LTE and the Evolution to LTE-Advanced Fundamentals - Part 1

Based on the 2nd Edition book

LTE and the Evolution to 4G Wireless – Design and Measurement Challenges

Frank Palmer and Jan Whitacre
Agilent Technologies

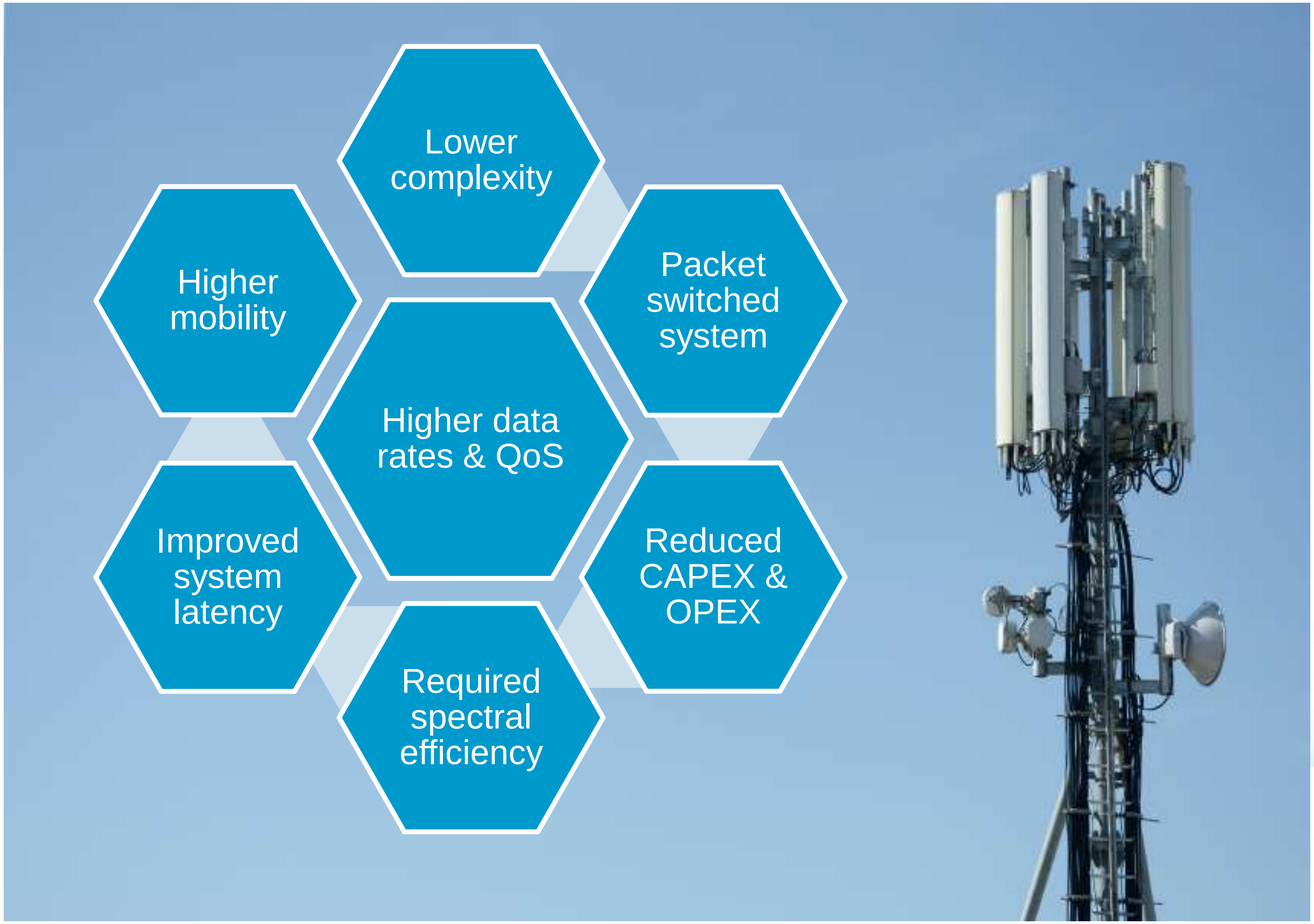
Agenda – Part 1

- Introduction to LTE
  - Evolution and Motivation
  - Major features and requirements
- Air Interface Concepts
  - Frequency bands
  - Channel bandwidths
  - OFDM/OFDMA/SCFDMA
  - Structure – frame, slots, resource blocks & elements
  - Physical signals and channels
- Transmitter & Receiver Test Fundamentals
- Question and Answer

Agenda – Part 2

- MIMO Concepts
- LTE-Advanced Major Features and Design Challenges
  - Carrier Aggregation
  - Enhanced Uplink Multiple Access (clustered SCFDMA)
  - High Order MIMO (8x8)
  - Other Study Items
- RF Conformance and Acceptance Testing
- Question and Answer

LTE – Motivation and Goals



International Telecommunications Union

↓

ITU-Radio Working Party 8F (now WP 5D)

↓

International Mobile Telephony

IMT-2000 “aka 3G”

Key Requirements

- 2048 kbps for indoor office
- 384 kbps for outdoor to indoor and pedestrian
- 144 kbps for vehicular
- 9.6 kbps for satellite
- NO requirement on spectral efficiency

IMT-Advanced “ aka True 4G”

Key Requirements

- Worldwide functionality & roaming
- Compatibility of services
- Interworking with other radio access systems
- Higher peak data rates to support advanced services and applications (high mobility:100 Mbps, low mobility:1 Gbps)

All “IMT” technologies have access to designated IMT spectrum

3GPP UMTS Long-Term Evolution

1999 → 2013

Release	Stage 3: Core specs complete	Main feature of Release
Rel-99	March 2000	UMTS 3.84 Mcps (W-CDMA FDD & TDD)
Rel-4	March 2001	1.28 Mcps TDD (aka TD-SCDMA)
Rel-5	June 2002	HSDPA
Rel-6	March 2005	HSUPA (E-DCH)
Rel-7	Dec 2007	HSPA+ (64QAM DL, MIMO, 16QAM UL). LTE & SAE Feasibility Study, Edge Evolution
Rel-8	Dec 2008	LTE Work item – OFDMA air interface SAE Work item – New IP core network UMTS Femtocells, Dual Carrier HSDPA
Rel-9	Dec 2009	Multi-standard Radio (MSR), Dual Carrier HSUPA, Dual Band HSDPA, SON, LTE Femtocells (HeNB) LTE-Advanced feasibility study
Rel-10	March 2011	LTE-Advanced (4G) work item, CoMP Study Four carrier HSDPA
Rel-11	Sept 2012	CoMP, eDL MIMO, eCA, MIMO OTA, HSUPA TxD & 64QAM MIMO, HSDPA 8C & 4x4 MIMO, MB MSR
Rel-12	March 2013 stage 1	RAN features being decided Jun 2012

LTE Major Features

Feature	Capability					
Access modes	FDD & TDD					
Channel BW 1RB = 12 subcarriers = 180 kHz	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
	6 RB	15 RB	25 RB	50 RB	75 RB	100 RB
Transmission Scheme	**Downlink:** OFDMA (Orthogonal Frequency Division Multiple Access) **Uplink:** SC-FDMA (Single Carrier Frequency Division Multiple Access					
Modulation Formats	QPSK, 16QAM, 64QAM					
MIMO Technology	**Downlink:** Tx diversity, Rx diversity, Single-User MIMO (up to 4x4), beamforming **Uplink:** Multi-User MIMO					
Peak Data Rates	**Downlink:** 300 Mbps (4x4 MIMO, 20 MHz, 64QAM) **Uplink:** 75 Mbps (20 MHz BW, 64QAM)					
Bearer services	Packet only – no circuit switched voice or data services are supported ➔ voice must use VoIP					
Transmission Time Interval (TTI)	1 ms					

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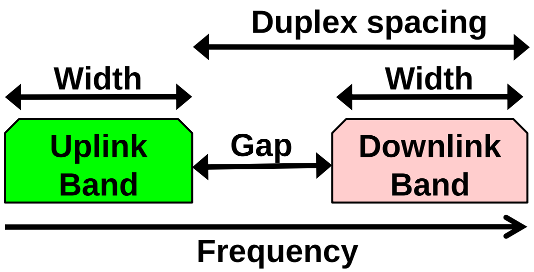
LTE FDD Frequency bands (36.101 table 5.5-1)

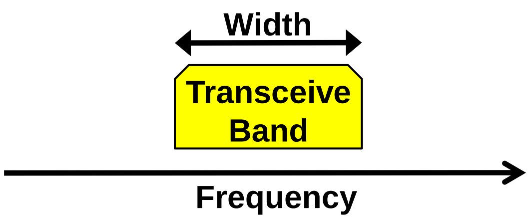
Band	Uplink MHz		Downlink MHz		Width	Duplex	Gap
1	1920	1980	2110	2170	60	190	130
2	1850	1910	1930	1990	60	80	20
3	1710	1785	1805	1880	75	95	20
4	1710	1755	2110	2155	45	400	355
5	824	849	869	894	25	45	20
6	830	840	865	875-	10	35	25
7	2500	2570	2620	2690	70	120	50
8	880	915	925	960	35	45	10
9	1749.9	1784.9	1844.9	1879.9	35	95	60
10	1710	1770	2110	2170	60	400	340
11	1427.9	1447.9	1475.9	1495.9	20	48	28
12	698	716	728	746	18	30	12
13	777	787	746	756	10	-31	21
14	788	798	758	768	10	-30	20
15*	1900	1920	2600	2620	20	700	680
16*	2010	2025	2585	2600	15	575	560
17	704	716	734	746	12	30	18
18	815	830	860	875	15	45	30
19	830	845	875	890	15	45	30
20	832	862	791	821	30	-41	11
21	1447.9	1462.9	1495.9	1510.9	15	48	33
22	3410	3490	3510	3590	80	100	20
23	2000	2020	2180	2200	20	180	160
24	1626.5	1660.5	1525	1559	34	-101.5	67.5
25	1850	1915	1930	1995	65	80	15
26	814	849	859	894	35	45	10
27	807	824	852	869	17	45	28
28	703	748	758	803	45	55	10



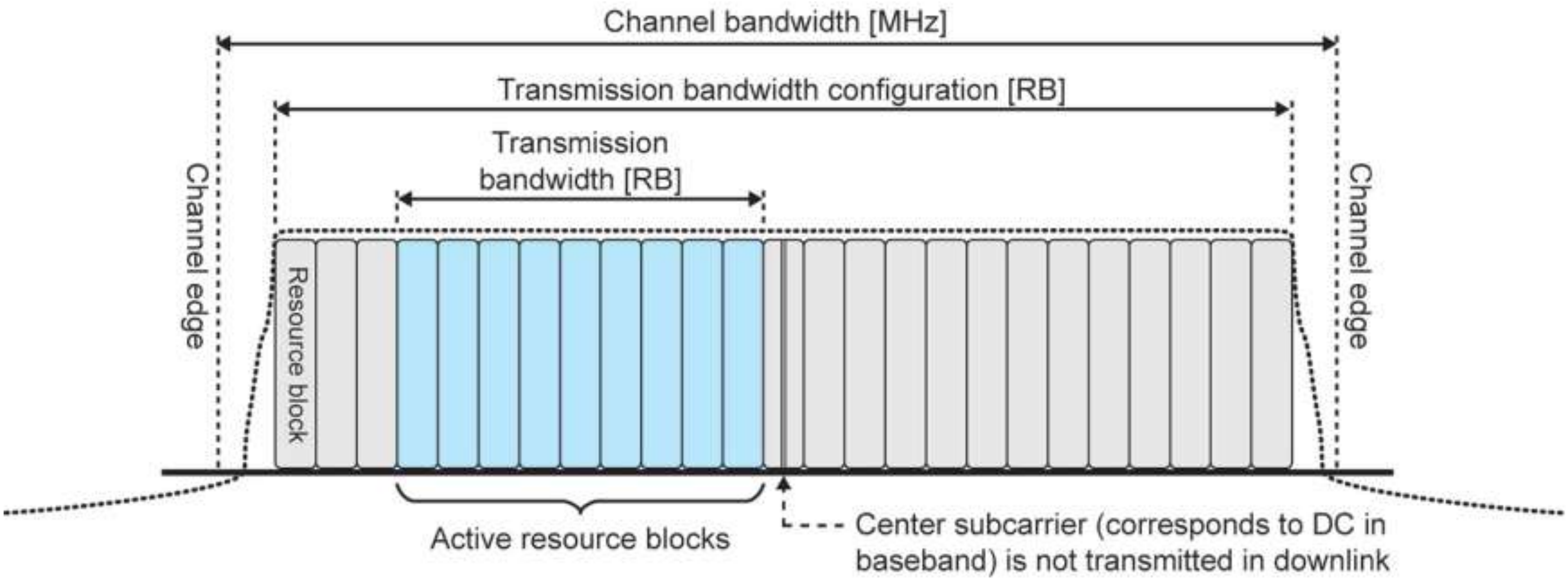
- There is a lot of overlap between band definitions for regional reasons
- The Duplex spacing varies from 30 MHz to 799 MHz
- The gap between downlink and uplink varies from 10 MHz to 680 MHz
- Bands 15 and 16 are specified by ETSI only for use in Europe

LTE TDD Frequency bands

Band	Uplink MHz		Downlink MHz		Width
33	1900	1920	1900	1920	20
34	2010	2025	2010	2025	15
35	1850	1910	1850	1910	60
36	1930	1990	1930	1990	60
37	1910	1930	1910	1930	20
38	2570	2620	2570	2620	50
39	1880	1920	1880	1920	40
40	2300	2400	2300	2400	100
41	2496	2690	2496	2690	194
42	3400	3600	3400	3600	200
43	3600	3800	3600	3800	200
44	703	803	703	803	100

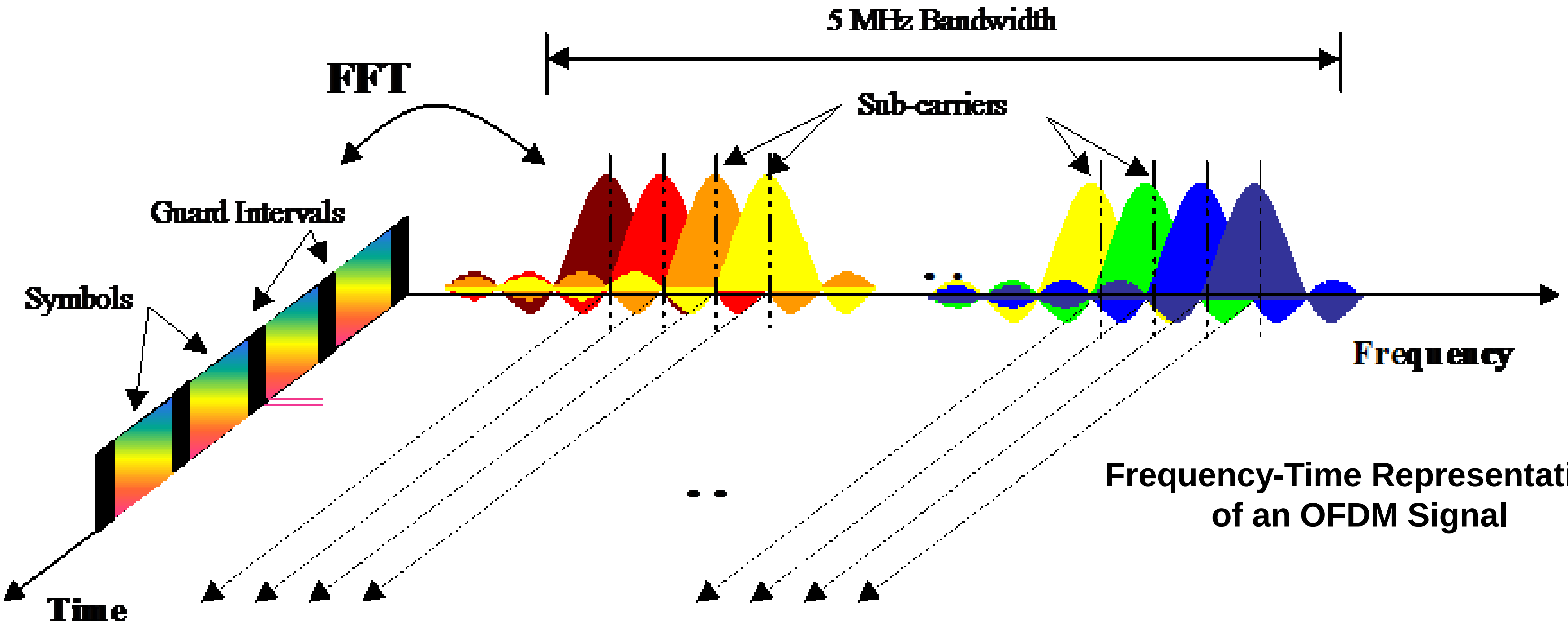


Channel Bandwidths



Channel Bandwidth (MHz)	1.4	3	5	10	15	20
Transmission bandwidth configuration (MHz)	1.06	2.7	4.5	9	13.5	18
Transmission bandwidth configuration (RB)	6	15	25	50	75	100

