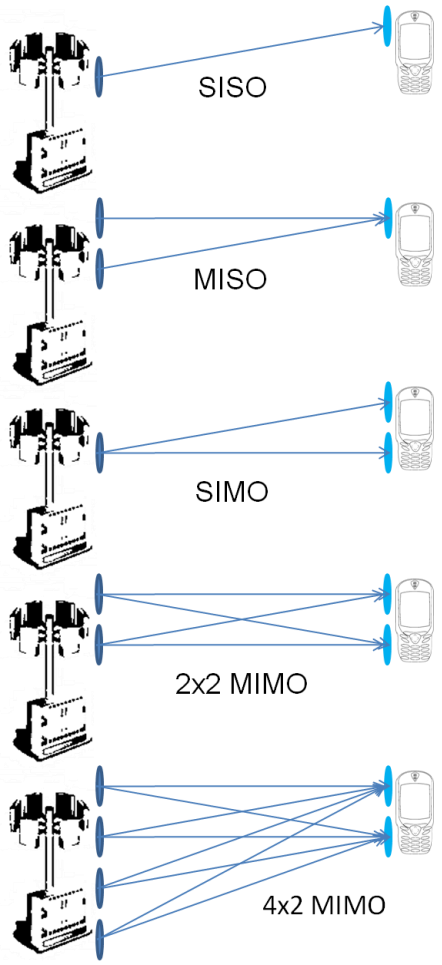
- **Multi-carrier OFDM signal exhibits high PAPR (Peak to Average Power Ratio) due to in-phase addition of subcarriers.**
- **Power Amplifiers (PAs) must accommodate occasional peaks and this results low efficiency of PAs, typically only 15-20% efficient. Low PA efficiency significantly shortens battery 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

Multiple Antenna Techniques

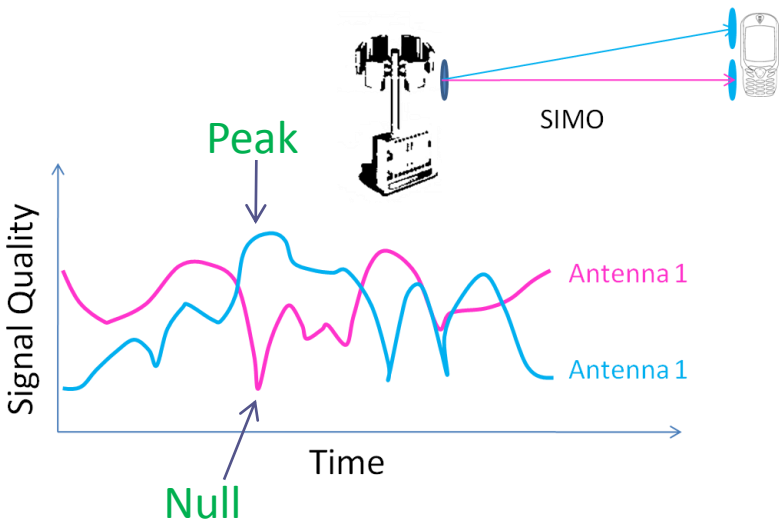
- **SISO (Single Input Single Output)**
  - Traditional radio
- **MISO (Multiple Input Single Output)**
  - Transmit diversity (STBC, SFBC, CDD)
- **SIMO (Single Input Multiple Output)**
  - Receive diversity, MRC
- **MIMO (Multiple Input Multiple Output)**
  - SM to transmit multiple streams simultaneously; can be used in conjunction with CDD; works best in high SNR environments and channels de-correlated by multipath
  - TX and RX diversity, used independently or together; used to enhance throughput in the presence of adverse channel conditions
- **Beamforming**

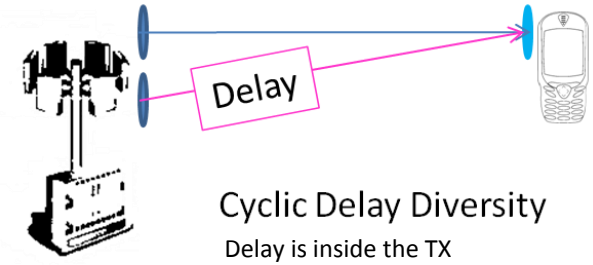


SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio

MIMO Based RX and TX Diversity

- **When 2 receivers are available in a MIMO radio MRC can be used to combine signals from two or more antennas, improving SNR**
- **MIMO also enables transmit diversity techniques, including CDD, STBC, SFBC**
- **TX diversity spreads the signal creating artificial multipath to decorrelate signals from different transmitters so as to optimize signal reception**





MIMO = multiple input multiple output
SIMO = single input multiple outputs
SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio

