

EFREI M1

Mobile Networks

LTE

Paul Simmons

Tamum Consulting January 2013

paul@tamum.com

Mobile Networks: LTE-1

- Introduction: LTE context
- LTE Spectrum
- LTE Radio Interface
- Bibliography

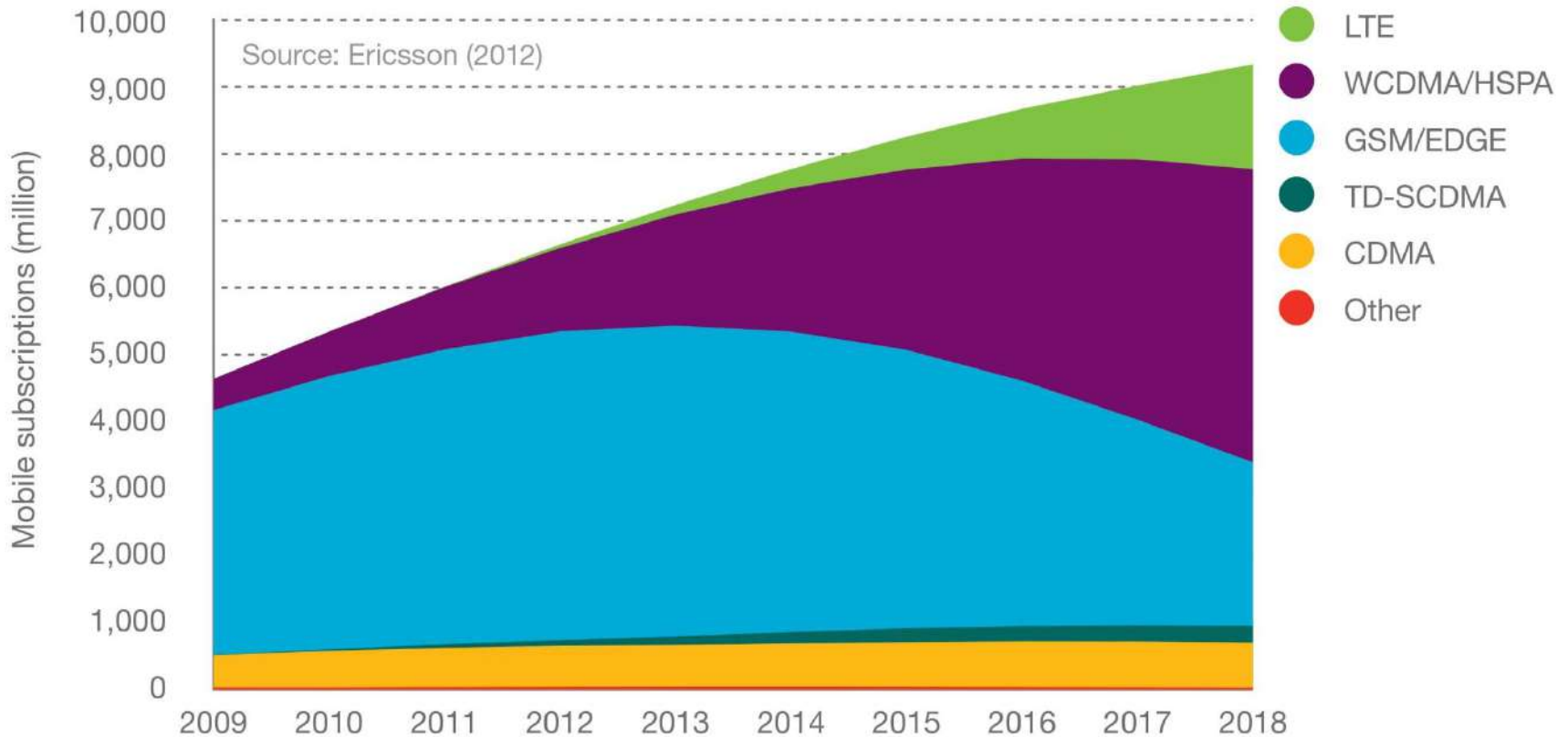
LTE: The fastest growing cellular technology in history

- 2010: Verizon launches its LTE network in US
- Mid-2012 LTE covers around 7% of world population
- End 2012: 57 million LTE users:
 - 51% in North America,
 - 45% in APAC
 - 4% in Europe
- Jan 2013: GSA (Global mobile Suppliers Association) announces:
 - 145 commercial LTE networks in 66 countries
 - 666 LTE Devices
- 2017 50% of global population coverage expected

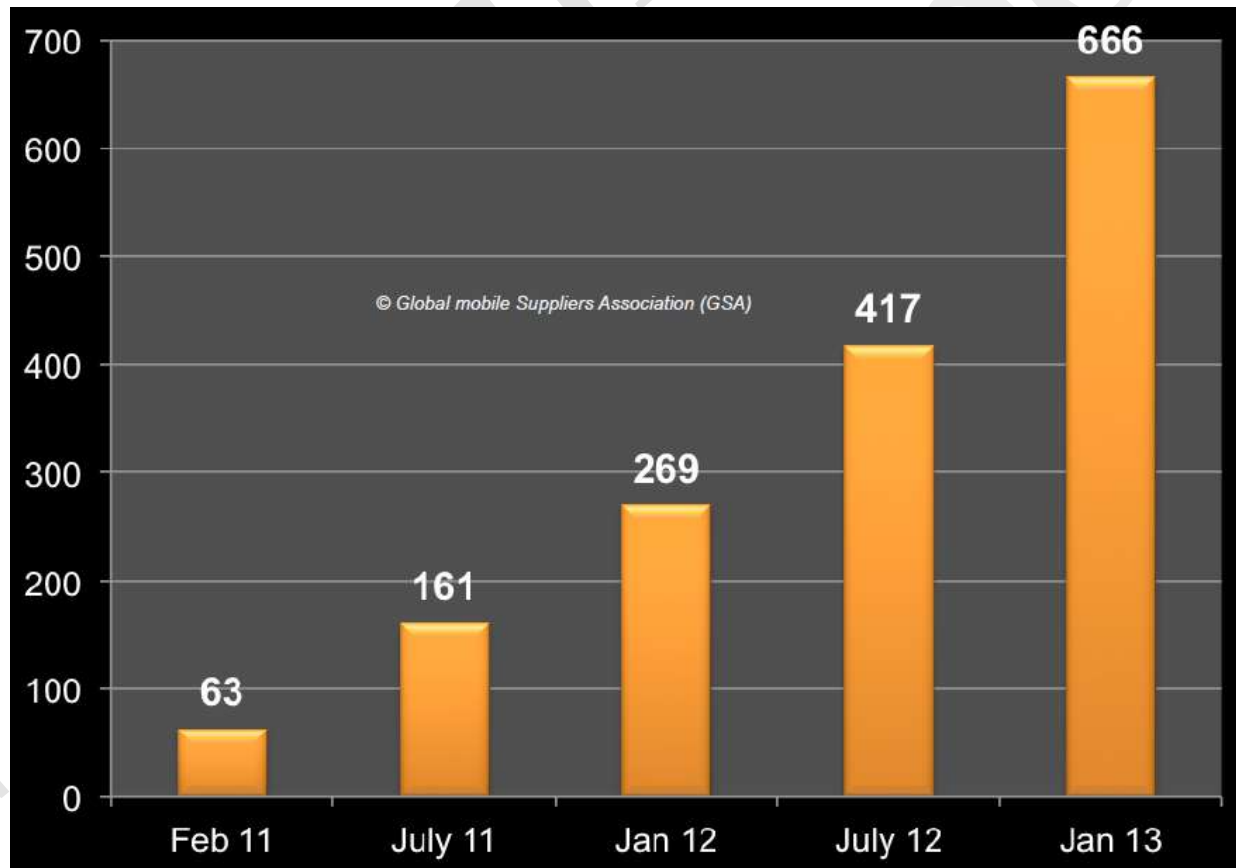
LTE in Europe

- Dec 2009 TeliaSonera Sweden launches LTE in 2600 MHz, later 800 and 1800 MHz
- 2010 Germany launches at 2600 MHz
- 2010 Finland launches at 1800 and 2600 MHz
- 2011 Germany launches at 800 MHz, 1800 MHz
- 201112 Several states launch at 1800 MHz
- 2012 France at 2600, 800 MHz
- Oct 2012 EE UK launches at 1800 MHz
- 2013 less than 1% connections in Europe are LTE

Mobile subscriptions by technology



Number of LTE devices



Google's priorities for 2011

“As I think about Google's strategic initiatives in 2011, I realize they're all about mobile.”

“ First, we must focus on developing the underlying fast networks (generally called *LTE*). These will be 8-to-10-megabit networks, roughly 10 times what we have today, which will usher in new and creative applications, mostly entertainment and social, for these phone platforms.”

[2: mobile money]

[3: increase the availability of inexpensive smartphones in the poorest parts of the world]



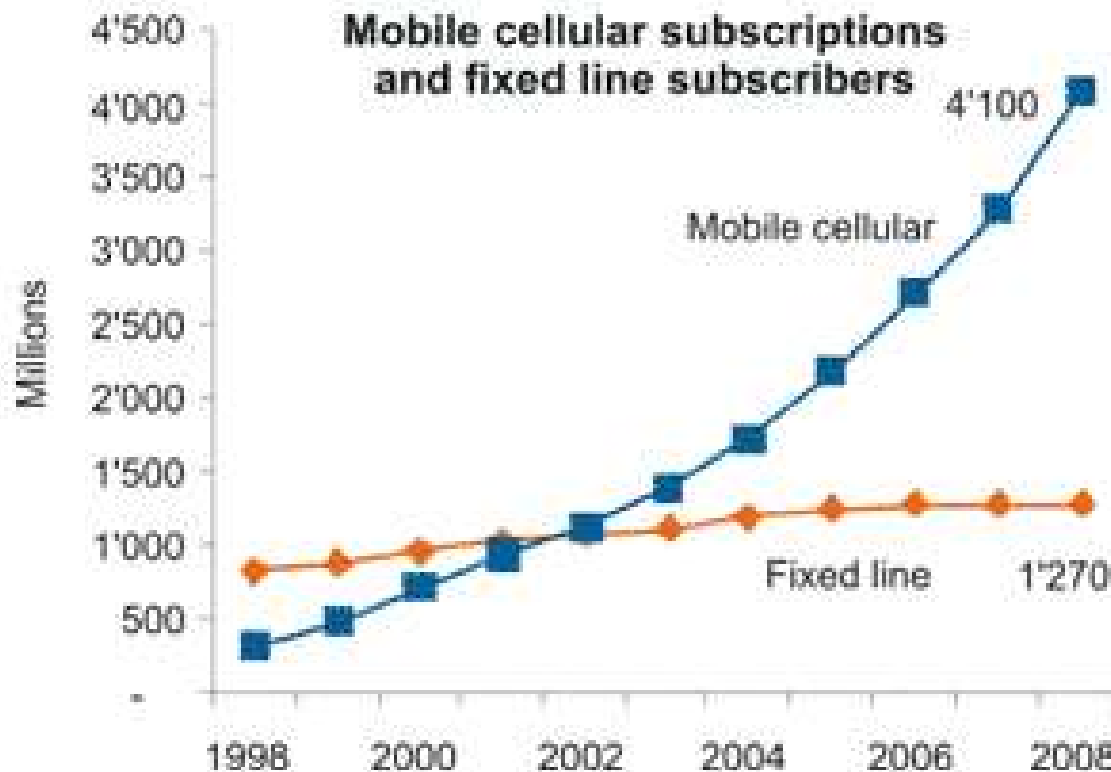
Eric Schmidt, Google CEO on Jan 20, 2011
(Harvard Business Review)

LTE as a modem

- Main drive for LTE comes from demand for faster data services

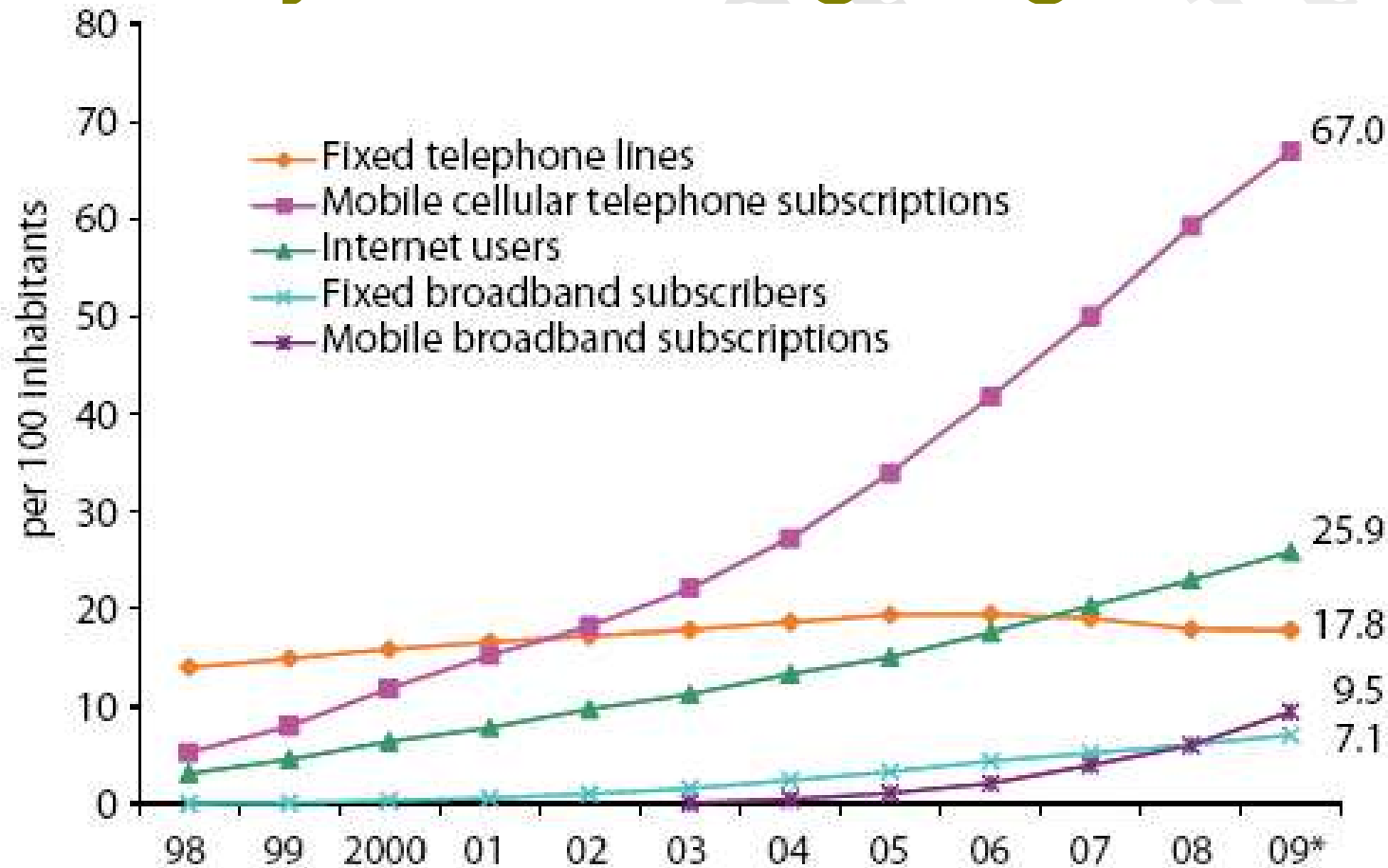


2001: Telephone goes wireless



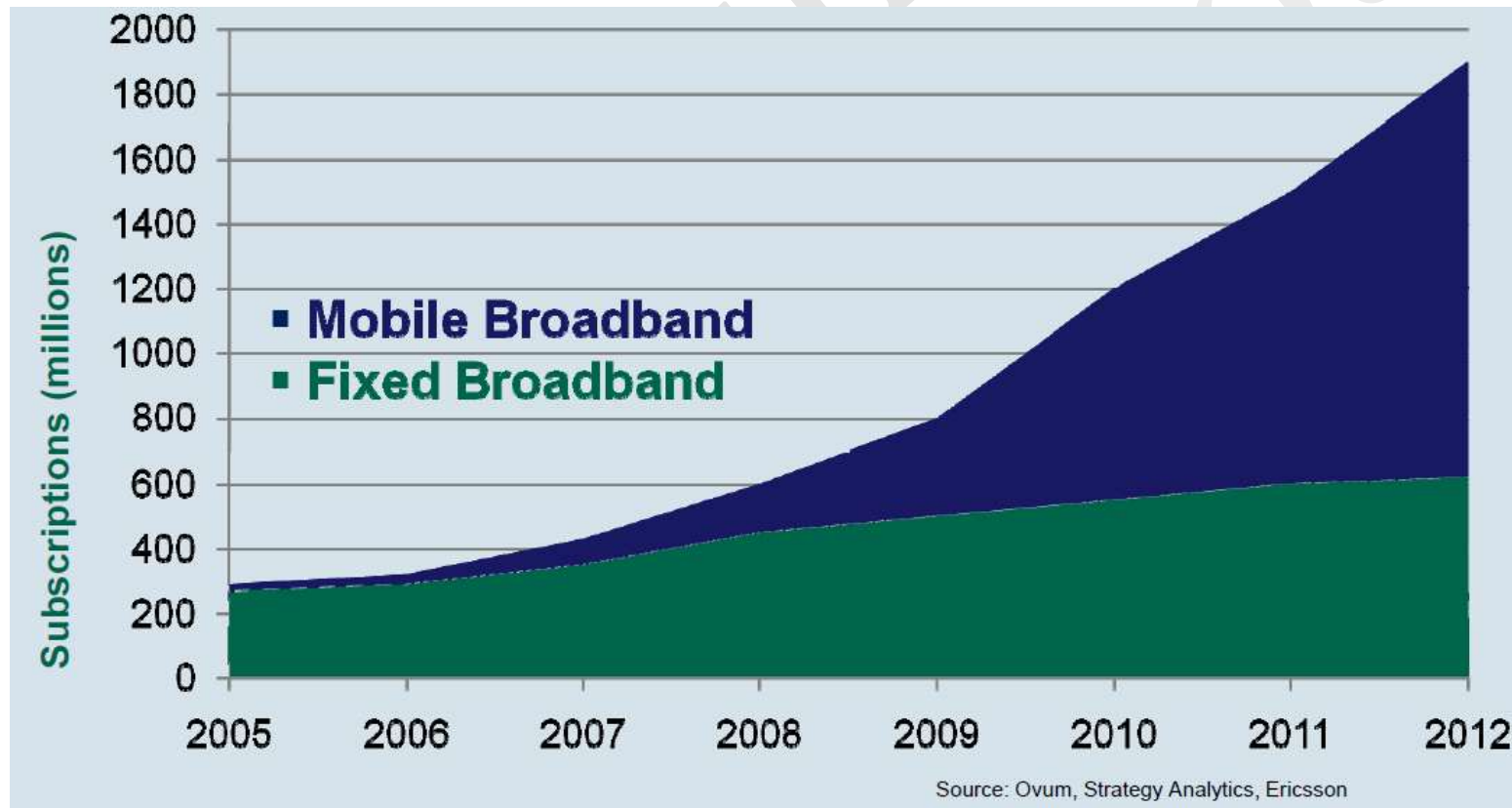
Source: ITU World Telecommunication/ICT database