Orthogonal Frequency Division Multiplexing



Frequency-Time Representation of an OFDM Signal

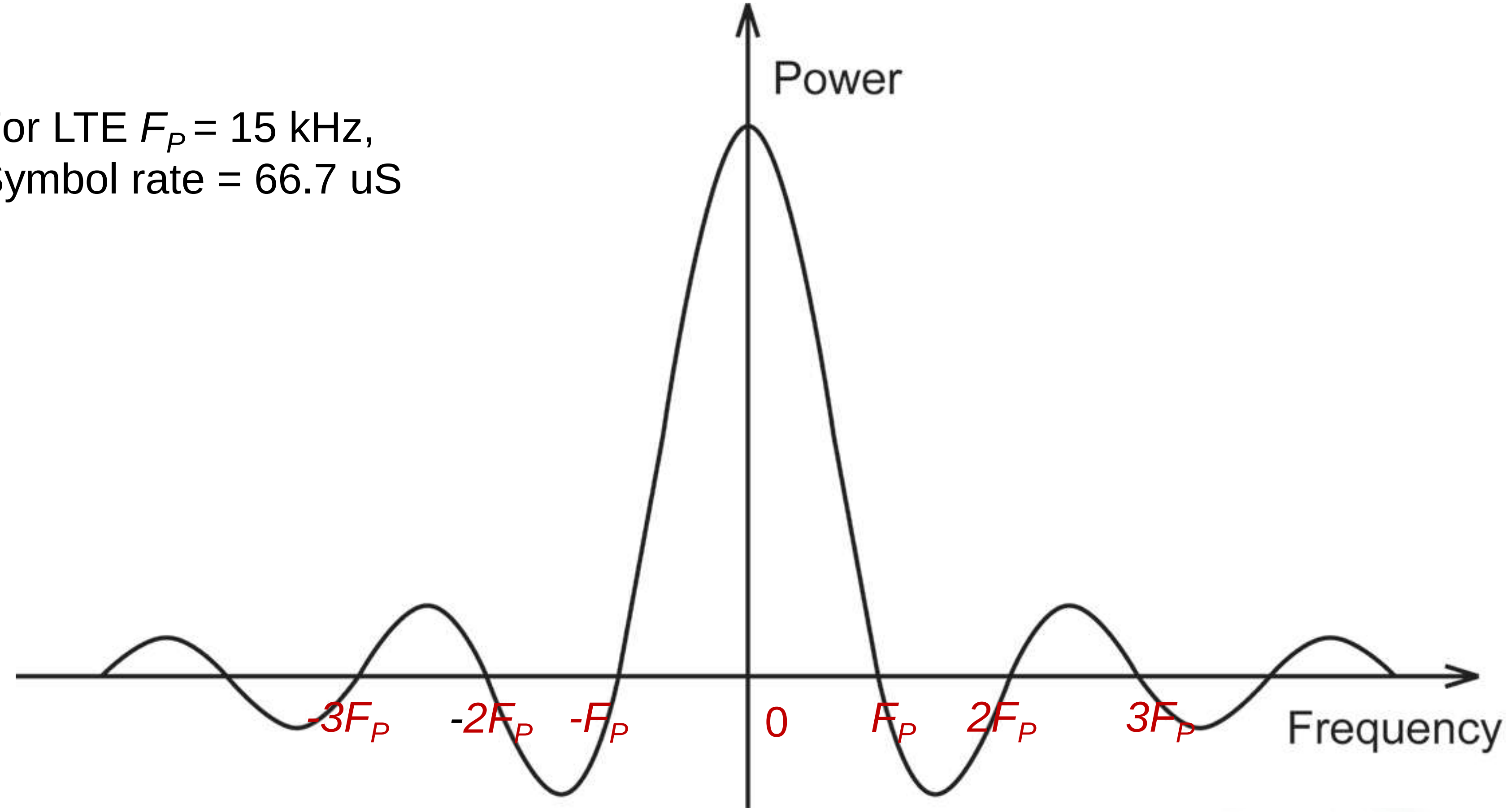
OFDM is a digital multi-carrier modulation scheme

- large number of closely-spaced orthogonal sub-carriers (e.g. 300/5 MHz BW)
- sub-carriers modulated with a conventional modulation format (e.g. QPSK, 16/64QAM)
- low symbol rate similar to conventional single-carrier modulation schemes in the same bandwidth.

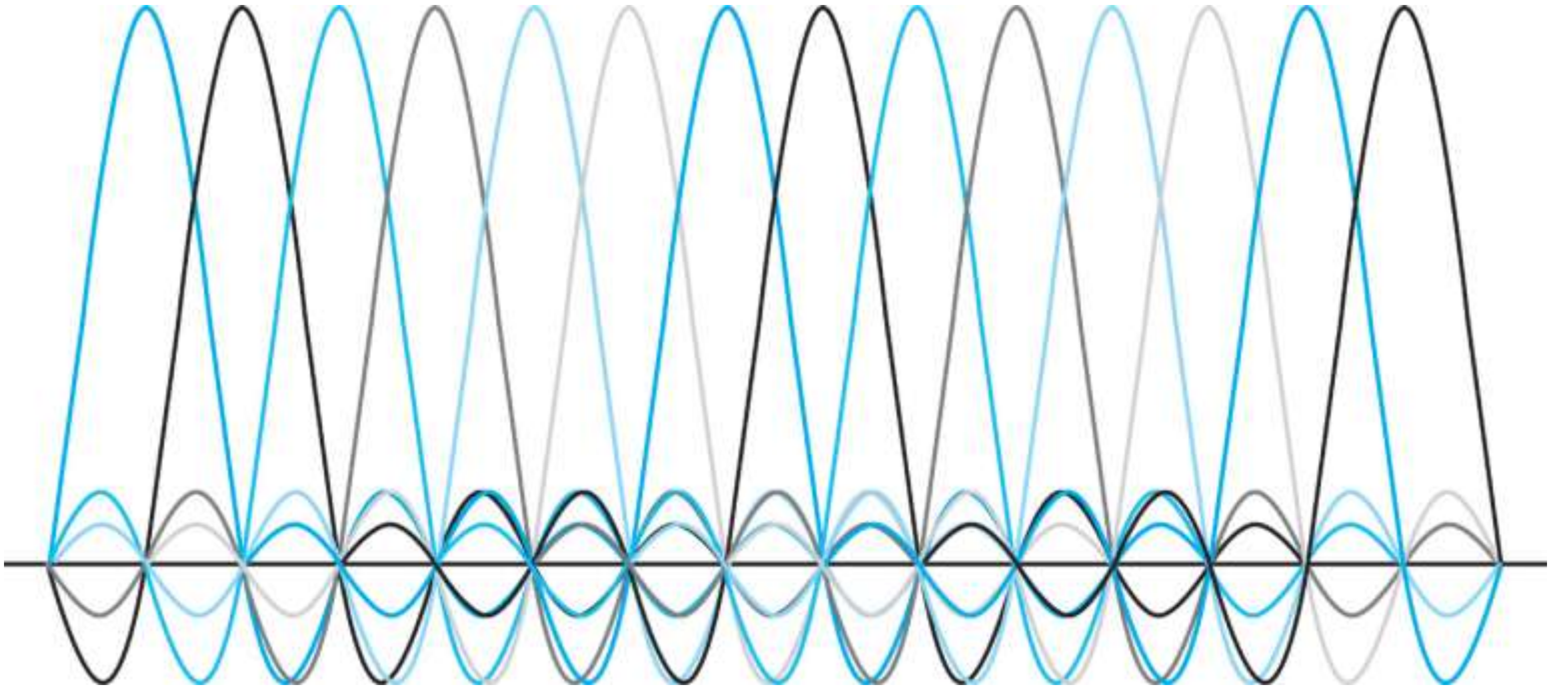
Spectrum of single modulated OFDM subcarrier

The Spectrum of a Complex Tone Pulse is a Sinc or sin(x)/x with Zeros at Multiples of $F_P = 1/T_P$

For LTE F_P = 15 kHz,
Symbol rate = 66.7 uS



Spectrum of multiple OFDM subcarriers



OFDM Operates as a Number of Orthogonal (Non-Interfering) Narrowband Systems

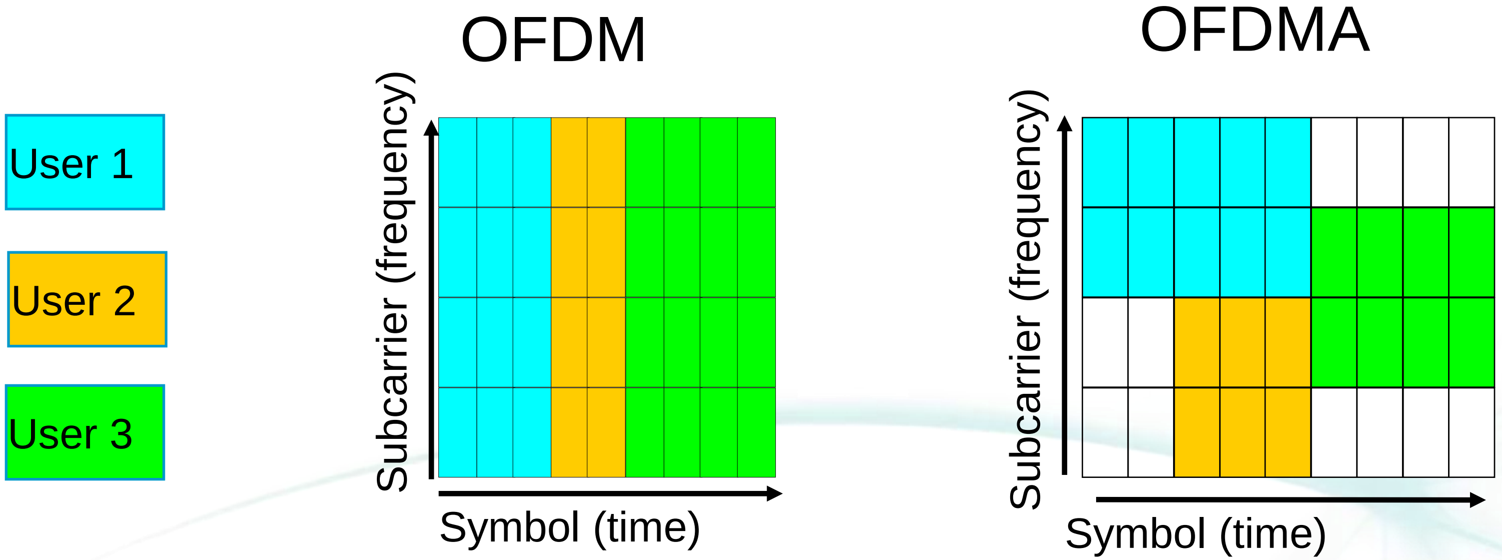
•Carrier spacing creates orthogonality.

•Phase noise, timing and frequency offsets decrease orthogonality.

OFDMA

LTE uses OFDMA (Orthogonal Frequency Division Multiple Access)

- more advanced form of OFDM where subcarriers are allocated to different users over time



User allocation in time domain only

User allocation in time and frequency domain

Orthogonal Frequency Division Multiplexing

OFDM advantages

- Multiple subcarriers allows
  - Scalable channel bandwidth
  - Frequency selective scheduling within the channel
- Wide channels are possible which support higher data rates
- Resistance to multi-path due to very long symbols

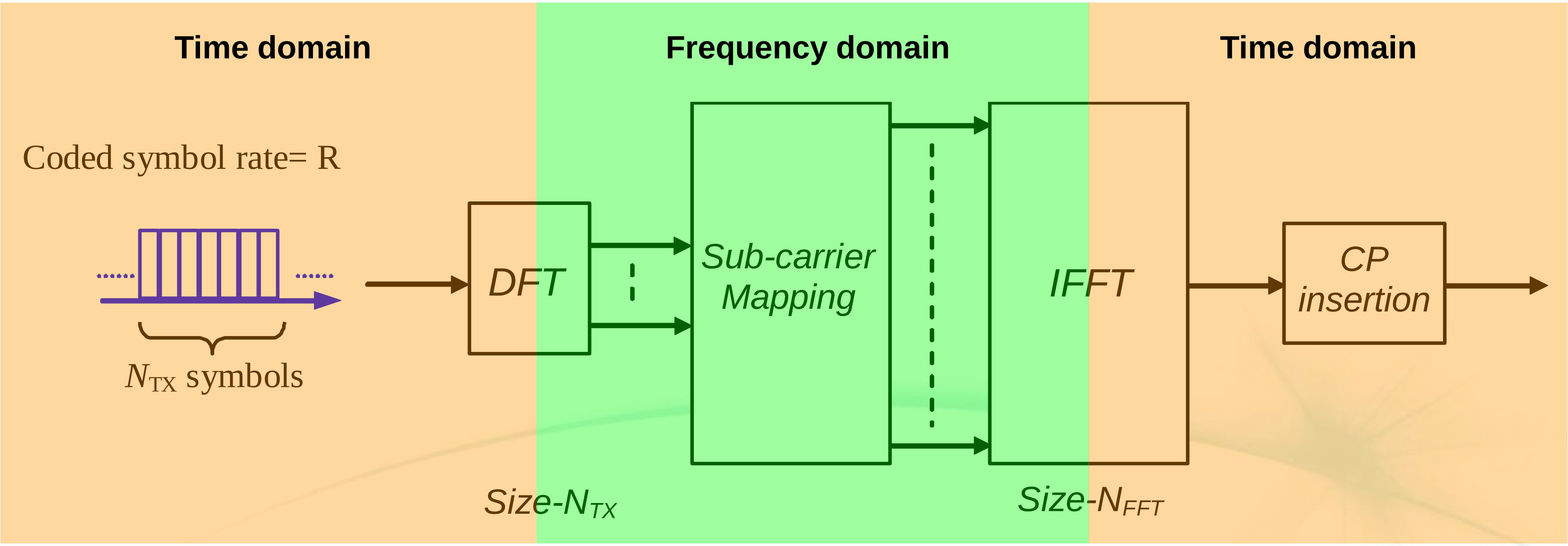
OFDM disadvantages

- Sensitive to frequency errors and phase noise due to close subcarrier spacing
- Sensitive to Doppler shift which creates interference between subcarriers
- Pure OFDM creates high PAR which is why SC-FDMA is used on UL

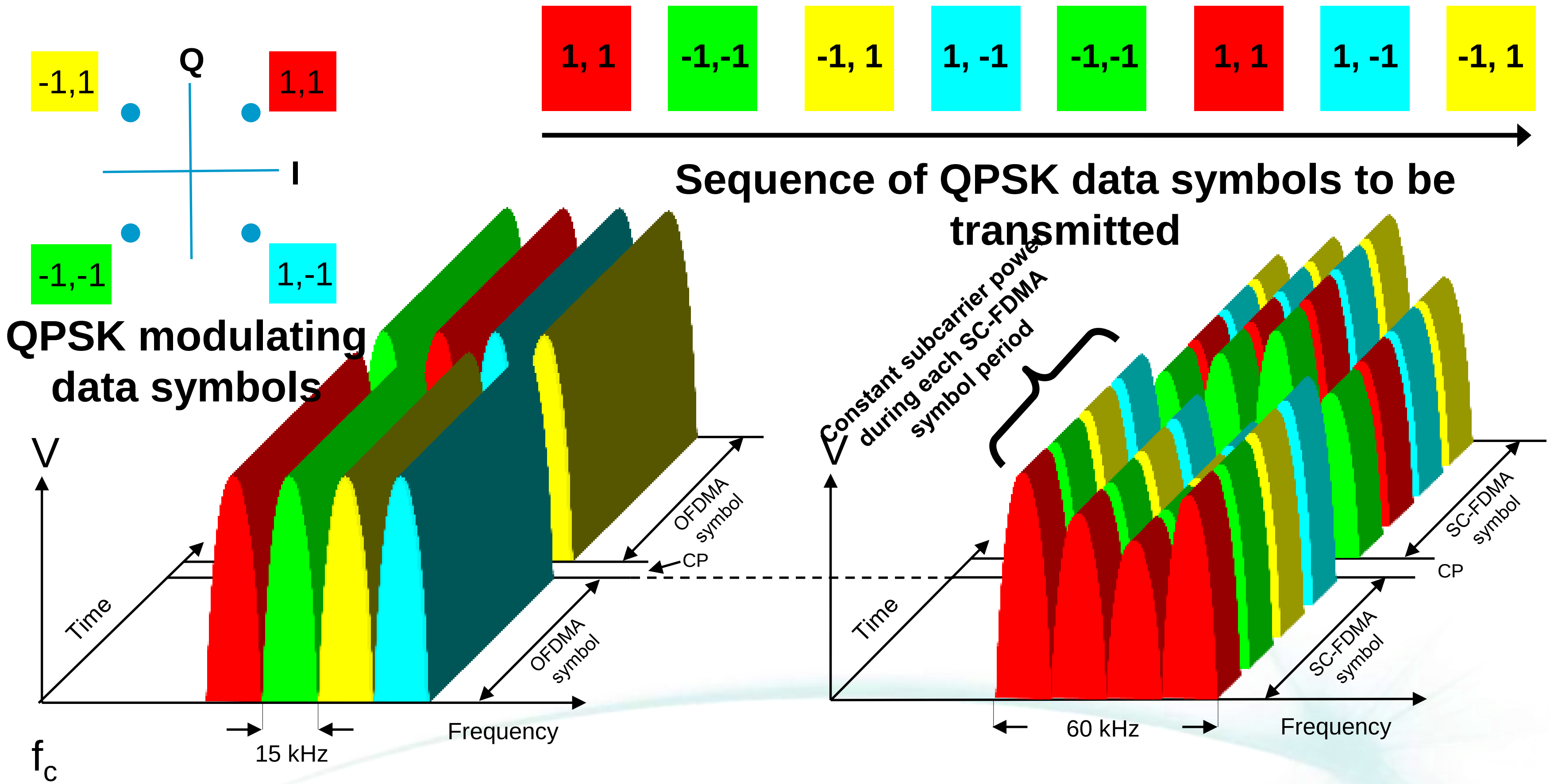
Single Carrier FDMA:
The new LTE uplink transmission scheme

