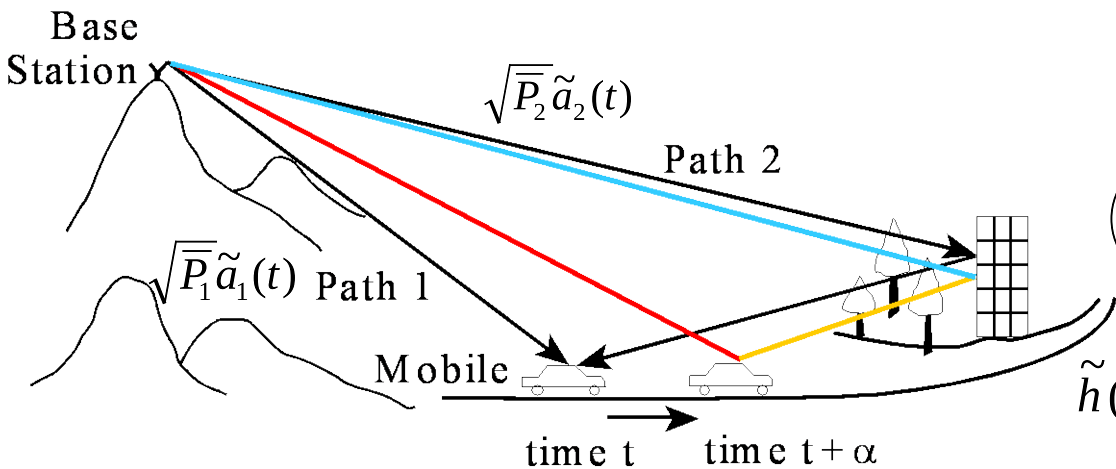
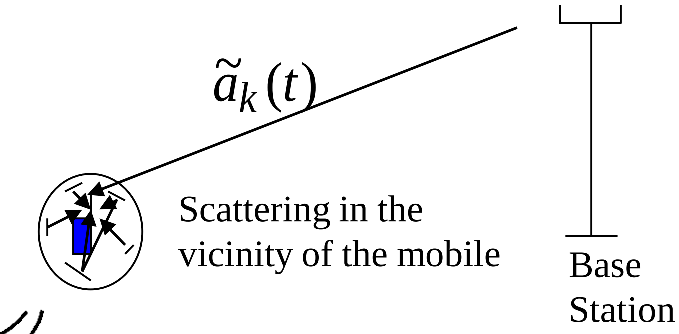
Fading & OFDM Implementation Details

EECS 562

Discrete Mulitpath Channel

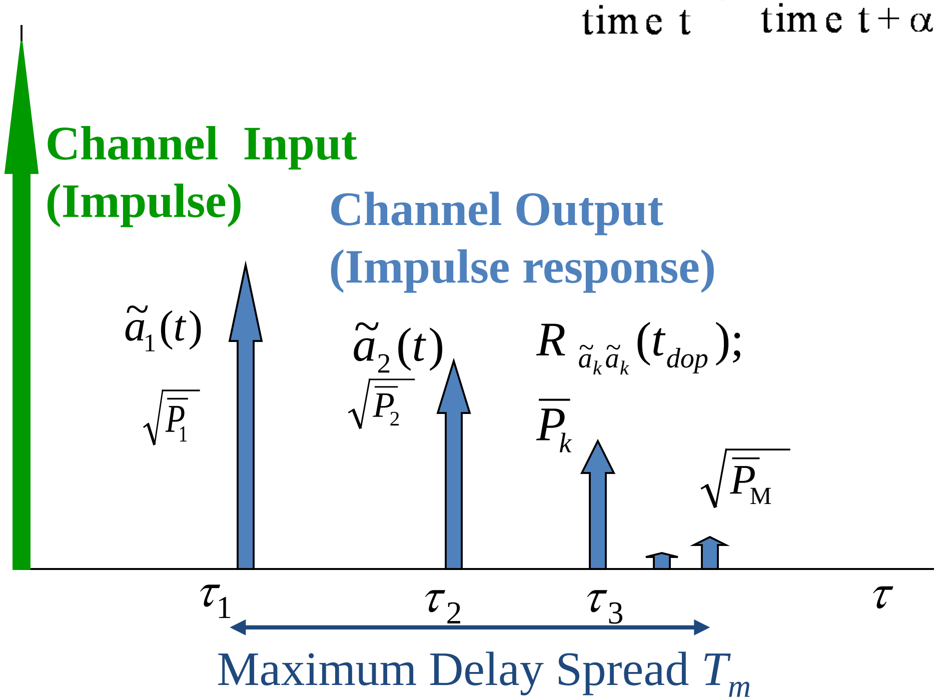




$$\tilde{h}(\tau,t)=\sum_{k=1}^{M}\sqrt{P_k}\,\tilde{a}_k(t)\delta(\tau-\tau_k);$$

$$\tilde{Y}(t)=\sum_{k=1}^{M}\sqrt{P_k}\,\tilde{a}_k(t)\tilde{X}(t-\tau_k)$$

$$\tilde{H}(f,t)=\sum_{k=1}^{M}\sqrt{P_k}\,\tilde{a}_k(t)\exp(-2\pi jf\tau_k)$$



$$R_{\tilde{h}\tilde{h}}(\tau_{delay},t_{dop})=\sum_{k=1}^{M}P_k R_{\tilde{a}_k\tilde{a}_k}(t_{dop})\delta(\tau_{delay}-\tau_k)$$

$$Note: E\{|\tilde{a}_k(t)|^2\}=1$$

$$If\ \ E\{|\tilde{X}(t)|^2\}=1,\ then\ E\{|\tilde{Y}(t)|^2\}=\sum_{k=1}^{M}P_k$$

From: Wireless Communication Systems K. Sam Shanmugan, 2011

Impact of Multipath Fading

- Multipath introduces ISI if the differential delay between the paths is > a fraction of symbol time
- If the differential delay is small compared to T_s then all the rays can be combined into one
- Fading introduces fluctuations in received signal power