Today: Internet going mobile



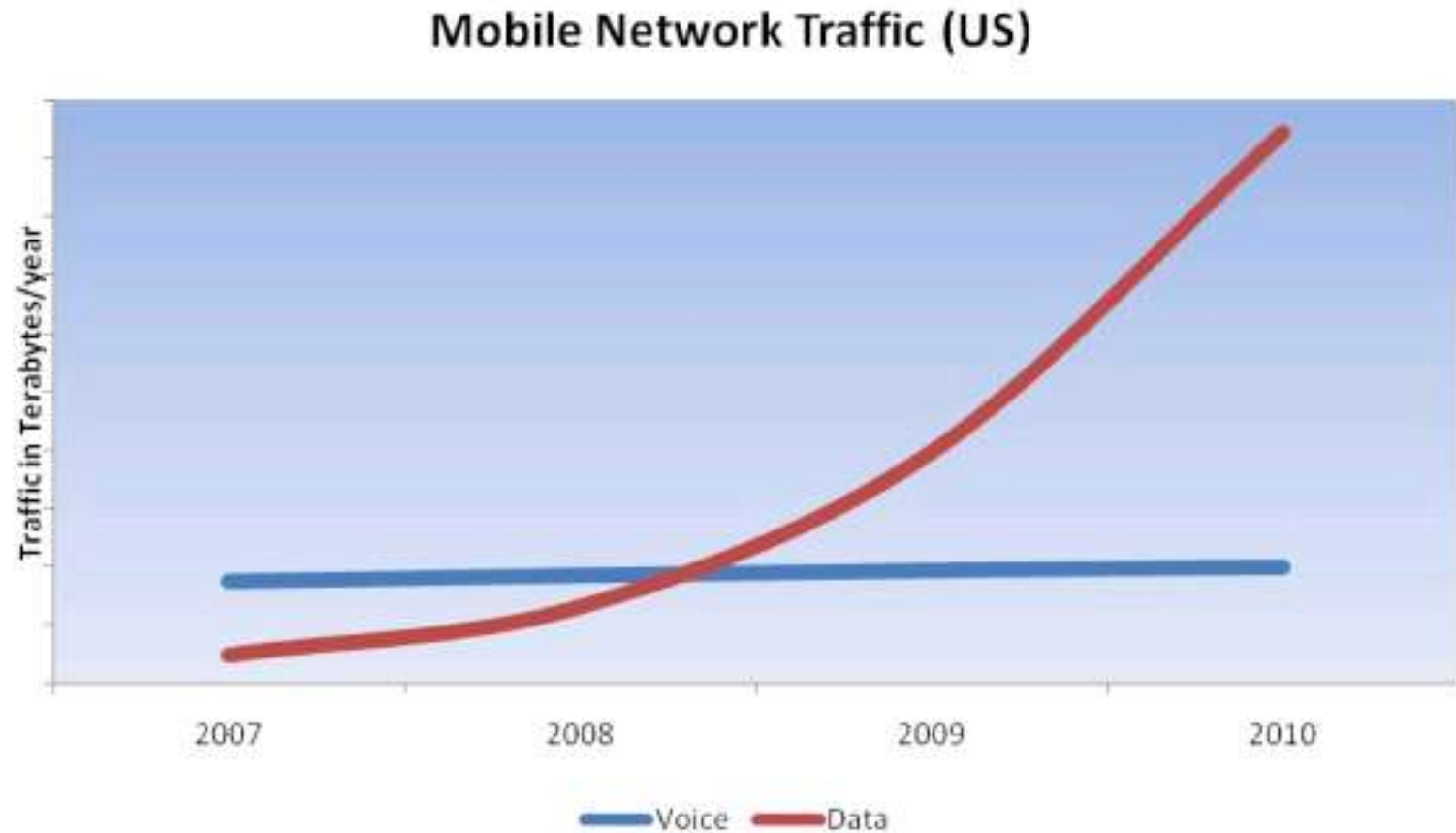
Source: ITU World Telecommunication/ICT database

Mobile Broadband Growth



Mobiles are overtaking PCs as internet connectors

Mobile data traffic overtakes voice

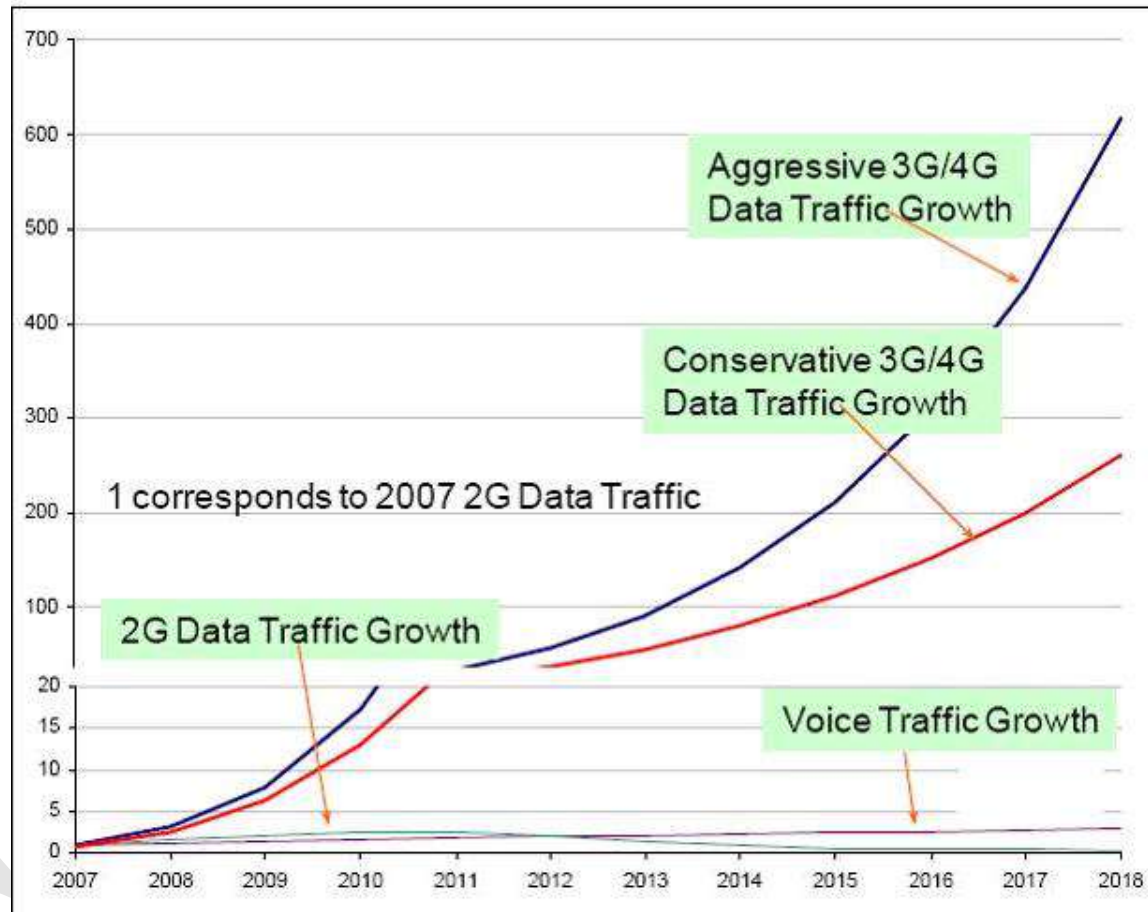


It is estimated this crossover happened for total world mobile traffic in Dec 2009

The rise of the mobile internet

- More people have “mobile telephones” than “personal computers”
 - Cibercafés provide a middle solution
 - Mobile networks increasingly provide data services
 - 1 billion* mobile internet users by end 2011
- VOIP increasing
- Mobile data traffic has overtaken mobile voice
 - Advances in portable screen technology will drive bandwidth demand
- “Mobile telephones” become “smartphones”:
 - small portable wireless computers
 - telephony secondary to internet access and other applications

Mobile data growth predictions



What limits to growth?

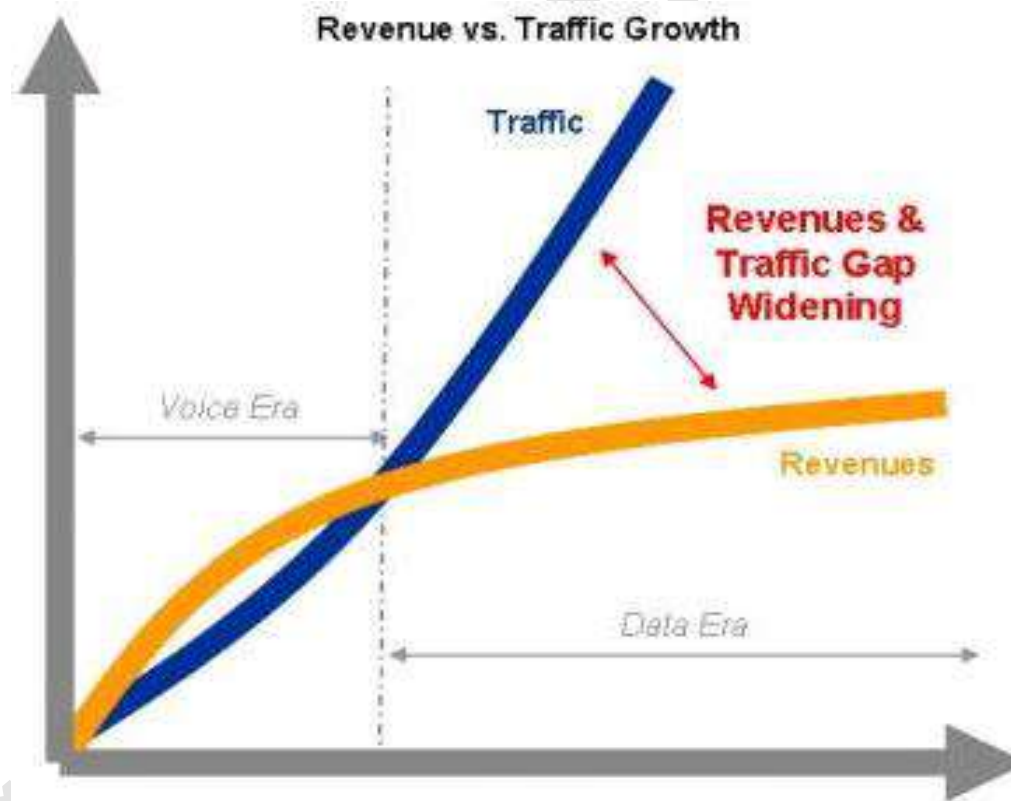
The “internet of things” could connect $\sim 10^{14}$ objects

How much will people pay for data?

Service	Data Volume	Price €*	€/MB
Voice	10kbps	0.2	3
SMS	160B	0.1	640
Video	384kbps	0.4/min	0.13
Data	-	22/3GB	0.01

*Source Cambridge broadband networks, UK prices 2010

Data bps price low, decreasing



LTE needs to significantly reduce cost per delivered bit

Requirements for a new generation of wireless data

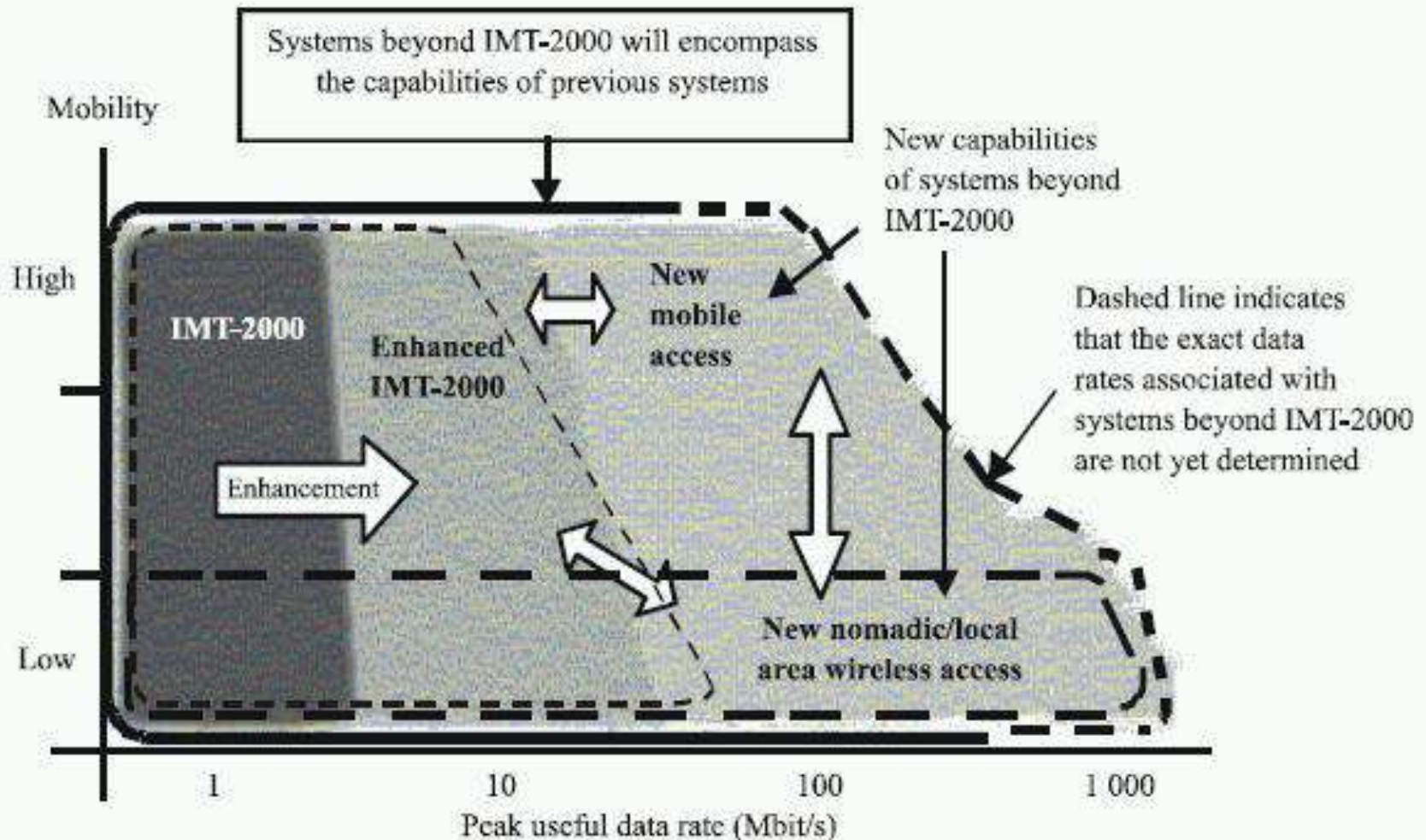
- Higher data bandwidth throughput per user: average
- Higher “peak” data bandwidth capability for some users sometimes
- Lower data cost (per access, bit, bps)
- Lower latency (ping time)



3GPP: UMTS Long Term Evolution (LTE)