Distributed-Input-Distributed-Output (DIDO)

Distributed-Input-Distributed-Output (DIDO) Wireless Technology

A New Approach to Multiuser Wireless

Steve Perlman, President & CEO, Rearden Companies
Antonio Forenza, Ph.D., Principal Scientist, Rearden Companies
www.rearden.com

1. *Abstract*

Distributed-Input-Distributed-Output (DIDO) wireless technology is a breakthrough approach that allows each wireless user to use the full data rate[1] of shared spectrum simultaneously with all other users, by eliminating interference between users sharing the same spectrum. With conventional wireless technologies the data rate available per user drops as more users share the same spectrum to avoid interference, but with DIDO, the data rate per user remains steady at the full data rate of the spectrum as more users are added.

As a result, DIDO profoundly increases the data capacity of wireless spectrum, while increasing reliability and reducing the cost and complexity of wireless devices. DIDO deployment is far less expensive than conventional commercial wireless deployment, despite having vastly higher capacity and performance, and is able to use consumer Internet infrastructure and indoor access points.

The potential of DIDO is to have unlimited number of simultaneous users, all streaming high-definition video, utilizing the same spectrum that a single user would use with conventional wireless technology, with no degradation in performance, no dead zones, no interference between users, and no reduction in

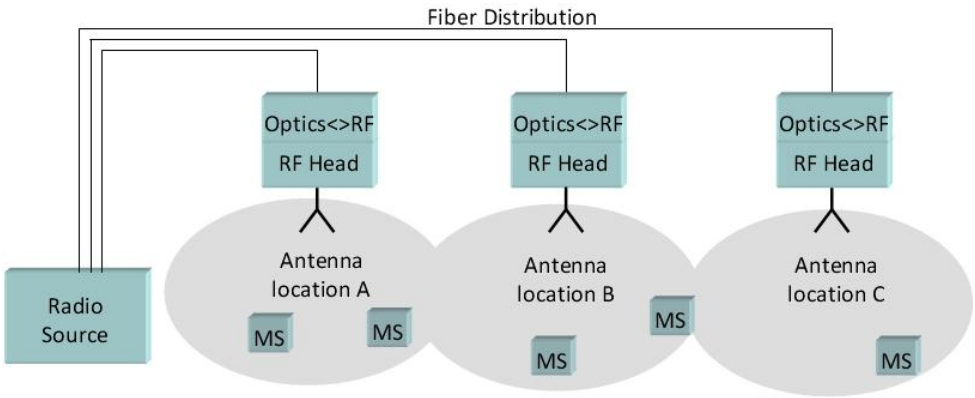
Recent white paper from Rearden Companies

Distributed Antenna System

+

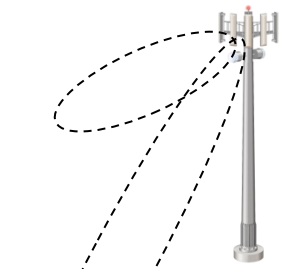
Beamforming

?