SC-FDMA is a <u>hybrid</u> transmission scheme:

- low peak to average (PAR) of single carrier schemes
- frequency allocation flexibility and multipath protection of OFDMA



Comparing OFDMA and SC-FDMA
QPSK example using M=4 subcarriers



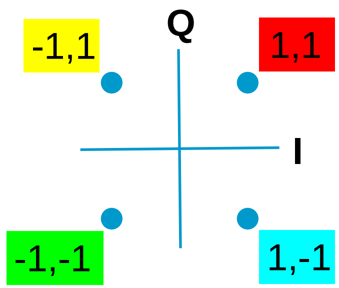
OFDMA
Data symbols occupy 15 kHz for one OFDMA symbol period

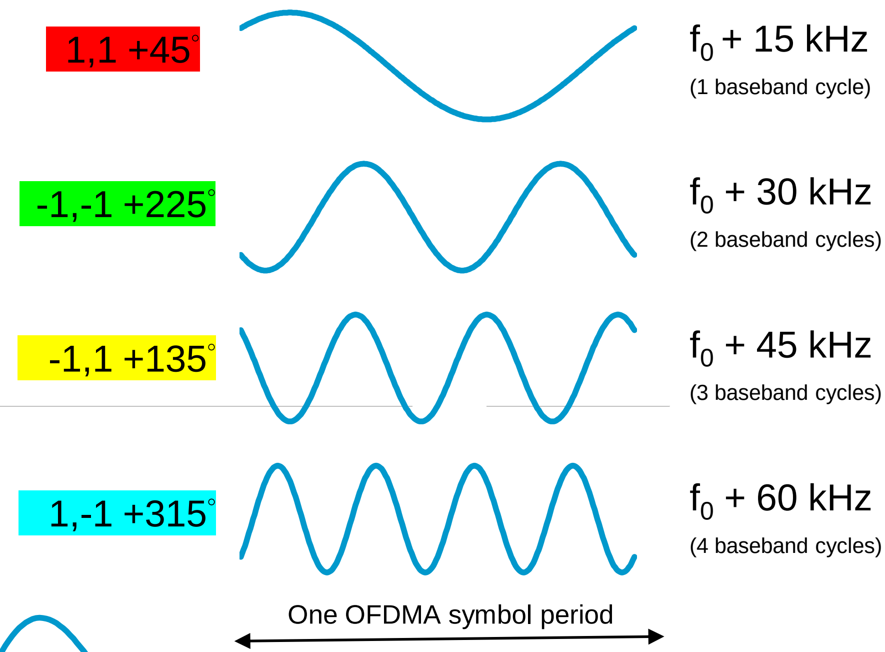
SC-FDMA
Data symbols occupy M*15 kHz for 1/M SC-FDMA symbol periods

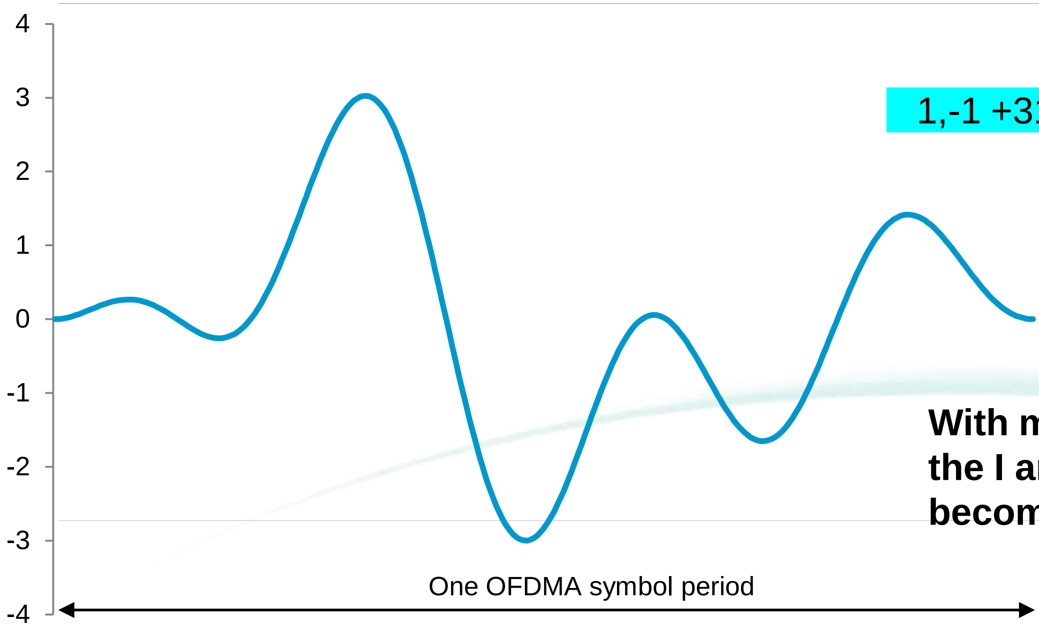
OFDMA modulation
QPSK example using M=4 subcarriers

Each of M subcarriers is encoded with one QPSK symbol

M subcarriers can transmit M QPSK symbols in parallel







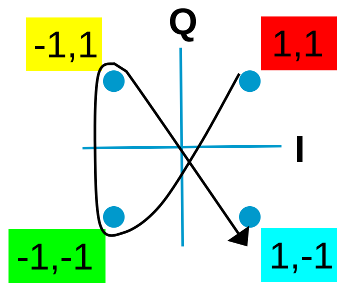
With many subcarriers the I and Q waveforms become Gaussian

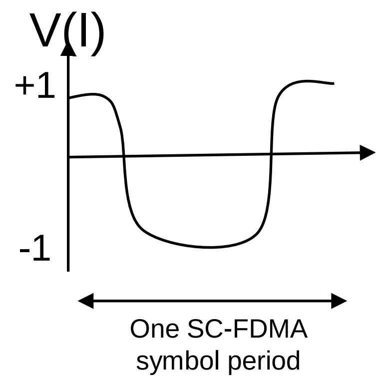
SC-FDMA signal generation
QPSK example using M=4 subcarriers

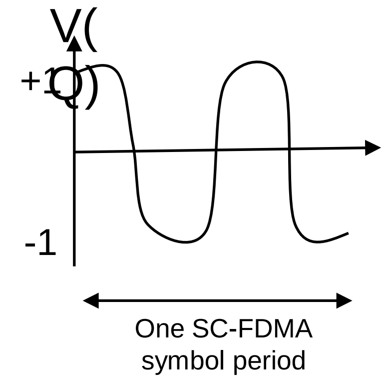
To transmit the sequence:

1, 1   -1,-1   -1, 1   1,-1

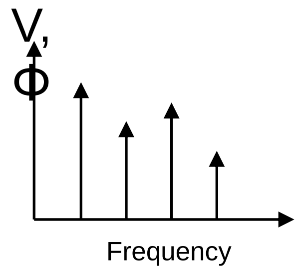
create a time domain representation of the IQ baseband sequence



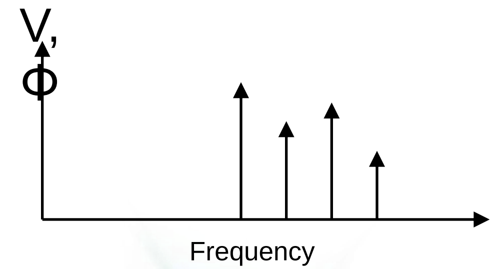




Perform a DFT of length M and sample rate M/(symbol period) to create M FFT bins spaced by 15 kHz

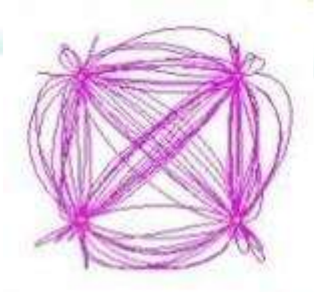


Shift the M subcarriers to the desired allocation within the system bandwidth



Perform an IFFT to create a time domain signal of the frequency shifted original

Insert the cyclic prefix between SC-FDMA symbols and transmit



Important Note: The PAR is the same as the original QPSK data symbols

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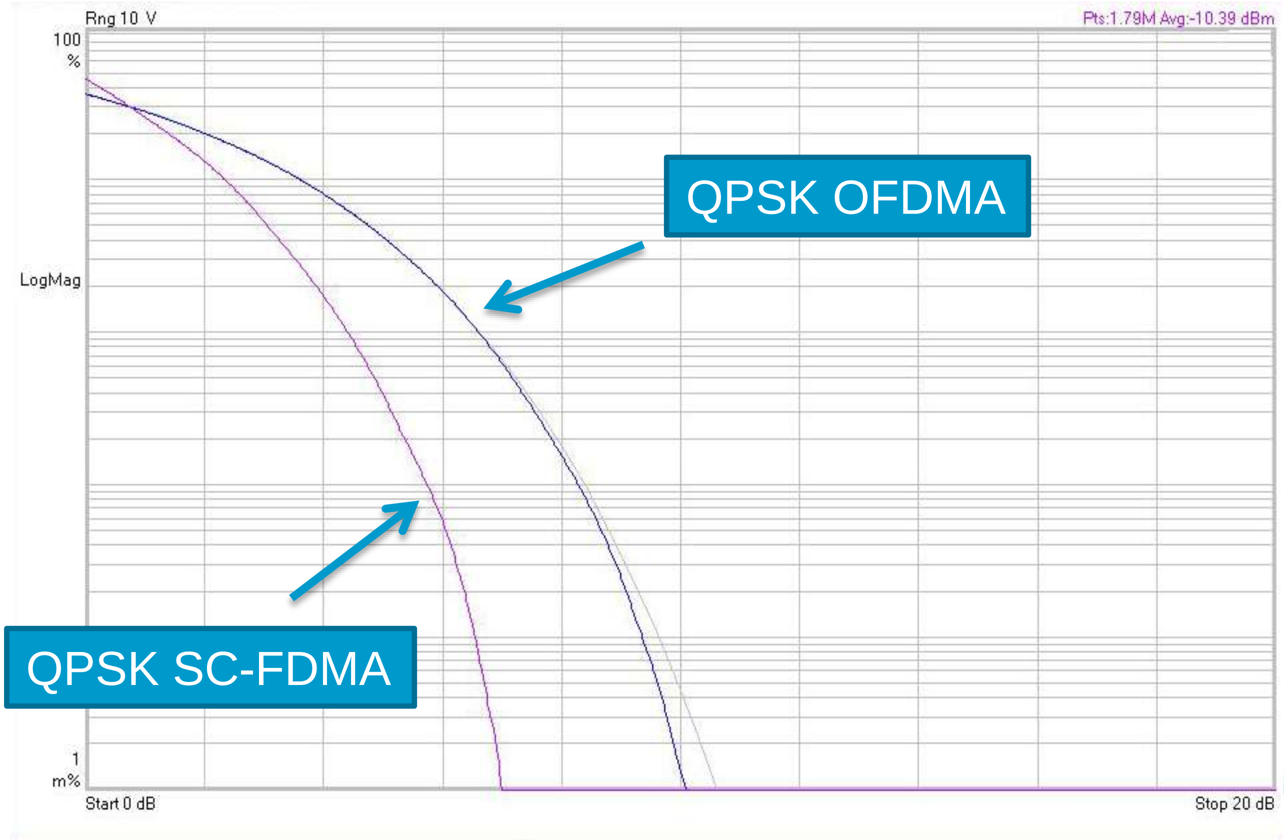
Complimentary cumulative distribution function

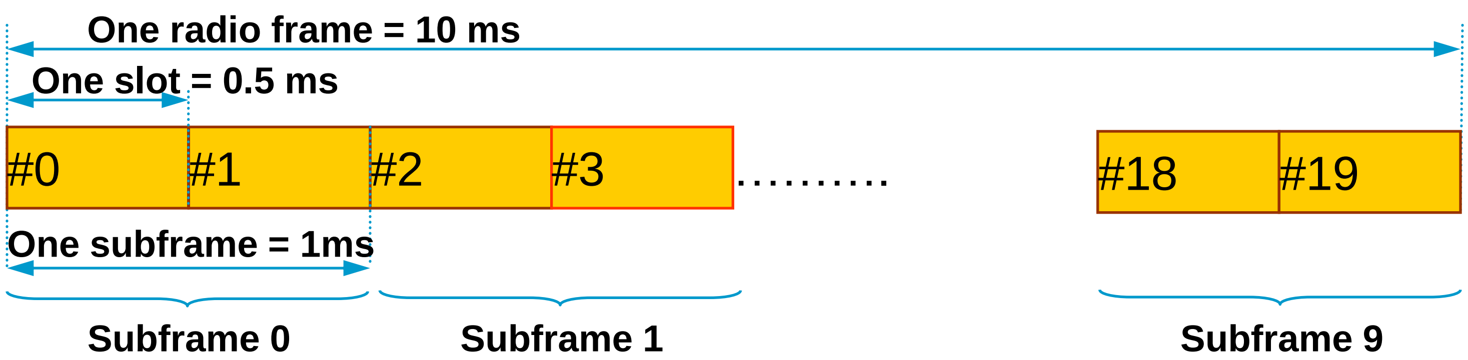


- SC-FDMA has lower PARs
- Extra headroom lowers costs in the power amplifier and reduces battery drain.