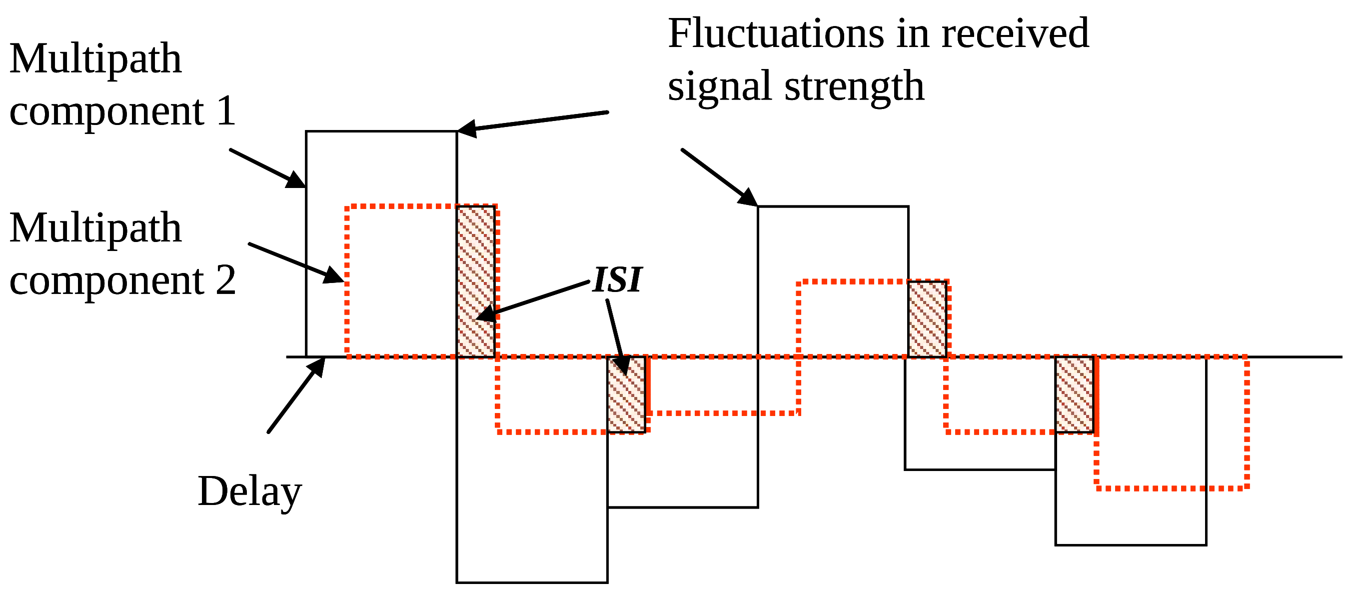


Figure Effects of multipath fading

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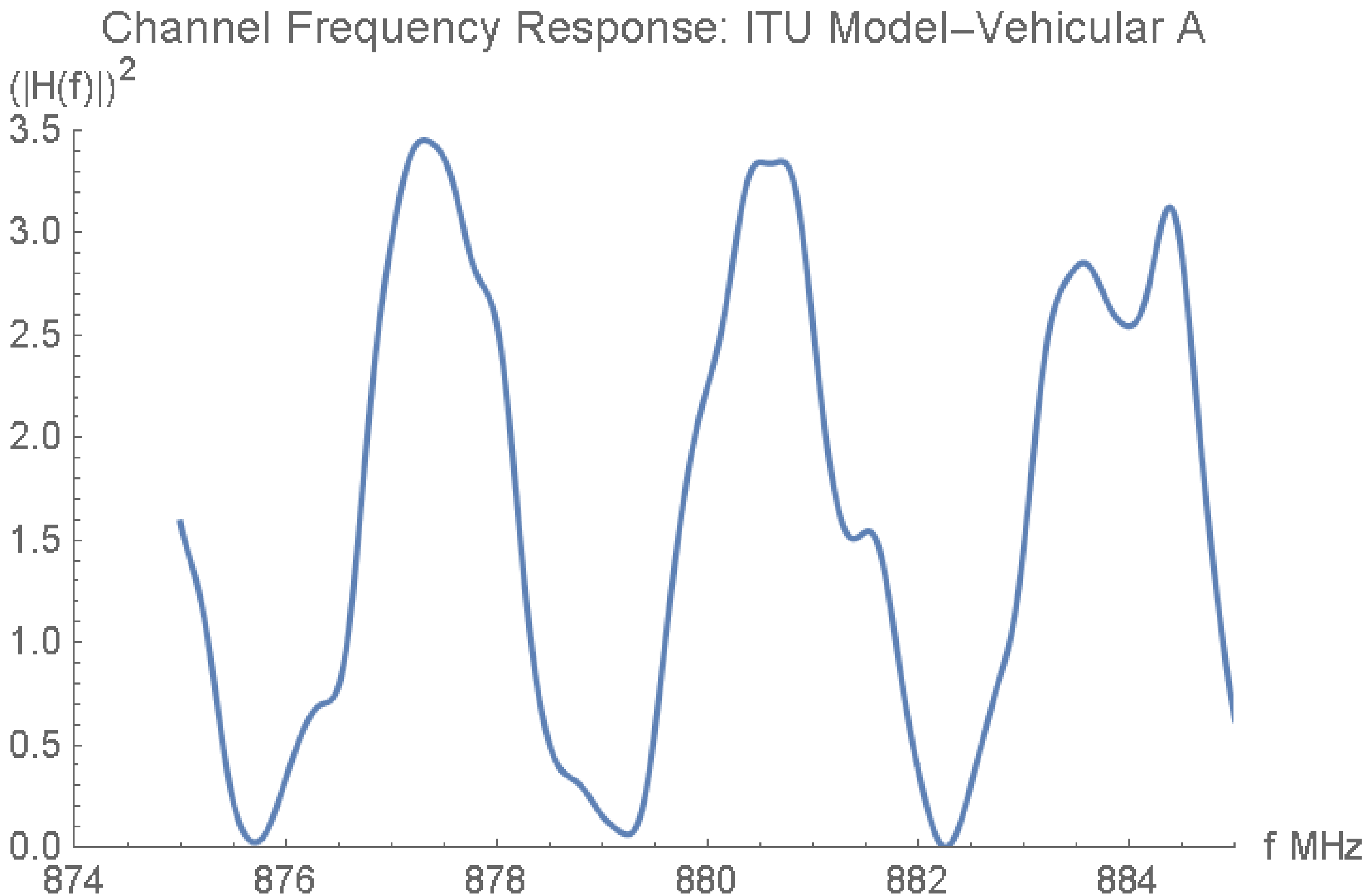
Model	Pedestrian A		Pedestrian B		Vehicular A		Vehicular B	
Tap	Delay (μs)	Power (dB)	Delay (μs)	Power (dB)	Delay (μs)	Power (dB)	Delay (μs)	Power (dB)
1	0	0	0	0	0	0	0	-2.5
2	.11	-9.7	.2	-.9	.31	-1.0	.30	0
3	.19	-19.2	.8	-4.9	.71	-9.0	8.9	-12.8
4	.41	-22.8	1.2	-8.0	1.09	-10.0	12.9	-0.0
5	-	-	2.3	-7.8	1.73	-15.0	17.1	-25.2
6	-	-	3.7	-23.9	2.51	-20.0	20	-16.0

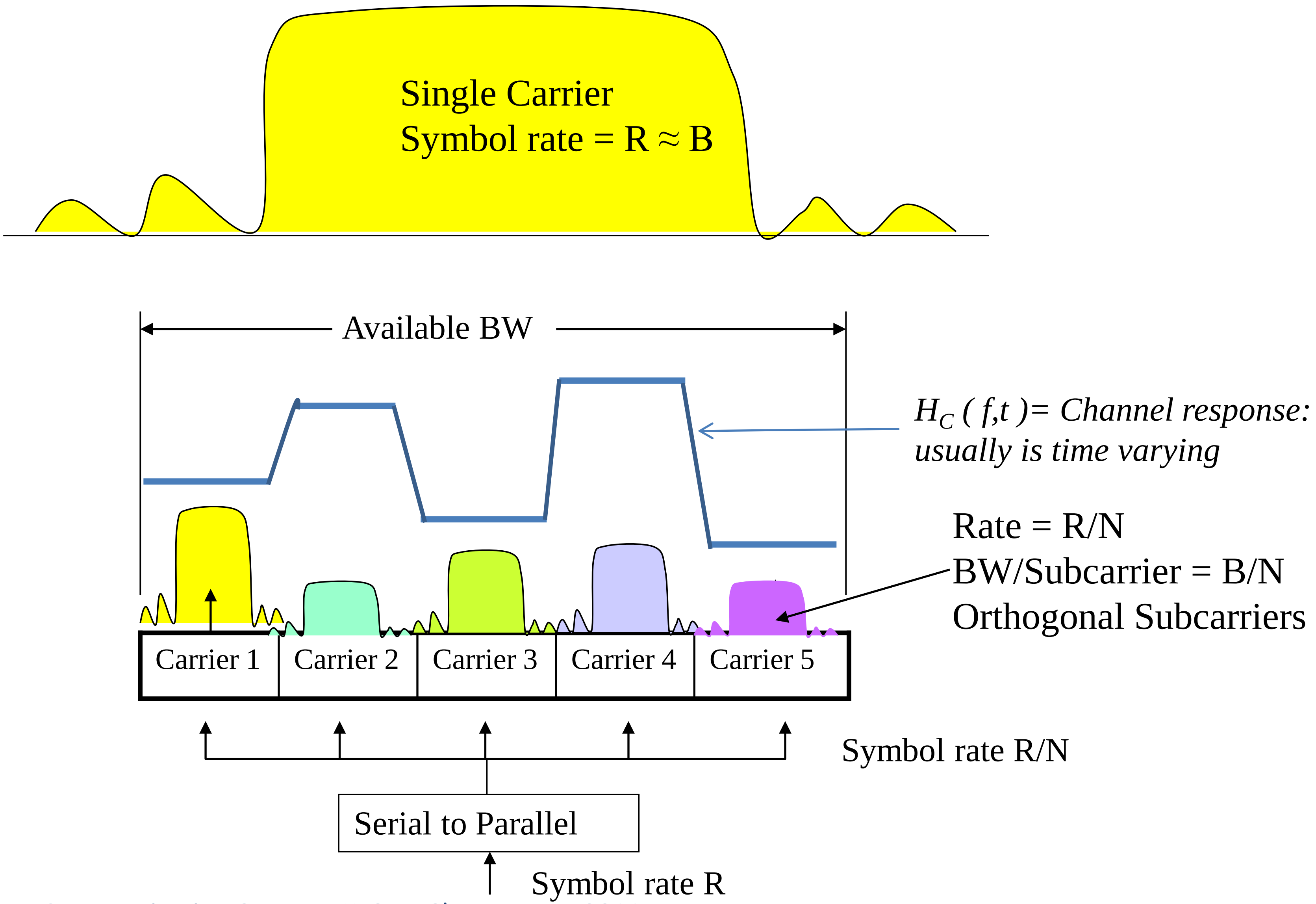
T. Sorensen, P. Mogensen, and F. Frederiksen, "Extension of the ITU channel models for wideband

(OFDM) systems," in *Proc. of IEEE Vehicular Technology Conference*, 2005.



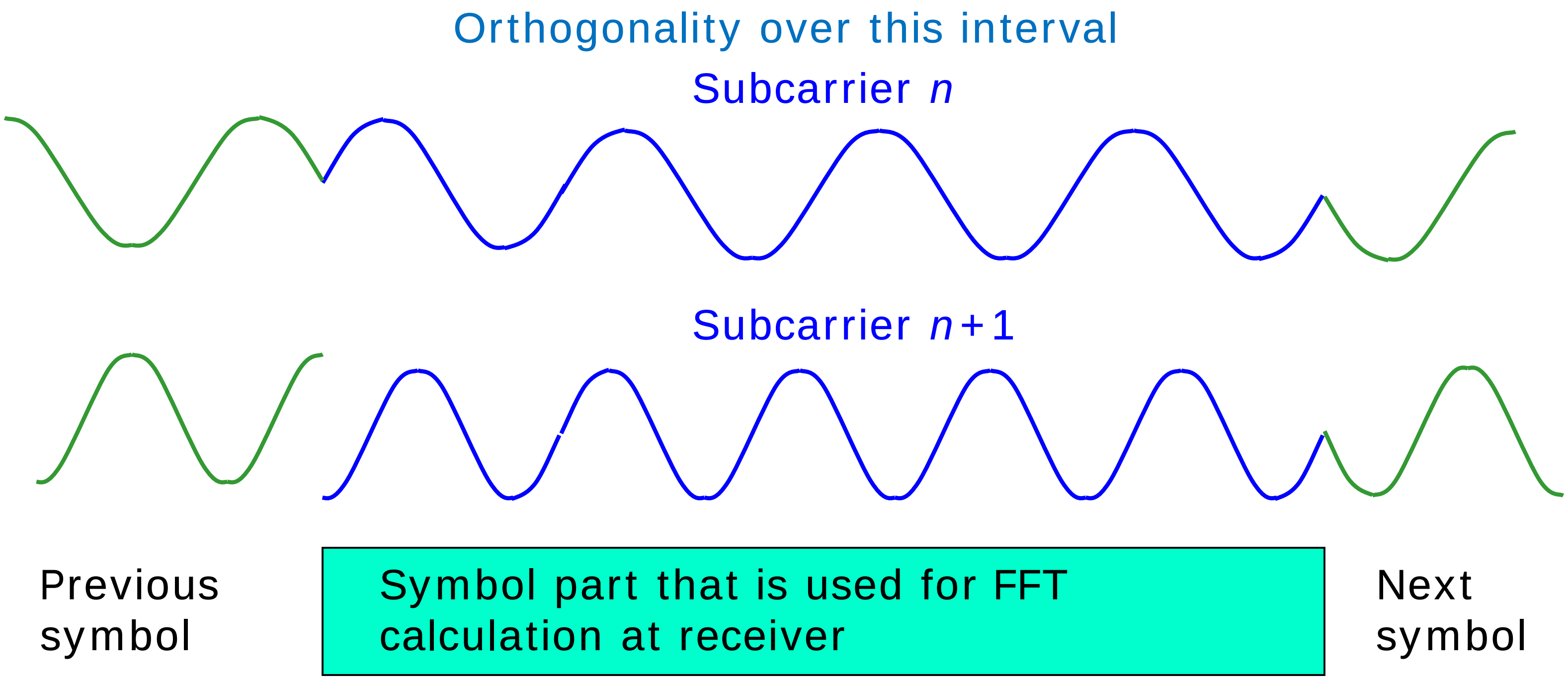
Channel Frequency Response: ITU Model–Vehicular A
(|H(f)|)^2
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
874
876
878
880
882
884
f MHz