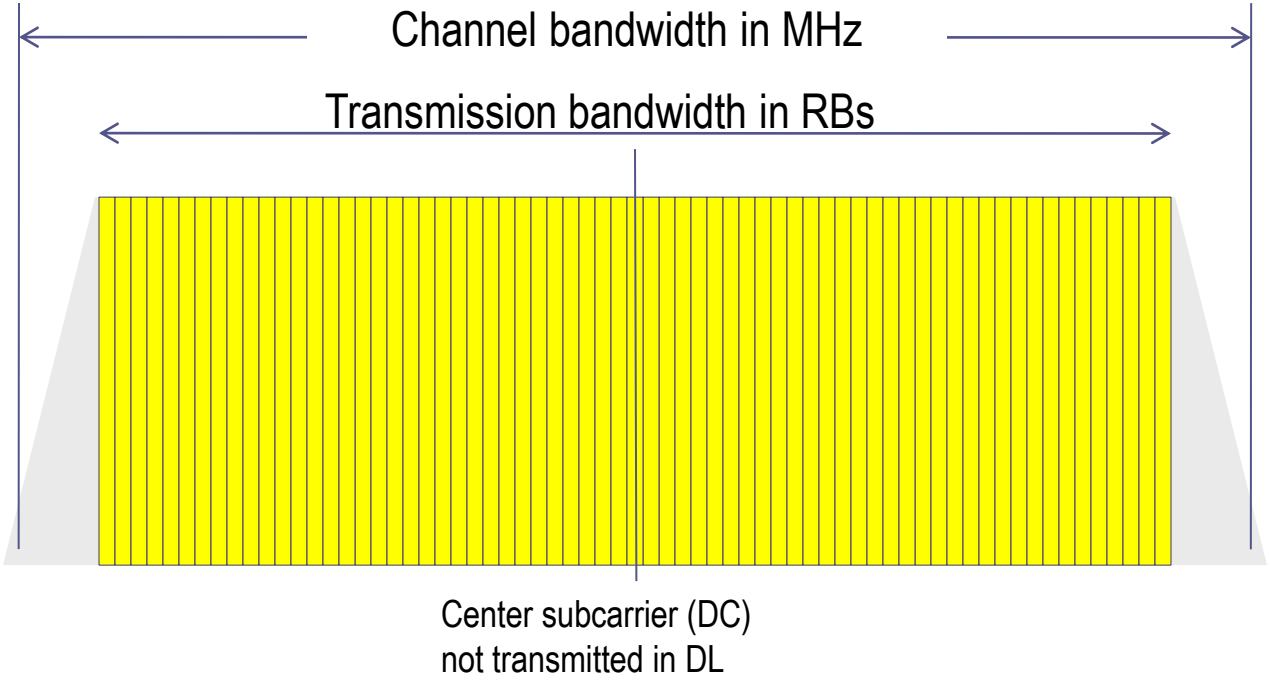
Distributed Antenna System

+



Beamforming

LTE Scalable Channel Bandwidth

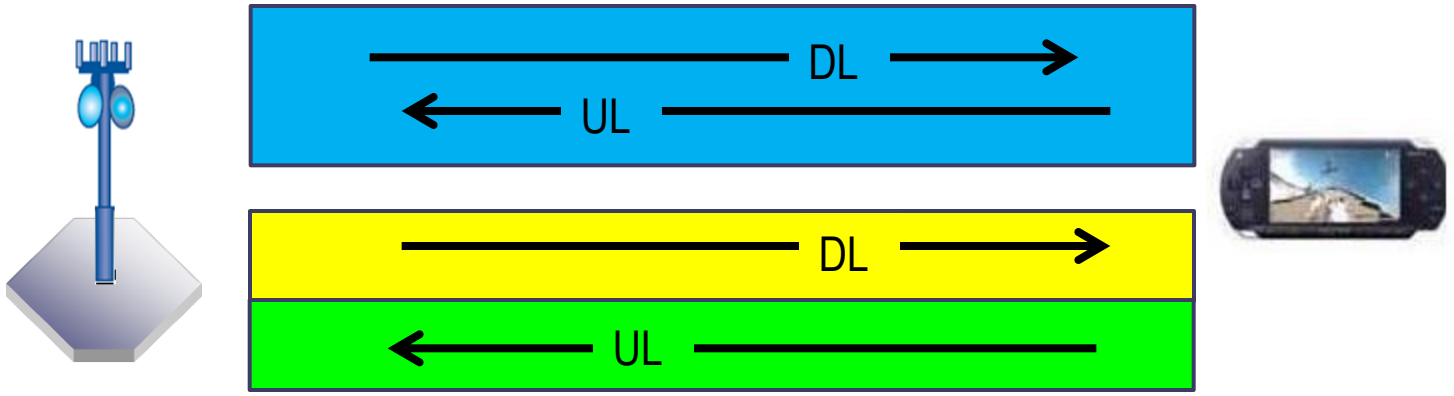


Channel bw	1.4	3	5	10	15	20	MHz
Transmission bw	1.08	2.7	4.5	9	13.5	18	
# RBs per slot	6	15	25	50	75	100	