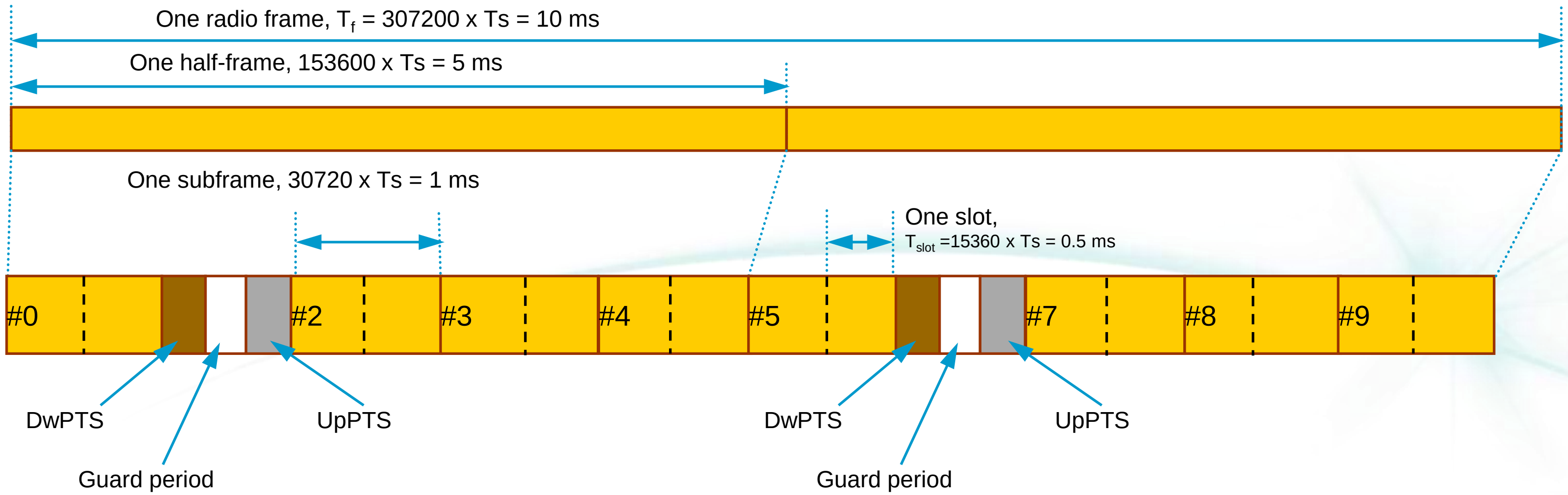
Physical Layer Definitions: Frame Structure

Frame Structure type 1 (FDD)

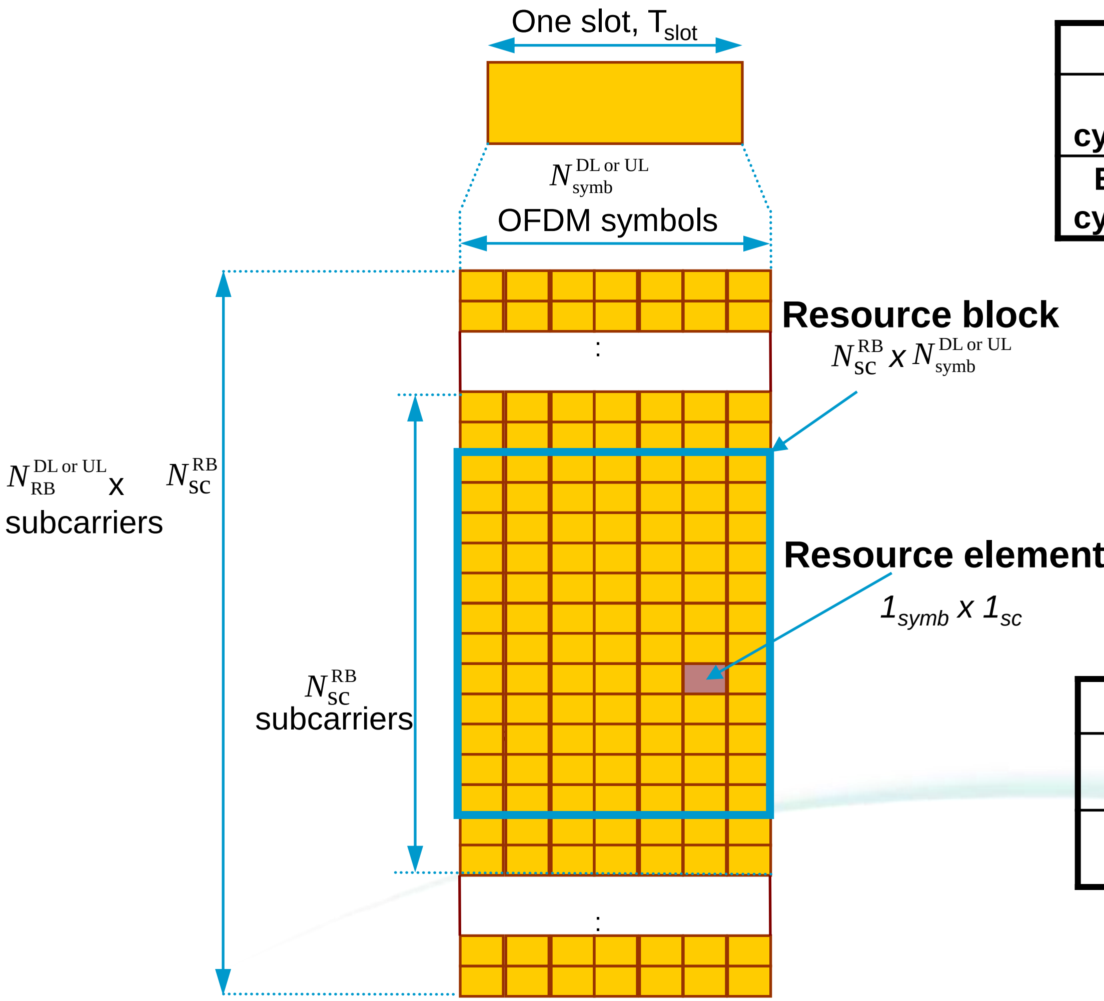
FDD: Uplink and downlink are transmitted separately



Frame Structure type 2 (TDD)



Slot Structure & Physical Resource Elements



Condition (DL)		N^{RB}_{sc}	N^{DL}_{symb}
Normal cyclic prefix	Δf=15kHz	12	7
Extended cyclic prefix	Δf=15kHz	12	6
	Δf=7.5kHz	24	3

Condition (UL)	N^{RB}_{sc}	N^{UL}_{symb}
Normal cyclic prefix	12	7
Extended cyclic prefix	12	6

LTE Physical Layer Signals & Channels

Physical signals

Downlink	Uplink
Primary synchronization signal	Demodulation reference signal (DMRS)
Secondary synchronization signal	Sounding reference signal (SRS)
Reference signals	

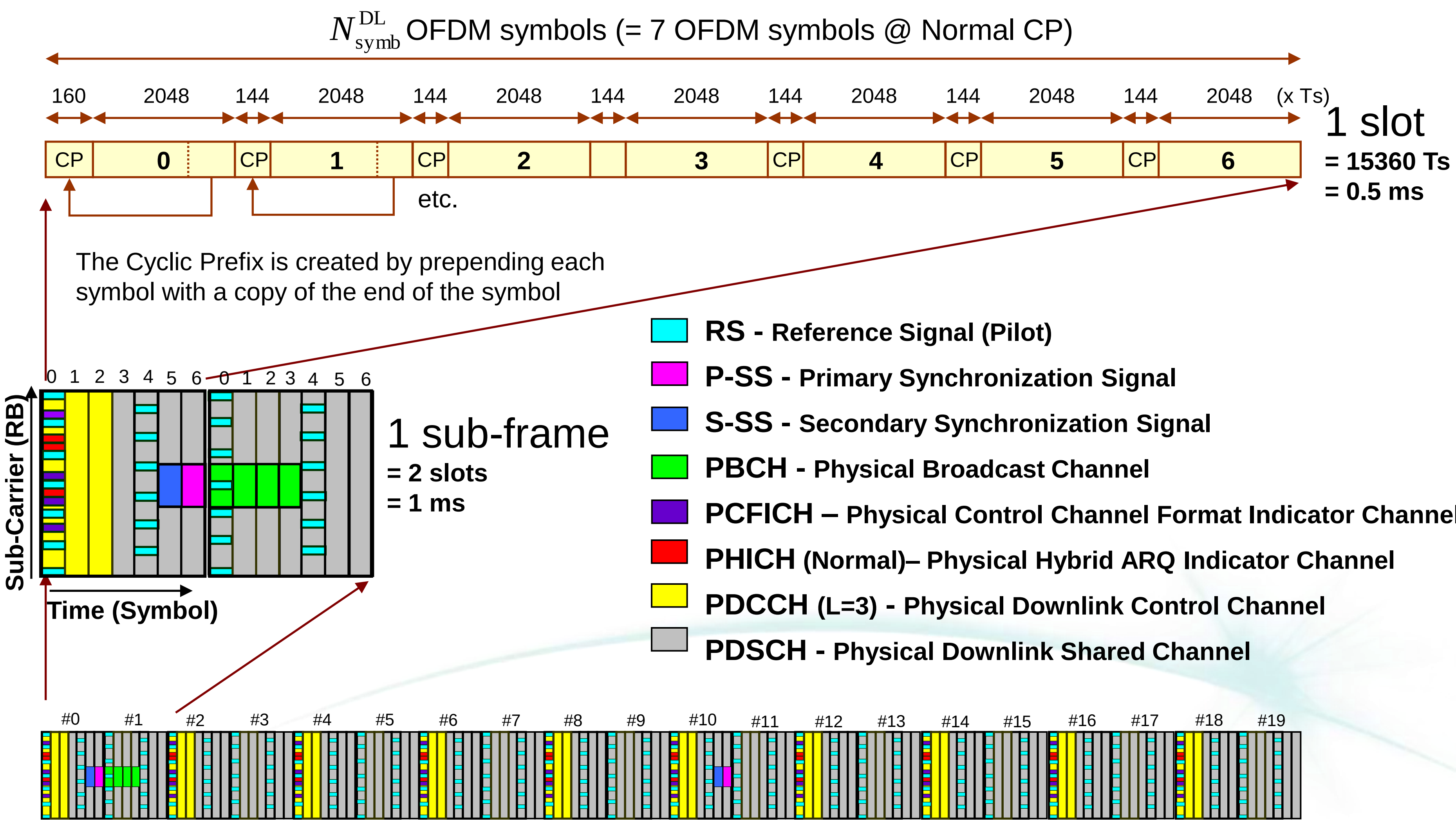
Generated in Layer 1 and are used for system synchronization, cell identification and radio channel estimation

Physical channels

Downlink	Uplink
Physical Downlink Shared Channel (PDSCH)	Physical Uplink Shared Channel (PUSCH)
Physical Broadcast Channel (PBCH)	Physical Uplink Control Channel (PUCCH)
Physical Downlink Control Channel (PDCCH)	Physical Random Access Channel (PRACH)
Physical Multicast Channel (PMCH)	
Physical Control Format Indicator Channel (PCFICH)	
Physical Hybrid Automatic Repeat Request (ARQ) Indicator Channel (PHICH)	

Carry data from higher layers including control, scheduling and user payload

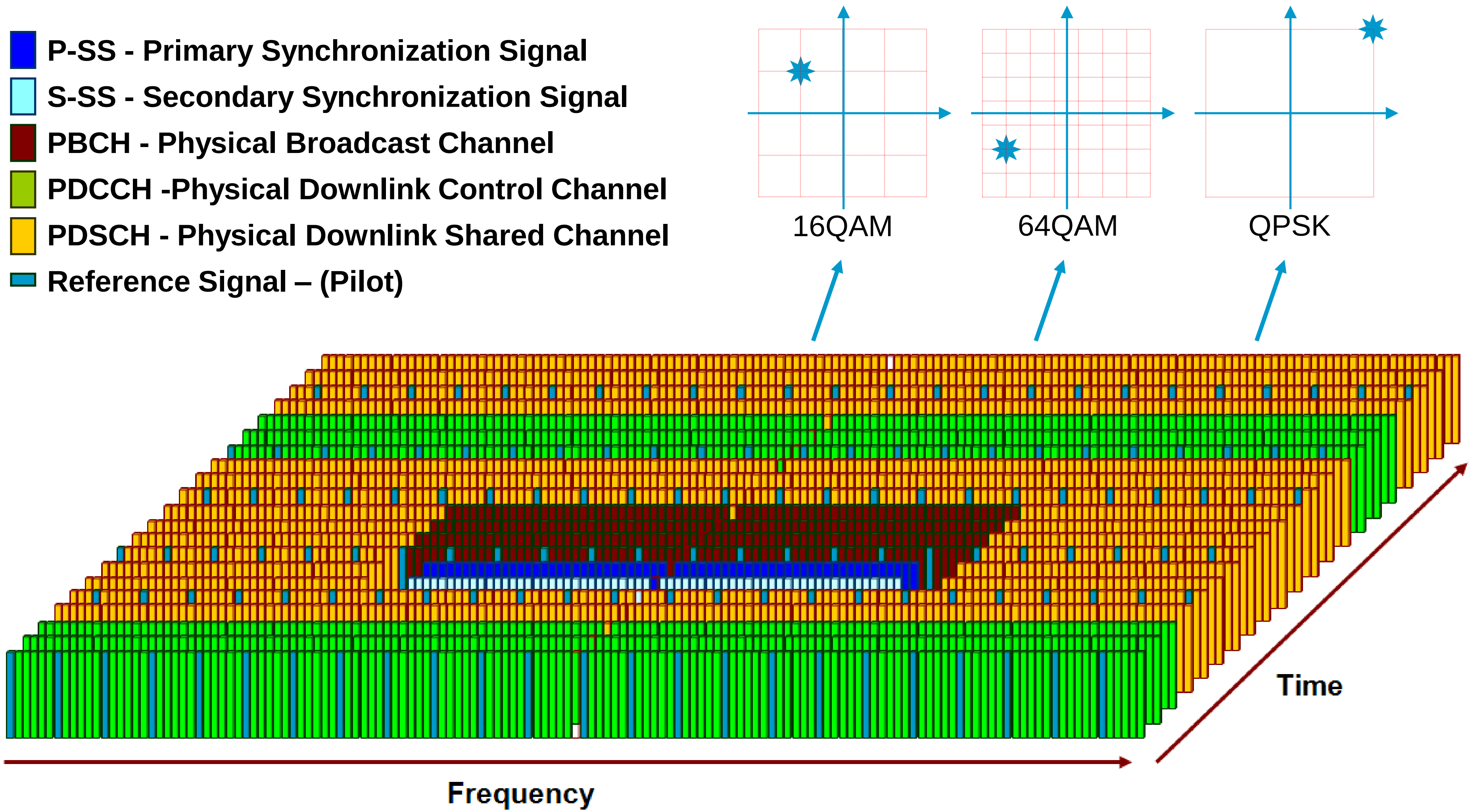
Downlink Frame Structure Type 1



- **RS - Reference Signal (Pilot)**
- **P-SS - Primary Synchronization Signal**
- **S-SS - Secondary Synchronization Signal**
- **PBCH - Physical Broadcast Channel**
- **PCFICH – Physical Control Channel Format Indicator Channel**
- **PHICH (Normal)– Physical Hybrid ARQ Indicator Channel**
- **PDCCH (L=3) - Physical Downlink Control Channel**
- **PDSCH - Physical Downlink Shared Channel**

LTE Downlink Mapping

- P-SS - Primary Synchronization Signal
- S-SS - Secondary Synchronization Signal
- PBCH - Physical Broadcast Channel
- PDCCH -Physical Downlink Control Channel
- PDSCH - Physical Downlink Shared Channel
- Reference Signal – (Pilot)



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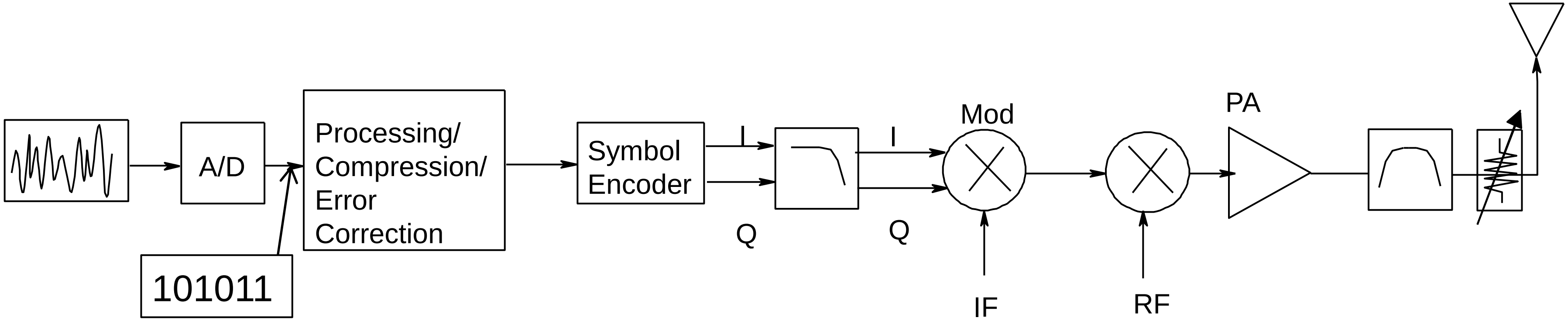
Transmitter Basics



- Channel Coding
- Map to I & Q
- Modulation Shaping Filter
- Modulate to IF
- Upconvert to RF
- Amplify, Filter, Send to Antenna