Single Carrier versus Multi Carrier



From: Wireless Communication Systems K. Sam Shanmugan, 2011

Required condition for OFDM-Orthogonality

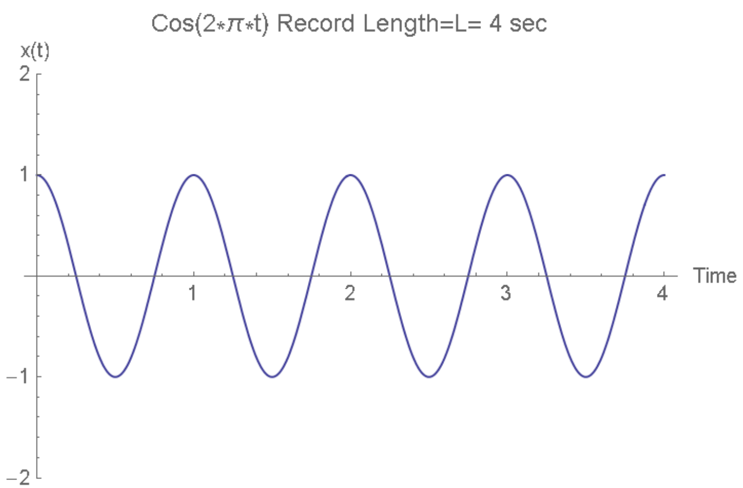


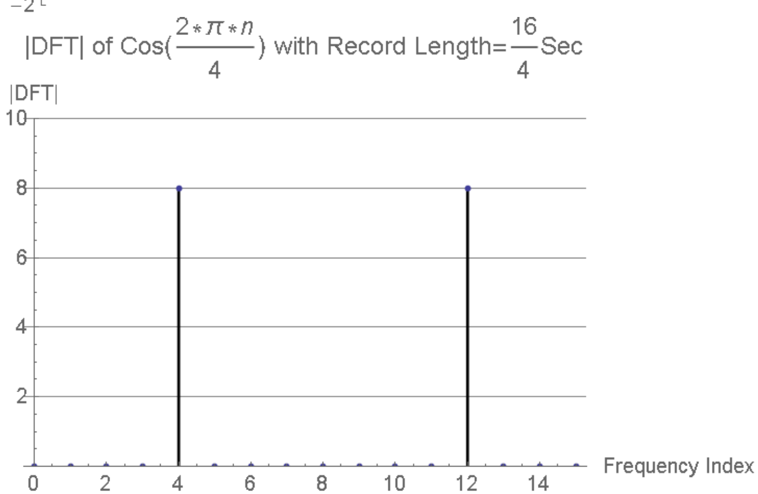
Note: using FFT at receiver → here no spectral leakage; Why??

Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

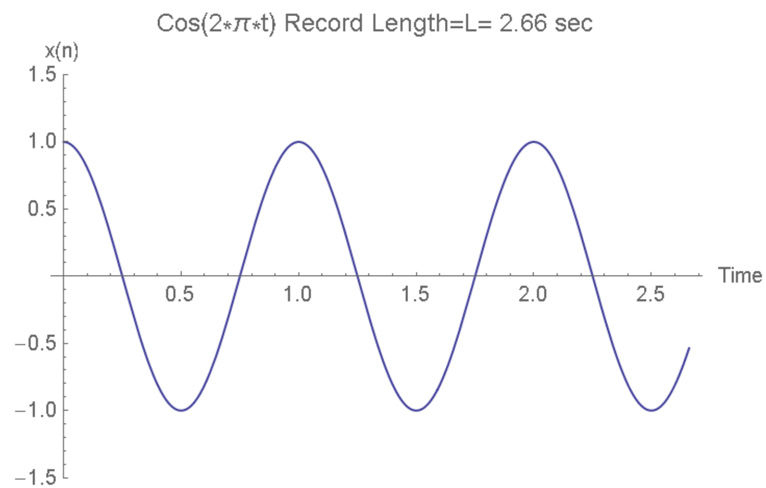
Review Spectral Leakage

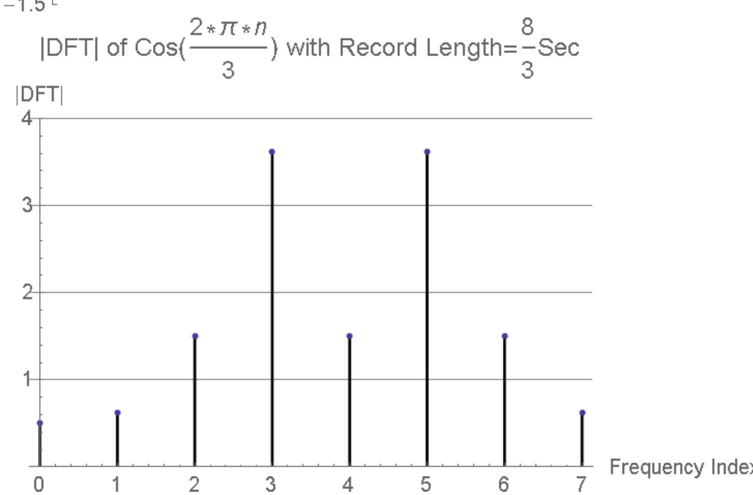
Without Spectral Leakage





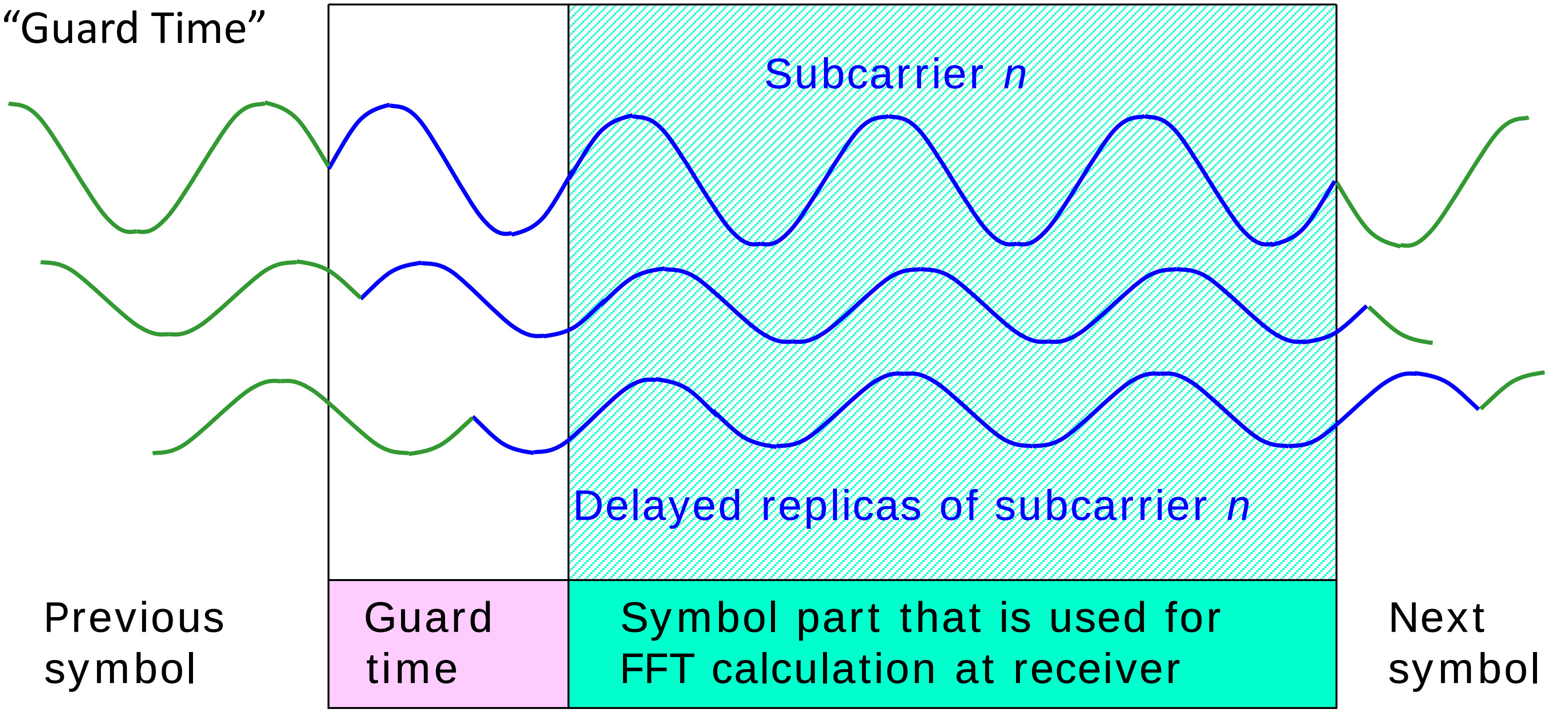
With Spectral Leakage





What happens with “Small” multipath

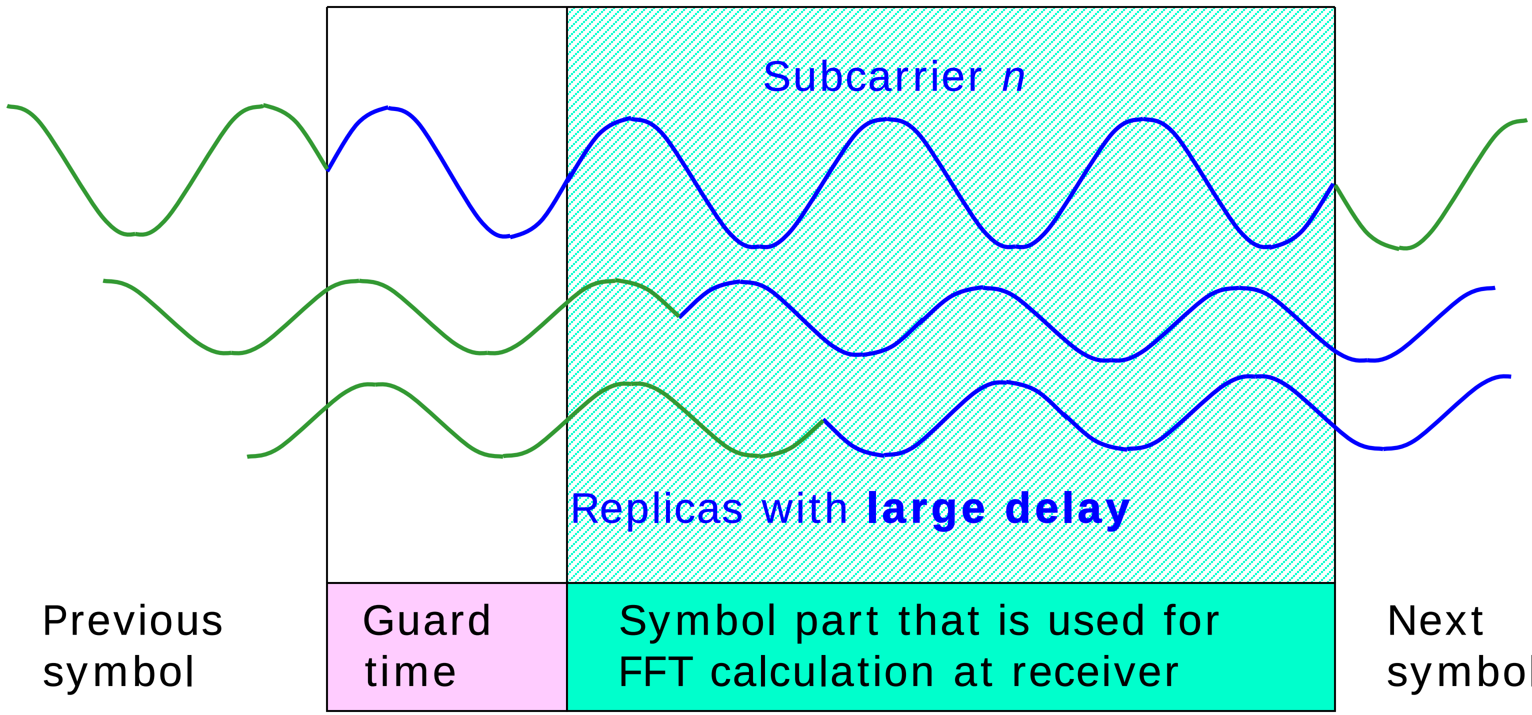
Introduce a “Guard Time”



Guard time not exceeded:
Delayed multipath replicas do not affect the orthogonality behavior of the subcarrier in frequency domain.
There are still spectral nulls at other subcarrier frequencies.

Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

What happens with “Large” multipath

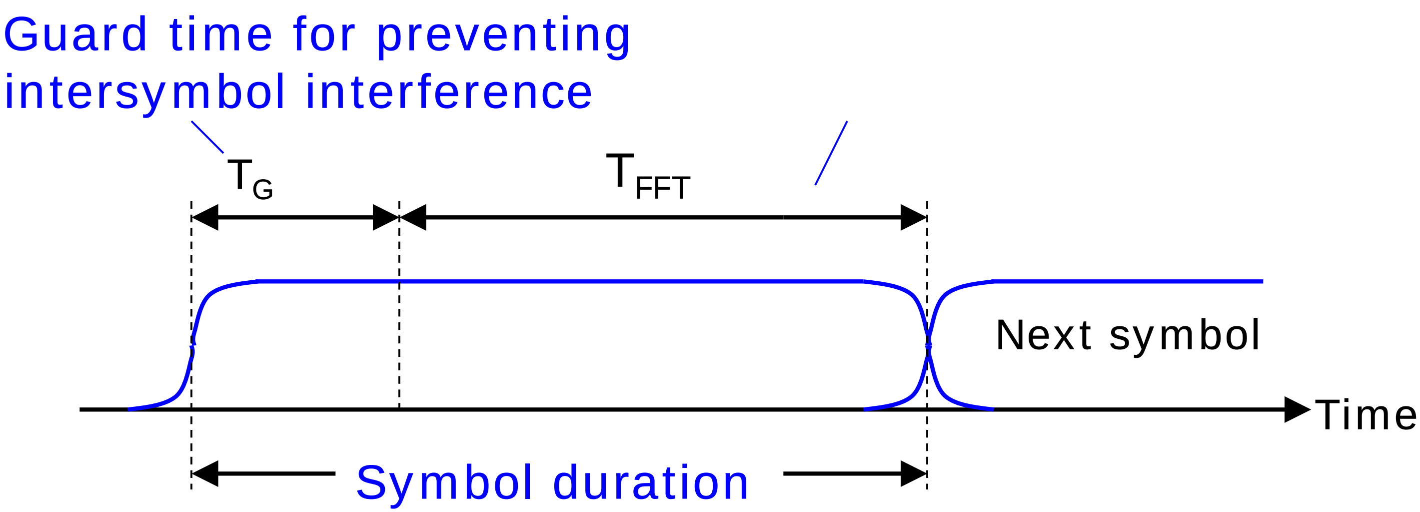


Guard time exceeded:

Delayed multipath replicas affect the orthogonality behavior of the subchannels in frequency domain.

There are no more spectral nulls at other subcarrier frequencies => this causes inter-carrier interference.

Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***



Example:

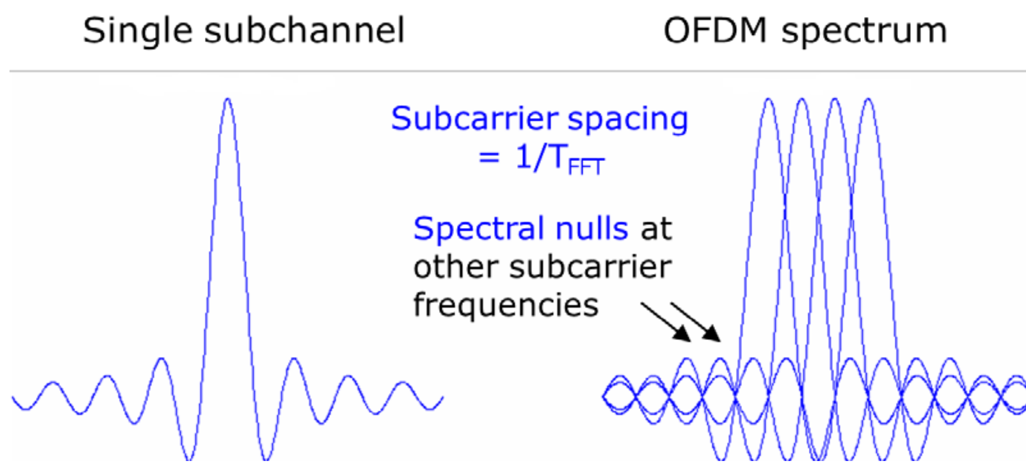
1) IEEE 802.11a&g:

   T_G = 0.8 us, TFFT = 3.2 us

2) Typical LTE paramters

   T_G = 4.7 us, TFFT = 1/15,000 = 66.7 us

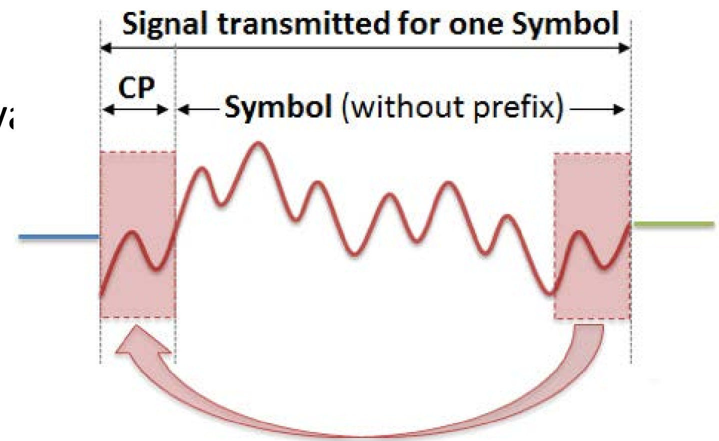
   Overhead = 4.7/(4.7+66.7) = ~6.6%



Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005****.ppt***

Cyclic Prefix-CP

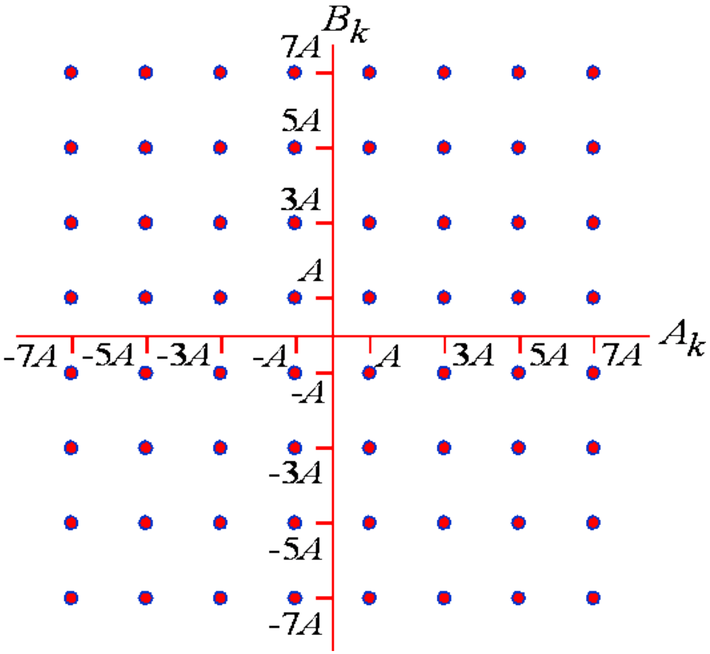
- The inter OFDM symbol interference can be eliminated by inserting a "guard time" of T_G sec or μ samples between OFDM blocks.
- The response due to the samples from the preceding block now falls within the guard interva and does not spill into the samples of the next symbol.
- The output of the channel corresponding to the samples inserted during the guard interval are discarded before the FFT is taken to recover the input symbols.
- While the samples inserted during the guard interval can be arbitrary, the common practice is to insert
  - Zeros,
  - A **"cyclic prefix (CP)"** in which of the last μ samples of a block are inserted as guard samples at the beginning of the block
- "cyclic prefix (CP)"
  - helps in channel estimation – known signal