FDD vs. TDD

- **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

TD-LTE



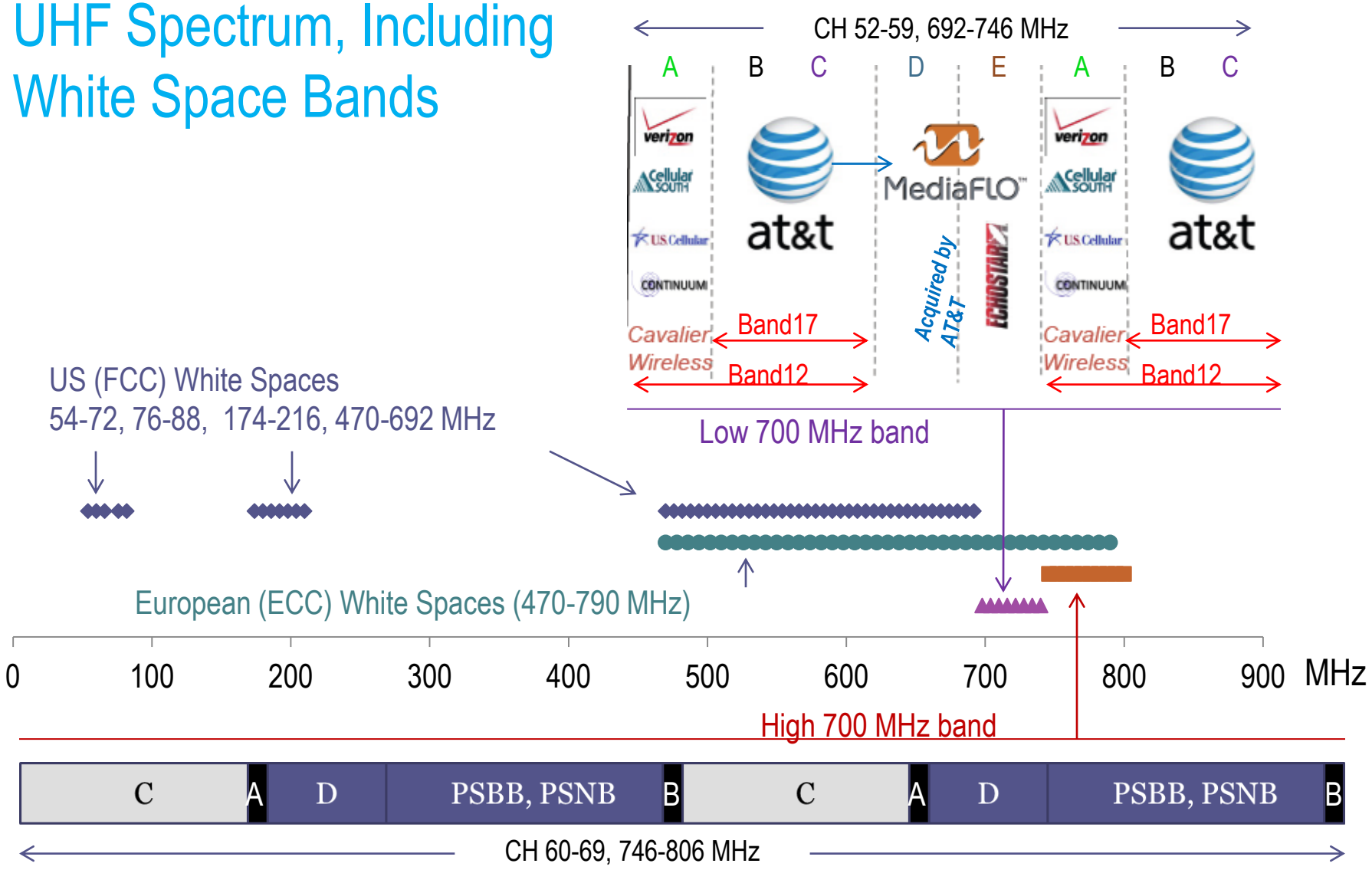
octoScope

LTE Frequency Bands - FDD

Source: 3GPP TS 36.104; V10.1.0 (2010-12)