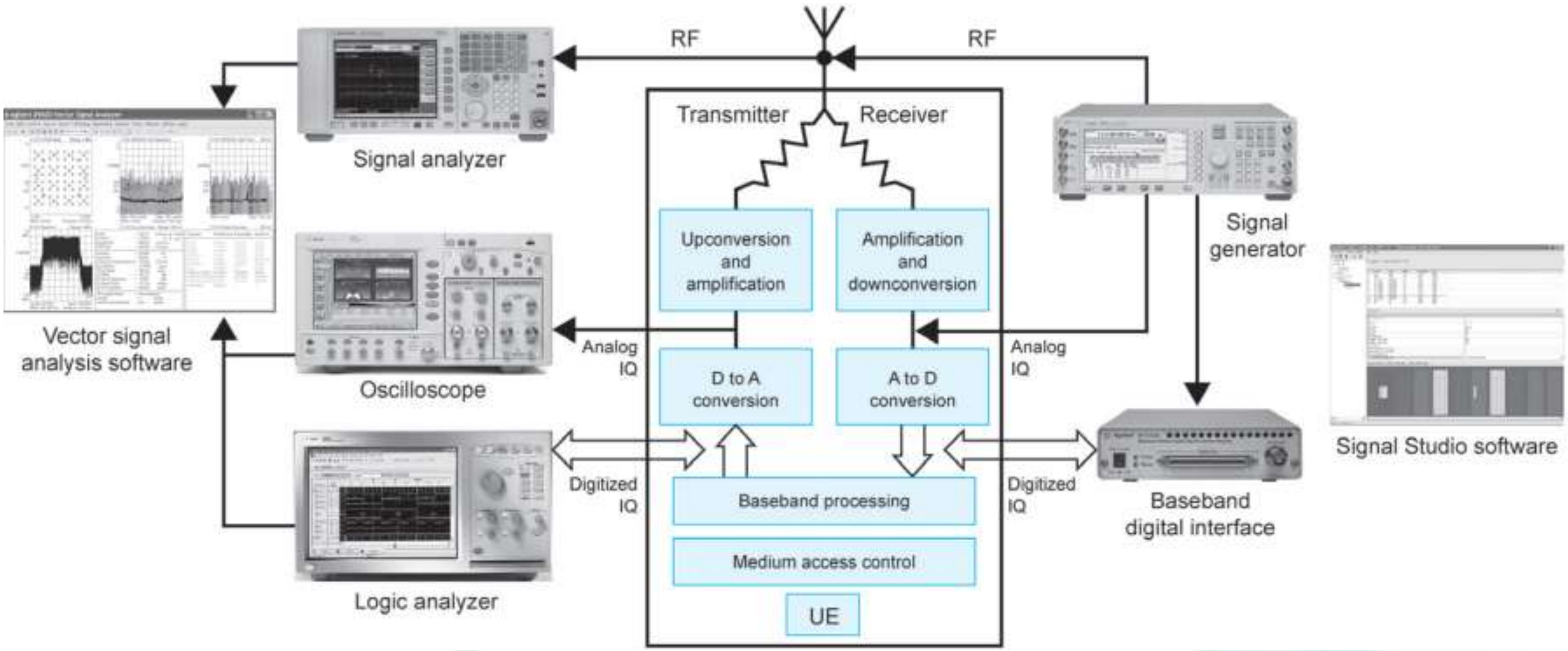
- Characteristics tests
  - Output power
  - Transmitted signal quality
  - Unwanted emissions

Transmitter Testing – Characteristics

Output power	eNB 36.141	UE 36.521-1
Max output power	6.2	
Transmit power		6.2
Output power dynamics	6.3	6.3
Transmit on/off power	6.4	
Transmitted signal quality		
Frequency error	6.5.1	6.5.1
EVM	6.5.2	
Transmit modulation quality		6.5.2
Time alignment between Tx branches	6.5.3	
DL RS power	6.5.4	

Unwanted emissions	eNB 36.141	UE 36.521-1
ACLR	6.6.2	6.6.2
Spurious emissions	6.6.4	6.6.3
Transmitter intermodulation	6.7	6.7
Occupied BW	6.6.1	6.6.1
Oper. band unwanted emissions	6.6.3	
Spectrum emission mask		6.6.2

Measuring Signals at Different Locations in the Transmitter



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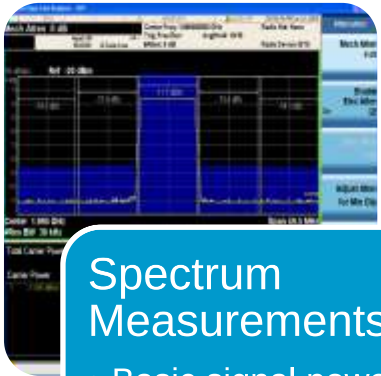
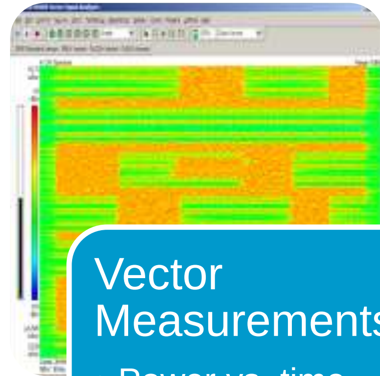
A Systematic & Structured Approach



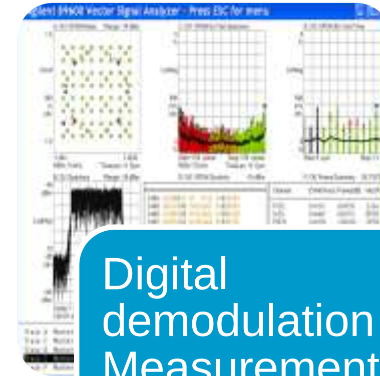
Spectrum Measurements

- Basic signal power and frequency characteristics



Vector Measurements

- Power vs. time, CCDF, spectrograms



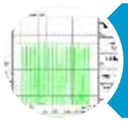
Digital demodulation Measurements

- Constellation and modulation quality analysis, advanced analysis

More productive and efficient to follow a verification sequence when measuring complex signals

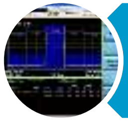
Verifying Transmitter – Spectrum and Vector Meas

Channel power

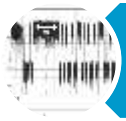


Amplitude flatness

Center frequency



Occupied bandwidth

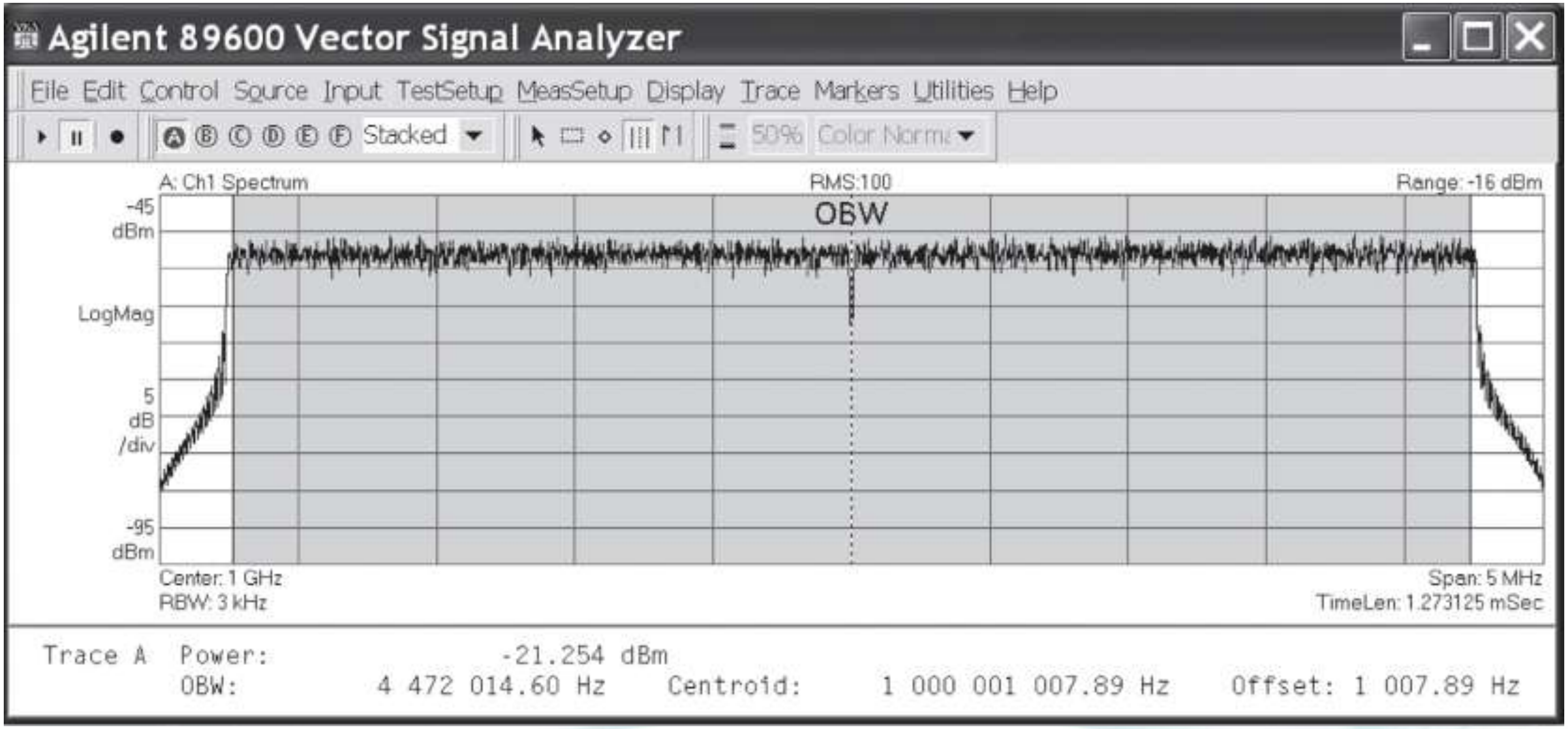


Power vs time

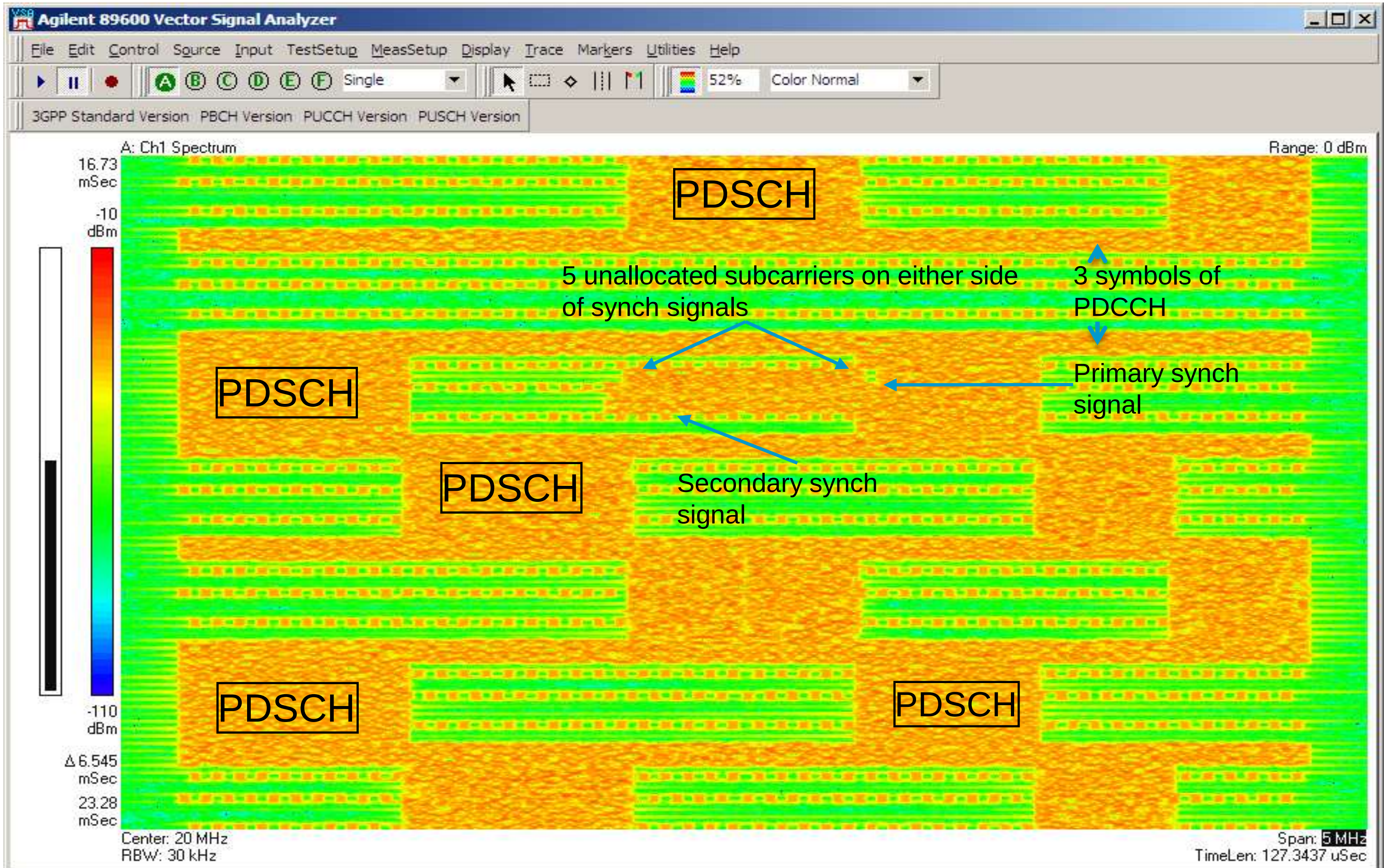
CCDF

Spectrum vs time

Occupied Bandwidth



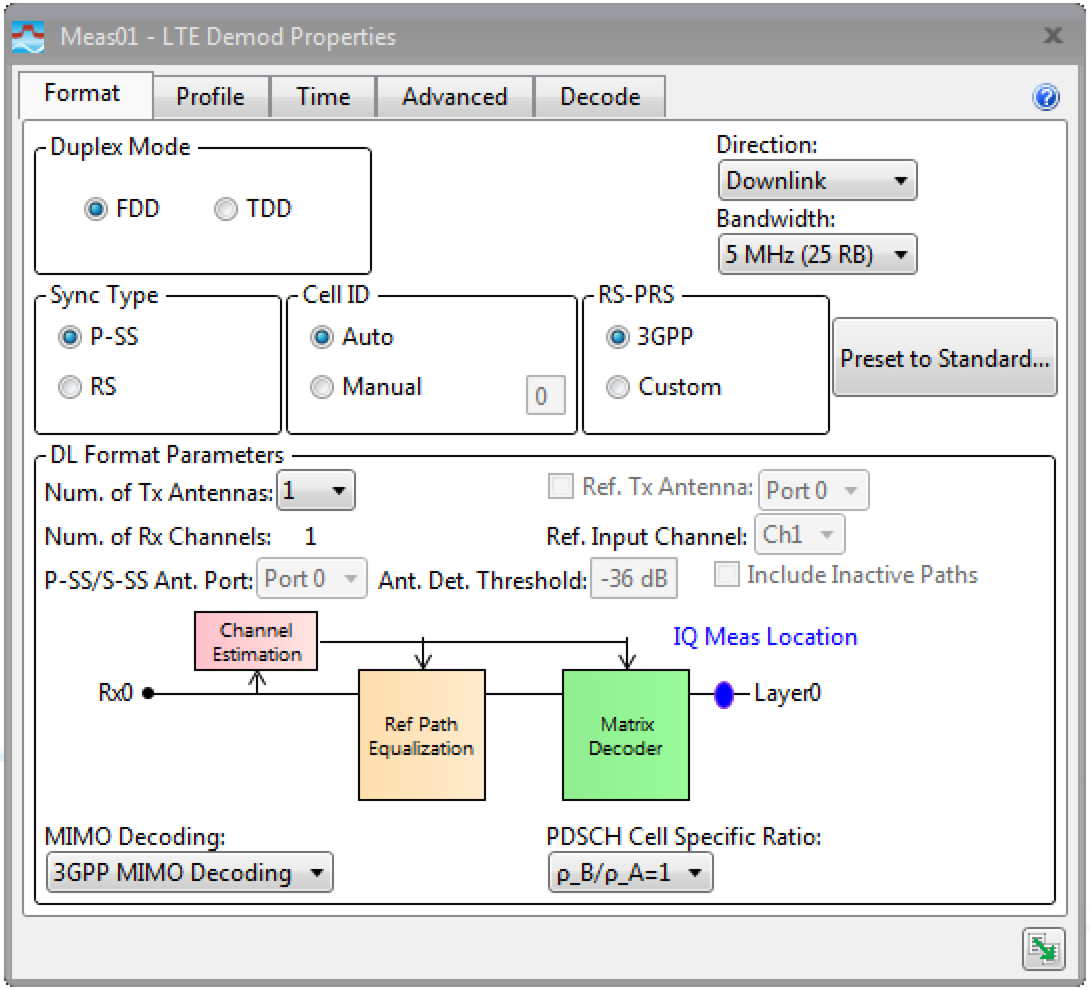
Spectrograph



Analysis of Signals After Digital Demodulation

Measurement example for setup, including:

- UL / DL
- FDD / TDD
- Bandwidth & Span
- Sync type



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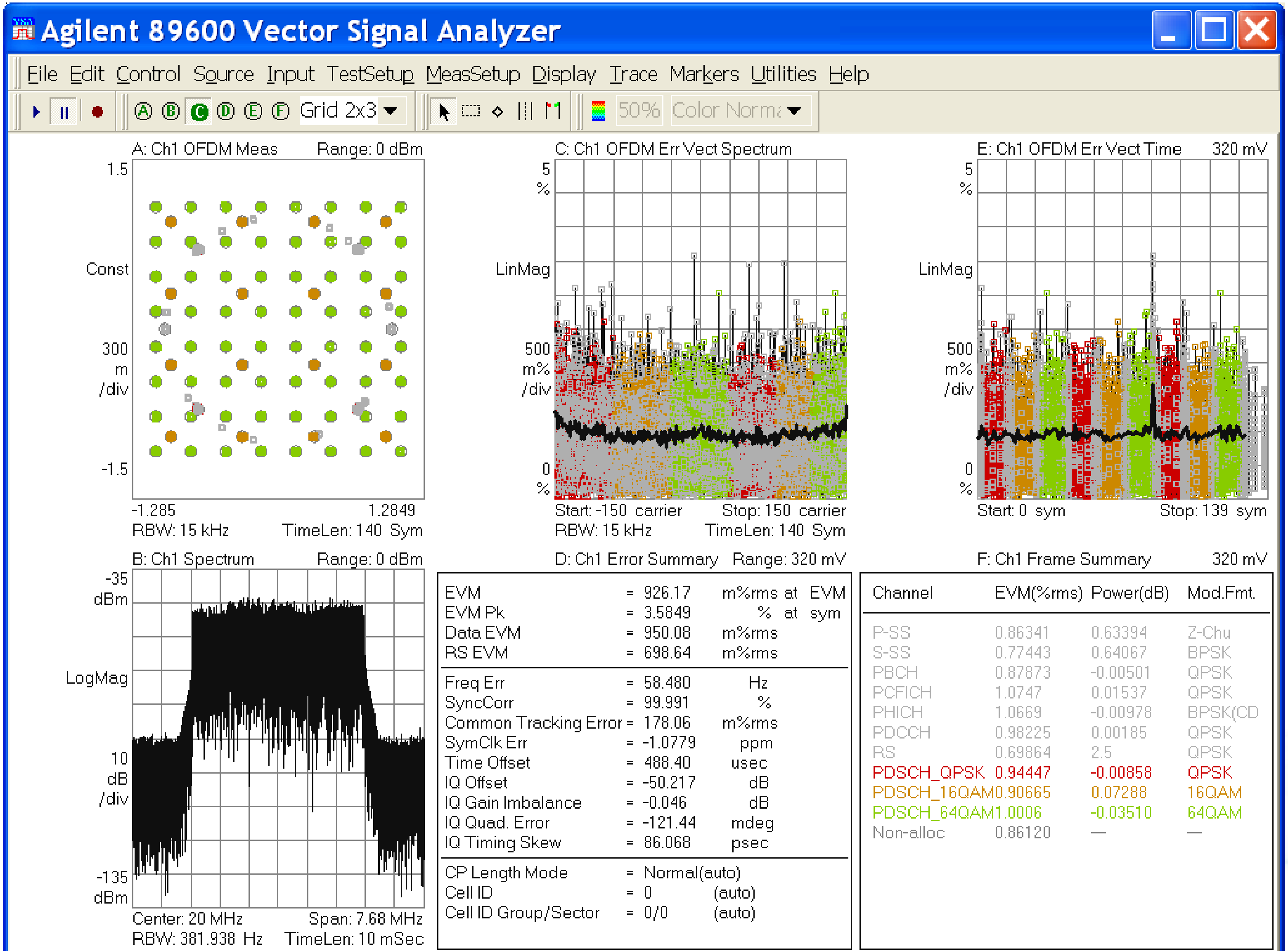
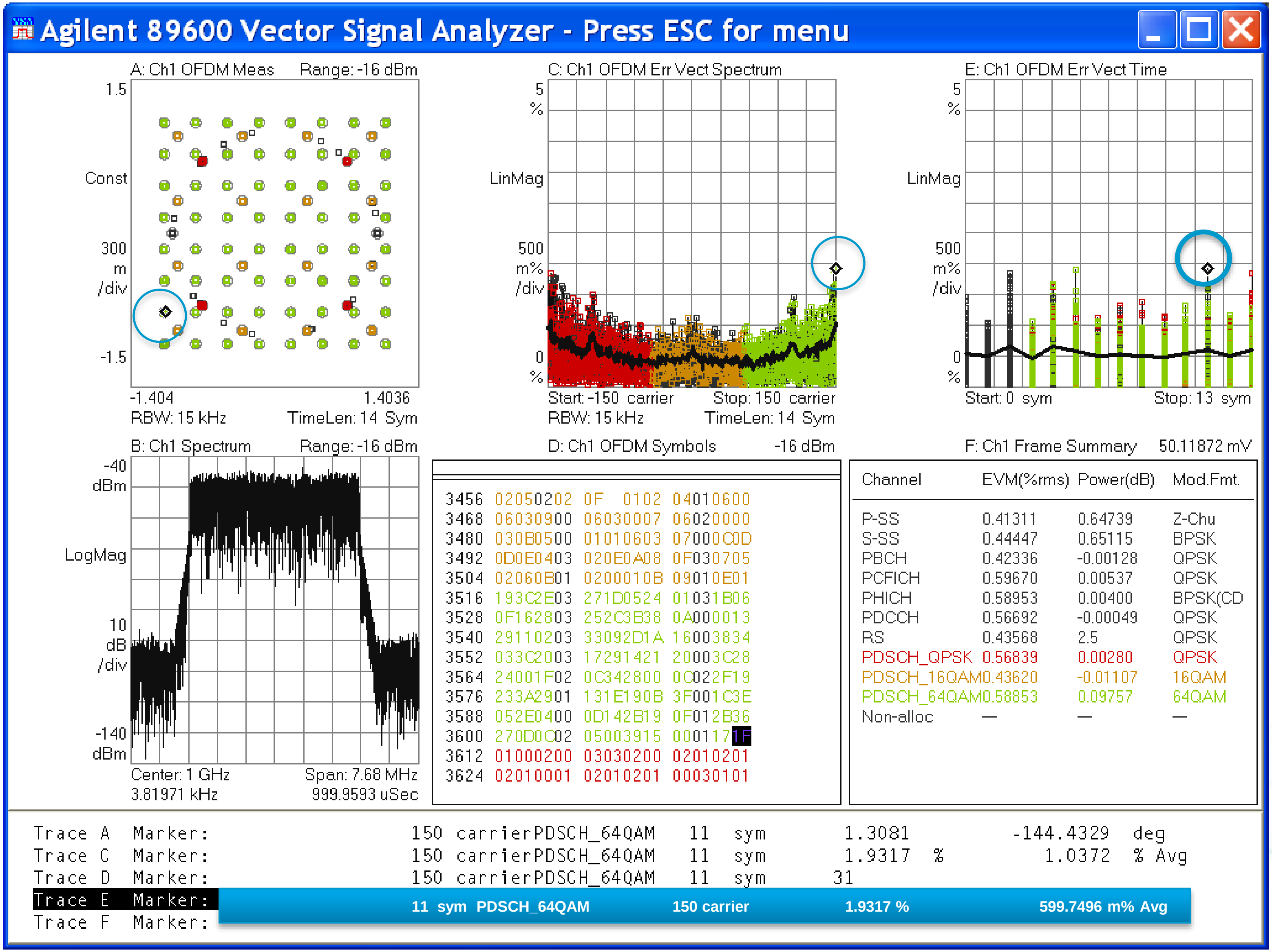
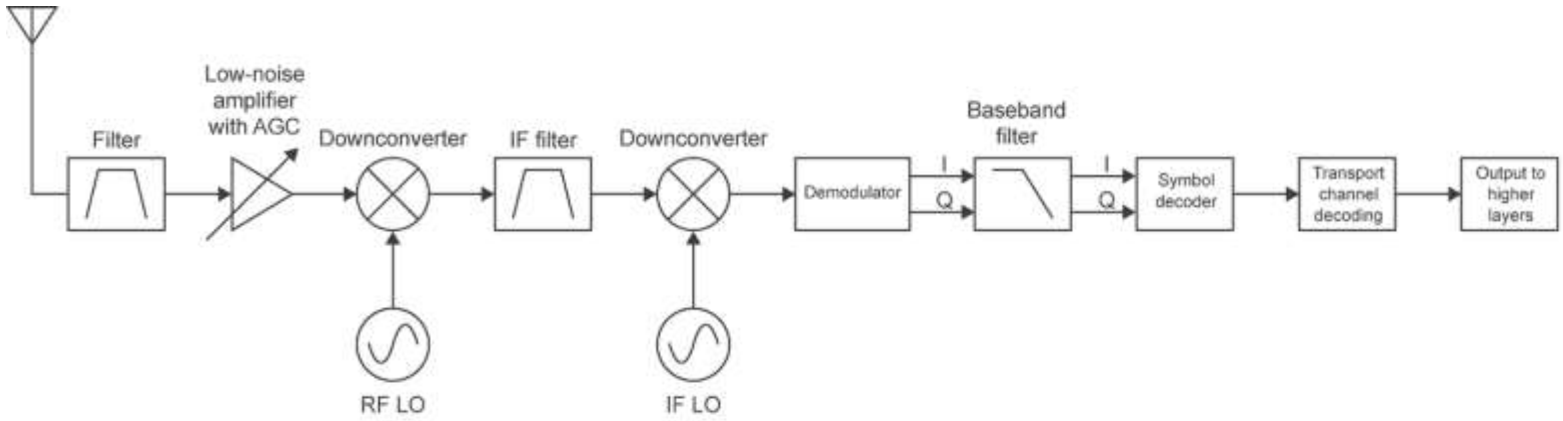
Analysis of Signals After Digital Demodulation



Analysis of Signals After Digital Demodulation



Receiver Basics



- Downconvert to IF/BB
- Filter
- Demodulate
- Decode and Process Bits
- Convert to Analog (if necessary)

- Characteristics tests - open loop
  - Sensitivity and Dynamic Range
  - Susceptibility to interference
  - Unwanted emissions

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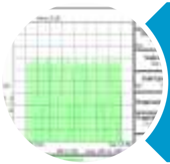
Receiver Testing – Characteristics

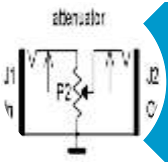
Sensitivity and dynamic range	eNB 36.141	UE 36.521.1
Reference sensitivity level	7.2	7.3
Dynamic range	7.3	
In-channel selectivity	7.4	
Max input level		7.4
Susceptibility to interference		
Blocking	7.6	7.6
Adjacent channel selectivity	7.5	7.5
Intermodulation characteristics		7.8
Receiver intermodulation	7.8	
Spurious response		7.7
Unwanted emissions		
Spurious emissions	7.7	7.9

Verifying RF receiver –front end

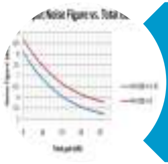


Amplitude flatness

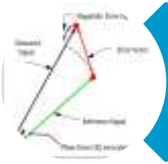
Phase linearity



Automatic gain control



Noise figure



Receiver EVM

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Common RF Front End Measurements

Phase Linearity

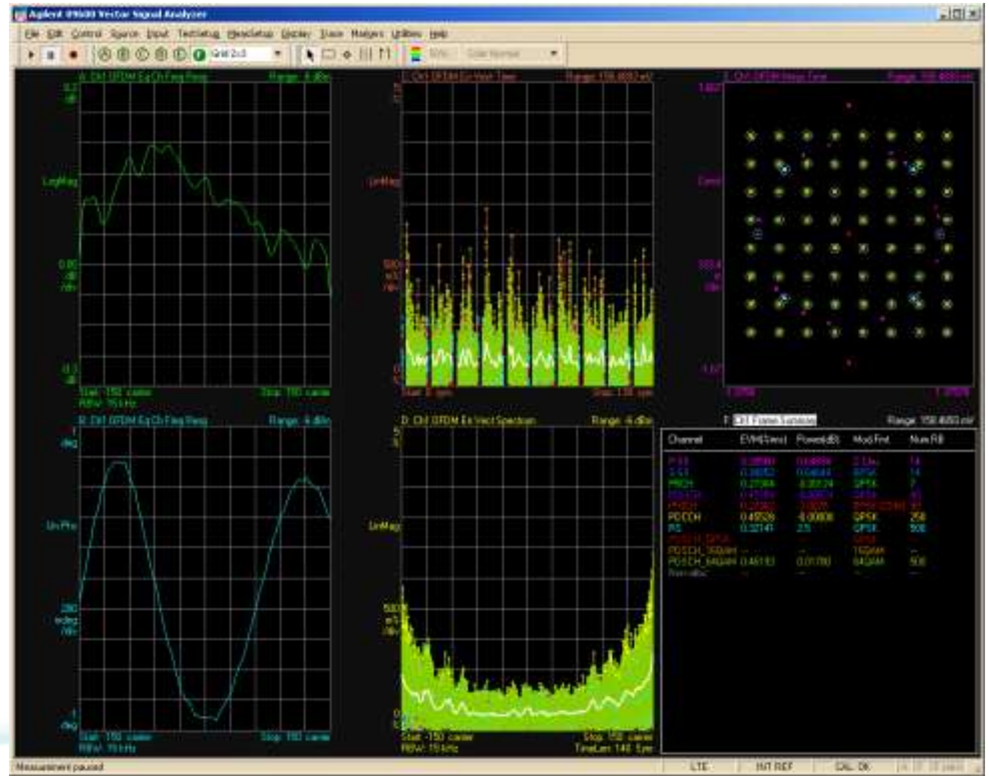
Issues

- LTE can correct some amplitude / phase errors with RS
- Errors will manifest themselves as EVM
- Important because LTE BW is wider than other cellular standards
- Need to test individual components, i.e. Amplifiers, Filters, Mixers, etc

How to test

- VSA can measure phase linearity and also amplitude flatness of modulated LTE signal
- Hard to test with traditional signal generator and spectrum analyzer
- High degree of integration may make network analyzer impractical

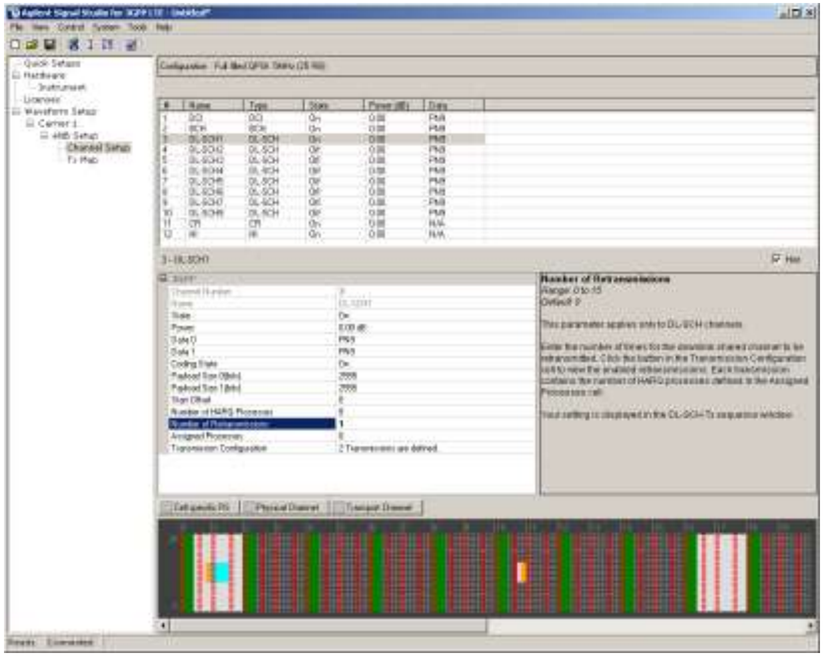
89600A VSA Measurement



Baseband Measurements

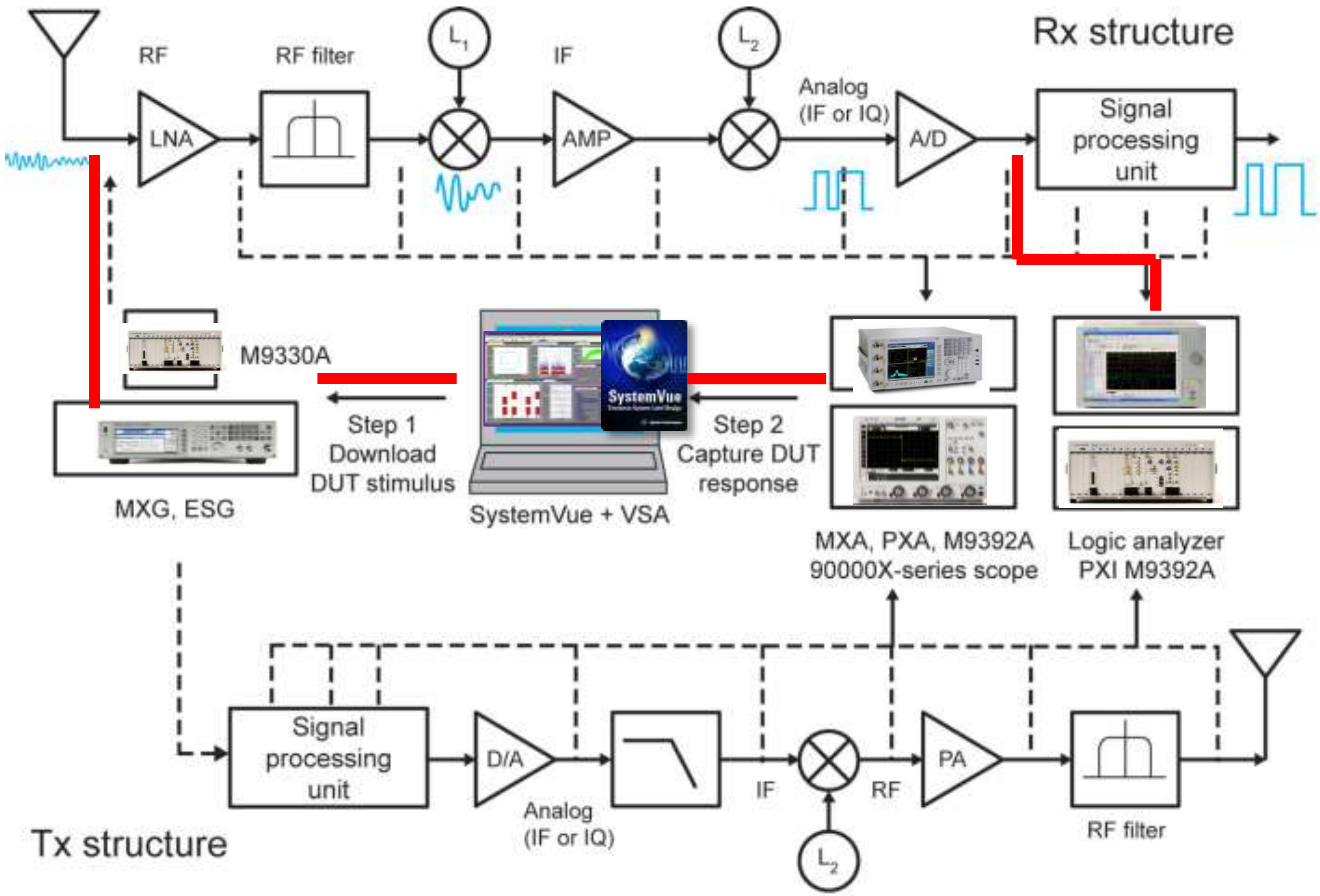
Baseband Measurement Goals

- Determine if RX can correctly demodulate and decode data
  - Different RB allocation
  - Different modulation types
  - Different LTE system BW
- Functional testing of HARQ capability
- Determine performance RX under impaired conditions
- Pre-conformance testing
  - Receiver Characteristics
    - Open Loop
    - Require interfering carriers
  - Performance Requirements
    - Closed Loop
    - Requires fading