- 2004 Toronto 3GPP workshop set high level requirements:
 - Reduced cost per bit (better spectral efficiency)
 - More services at lower cost, better user experience
 - Flexibility of use of frequency bands
 - Simplified architecture, open interfaces
 - Reasonable terminal power consumption
- 2005 3GPP final requirements added:
 - Reduced signalling delays and user data latency
 - Increased user data rate, including cell-edge
 - Seamless mobility, including with GSM and UMTS

ITU-R plan

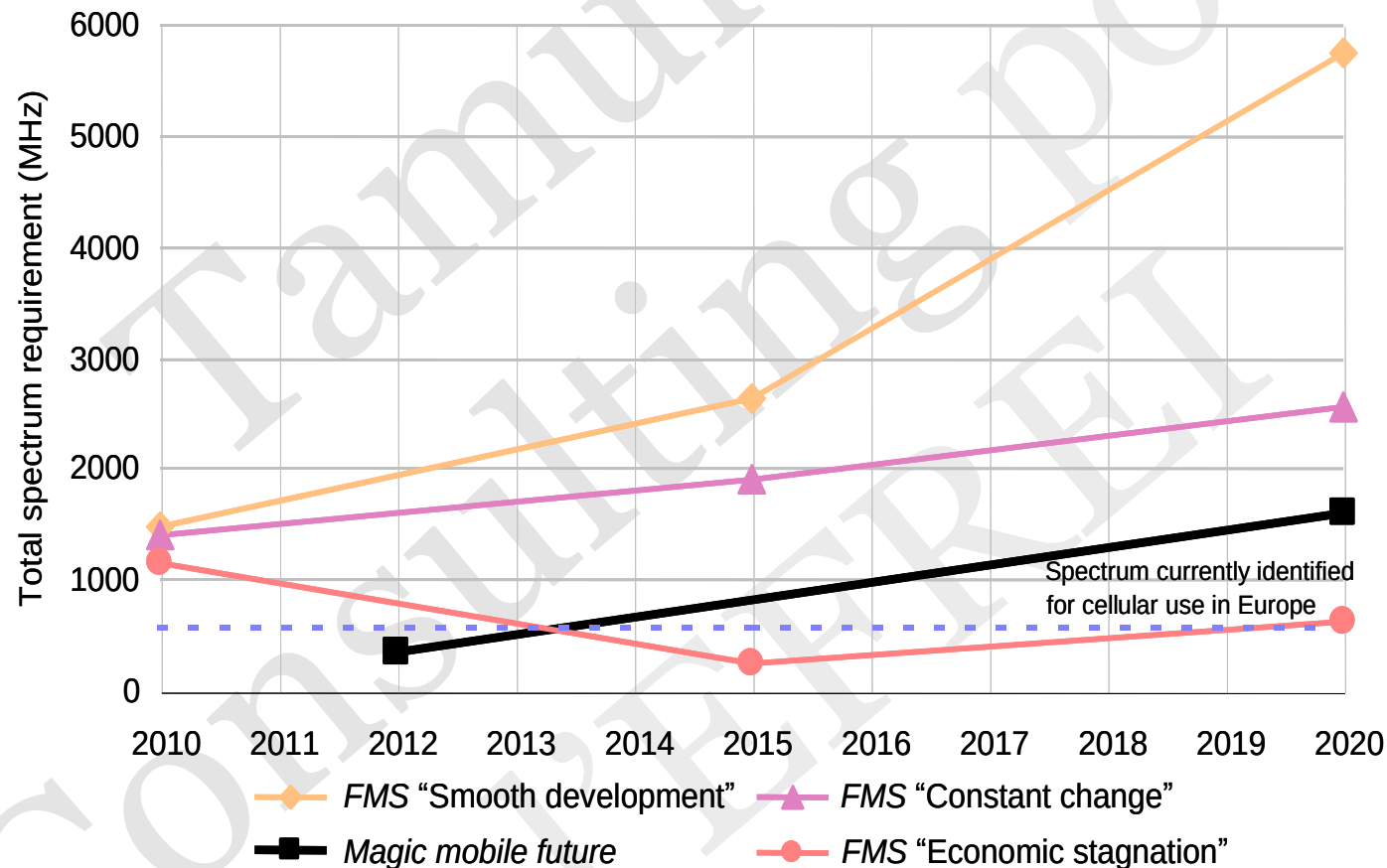


Spectrum issues

- Higher bandwidth needs more spectrum (Shannon Hartley Limit)
- GSM and UMTS are single carrier bandwidth (200kHz and 5MHz)
- To exploit new spectrum, a more flexible allocation is useful



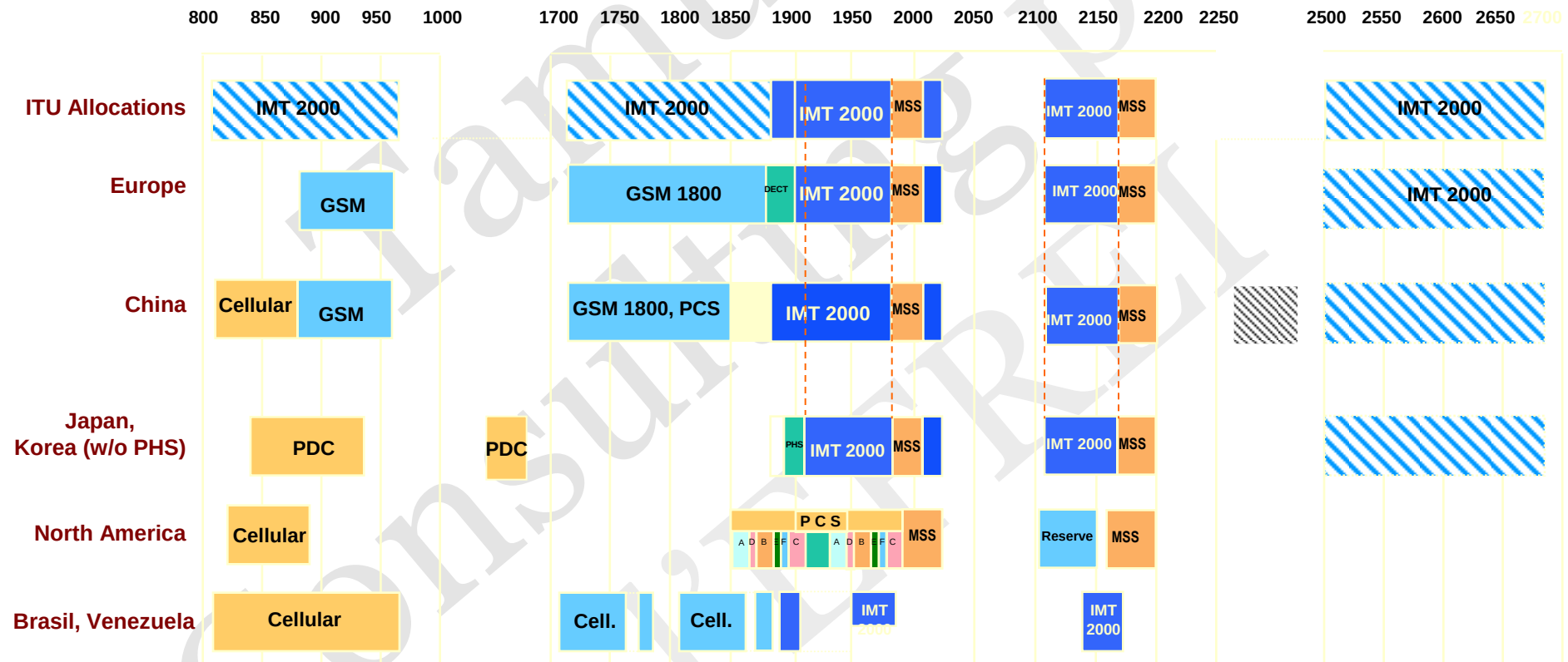
UMTS forum 2006: Existing bands not enough for IMT-Advanced services after year 2015



Need identified for more spectrum sent to WRC-07:

1. Mobile market and subscriber growths continues to be strong
2. High bit rate services experienced in cable and fixed networks will be expected from mobile networks as users demand the same services and same quality
3. More spectrum will be needed for IMT-Advanced services in a response to increased traffic
4. Bands for IMT-Advanced should be globally common and low enough (preferably below 6GHz)
5. WRC-07 decision would enable IMT-Advanced deployment in year 2015-2020 timeframe

Mobile Spectrum After WRC 2000



IMT-2000 Spectrum for “3rd generation” systems
 PCS: Personal Communication System

MSS: Mobile Satellite System
 PDC: Personal Digital Cellular

FDD and Paired Spectrum

- Frequency Division Duplex (FDD)
 - requires separate frequency channels in uplink and downlink
 - filtering requirements are stronger between duplex channels than adjacent channels
 - Thus uplink channels and downlink channels are grouped in separate band allocations as paired spectrum with a frequency offset
 - Requires fixed up/downlink bandwidth allocations
 - Generally, but not necessarily, equal bandwidth
 - Up and downlink propagation may differ
 - Generally for mobile networks, lower frequency is mobile transmit (better propagation); some exceptions
 - Full duplex requires a duplexer: half-duplex FDD (as in normal GSM mobiles) does not

TDD and Unpaired Spectrum

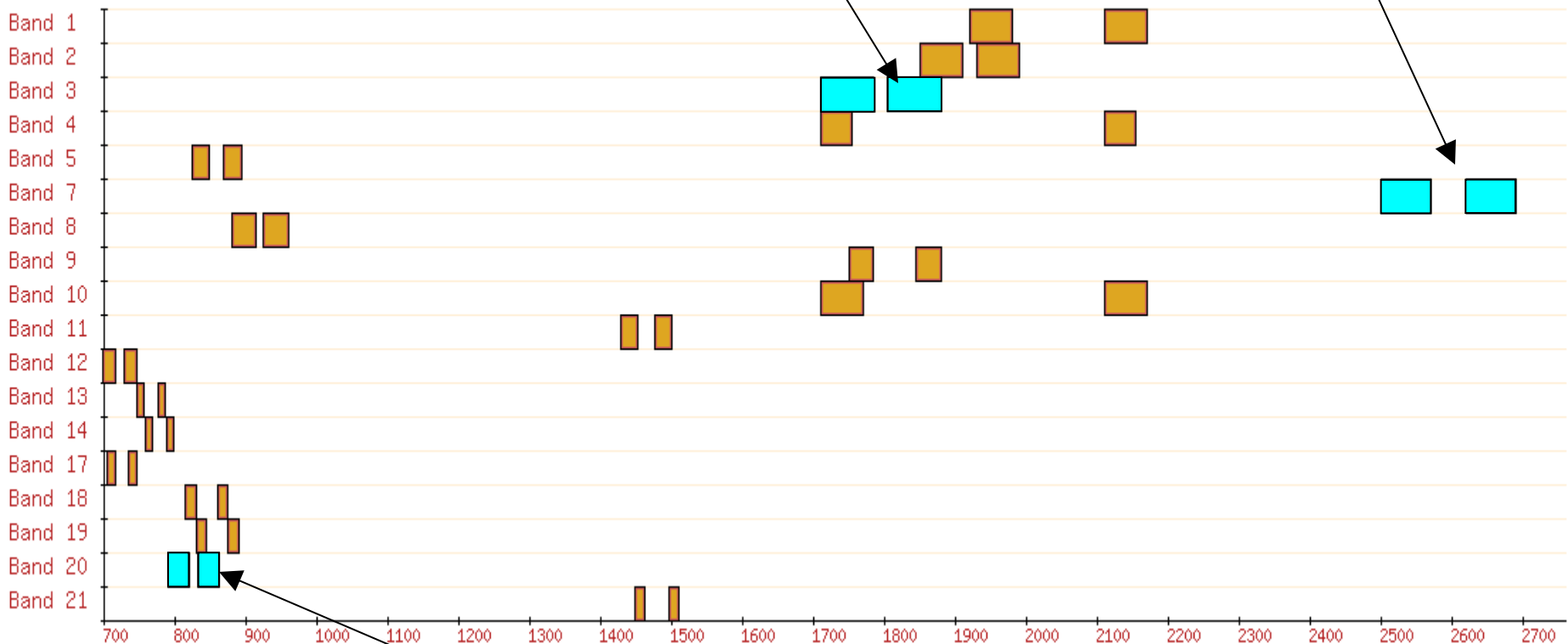
- Time Division Duplex (TDD):
 - can operate in a single frequency channel
 - Requires time synchronization with neighbouring cells: generally harder than frequency synchronization
 - Requires time synchronisation within cell
 - loss of channel capacity to system time delays
 - TDD channels can be assigned to unpaired spectrum
 - Flexible up/downlink bandwidth allocation
 - Uplink and downlink path propagation similar
 - Traditionally used for small-scale systems, The current WiMax standard is TDD, and some countries (e.g. China) and companies have been driving it within UMTS and LTE.

LTE-FDD defined Spectrum

■ Important region 1 early target bands

Band 3: 1800MHz

Band 7: 2.6GHz

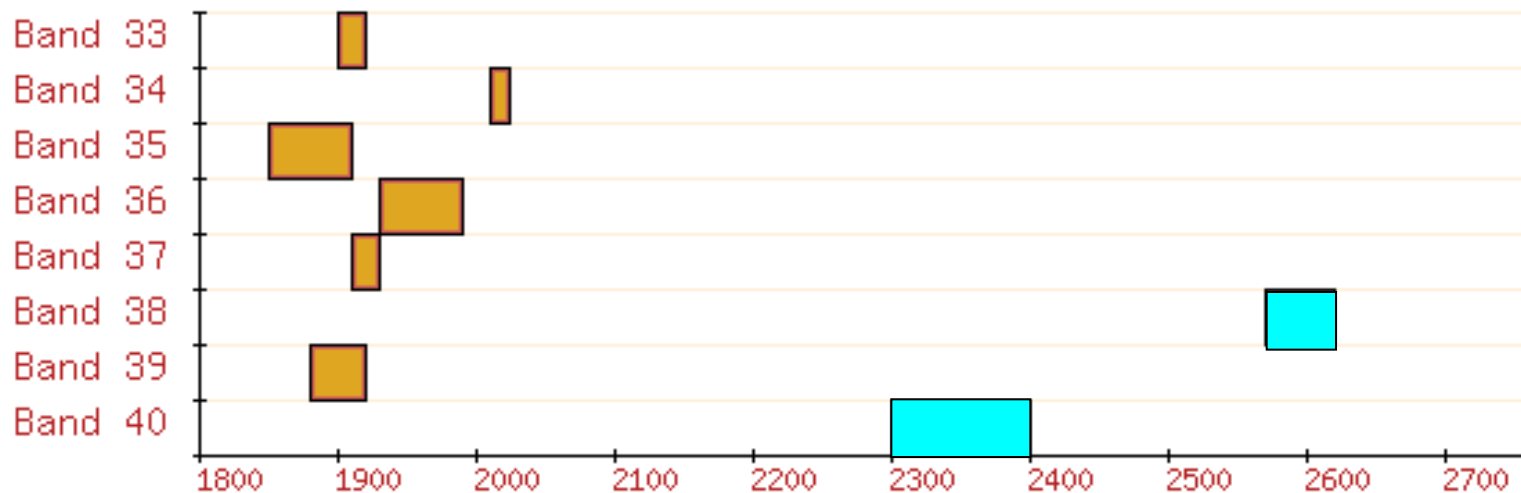


Band 20: 800MHz

LTE-TDD defined spectrum



Important early bands



Complete list of all LTE spectrum bands in TS 36.101

How to decide spectrum use

1. Lobbying by industry, governments and organisations into ITU, WRC
2. Recommendations by ITU
3. Agreements by regional bodies (e.g. CEPT)
4. Final decisions by governments
5. Governments then license spectrum by unilateral decision, “beauty contest” or auction
6. Auction price set by marketplace:
 - In 2000, German government auctioned the 2.1GHz (UMTS) band for €51 bn
 - In 2010 Germany government auctioned the (much larger) 2.6GHz band for €3 bn

LTE Spectrum bandwidth

- As we approach the Shannon limit in LTE, large amounts of spectrum are needed to achieve the maximum throughput requirements: 20MHz per mobile
- However, for historical, economic and technical reasons, the radio spectrum is very fragmented. Therefore a desirable characteristic of LTE is that it can make use of a wide variety of bandwidths
- Therefore the LTE standard allows 6 channel bandwidths: 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz, 20MHz.



Spectrum Co-existence

- In order to protect users of different spectrum bands, it is necessary to specify certain system characteristics, and to perform technical co-existence studies
- In particular, it is important to protect certain applications:
 - emergency services
 - aviation
 - medical and scientific applications, e.g. radio astronomy
- In-band interference studies are also necessary to ensure the viability of a system

Receiver Blocking

- Receiver blocking is the effect of a strong out-of-band signal, present at the input of the receiver, on the receiver's ability to detect an in-band wanted signal.
- Receiver sensitivity is the minimum power, measured at the antenna port, at which the frame error rate (FER) or bit error rate (BER) are below a certain specified limit. [ITU-R Recommendation **M.1455**]
- The blocking signal degrades the specified receiver sensitivity by a certain number of dB's.