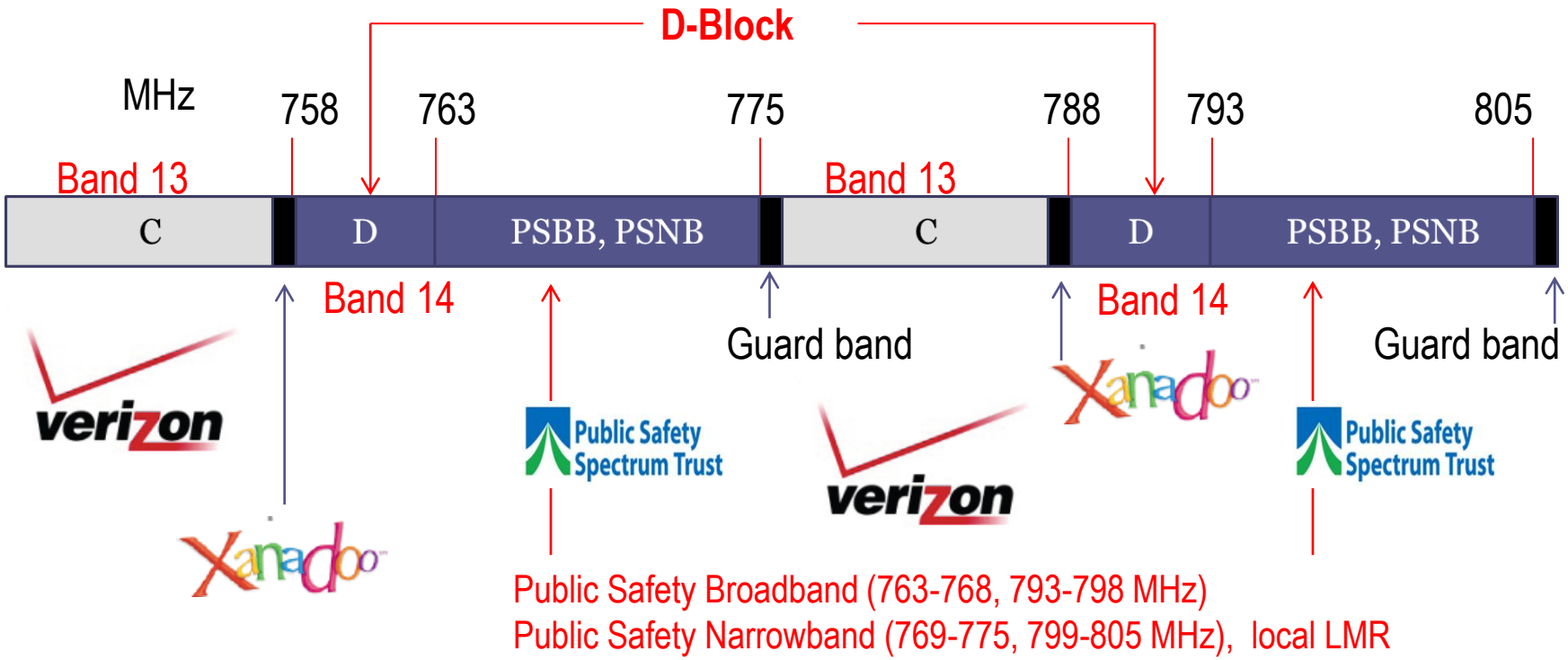
Band	Uplink (UL)	Downlink (DL)	Regions
1	1920 -1980 MHz	2110 - 2170 MHz	Europe, Asia
2	1850 -1910 MHz	1930 - 1990 MHz	Americas, Asia
3	1710 -1785 MHz	1805 -1880 MHz	Europe, Asia, Americas
4	1710 -1755 MHz	2110 - 2155 MHz	Americas
5	824-849 MHz	869 - 894 MHz	Americas
6	830 - 840 MHz	875 - 885 MHz	Japan
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 (Verizon)
14	788 - 798 MHz	758 - 768 MHz	Americas (D-Block, public safety)
17	704 - 716 MHz	734 - 746 MHz	Americas (AT&T)
18	815 – 830 MHz	860 – 875 MHz	
19	830 – 845 MHz	875 – 890 MHz	
20	832 – 862 MHz	791 – 821 MHz	
21	1447.9 – 1462.9 MHz	1495.9 – 1510.9 MHz	

UHF Spectrum, Including White Space Bands



ECC = Electronic Communications Committee

High 700 MHz Band



LMR = land mobile radio

TV Channels and White Space Allocation

US – FCC

	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
White Spaces	21-51*	512-692 MHz	

*Channel 37 (608-614 MHz) is reserved for radio astronomy
**Shared with public safety

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

http://www.fcc.gov/mb/engineering/usallochrt.pdf

Europe – ECC

	Channel #	Frequency Band	
	5-12	174-230 MHz	VHF
White Spaces	21-60	470-790 MHz	UHF
	61-69	790-862 MHz	

LTE Frequency Bands - TDD

TD-LTE

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
41	2496 – 2690 MHz	Americas (Clearwire LTE)
42	3400 – 3600 MHz	
43	3600 – 3800 MHz	

Source: 3GPP TS 36.104; V10.1.0 (2010-12)

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.

octoScope

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
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