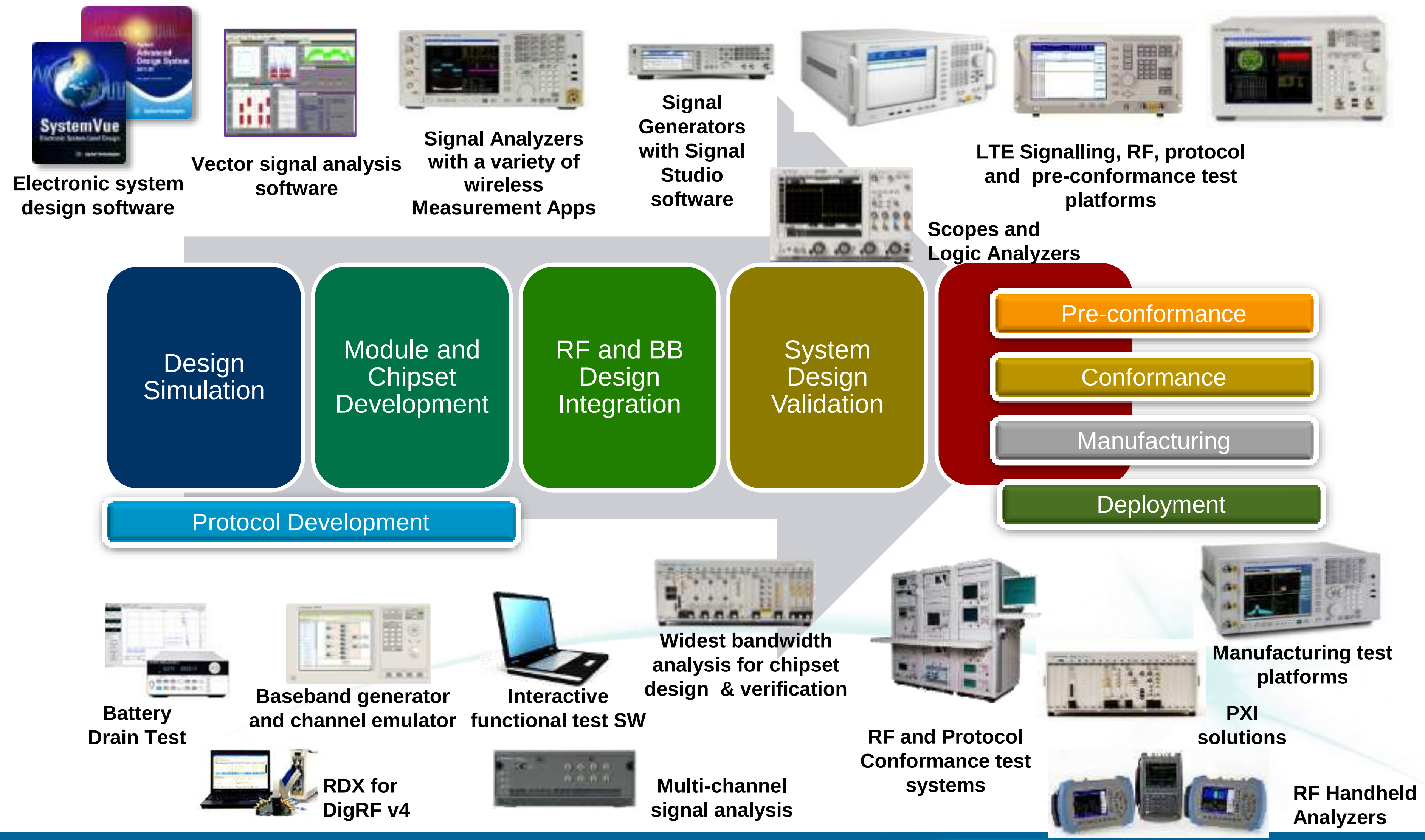


RDX for DigRF v4

Combining Simulation and Test to Measure EVM, BER/BLER and throughput at stages in TxRx Chain



Testing Needs Across the Ecosystem/life-cycle



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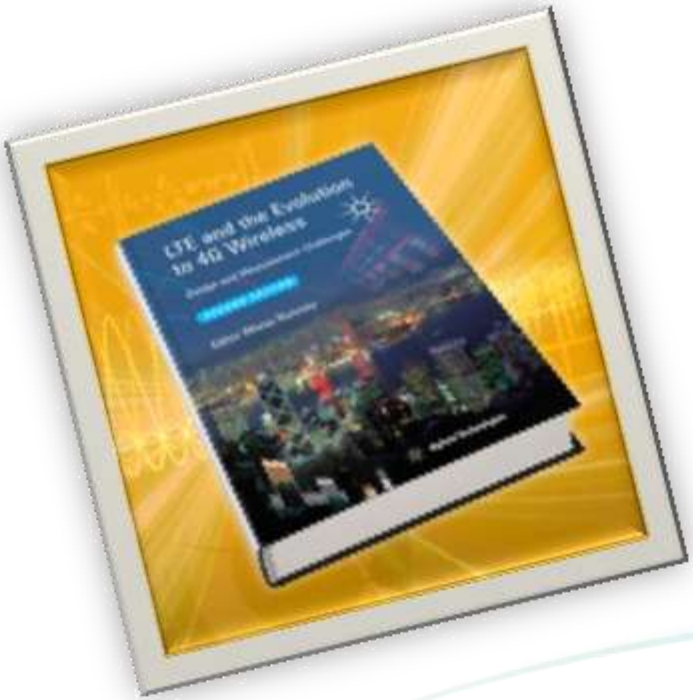
Q & A



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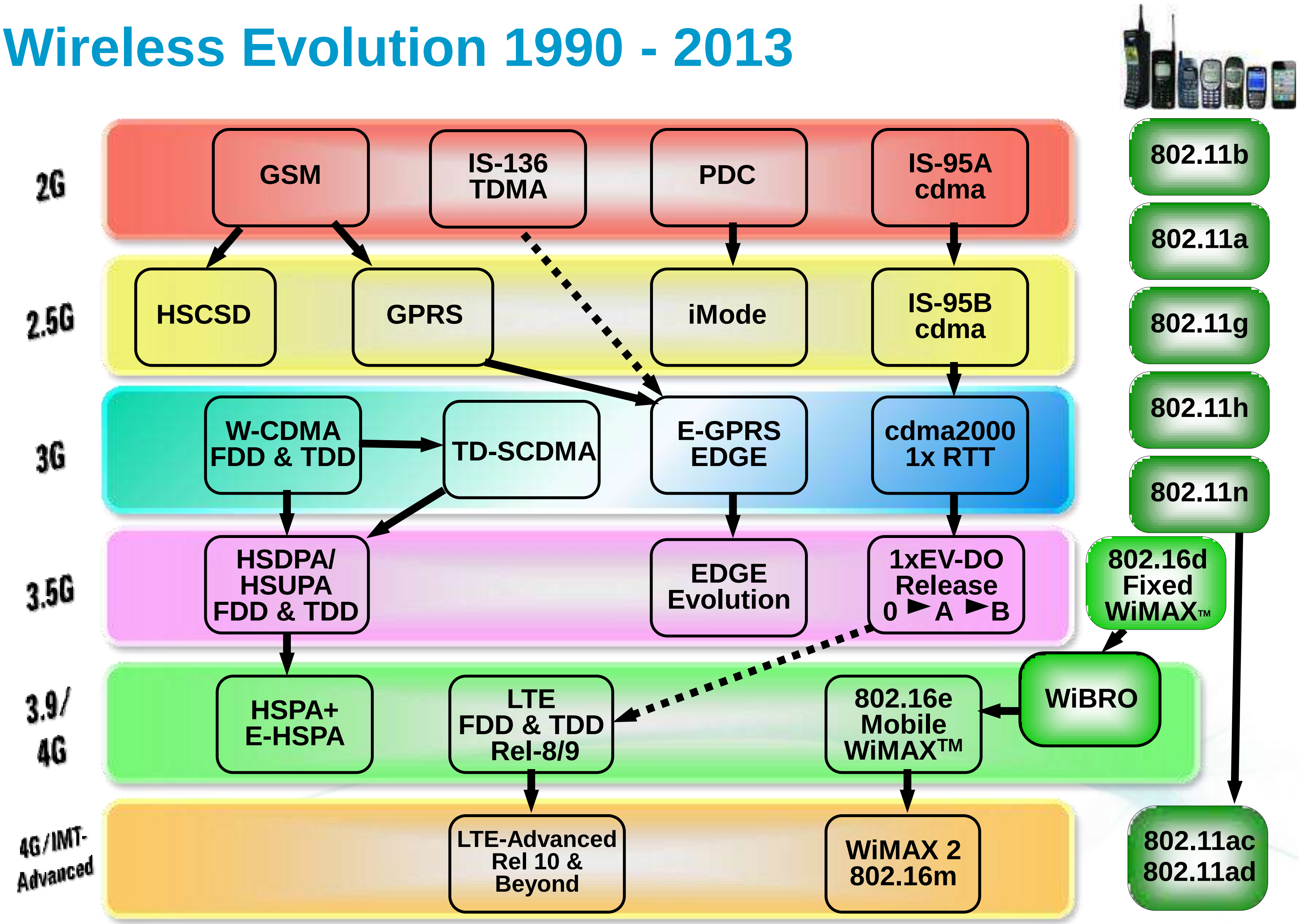
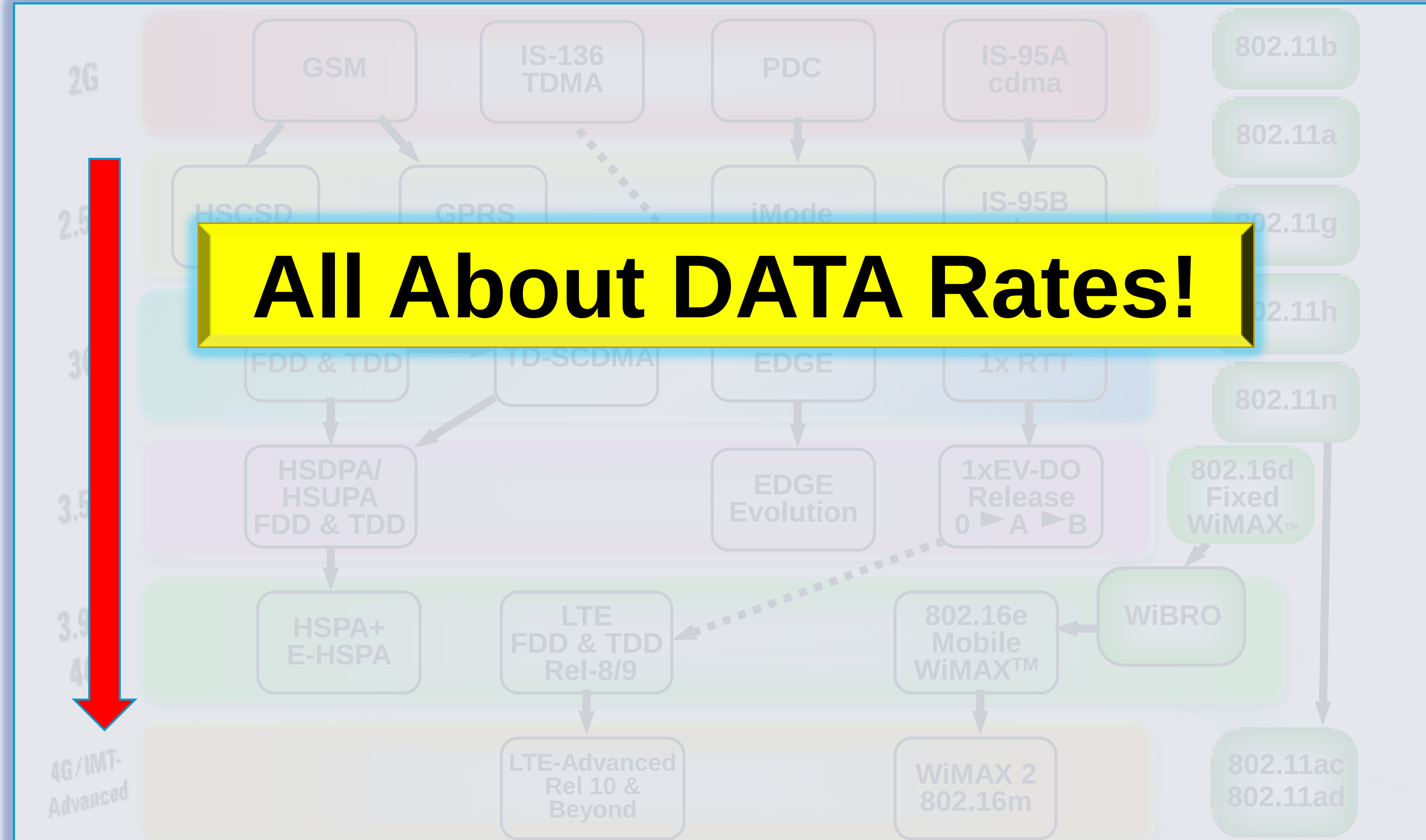
Wireless Evolution 1990 - 2013



Wireless Evolution 1990 - 2012



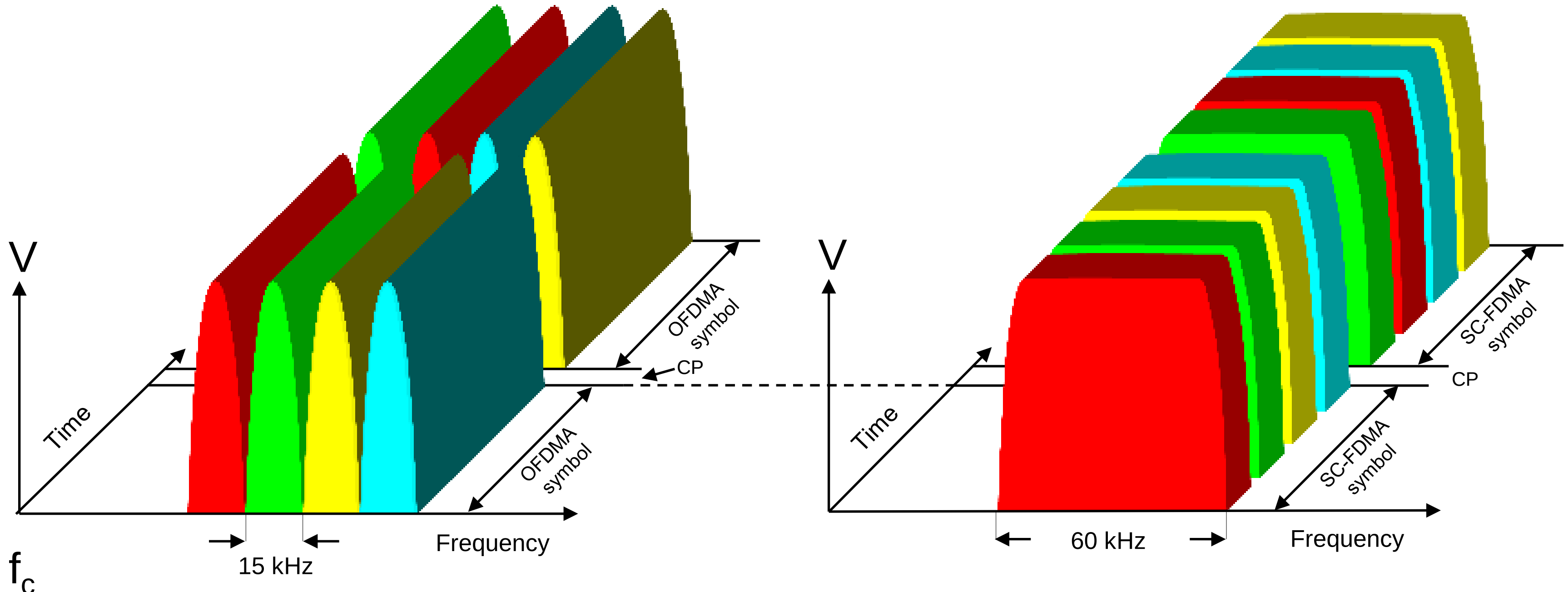
New Frequency Bands : Release 12

Three new FDD frequency bands will be defined:

Band/Usage	Uplink MHz	Downlink MHz	Width
TBD/ITU Region 2	1646.7 1651.7	1670 1675	5
TBD/Brazil	451 458	461 468	50
TBD/US WCS	2305 2315	2350 2360	10
Study Item	1980 2010	2170 2200	30

- Study item:
  - Currently widely allocated for satellite communications but terrestrial use now being considered, particularly for ITU Region 3 (Asia).
  - The potential for 110 MHz pairing with band 1 is also being considered.