Receiver Selectivity

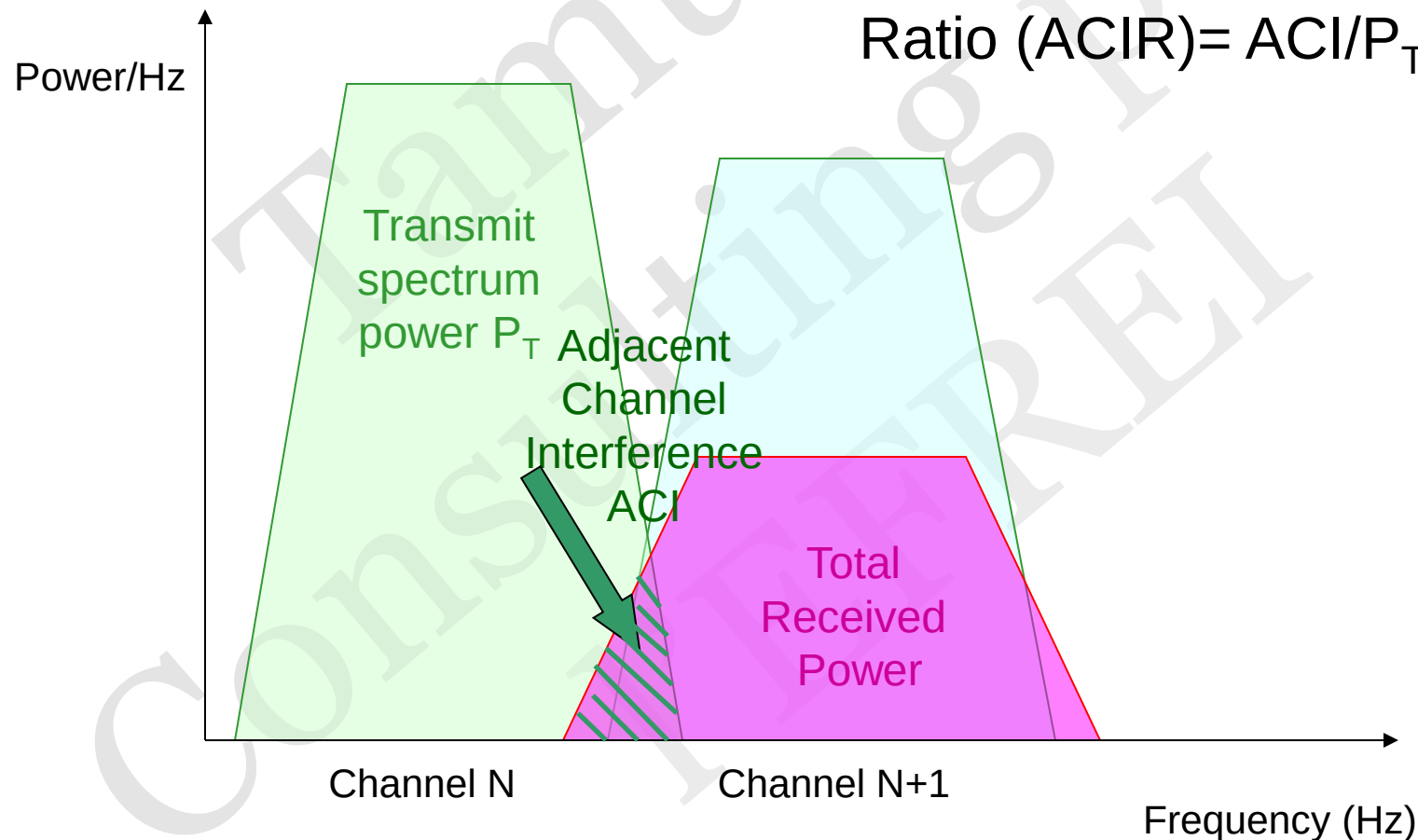
- Selectivity is a measure of the performance of a radio receiver to respond only to the radio signal it is tuned to (such as a radio station) and reject other signals nearby in frequency, such as another broadcast on an adjacent channel.
- Selectivity is usually measured as a ratio in decibels (dBs), comparing the signal strength received against that of a similar signal on another frequency. If the signal is at the adjacent channel of the selected signal, this measurement is also known as adjacent-channel rejection ratio (ACRR).

Spurious Emissions

- ITU-R Recommendation M.329-7 defines spurious emissions as “Emission on a frequency, or frequencies, which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information.
- Spurious emissions include **harmonic** emissions, **parasitic** emissions, **intermodulation** products and **frequency conversion** products but exclude out-of-band emissions.”
- Spurious emissions are generated by non-linear components in the transmitter in the process of carrier signal generation, mixing, modulation and amplification.

Adjacent Channel Interference

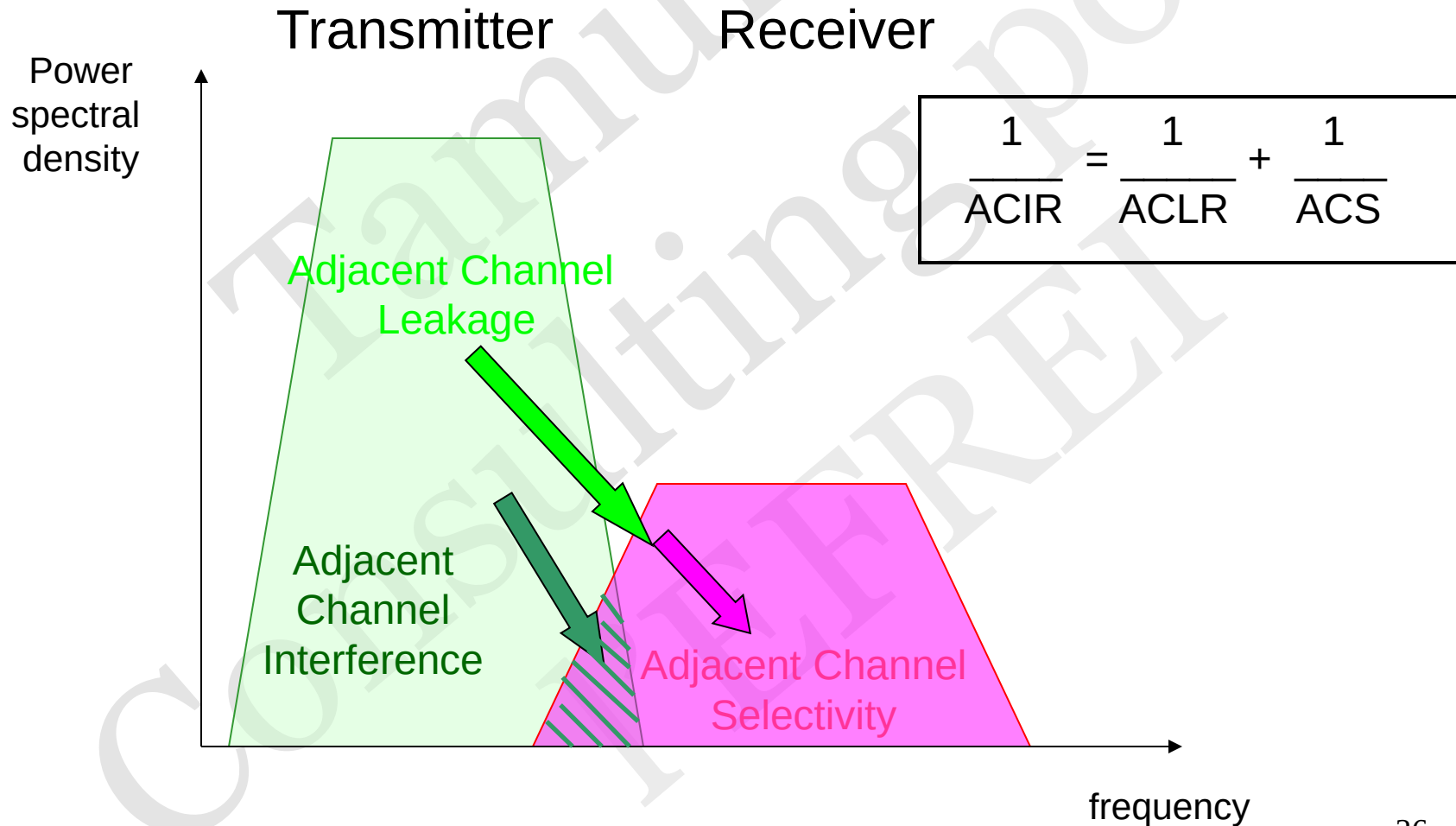
Adjacent Channel Interference
Ratio (ACIR) = ACI/P_T



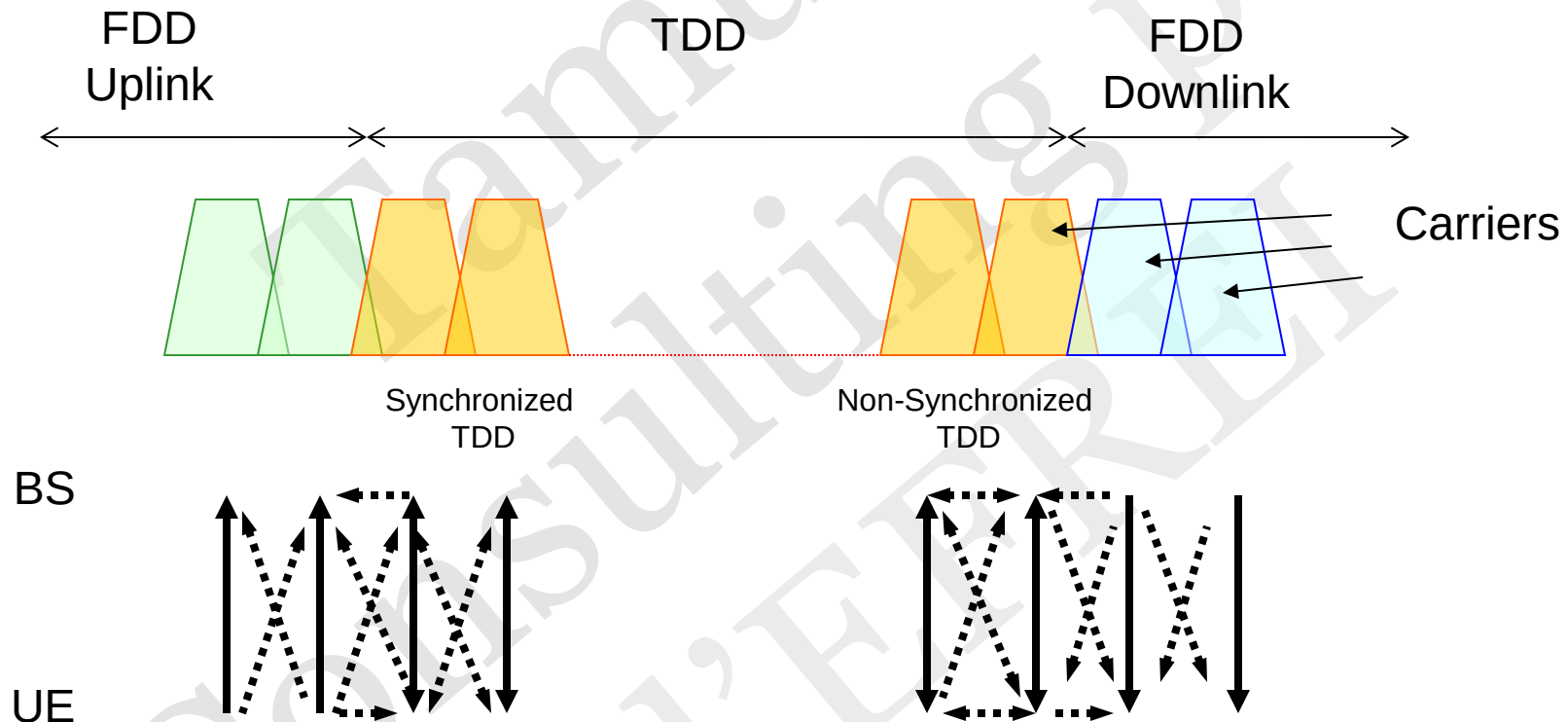
Adjacent Channel Interference Components

- Adjacent Channel Leakage Ratio (ACLR) is defined as the attenuation of the transmit power which is “spilled” into the adjacent channels (due to filtering imperfections). It is measured relative to the carrier signal power and expressed as dBc attenuation values.
- Adjacent Channel Selectivity (ACS) is a measure of the receiver’s ability to reject signals from adjacent channels while receiving a wanted signal on its tuned frequency. It is specified as the ratio (in dB) of the adjacent channel signal level to the assigned channel signal level in which a reference BER/FER is maintained.
 - $ACIR^{-1} = ACLR^{-1} + ACS^{-1}$

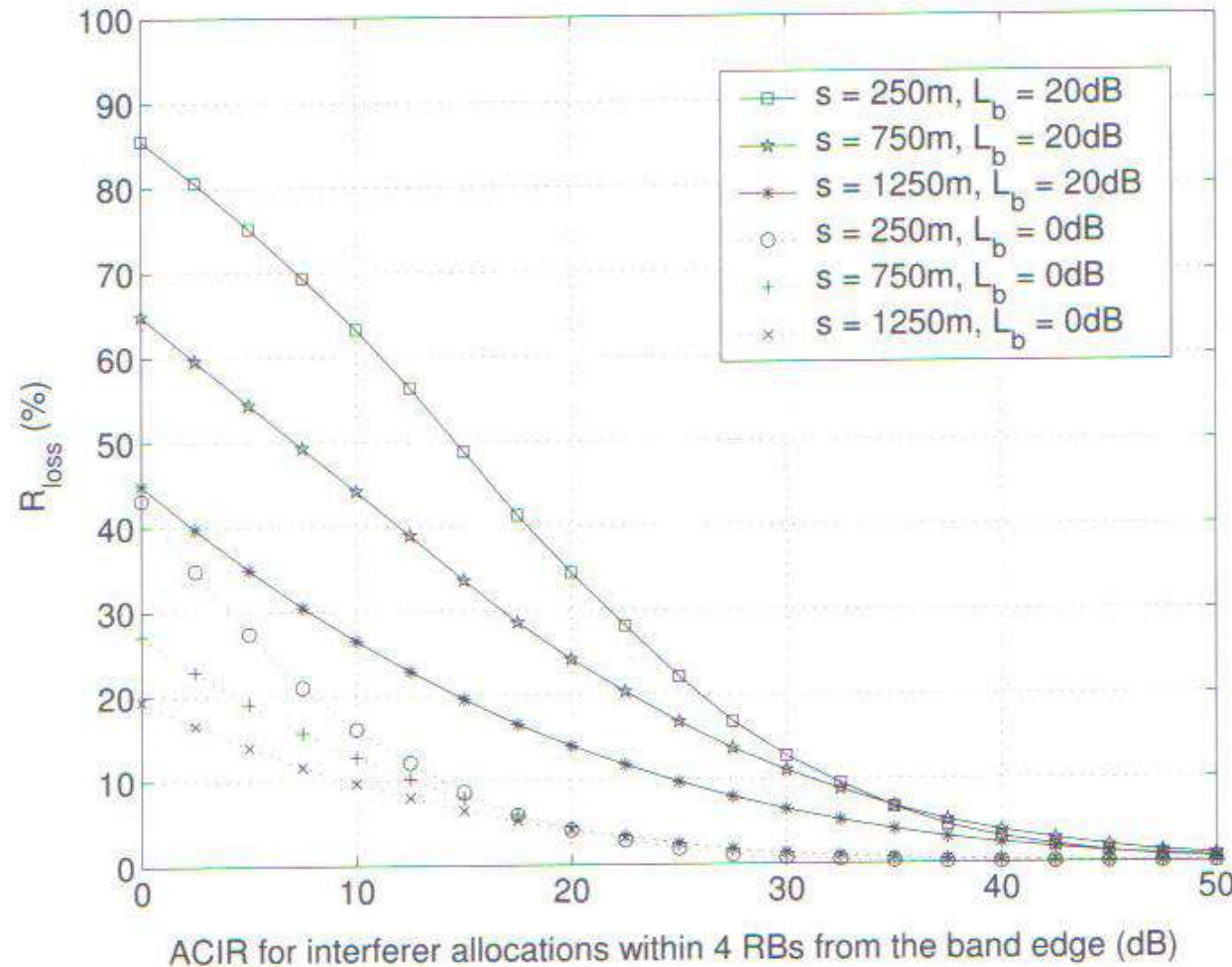
Adjacent Channel Interference Components



Adjacent Channel Interference Scenarios



Example: Throughput reduction due to UE-to-UE interference, separation s , building loss L_b



Source: Sesia et al. [ref.1]

Spectrum Re-farming

- Spectrum licences provide terms of use, often specifying the technology to be used, e.g. Mobile, or GSM Mobile
- Re-use of the spectrum e.g. changing from GSM to UMTS, is called re-farming, and usually requires a licence change
- In the case of a change to LTE, it may be possible to keep the same licence (if LTE is considered part of UMTS), but technical re-farming is required.