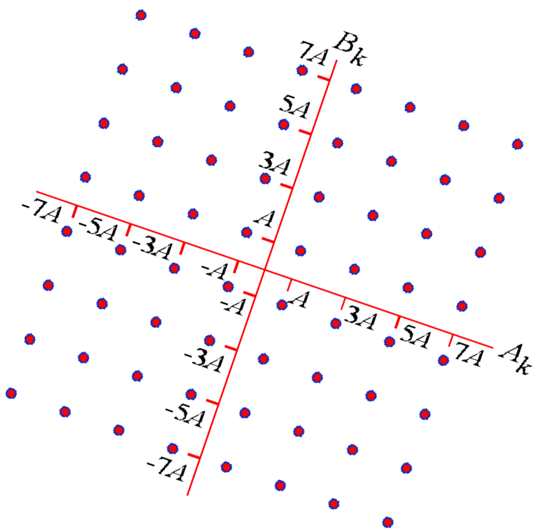
From: http://www.telecomhall.com/what-is-cp-cyclic-prefix-in-lte.aspx

Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

Correcting channel induced magnitude & phase scaling



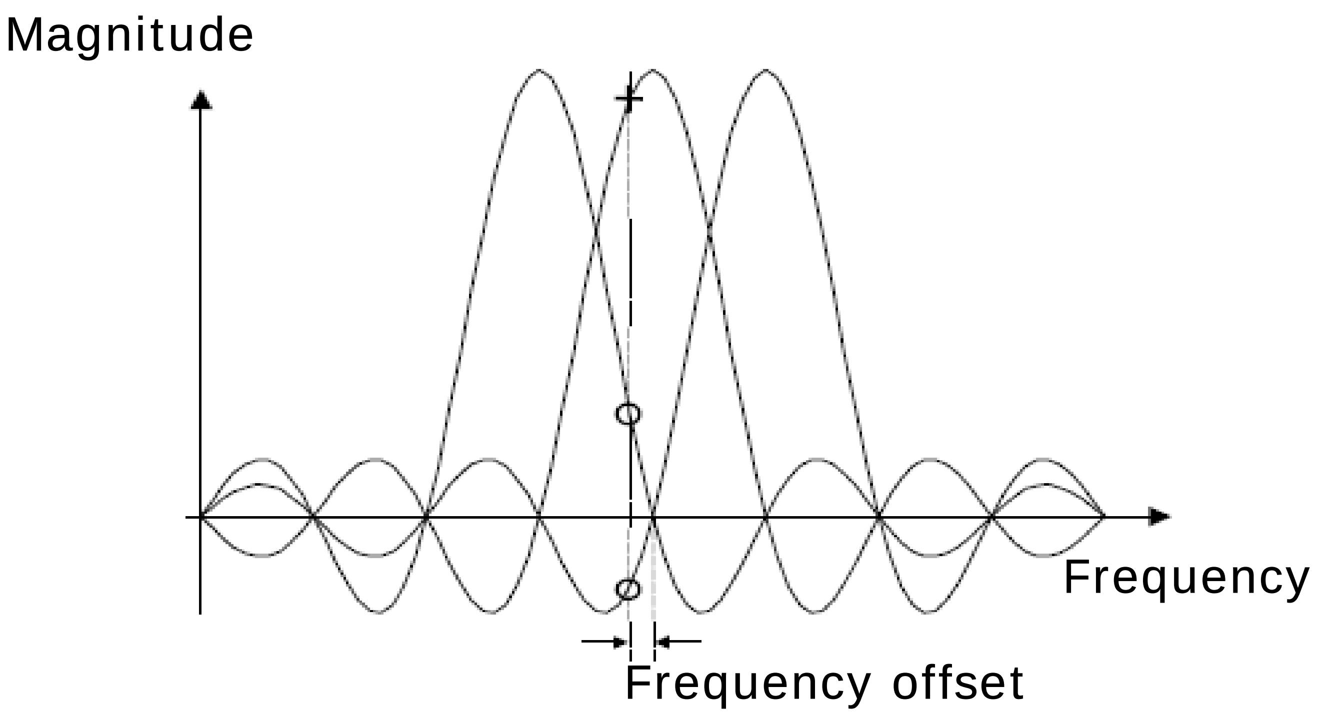
Transmitted 64 QAM Constellation



Received 64 QAM Constellation with only phase and amplitude offsets. No channel and no noise

Frequency offset at receiver

Frequency offset causes inter-carrier interference (ICI)

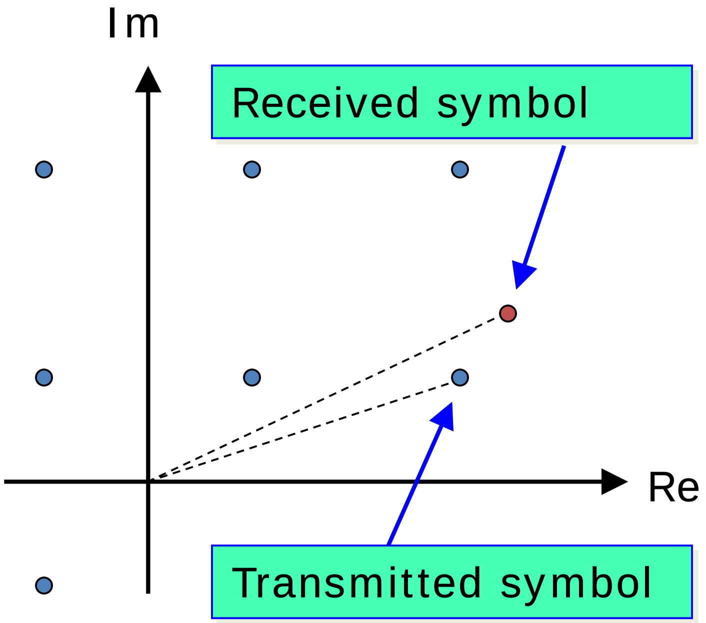


Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

Use of pilot subcarriers for amplitude and phase correction

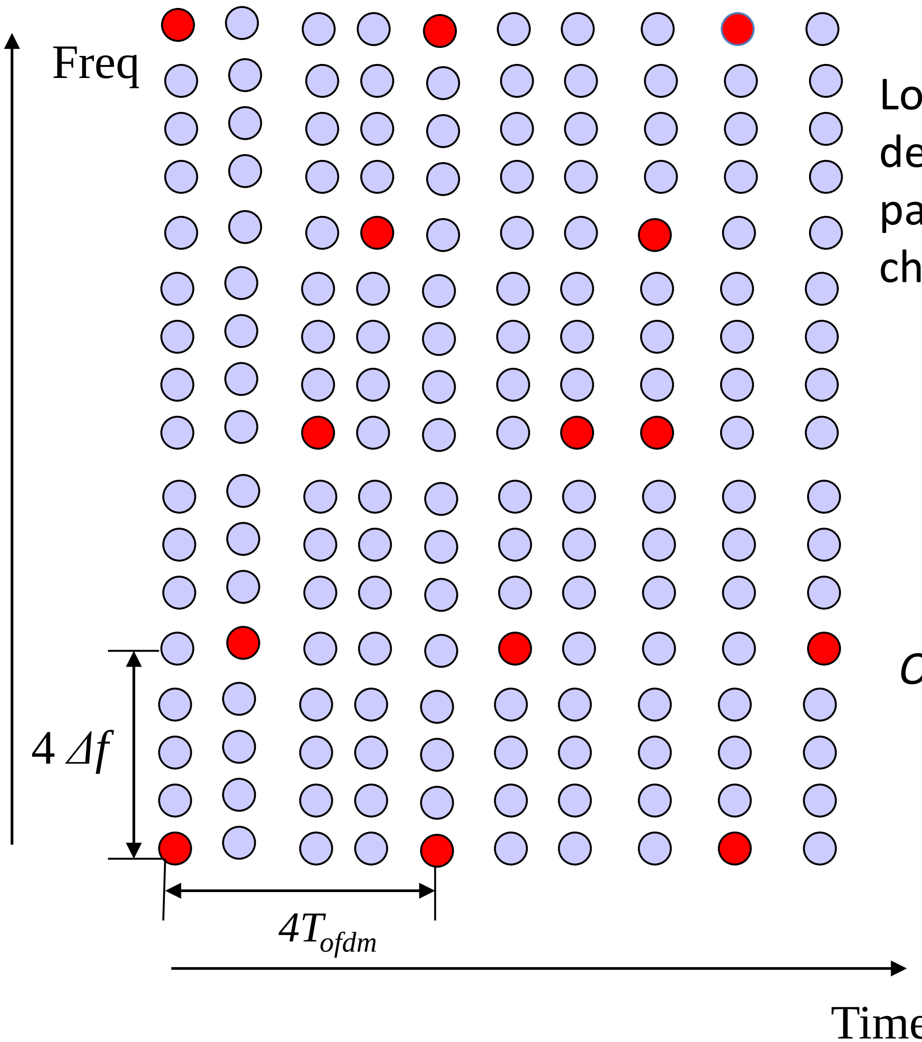
Pilot subcarriers contain signal values, amplitude, phase and frequency, that are known in the receiver.