Comparing OFDMA and SC-FDMA
PAR and constellation analysis at different BW

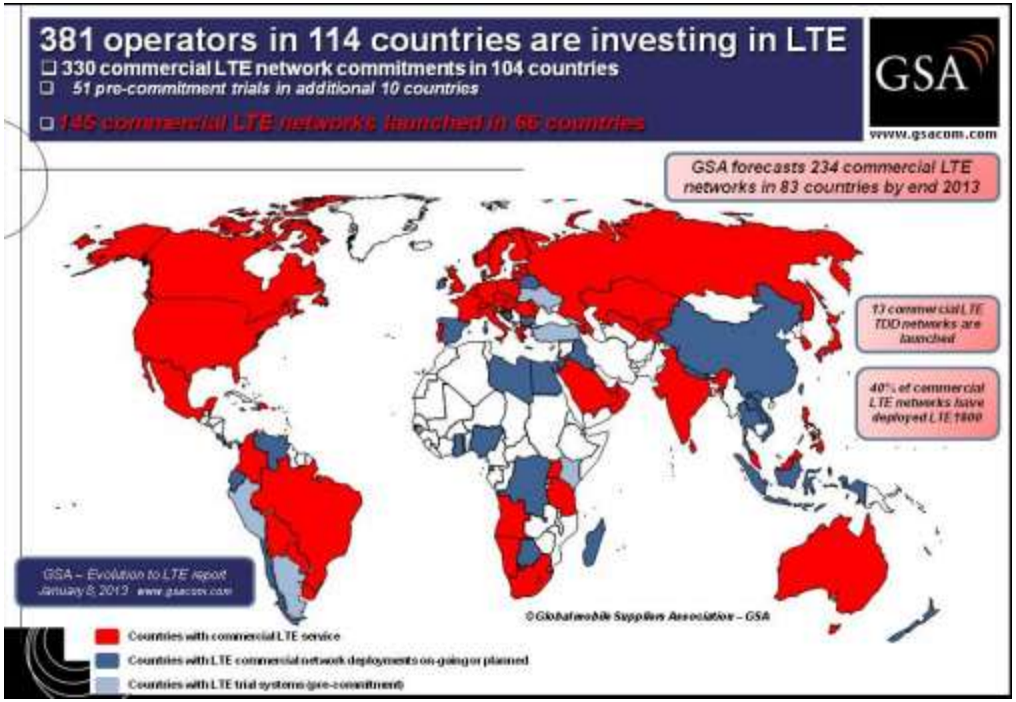


Transmission scheme	OFDMA		SC-FDMA	
Analysis bandwidth	15 kHz	Signal BW (M x 15 kHz)	15 kHz	Signal BW (M x 15 kHz)
Peak to average power ratio (PAR)	Same as data symbol	High PAR (Gaussian)	< data symbol (not meaningful)	Same as data symbol
Observable IQ constellation	Same as data symbol at 1/66.7 µs rate	Not meaningful (Gaussian)	< data symbol (not meaningful)	. Same as data symbol at M /66.7 µs rate

LTE is Growing Fast - Commercial Services in 2012

Luxembourg	Tango	01.10.12
Guam	DoCoMo Pacific	04.10.12
Tajikistan	Babilon-Mobile	06.10.12
Norway	Telenor	10.10.12
South Africa	Vodacom	10.10.12
USA	Alaska Communications	12.10.12
Mexico	Telefonica Movistar	15.10.12
Luxembourg	Orange	29.10.12
UK	EE	30.10.12
Uganda	Smile	Oct 2012
Belgium	Belgacom / Proximus	05.11.12
USA	Bluegrass Cellular	05.11.12
Antigua-Barb	Digicel	06.11.12
Mexico	Telcel	06.11.12
Italy	Vodafone	06.11.12
Italy	TIM	07.11.12
Montenegro	Telenor	08.11.12
Greece	Cosmote	16.11.12
Moldova	Moldcell	16.11.12
USA	Strata Networks	19.11.12
Moldova	Orange Moldova	20.11.12
Romania	Vodafone	20.11.12
Kuwait	Zain	21.11.12
France	Orange	22.11.12
USA	Shentel	23.11.12
Estonia	Tele2	27.11.12
France	SFR	28.11.12
Switzerland	Swisscom	29.11.12
South Africa	MTN	01.12.12
Romania	Orange	12.12.12
Brazil	Claro	13.12.12
Angola	Unitel	16.12.12
Bolivia	Entel Movil	16.12.12
Greece	Vodafone	17.12.12
Puerto Rico	Sprint Nextel	18.12.12
Kazakhstan	Altel	25.12.12
Sri Lanka	Dialog Axiata (LTE TDD)	30.12.12
Sri Lanka	Mobitel	31.12.12
Paraguay	Vox	Dec 2012
Malaysia	Maxis	01.01.13

Q4 2012

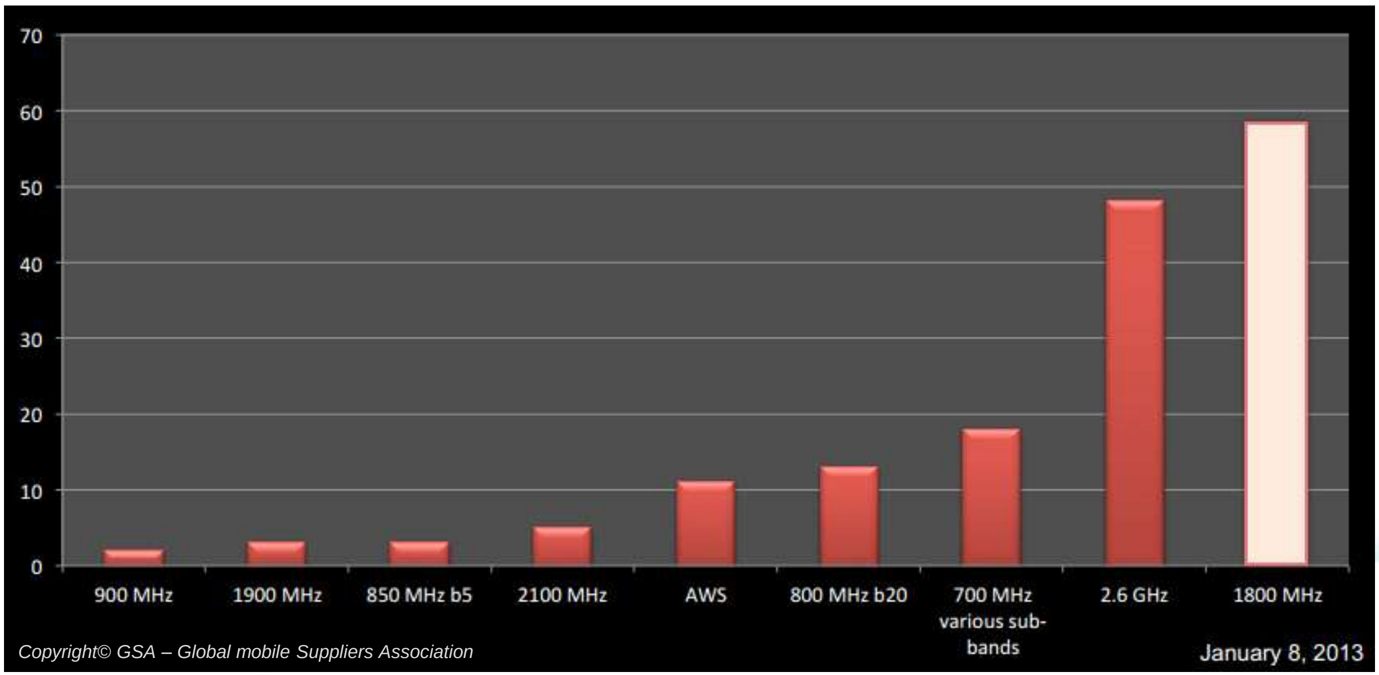


- **97** networks in 2012, **145** total
- **234** total deployments by end 2013

Source: Global mobile Suppliers Association

LTE Deployment Frequency Bands

LTE1800 most widely used band
- – 40% of commercial networks

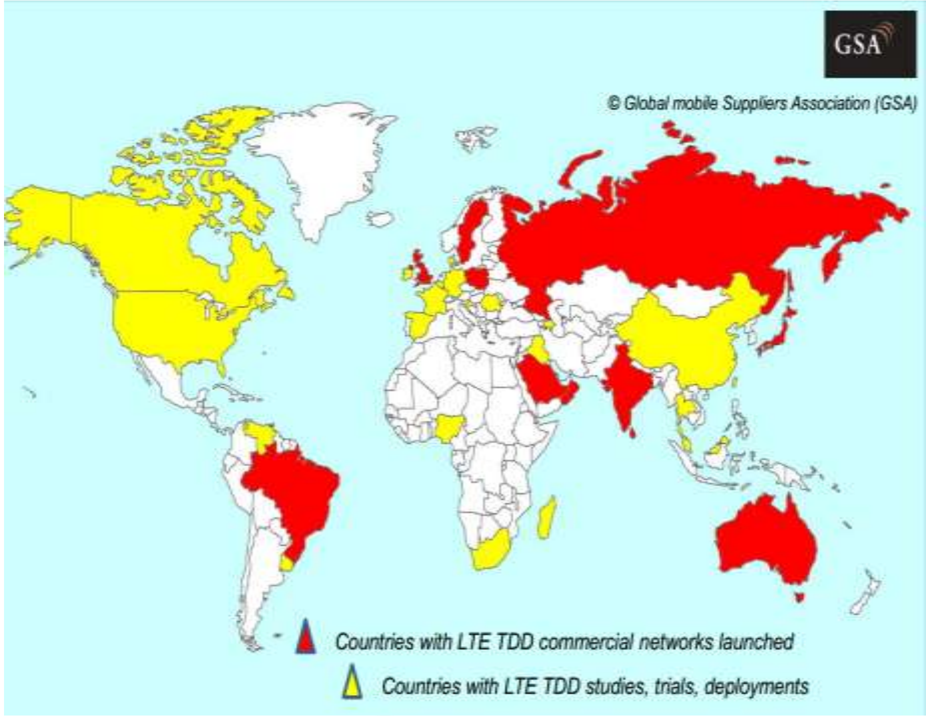


Country	Operator	Remarks
Angola	Movicel	LTE1800
Australia	Optus	LTE1800
Australia	Telstra	LTE1800
Azerbaijan	Azercell	LTE1800
Belgium	Proximus	LTE1800
Croatia	T-Hrvatski	LTE1800
Croatia	VIPNet	LTE1800
Czech Republic	Telefonica O2	LTE1800
Denmark	3	LTE1800/2600
Denmark	Telia	LTE1800/2600
Dominican Republic	Orange Dominicana	LTE1800
Estonia	EMT	LTE1800/2600
Estonia	Tele2	LTE1800/2600
Finland	DNA	LTE1800/2600
Finland	Elisa	LTE1800/2600
Finland	TeliaSonera	LTE1800/2600
Germany	Deutsche Telekom	LTE1800/2600/800
Greece	Cosmote	LTE1800
Greece	Vodafone	LTE1800
Hong Kong	CSL Limited	LTE1800/2600
Hong Kong	Smartone	LTE1800
Hungary	T Mobile	LTE1800
Hungary	Telenor	LTE1800
Italy	TIM	LTE1800
Italy	Vodafone	LTE1800
Japan	eAccess	band 9 (within LTE1800)
Kazakhstan	Altel	LTE1800
Kuwait	Zain	LTE1800
Latvia	LMT	LTE1800
Lithuania	Omnitel	LTE1800
Luxembourg	Orange	LTE1800
Luxembourg	Tango	LTE1800
Mauritius	Emtel	LTE1800
Mauritius	Orange	LTE1800
Namibia	MTC	LTE1800
Oman	Omantel	LTE1800 + TDD band 40
Philippines	Globe	LTE1800
Philippines	Smart	LTE850/1800/2100
Poland	Mobyland/CenterNet	LTE1800
Portugal	Optimus	LTE800/1800/2600
Romania	Orange	LTE1800
Romania	Vodafone	LTE1800
Saudi Arabia	Zain	LTE1800
Singapore	M1	LTE1800/2600
Singapore	SingTel	LTE1800/2600
Singapore	StarHub	LTE1800
Slovak Republic	Telefonica O2	LTE1800
Slovenia	Si.mobil	LTE1800
South Africa	MTN	LTE1800
South Africa	Vodacom	LTE1800
South Korea	KT	LTE1800
South Korea	SK Telecom	LTE850/1800
Sri Lanka	Mobitel	LTE1800
Switzerland	Swisscom	LTE1800/2600/800
Tajikistan	Babilon-Mobile	LTE1800/2100
UAE	Du	LTE1800
UAE	Etisalat	LTE1800/2600
UK	EE	LTE1800

Source: Global mobile Suppliers Association

LTE TDD (TD-LTE) Status

8 new network launches in 2012 – 23 other major plans



Thirteen commercial LTE TDD systems are launched

Country	Operator	Frequency	3GPP band
Hong Kong SAR	China Mobile HK (FDD & TDD)	2.3 GHz	Band 40
Poland	Aero2 (FDD and TDD)	2.6 GHz	Band 38
Saudi Arabia	Mobily	2.6 GHz	Band 38
Saudi Arabia	STC	2.3 GHz	Band 40
Brazil	Sky Brasil Servicos	2.6 GHz	Band 38
Japan	Softbank Mobile XGP/LTE TDD	2.6 GHz	Band 41
Australia	NBN Co	2.3 GHz	Band 40
India	Bharti Airtel	2.3 GHz	Band 40
Sweden	3 Sweden (FDD and TDD)	2.6 GHz	Band 38
UK	UK Broadband	3.5 GHz, 3.6 GHz	Bands 42, 43
Oman	Omantel (FDD and TDD)	2.3 GHz	Band 40
Russia	MTS (Moscow)	2.6 GHz	Band 38
Sri Lanka	Dialog Axiata	2.3 GHz	Band 40

Source: Global mobile Suppliers Association

Understanding 3GPP Release Structure

- The official scope of each 3GPP release is documented at: www.3gpp.org/releases

- Each release has dates for the three main development stages
  - Stage 1: Service description from a service-user's point of view.
  - Stage 2: Logical analysis, breaking the problem down into functional elements and the information flows amongst them across reference points between functional entities.
  - Stage 3: is the concrete implementation of the protocols appearing at physical interfaces between physical elements onto which the functional elements have been mapped.
- And some less formal stages
  - Stage 0: Used to describe 3GPP feasibility studies (study items)
  - Stage 4: Used to describe the development of test specifications

Tracking Work Items and Study Items

- A complete list of 3GPP work items back to Release 99 can be found at http://www.3gpp.org/ftp/Information/WORK_PLAN/

- Easy steps to find changed specifications for work items

1. www.3gpp.org/ftp/Specs/html-info/FeatureListFrameSet.htm
2. Click a Release (tabs at the top)
3. Click a Feature or Study Item (on the left)
4. See list of affected specifications:
   Click a unique ID # (UID) (on the left)