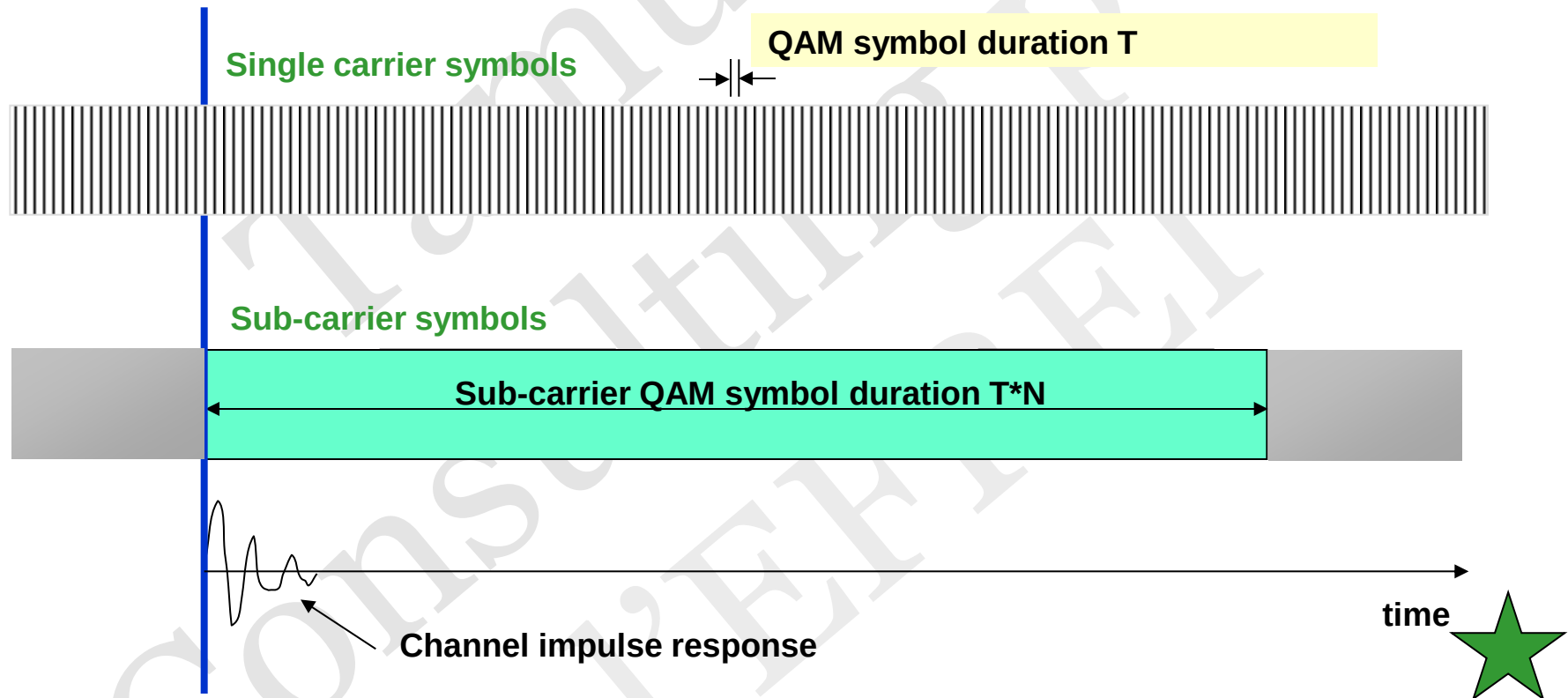


LTE Problem No.1 (LP1): Modulation and multiple access

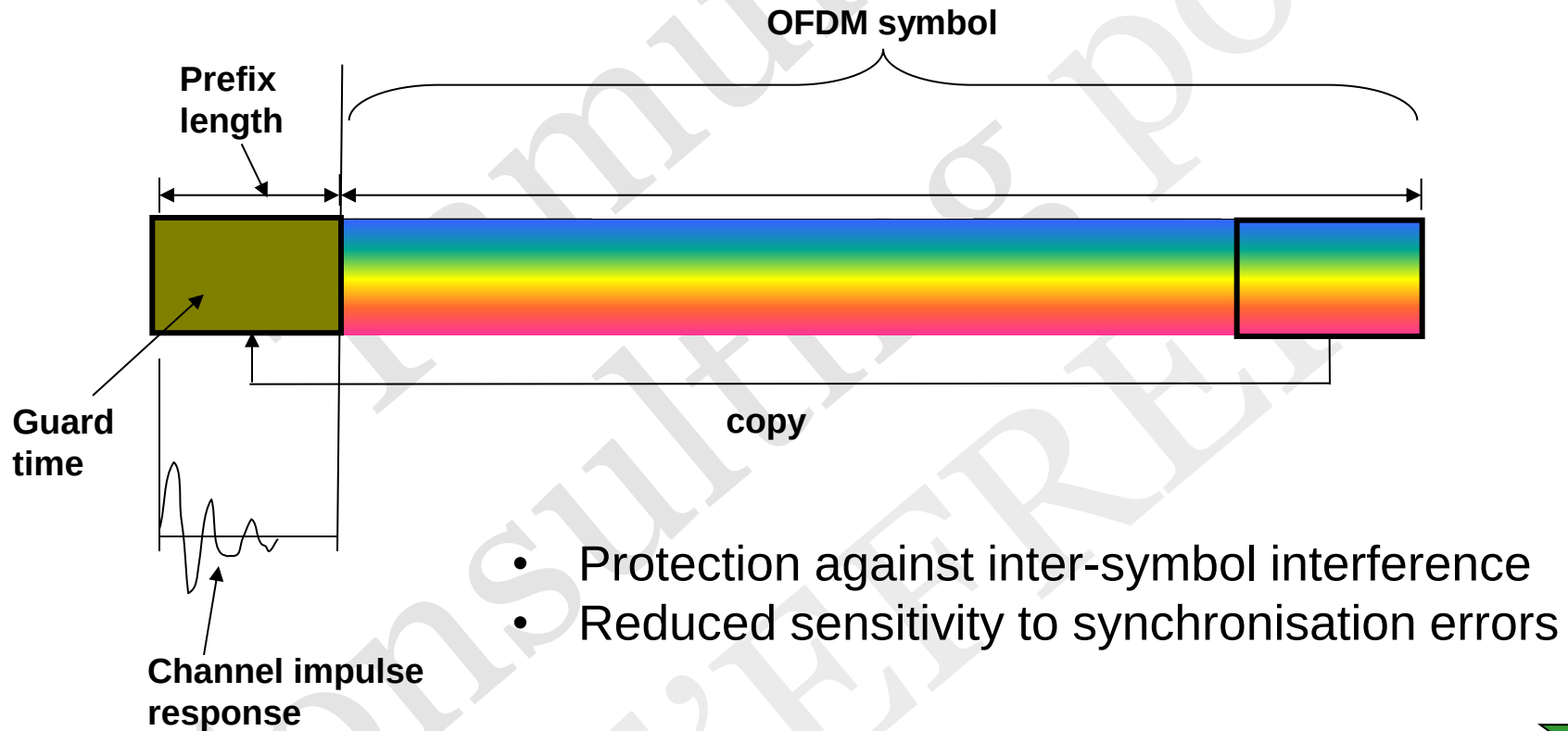
- Specific problem: how to provide high bit rate throughput to many radio users in many different bands
 - Radio channels are time dispersive with multipath effects
 - Users can have many different data rates
 - Spectrum bandwidth can vary in size



1. Reduce symbol frequency

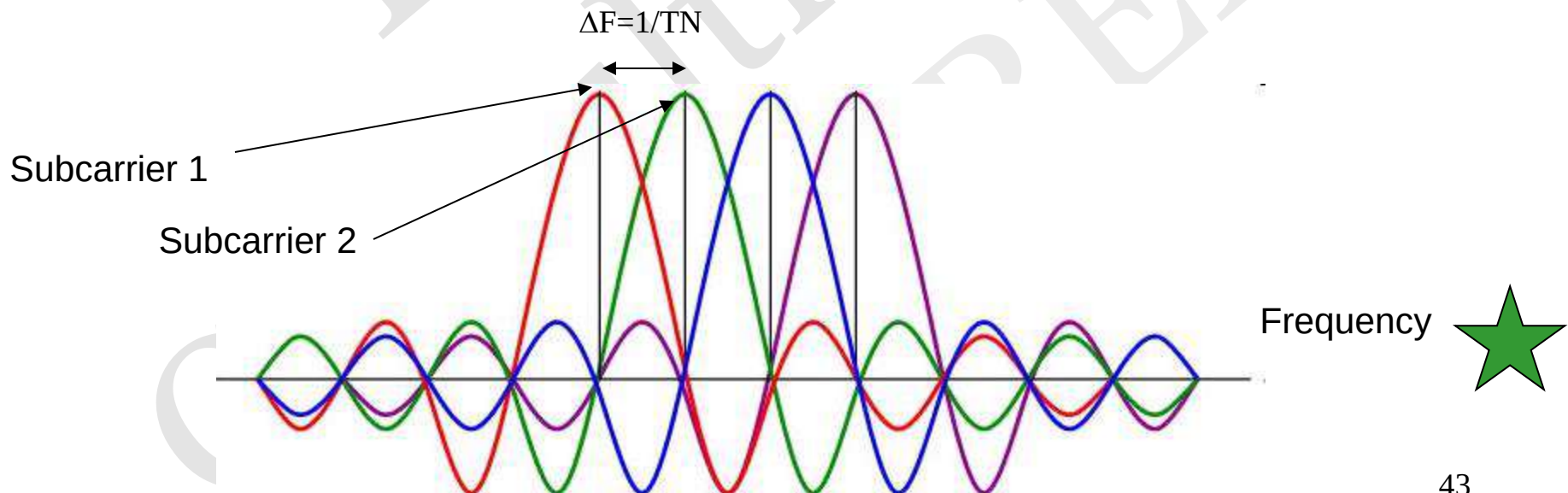


2. Set a guard interval

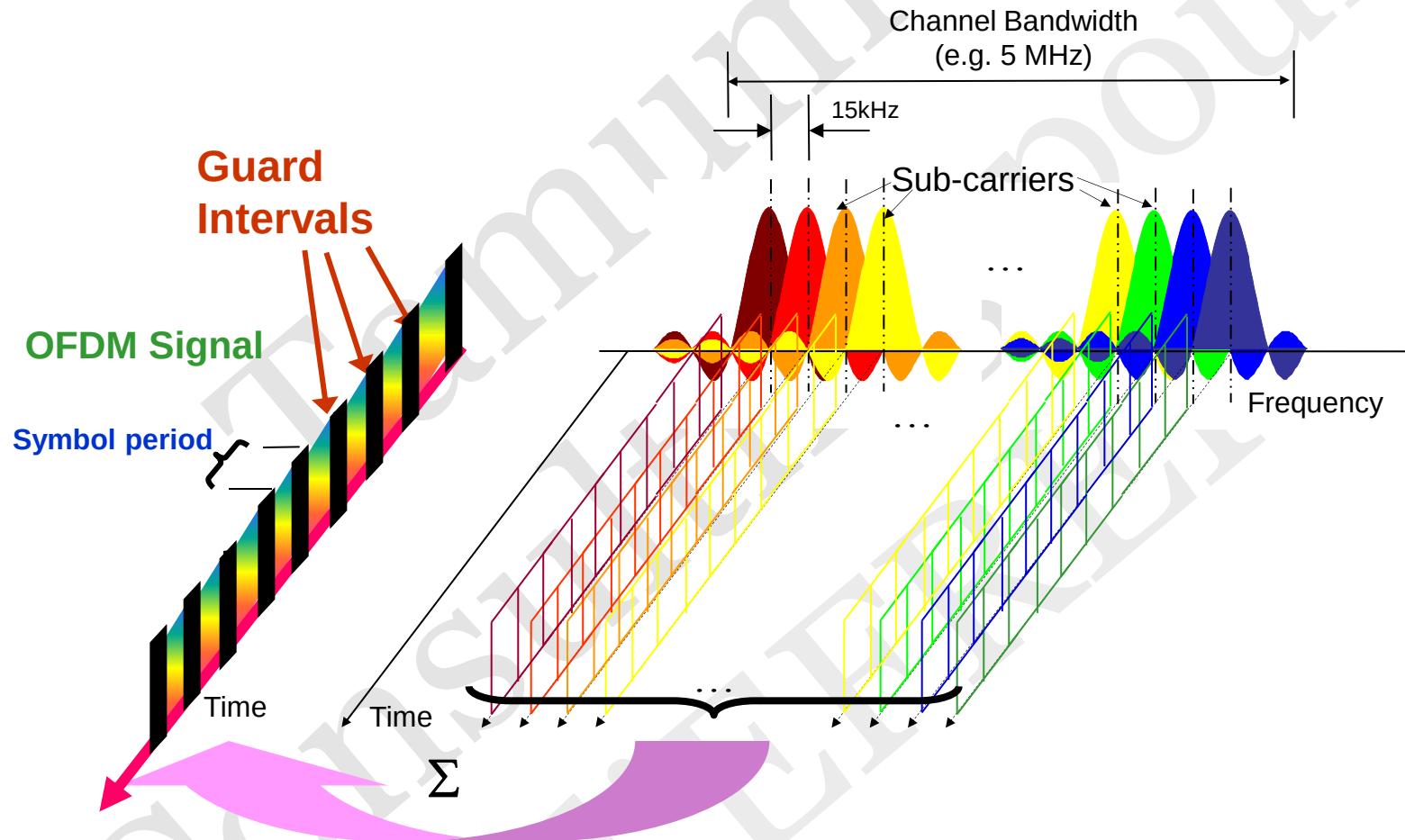


3. Orthogonalize

- A digital signal rectangular function period T , forms a sinc function in the frequency domain (Fourier transformation)
- Divide the digital signal into N slower streams, modulate the digital signal, function period $T \cdot N$, onto N subcarriers
- Space the subcarriers $1/TN$ apart in the frequency domain so that the nulls lie on the maxima of the other subcarriers.
- Thus the subcarriers do not interfere with each other, i.e. they are orthogonal.
- No guard band required: higher throughput than normal FDM



4. Transmit sub-carriers in parallel



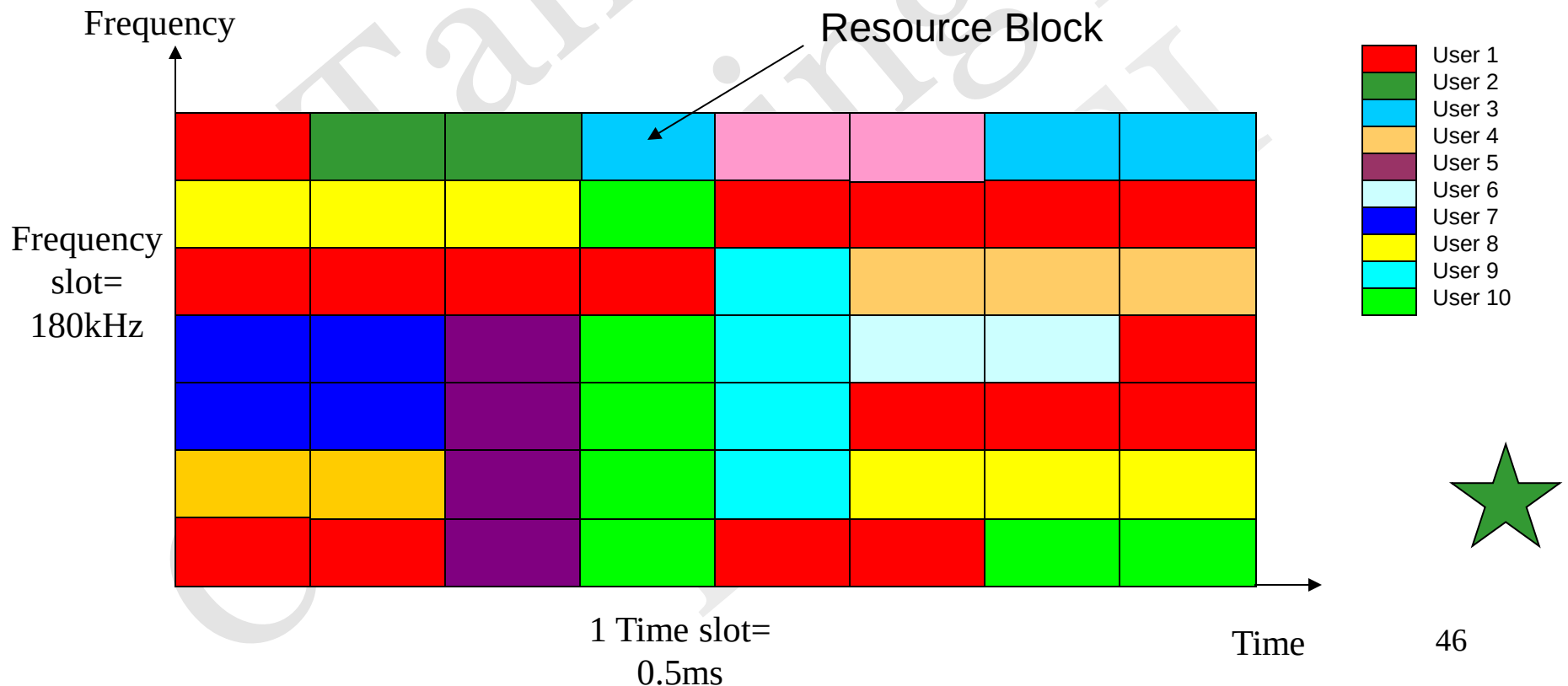
5. Parameterize

- Choose framing structure allowing latency reduction
 - Subframe (Transmission Time Interval, TTI)=1ms
 - Timeslots of 0.5ms
- Choose guard interval (GI)
 - Must be $>$ channel delay spread
 - Too long loses spectral efficiency
 - A “normal” channel uses a GI of $5\mu\text{s}$, 7 symbols per timeslot
 - Extended GI= $17\mu\text{s}$, 6 symbols per timeslot ($500\mu\text{s}$)
 - Contains a cyclic prefix (CP)
- Subcarrier spacing $\gg$ max Doppler shift ($\sim 1\text{kHz}$)
 - chosen at 15kHz