These pilot signals are used in the receiver for correcting the magnitude (important in QAM) and phase shift offsets of the received symbols (see signal constellation example on the right).



Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

Insertion of Pilot Symbols

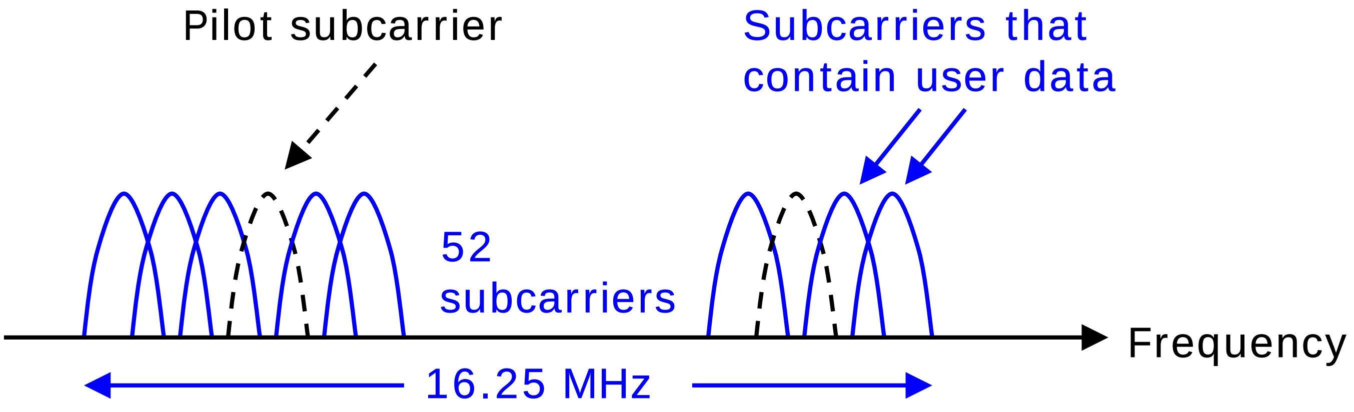


Location of pilot symbols depends upon system parameters and channel characteristics

● Pilot

OFDM Symbol Time= T_{ofdm}

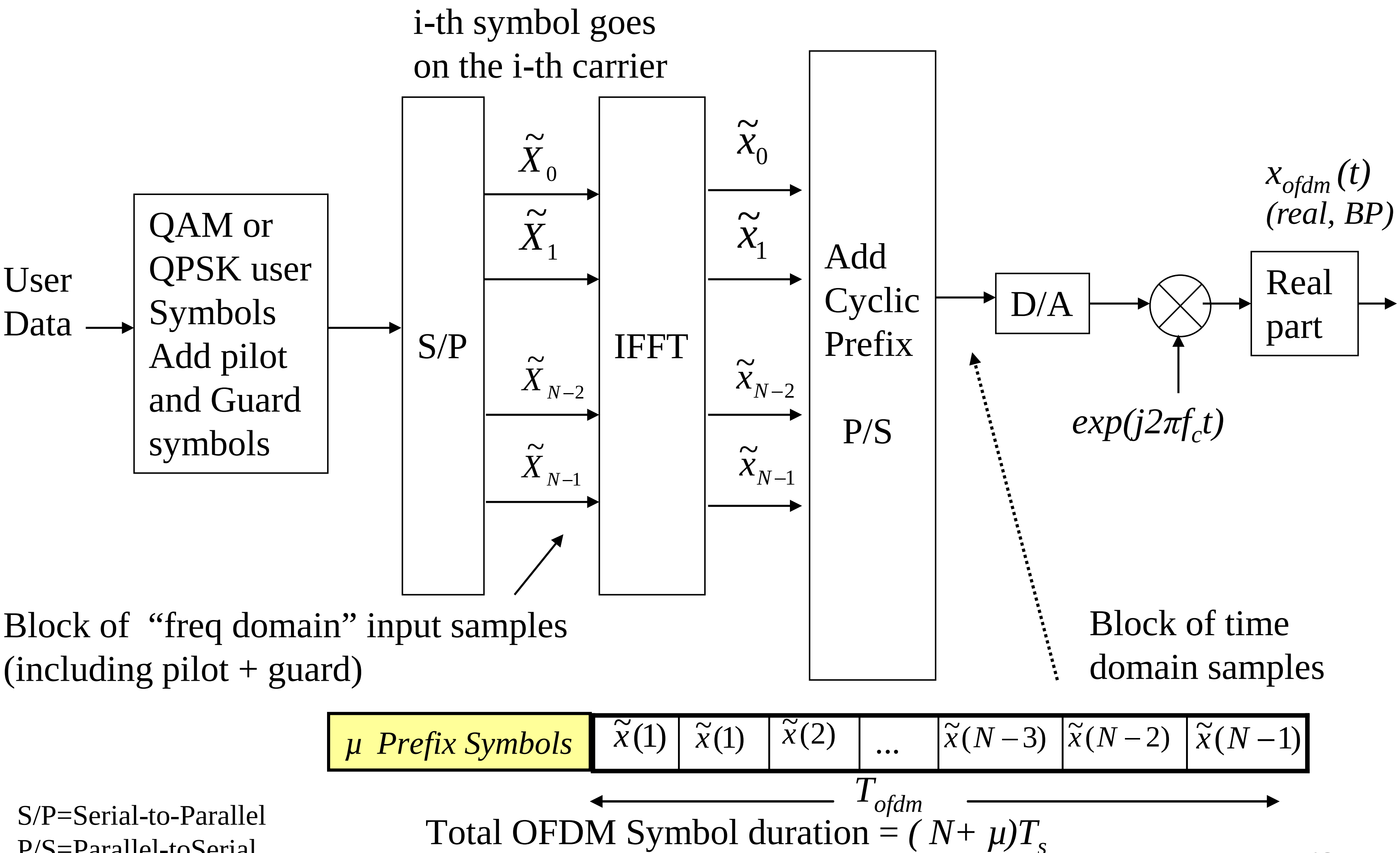
OFDM example: IEEE 802.11a&g (WLAN)



48 data subcarriers + 4 pilot subcarriers. There is a ”null” at the center carrier. Around each data subcarrier is centered a subchannel carrying a low bitrate data signal (low bitrate => no intersymbol interference).

Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

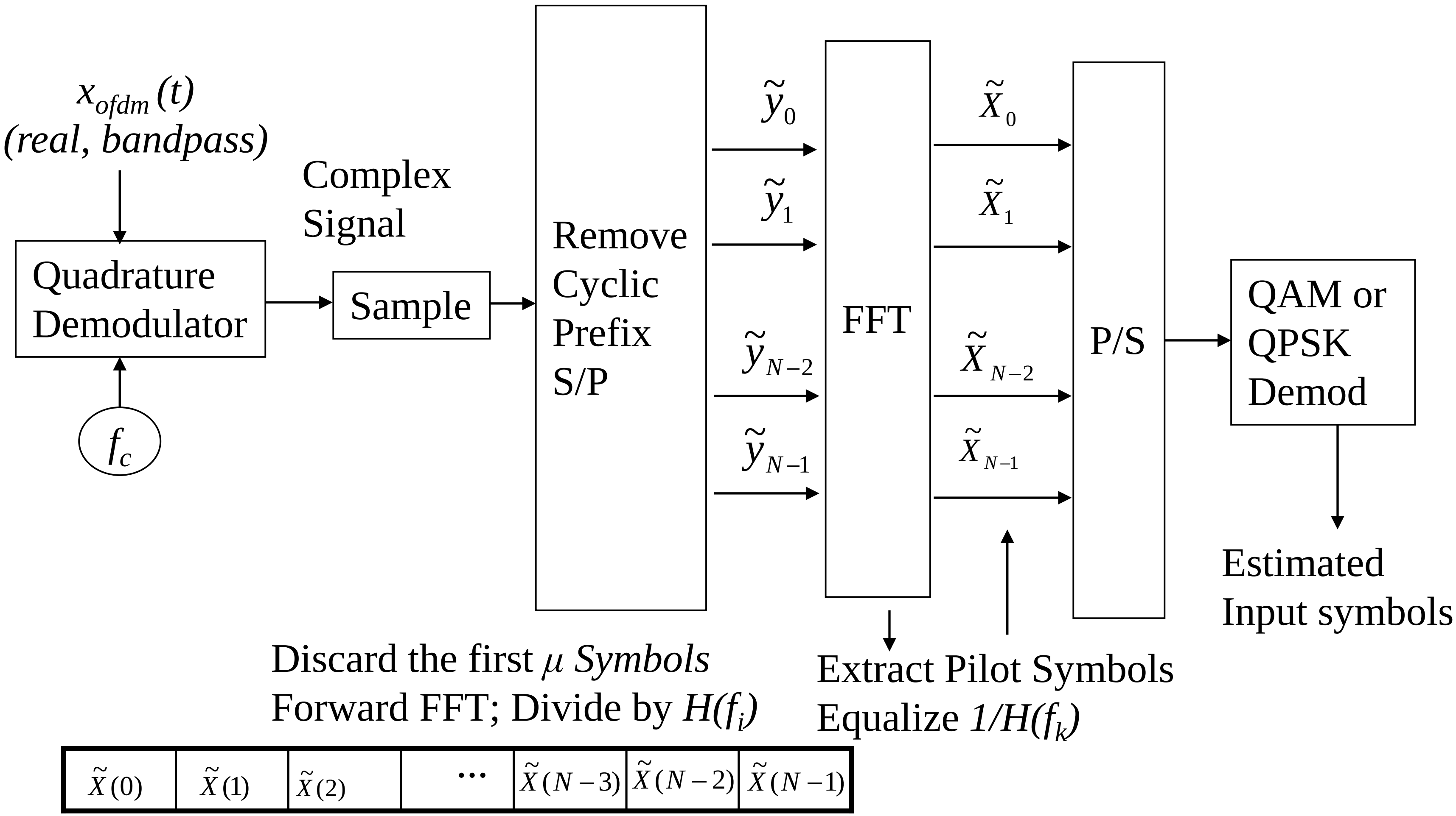
Implementation of OFDM Modulator and Demodulator with Cyclic Prefix: Modulator