WiMAX Forum Mobile Certification Profile R1 5 v1.3.0

Summary

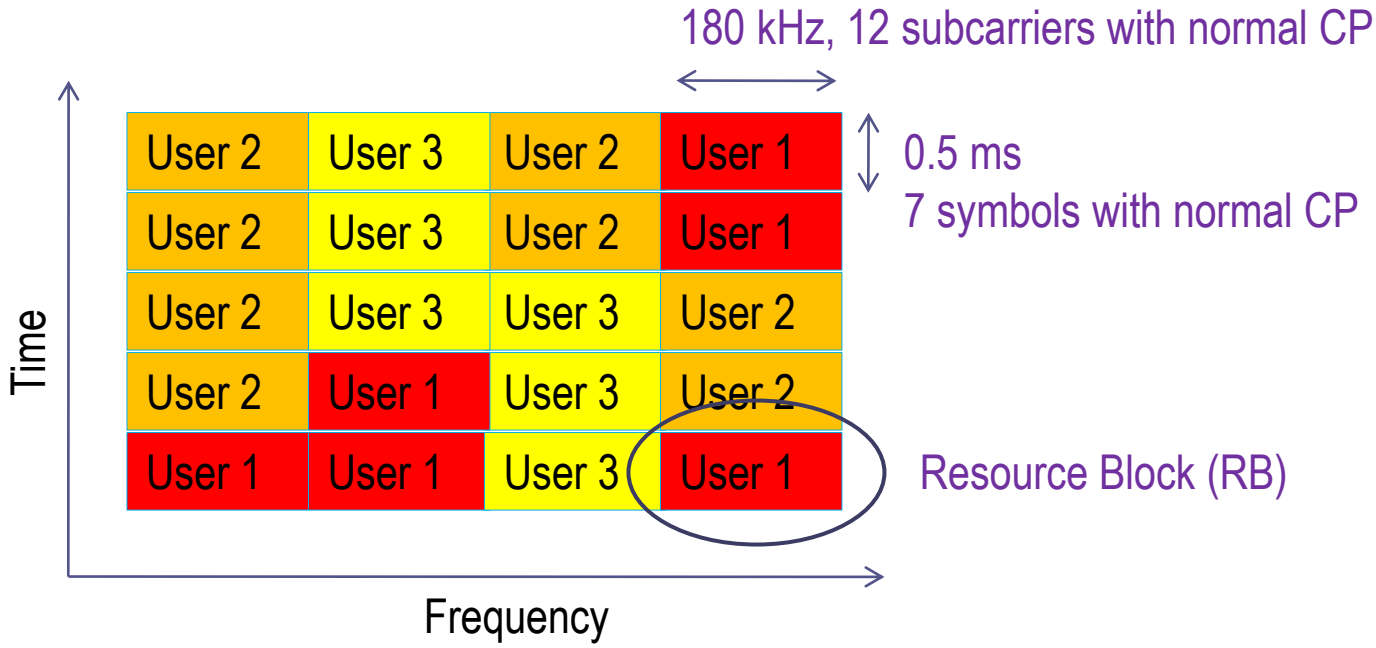
- **LTE is here**
  - Verizon and ATT
- **Beyond commercial markets LTE is also being embraced by**
  - Military and Public Safety markets
  - Intelligent Transportation Systems
  - Possibly Smart Grid
- **Carrier to carrier roaming remains to be seen**

For More Information

- White papers, presentations, articles and test reports on a variety of wireless topics