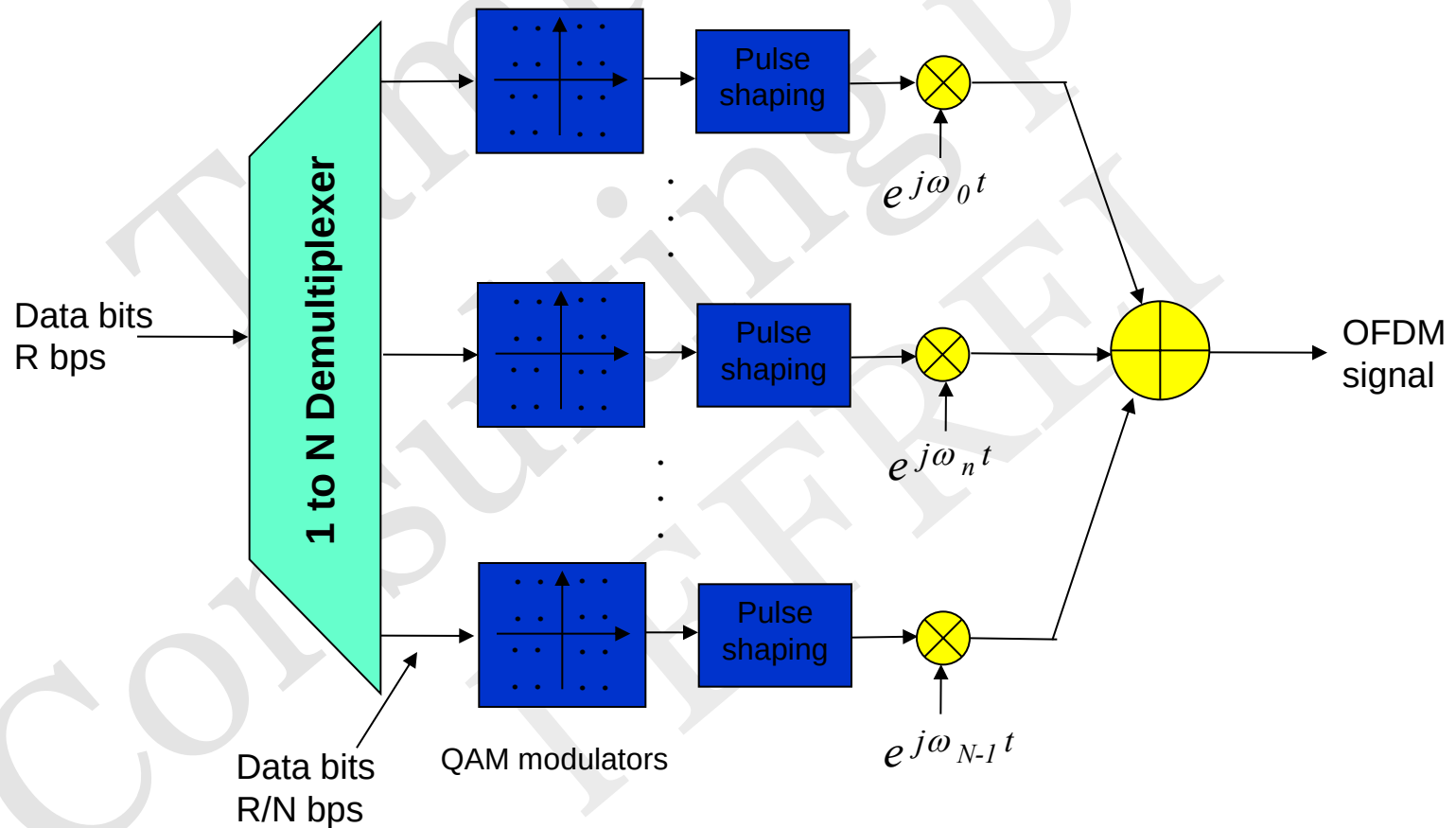


6. OFDMA/TDMA structure

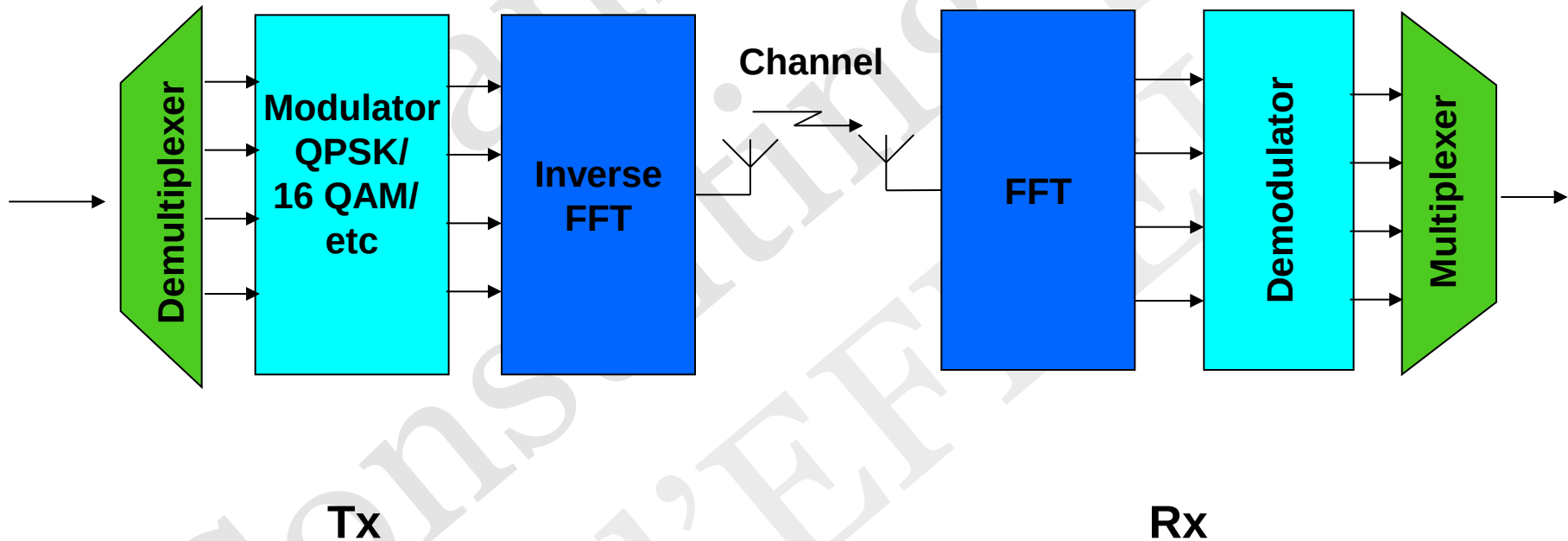
- LTE uses a combination of OFDMA and TDMA
- 12 subcarriers (180kHz) for 0.5ms = 1 Resource Block (RB)
- Corresponds to 84 symbols (84 Resource Elements, REs) for normal channel RB



OFDM signal generation



Transmission/reception

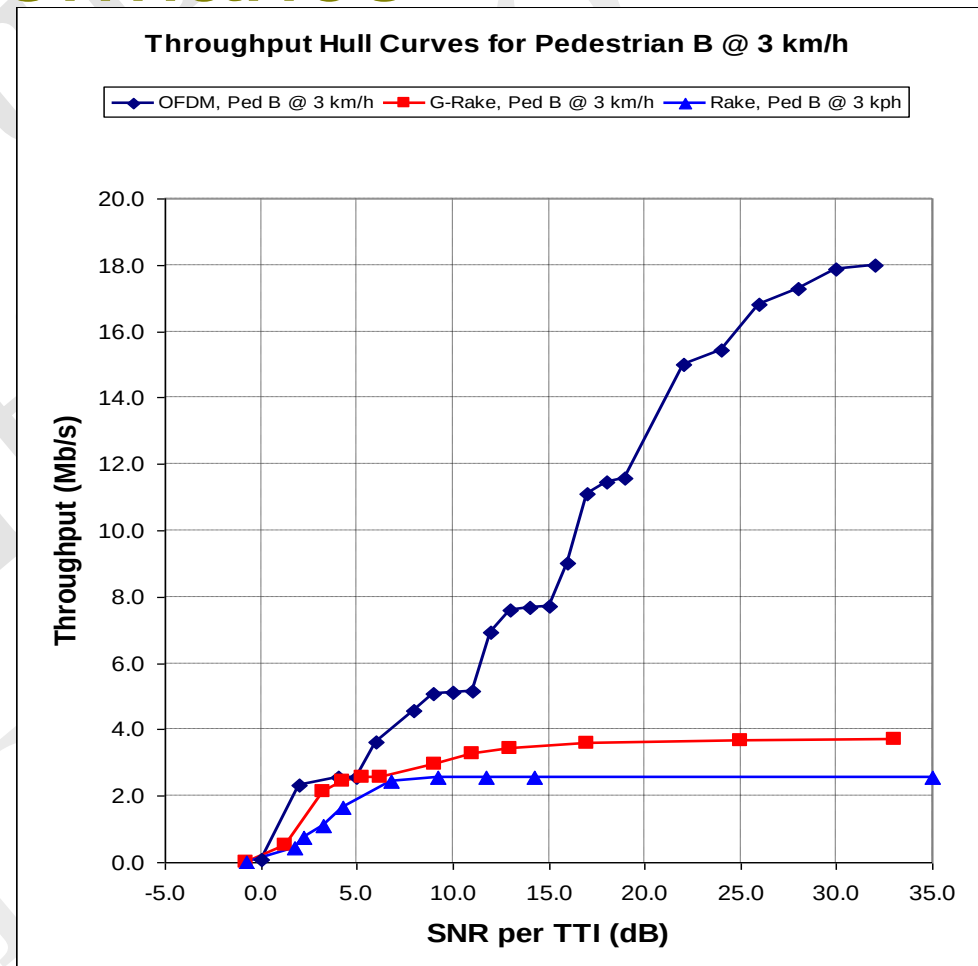


OFDM Cyclic Prefix

- The OFDM Guard Interval is not empty, it contains a redundant set of samples called the cyclic prefix (CP)
- The last G samples of the IFFT output of each symbol are appended to the beginning of the symbol, corresponding to the GI. This is the CP.
- At the receiver, the same number of samples are removed from the beginning of each symbol
- The resulting FFT provides a simple recovery of the transmitted symbol, without intersymbol interference (ISI)

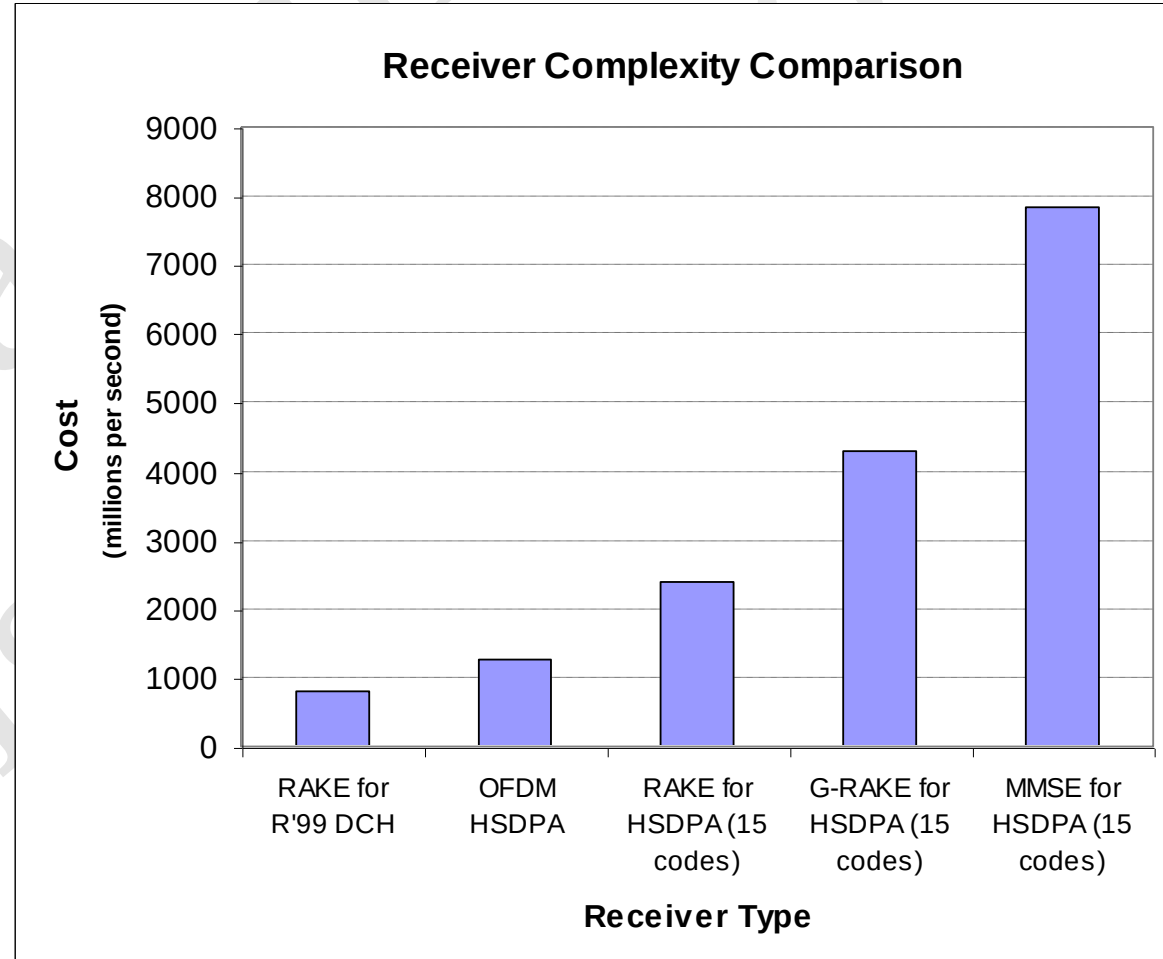
3GPP study on OFDM vs UMTS-performance

- Flat channel: OFDM vs. WCDMA have similar performance
- For multipath channels, OFDM has major performance gain over WCDMA, even with advanced rake receivers.



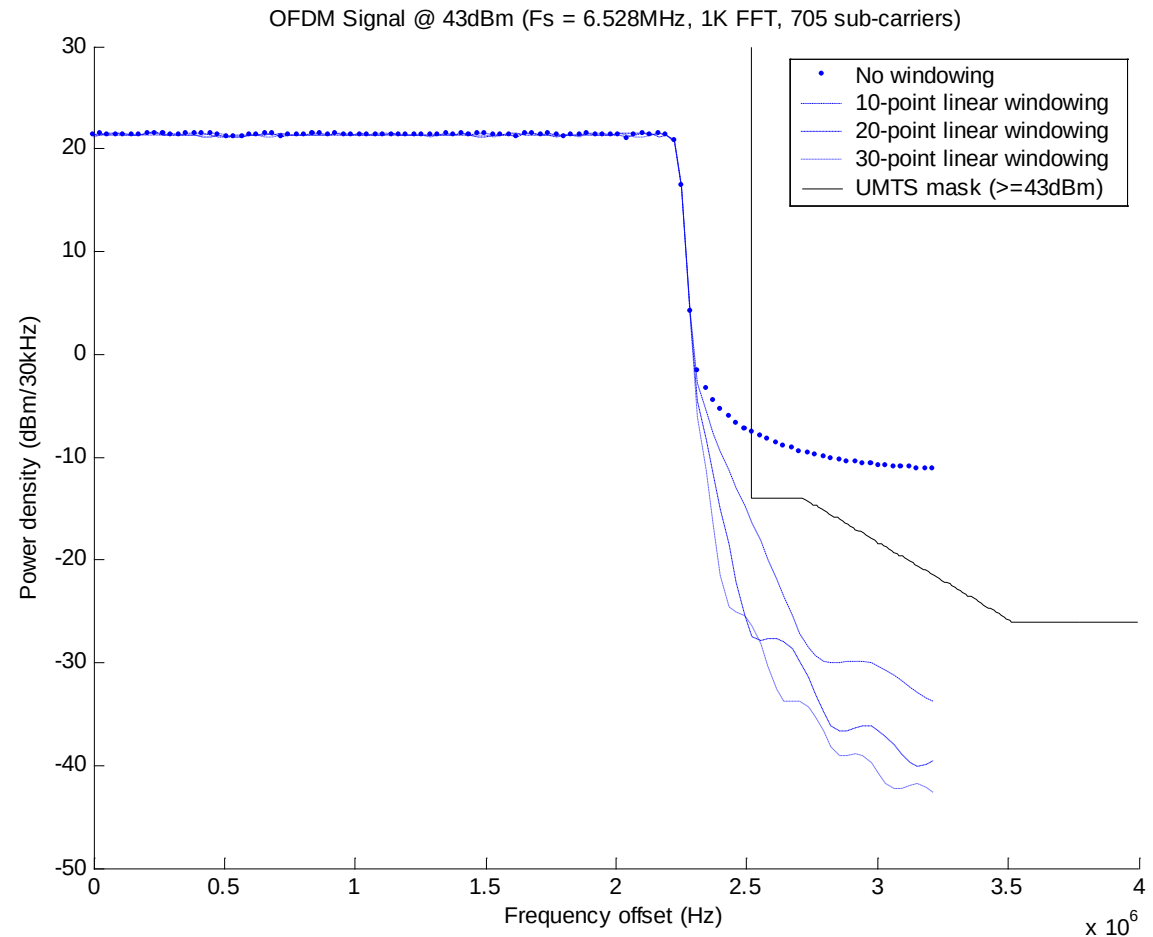
3GPP study-complexity

**Important
advantage for
OFDM over
WCDMA
advanced
receivers**



3GPP study- spectral compatibility

With simple windowing, OFDM respects UMTS emission mask requirement.