S/P=Serial-to-Parallel
P/S=Parallel-toSerial

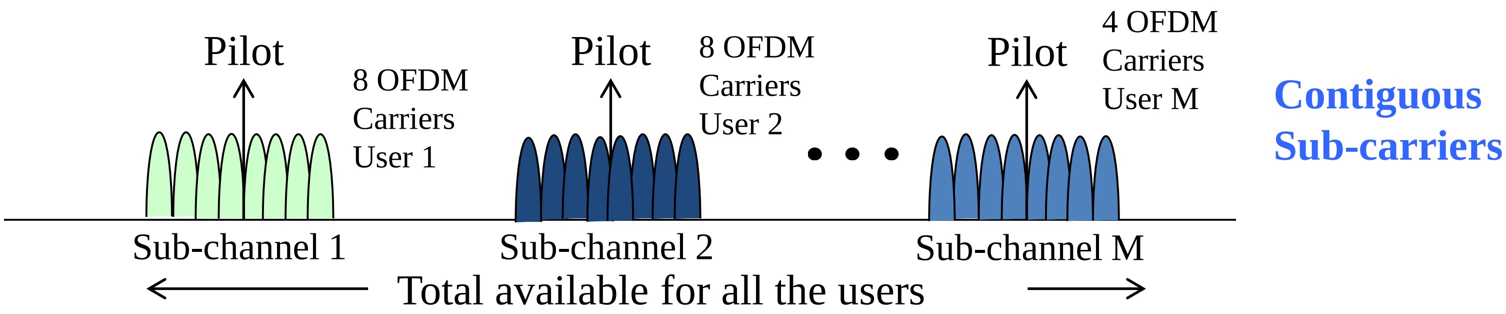
From: Wireless Communication Systems K. Sam Shanmugan, 2011

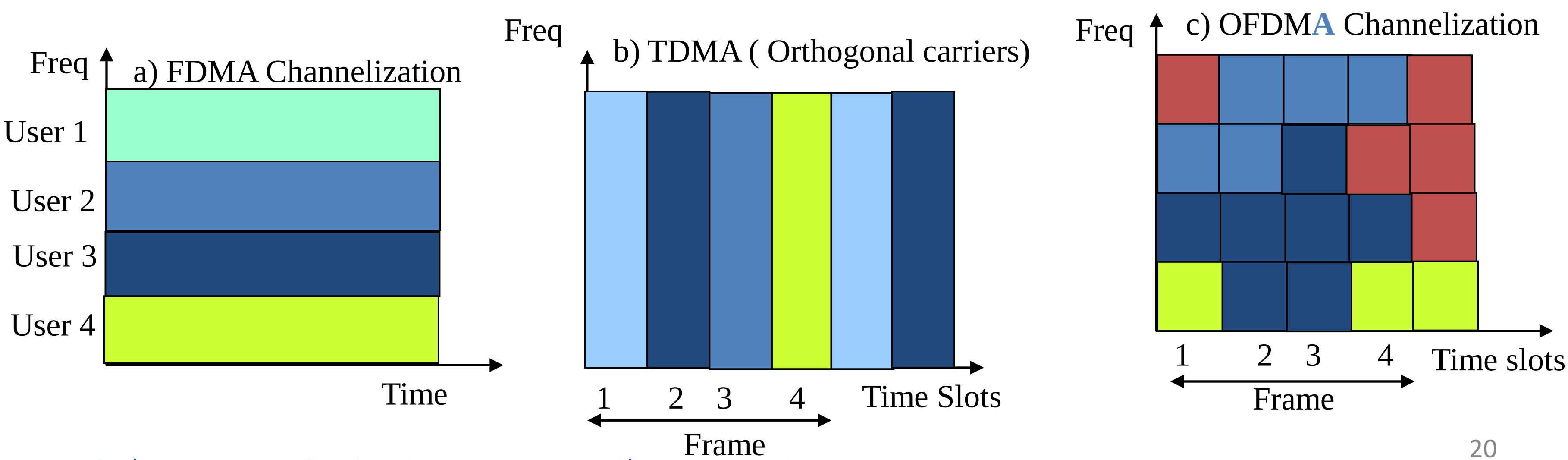
Implementation of OFDM Modulator and Demodulator with Cyclic Prefix : Demodulator



OFDM Multiple Access (OFDMA) –Down Link

- OFDM is a single user (Single "channel") systems
- FDMA assigns a fixed BW to each user on a dedicated basis
- OFDMA : Each user sub-channel occupies a subset of carriers (each sub-channel is assigned to a only one user at given time ; allocation may change over time)

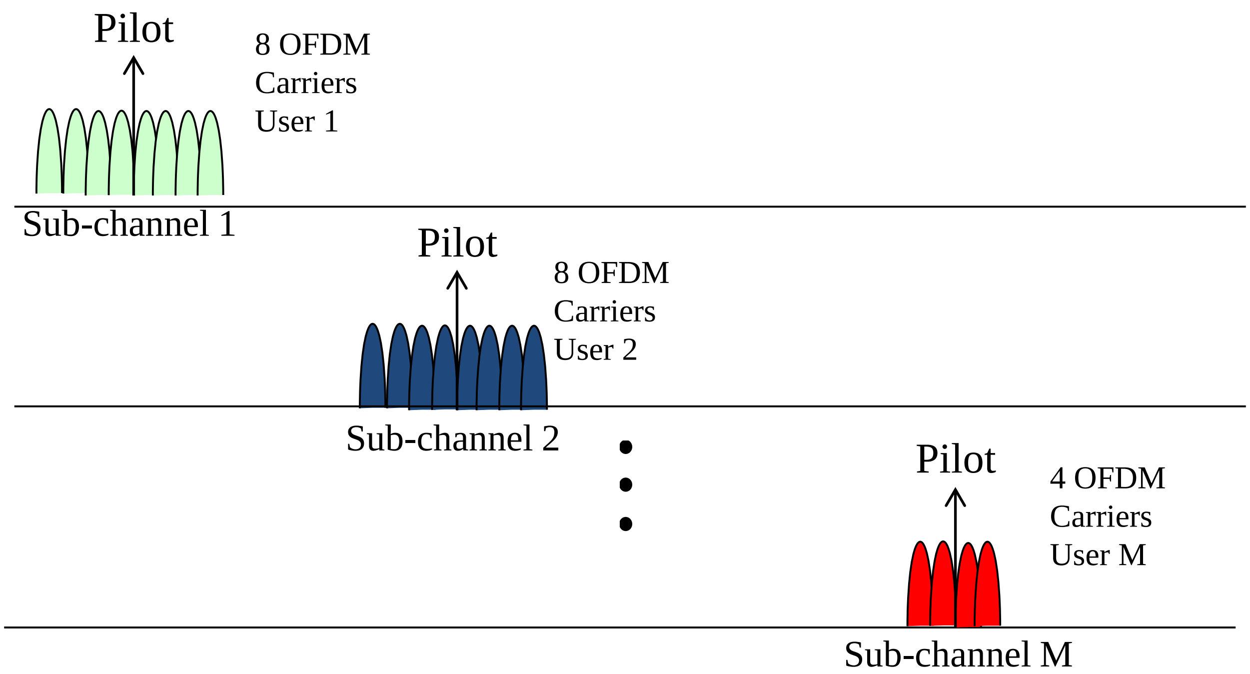




From: Wireless Communication Systems K. Sam Shanmugan, 2011

OFDM Multiple Access (OFDMA)

Uplink Sub-channel/sub-carrier assignment and time alignment



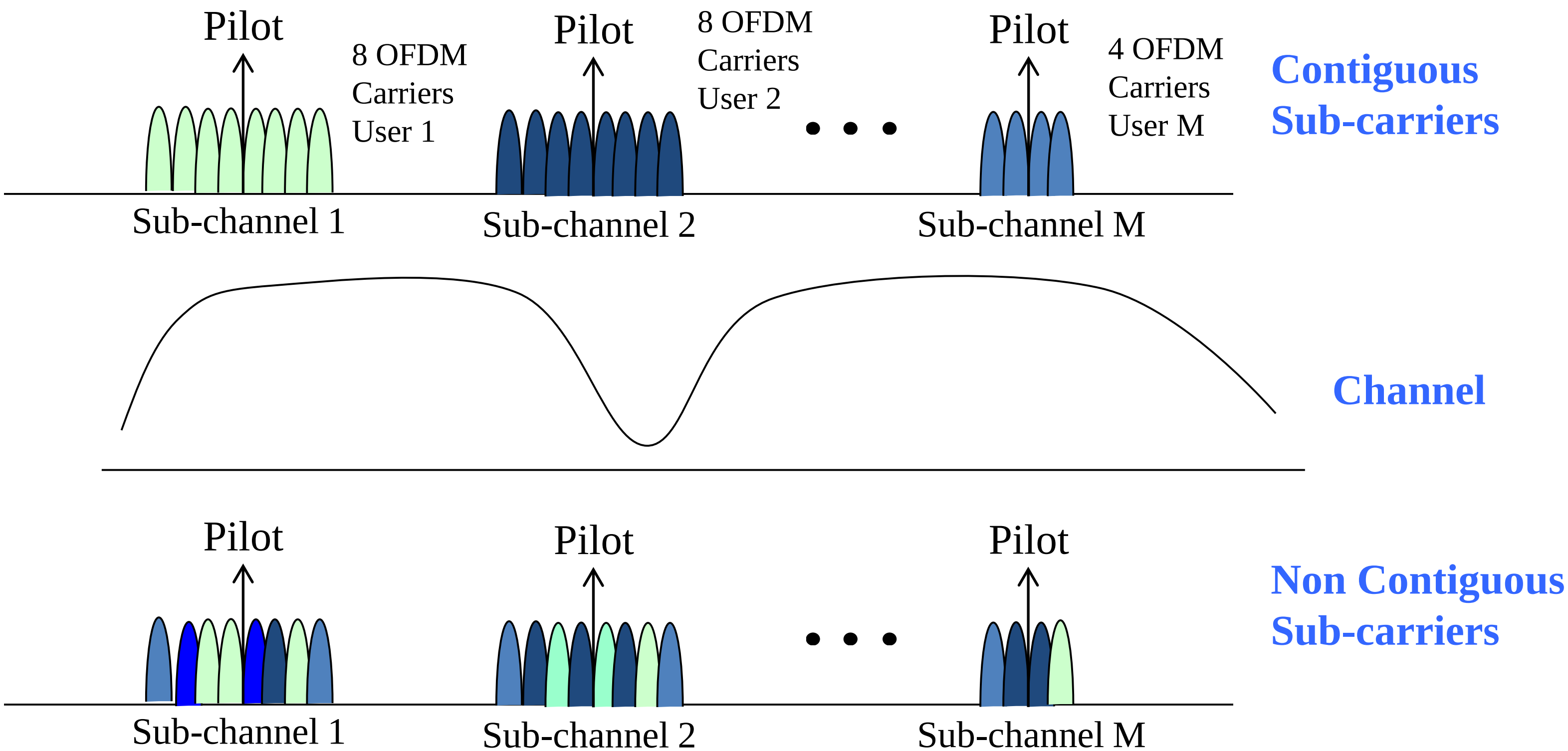
- In the uplink, each user occupies only a fraction of the total BW available