www.octoscope.com

LTE Resource Allocation

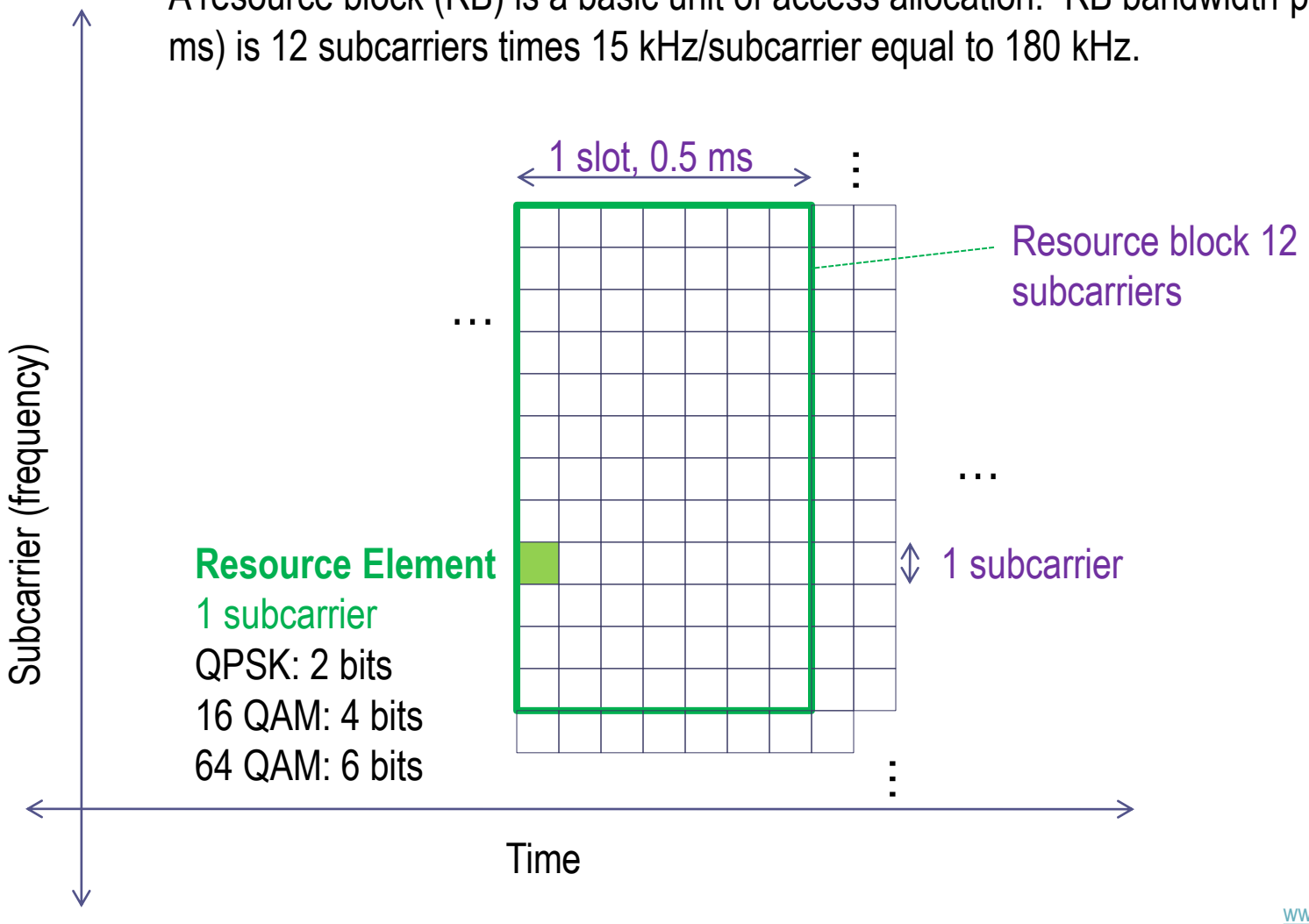


- **Resources are allocated per user in time and frequency. RB is the basic unit of allocation.**
- **RB is 180 kHz by 0.5 ms; typically 12 subcarriers by 7 OFDM symbols, but the number of subcarriers and symbols can vary based on CP**