Advantages of OFDM over WCDMA

	OFDMA	WCDMA
Performance in dispersive channels	Low sensitivity to time dispersion	Advanced receivers needed for $SF \geq 16$
Receiver complexity	Low (FFT)	High: advanced receivers
Sensitivity to time (non-) synchronisation	Low	High
Use of MIMO	Simplified by the presence of flat fading for the sub-carriers	Difficult in dispersive channels



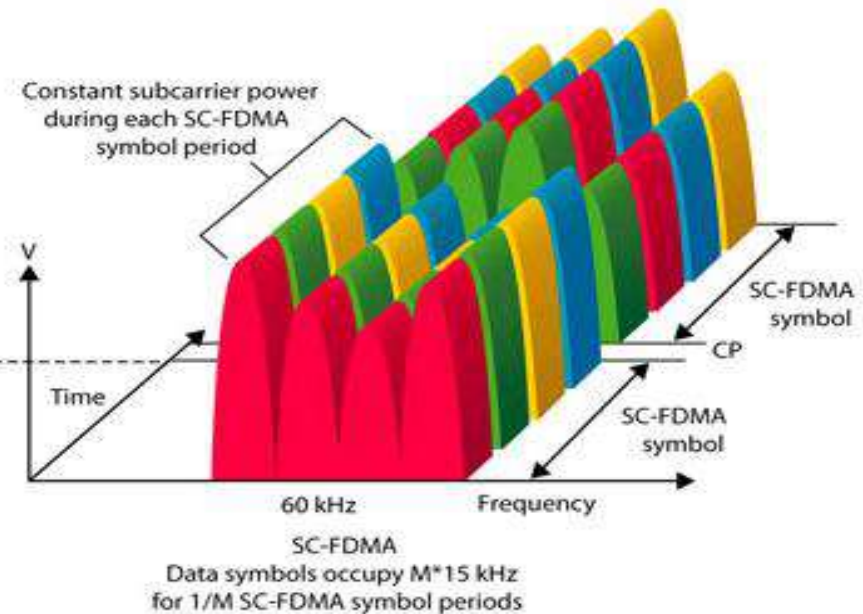
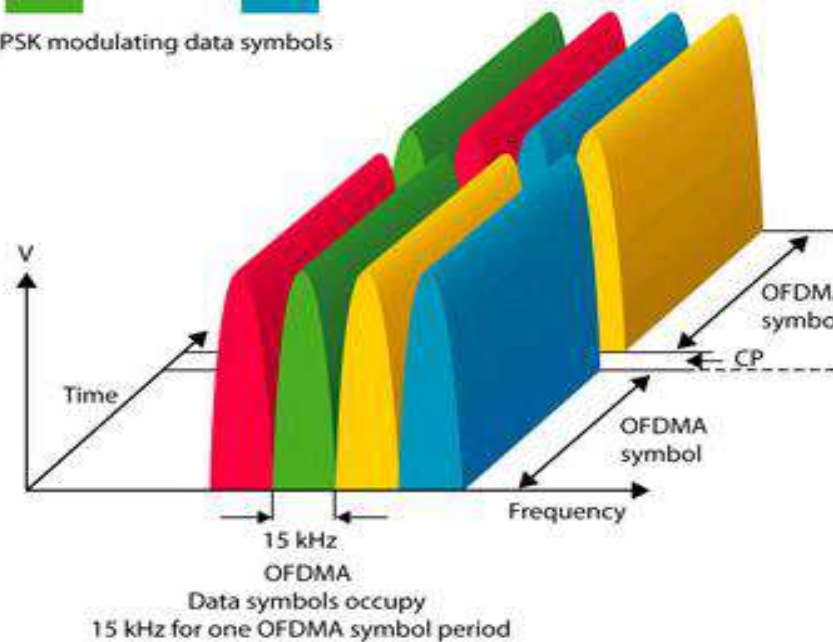
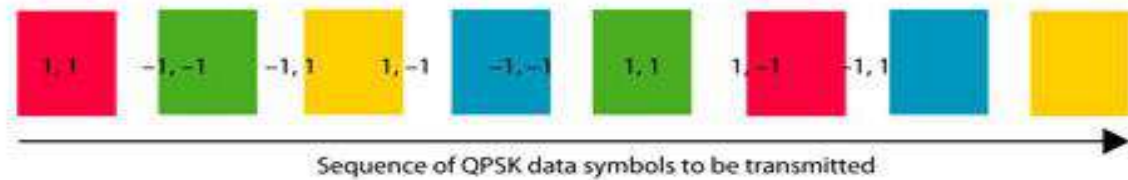
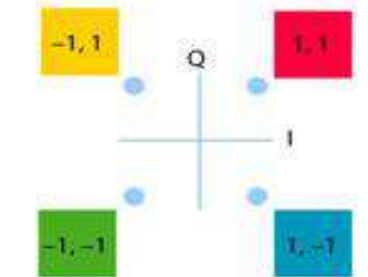
LTE Uplink

- The requirements on the uplink physical layer are slightly different from the downlink:
 - The mobile terminals are transmitting from different distances from the base station and each other
 - Mobile transmitter complexity and power requirement are more an issue than for the base station

LTE-uplink SC-FDMA

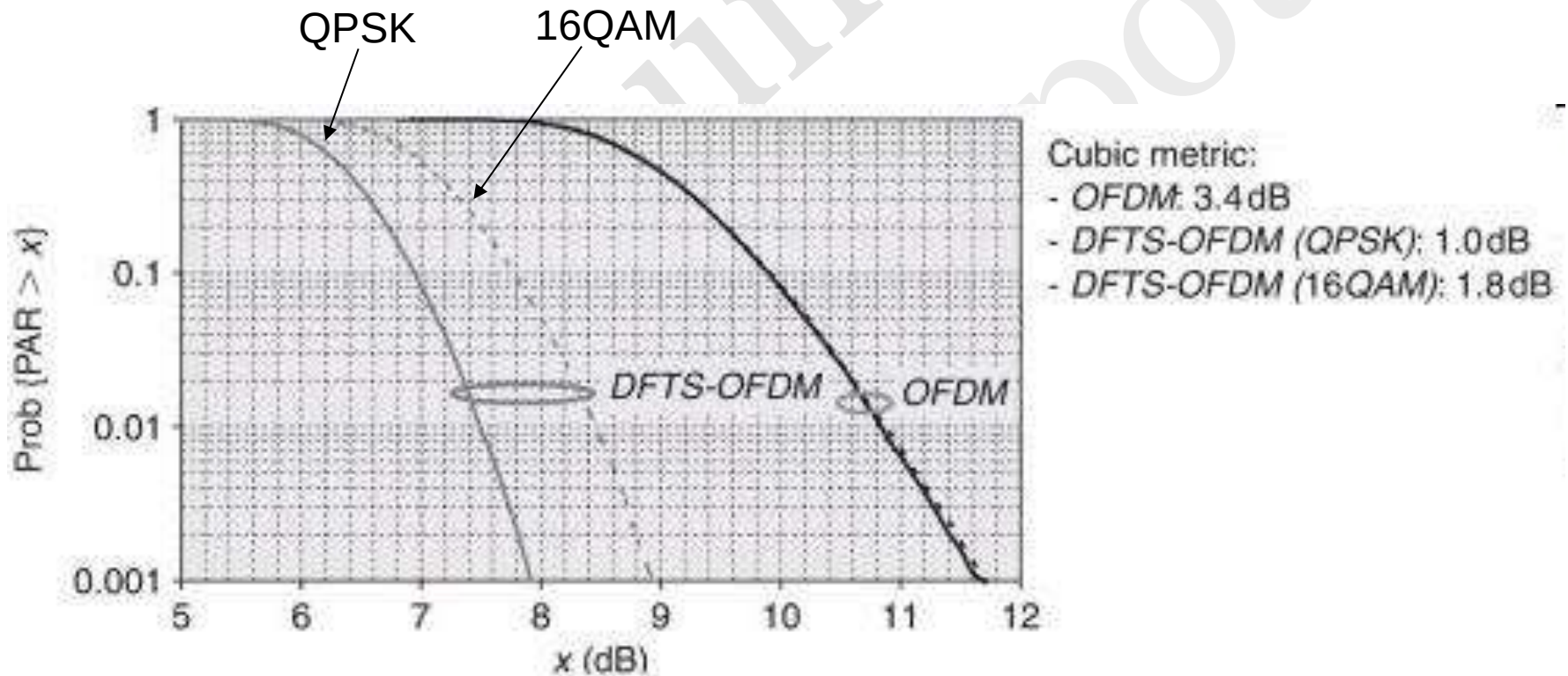
- Like normal OFDM, SC-FDMA uses multiple parallel orthogonal sub-carriers
 - Intersymbol interference (ISI) removed by use of Cyclic Prefix (CP)
- However, in SC-FDMA each sub-carrier carries a linear combination of all data symbols transmitted at the same time
- Conditions:
 - Mobiles transmit on different sets of subcarriers
 - Received signals are synchronized in time and frequency
 - T_{CP} is longer than delay spread + timing errors
- For compatibility with DL RB structure, LTE mobiles transmit on contiguous blocks of subcarriers

OFDMA and SC-FDMA



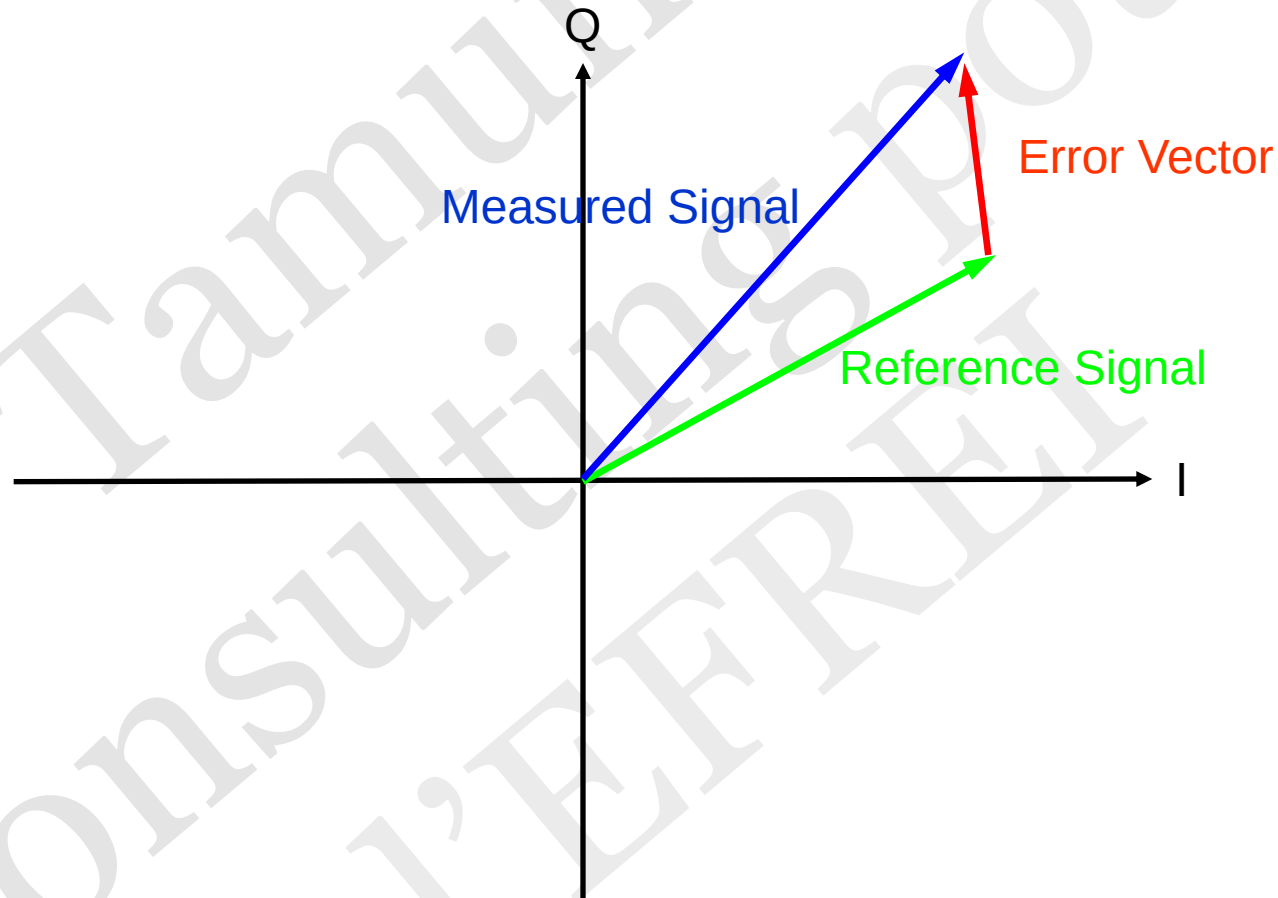
Source: Agilent

Peak to Average Power Ratio



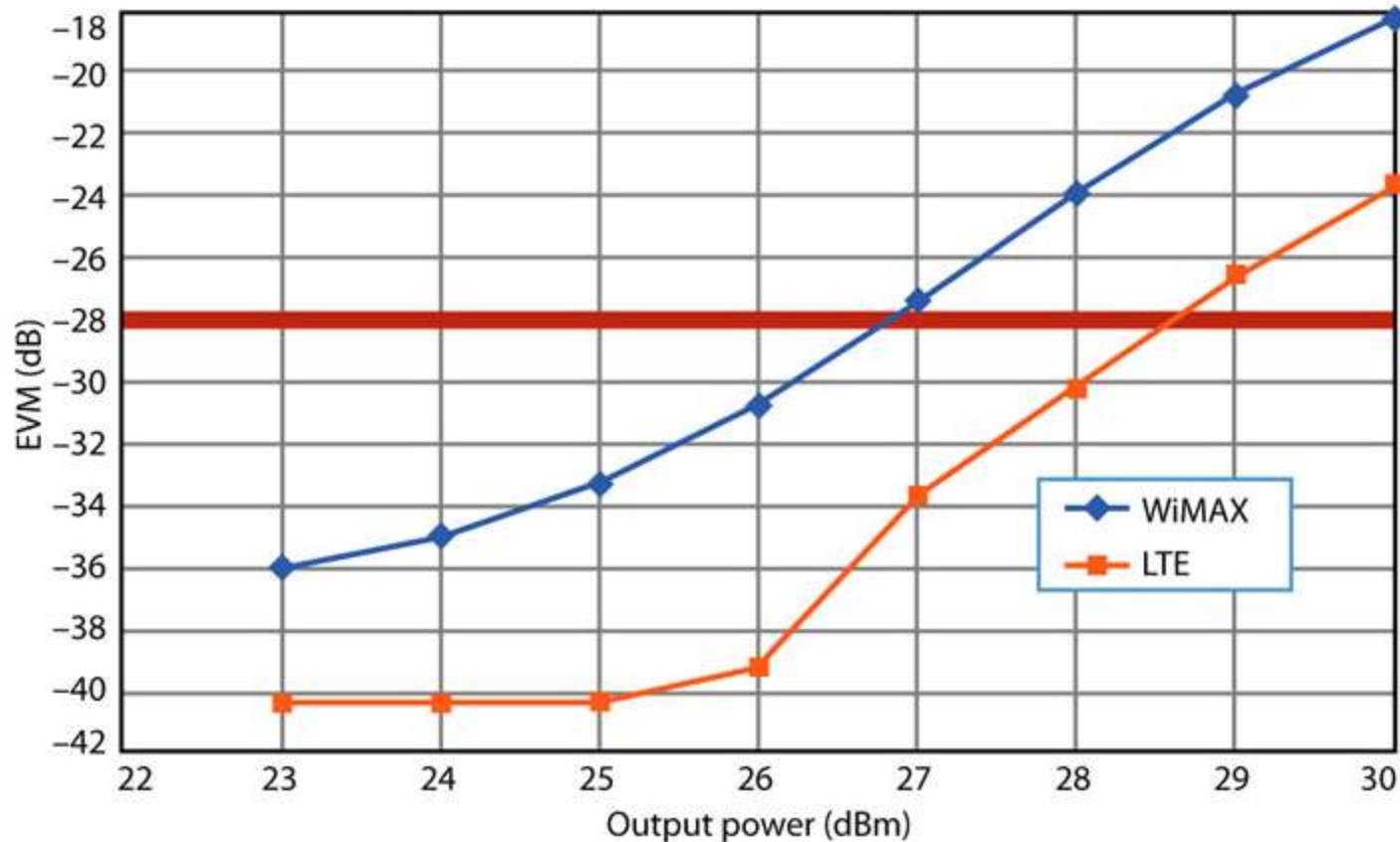
SC-FDMA (DFT-spread OFDM) has much lower PAPR and cubic metric than normal OFDM

Modulated Signal Error Vector



$$\text{EVM (Error Vector Magnitude)(dB)} = 10\log_{10}(P_{\text{error}}/P_{\text{reference}})$$

EVM vs Uplink power for LTE and WiMax (OFDM)



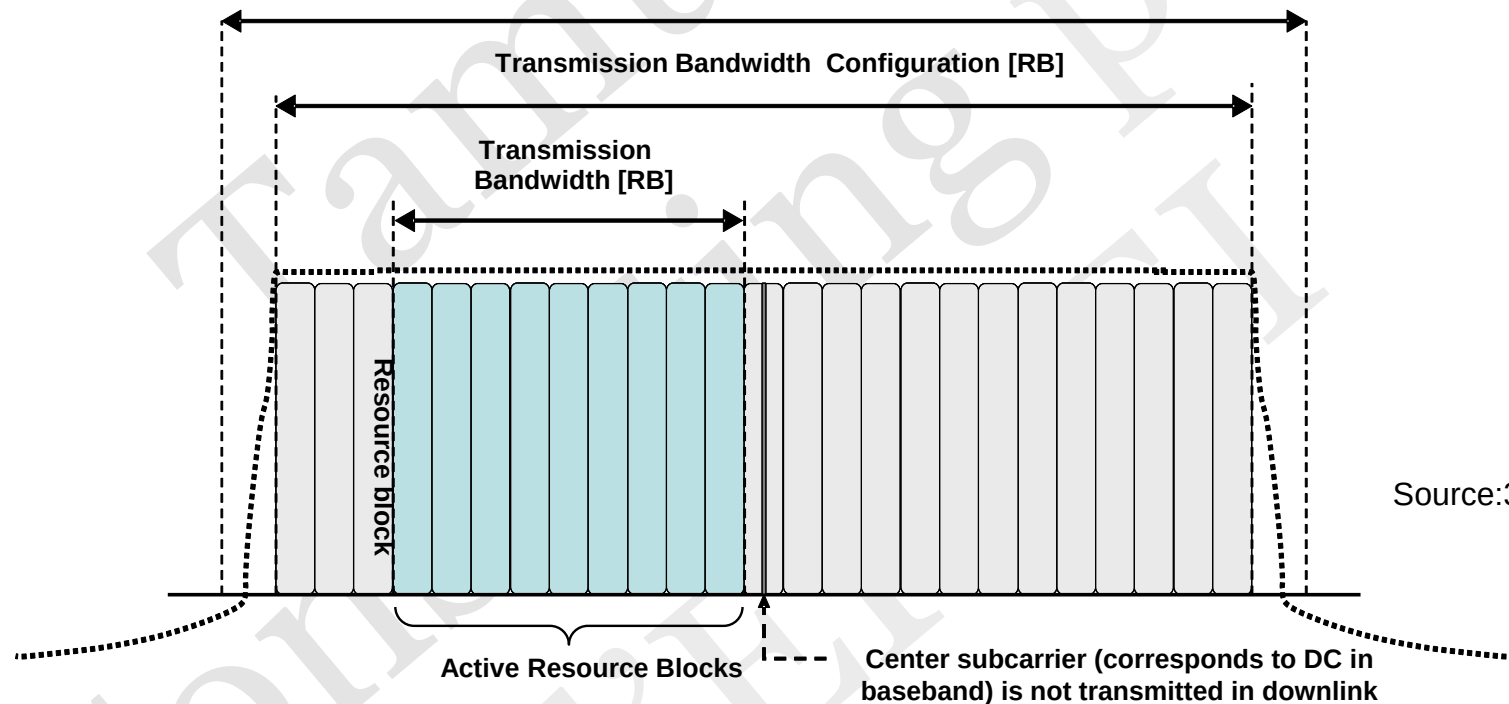
SC-FDMA parameters

- Low latency framing structure (as DL)
 - Subframe (Transmission Time Interval, TTI)=1ms
 - Timeslots of 0.5ms
 - TTI bundling permitted
- Guard interval/cyclic prefix (GI/CP) as DL
- Subcarrier spacing same as DL (15kHz)
- Uplink data transmissions use contiguous blocks of subcarriers

Frame Structure

- Two frame structures defined:
 - Type 1 for Frequency Division Duplex (FDD)
 - Type 2 for Time Division Duplex (TDD)
 - Type 2 has 7 sub-structures (configurations) according to uplink/downlink requirements
- Time unit $T_s = 1/(30.72\text{MHz} = 3.5^4 \cdot 2^{14} \text{ Hz})$ seconds
 - $= 32.55208333\dots\text{ns}$
 - Provides compatibility with UMTS: chip rate is $3.84\text{MHz} = 3.5^4 \cdot 2^{11} = 1/(T_s \times 8)$;
 - Provides compatibility with IS95 CDMA: chip rate is $1.2288\text{MHz} = 3.5^2 \cdot 2^{14} = 1/(T_s \times 25)$
 - Radio frame is $T_s \times 1024 \times 300 = 10\text{ms}$

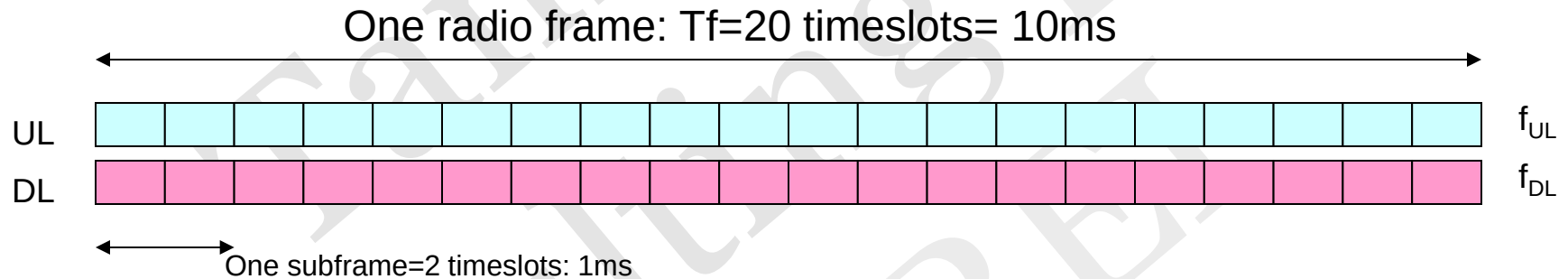
Transmission Bandwidth Configurations



LTE Carrier Bandwidths

Carrier Bandwidth B (MHz)	1.4	3	5	10	15	20
Sampling rate x 3.84MHz	0.5	1	2	4	6	8
Subcarriers n	72	180	300	600	900	1200
Transmission Bandwidth Configuration [Number of RBs]	6	15	25	50	75	100
BW efficiency (%) ($n \cdot 1.5 / B$)	77	90	90	90	90	90

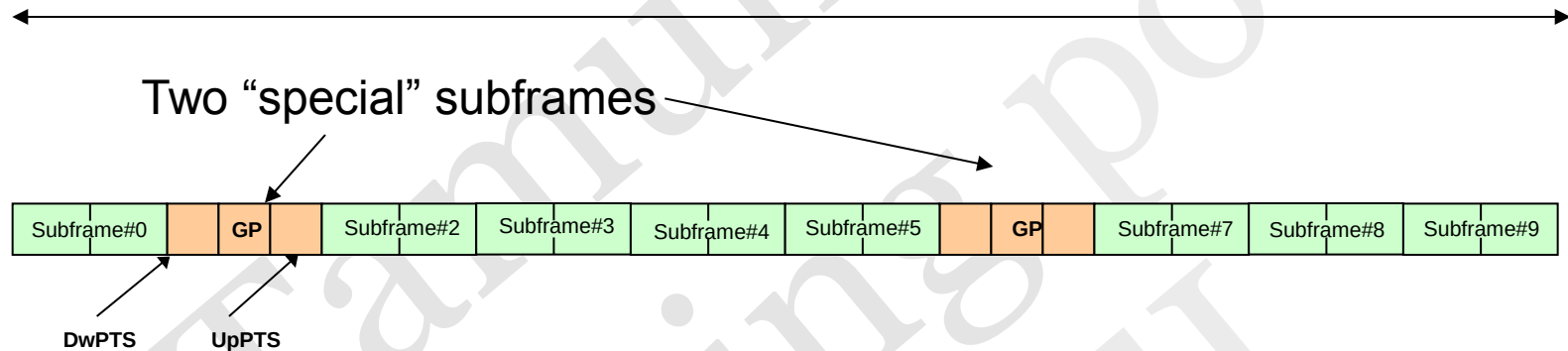
LTE radio frame structure:FDD



LTE radio frame structure:TDD

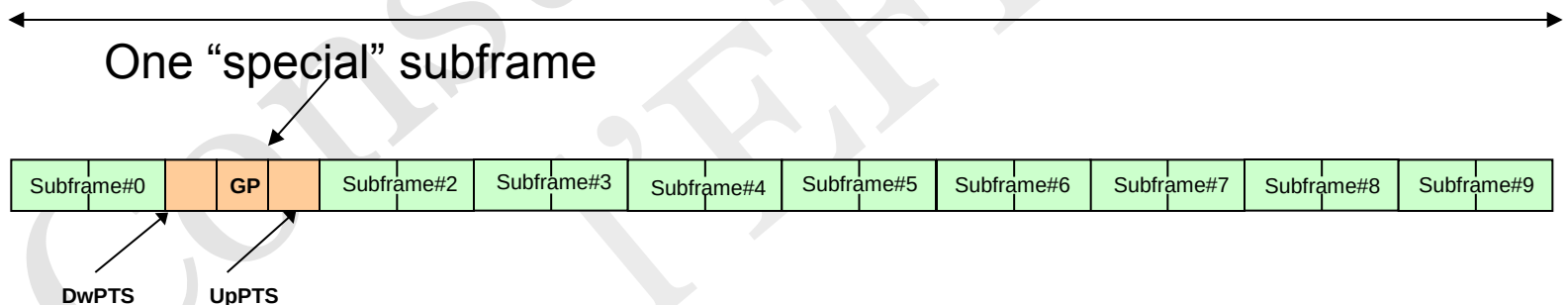
TDD for 5ms switch-point periodicity: 2 “special” subframes, 8 “data” subframes

One radio frame: 10 subframes = 10ms



TDD for 10ms switch-point periodicity: 1 “special” subframe, 9 “data” subframes

One radio frame: 10 subframes = 10ms



TDD Configurations

TDD Configuration	Switch-point Periodicity	Subframe Number										Uplink Subframes	Downlink Subframes
		0	1	2	3	4	5	6	7	8	9		
0	5ms	D	S	U	U	U	D	S	U	U	U	6	2
1	5ms	D	S	U	U	D	D	S	U	U	D	4	4
2	5ms	D	S	U	D	D	D	S	U	D	D	2	6
3	10ms	D	S	U	U	U	D	D	D	D	D	3	6
4	10ms	D	S	U	U	D	D	D	D	D	D	2	7
5	10ms	D	S	U	D	D	D	D	D	D	D	1	8
6	5ms	D	S	U	U	U	D	S	U	U	D	3	5

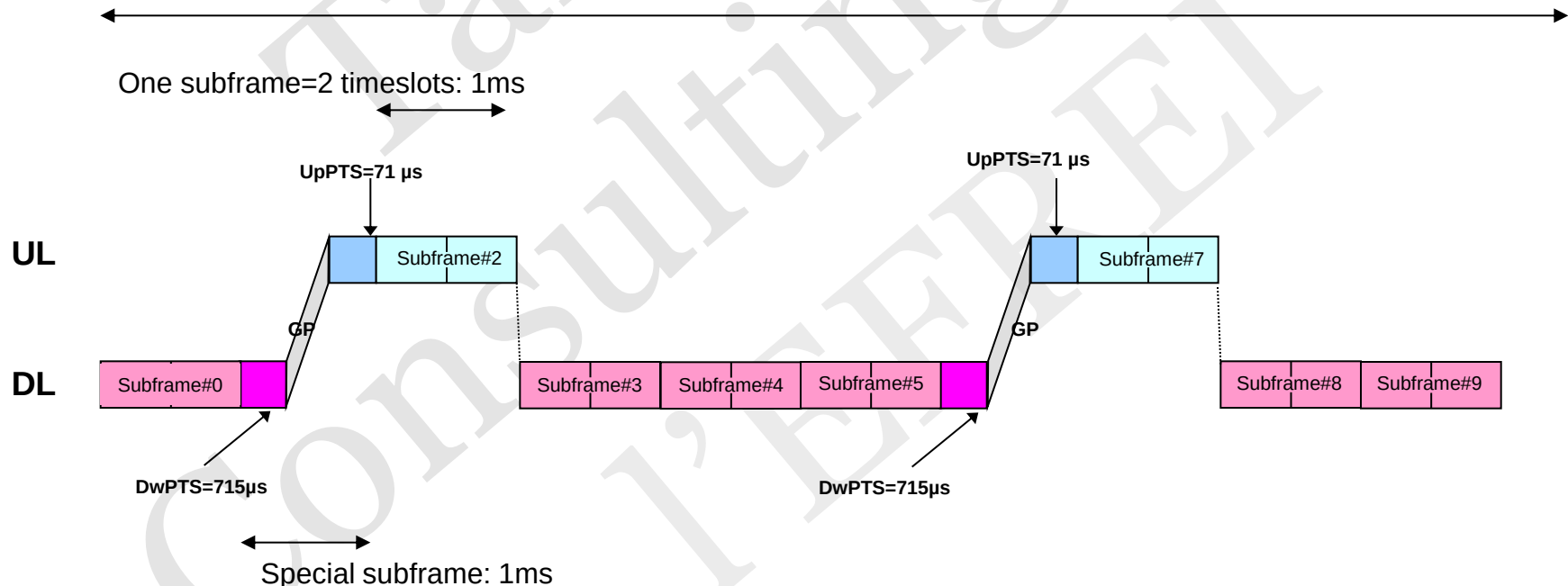
DwPTS and UpPTS have values depending on cycle prefix (uplink and downlink)

Example TDD radio frame structure

TDD Example for:

- 5ms switch-point periodicity,
- Configuration 2 (6 DL subframes, 2 Uplink)
- Normal Cyclic Prefixes Uplink and Downlink

One radio frame: 10 subframes = 10ms



Multiple Antennas

- One of the fundamental ways in which LTE increases potential data throughput is by a Multiple Input Multiple Output (MIMO) channel matrix



- According to the configuration of the antennas, this can provide:
 - Spatial multiplexing
 - Spatial diversity
 - “array gain” for beam forming
- MIMO is limited by the correlation between the antennas, which, at the mobile station in particular is quite high.



Choice of radio-I

- Experience on OFDM (DAB, DVB, DMB):
 - Robustness in time-dispersive radio channels against inter-symbol interference and multipath fading
 - Low-complexity receivers (simple frequency-domain equalization)
 - Simple combining of multiple transmitters
 - High spectral efficiency
- However
 - High PAPR=>linear=>Costly, power inefficient Tx
 - Sensitive to Doppler shift and Carrier Frequency Offset (CFO)

Choice of radio-II

- OFDMA chosen for downlink (BS Tx)
- SC-FDMA (lower PAPR) uplink (MS Tx)
 - Small low-cost, low-power transmitters
- Combine with 0.5ms TDMA
 - Compatible FDD and TDD modes
 - Time-compatible with UMTS and GSM
- Multiple antenna technology at Tx and Rx (MIMO)
 - Spatial multiplexing
 - Space diversity
 - Potential “array gain” for beam forming

LTE Problem No.1 (LP1): Modulation and multiple access

- Specific problem: how to provide high bit rate throughput to many radio users
- Solution:
 - use OFDM and OFDMA/TDMA on downlink
 - High performance
 - Simpler than WCDMA at high spectral efficiency
 - Spectrally Flexible
 - Use SC-FDMA on uplink
 - advantages as for OFDM/OFDMA +:
 - Lower terminal power complexity

The road to LTE

- 1991 First commercial GSM
- 1998 ETSI agreement on basic UMTS concepts.
Creation of 3GPP
- 2001 NTT DoCoMo launches FOMA (UMTS-based WCDMA)
- 2003 First European UMTS
- 2004 3GPP Toronto workshop on future technology
- 2009 10% of mobiles (400 million) UMTS
- 2009 First LTE trials
- 2010 Several LTE networks launched
- 2011 180 operators in 70 countries investing in LTE;
TD-LTE on trial
- LTE expected to be adopted by >80% wireless carriers

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Mobile Networks

LTE

Paul Simmons