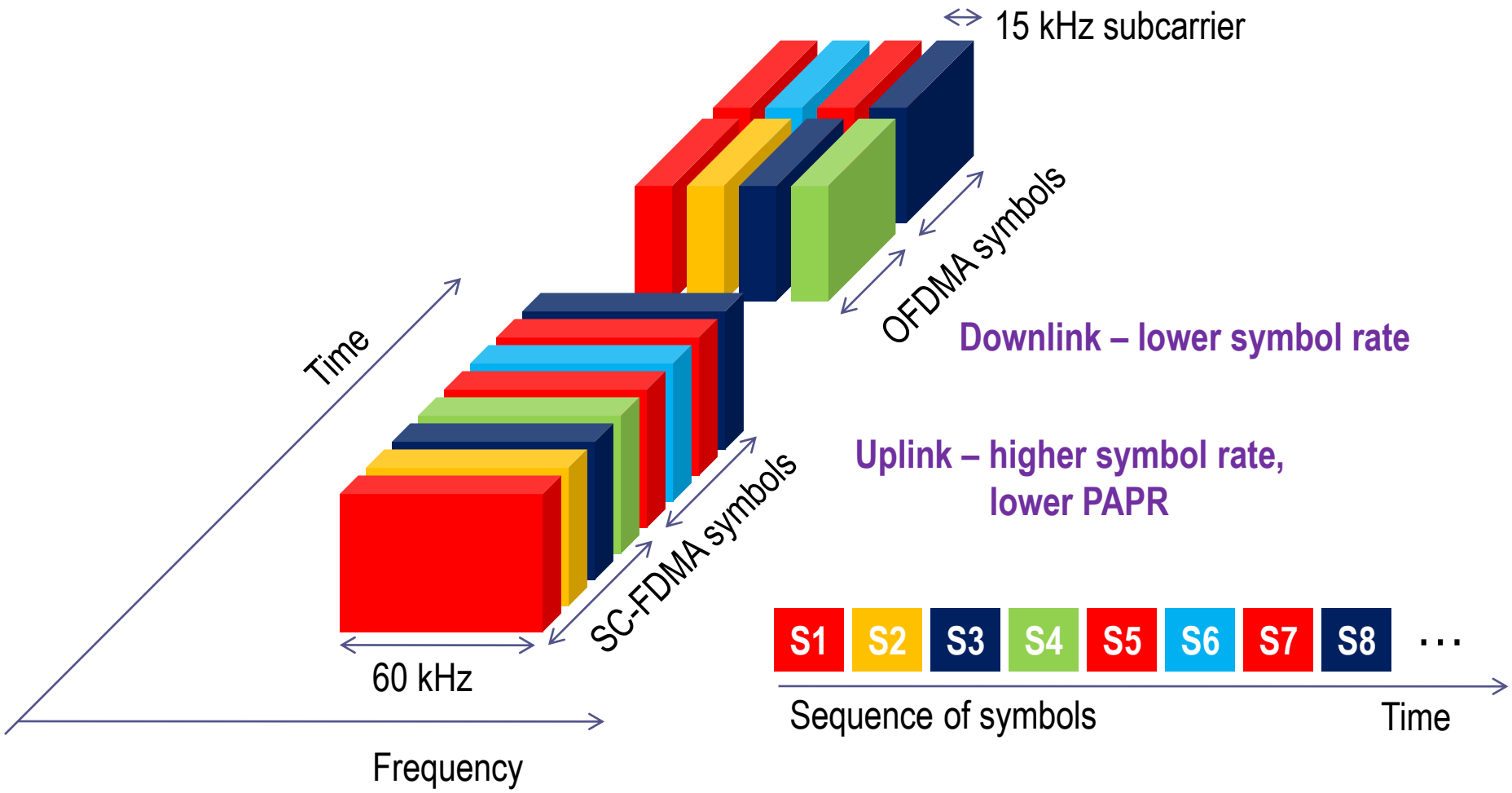
CP = cyclic prefix, explained ahead

Resource Block

A resource block (RB) is a basic unit of access allocation. RB bandwidth per slot (0.5 ms) is 12 subcarriers times 15 kHz/subcarrier equal to 180 kHz.

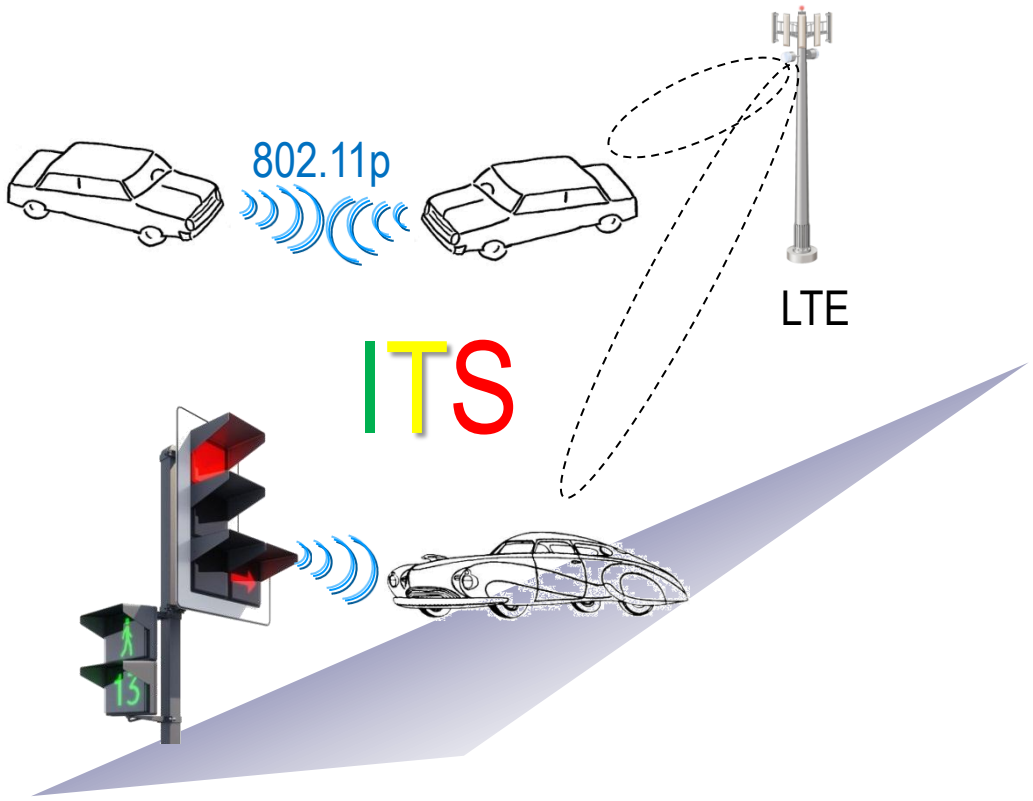


SC-FDMA vs. OFDMA



Intelligent Transportation Systems (ITS)

- **Emerging market**
- **Embracing 802.11p and LTE with sophisticated software stacks on top**



Voice over LTE Solutions

- **CSFB (3GPP 23.272) whereby voice calls are switched to 2G/3G CS networks**
- **VoLGA whereby voice calls are encapsulated in data packets traversing LTE networks**
- **Over-the-Top (OTT) voice, for example Skype operating over LTE networks**
- **GSMA's selected Voice over LTE (VoLTE) based on IMS**

CSFB = circuit switched fallback
CS = circuit switch
VoLGA = voice over LTE with Generic Access
OTT = over-the-top
VoLTE = voice over LTE
IMS = IP multimedia subsystem