  (The DL signal occupies the “entire” BW)
- The handset (UE) can be anywhere within a cell and hence the transmission from each user arrived with a random time offset at the Base Station
- In order to maintain orthogonality, these transmissions have to be time aligned (similar to the requirements for a TDMA system)

Frame

From: Wireless Communication Systems K. Sam Shanmugan, 2011

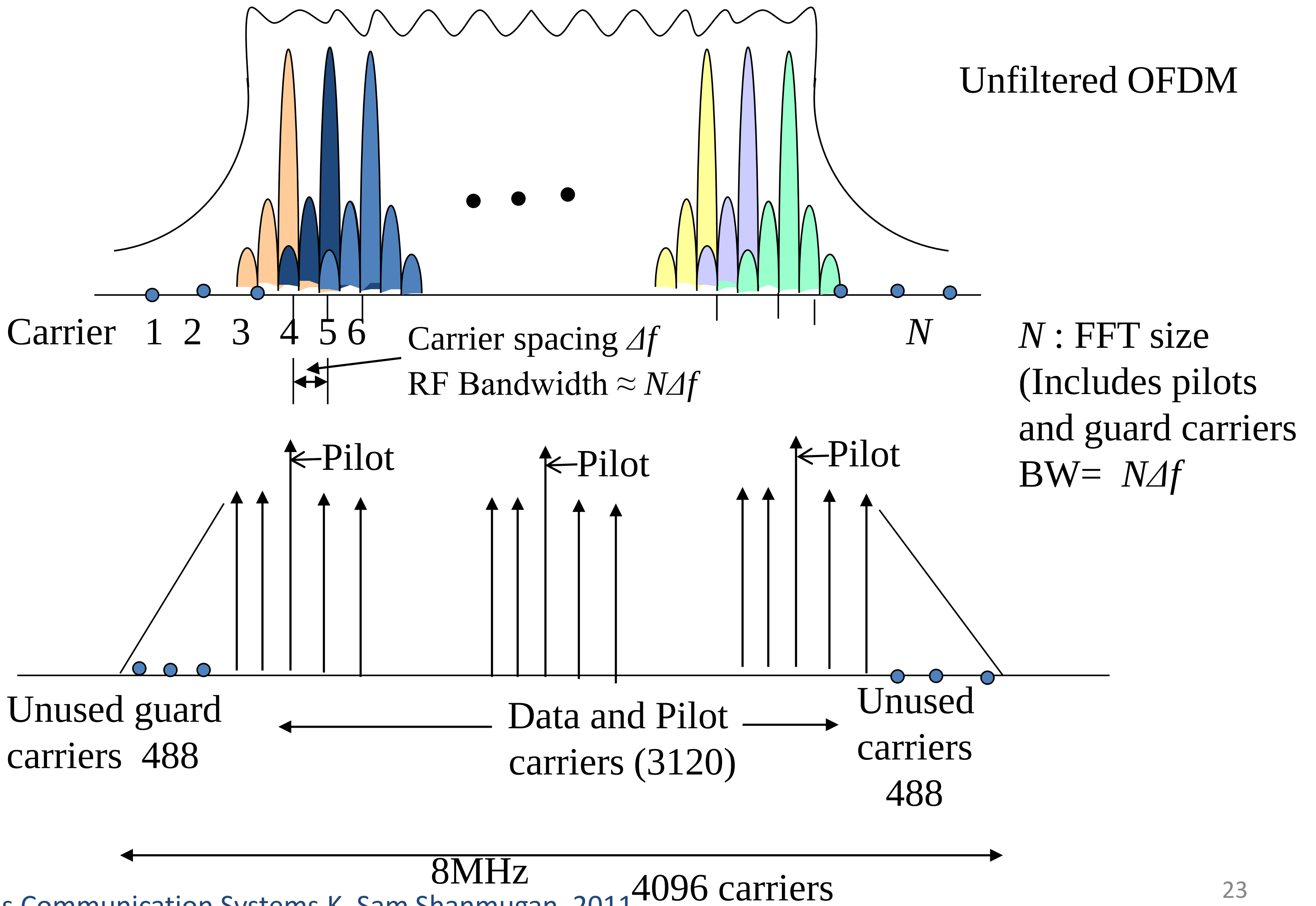
OFDM Multiple Access (OFDMA)
Non Contiguous Carrier Assignment - DL



- Non-contiguous carrier assignment provides additional frequency diversity
- With channel coding, coded bits of a user should be assigned to noncontiguous carriers of the user (This is analogous to interleaving in time domain)

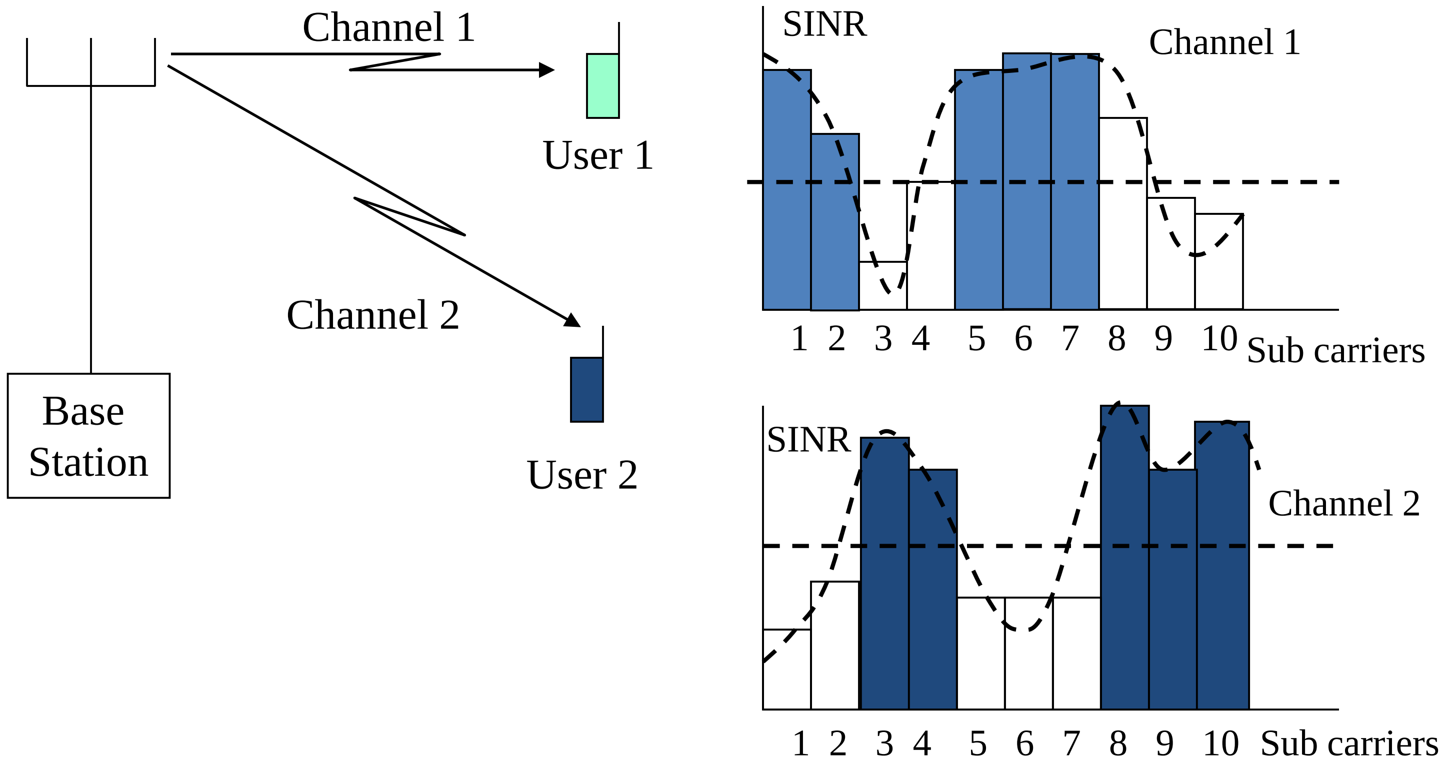
From: Wireless Communication Systems K. Sam Shanmugan, 2011

Example of OFDM Spectrum with Pilot and Guard Carriers



From: Wireless Communication Systems K. Sam Shanmugan, 2011

Subcarrier Assignment Multi-user Diversity



- Depending on the user location some of the sub-channels will have higher SINR than others (due to independent fading of different channels, narrowband interference etc

- Judicious allocation of channels (based in channel side information) can be used to maximize capacity and or QoS

From: Wireless Communication Systems K. Sam Shanmugan, 2011

AMC

In moble communications systems there can be different signal-to-noise ratio values of different groups subcarriers different users:

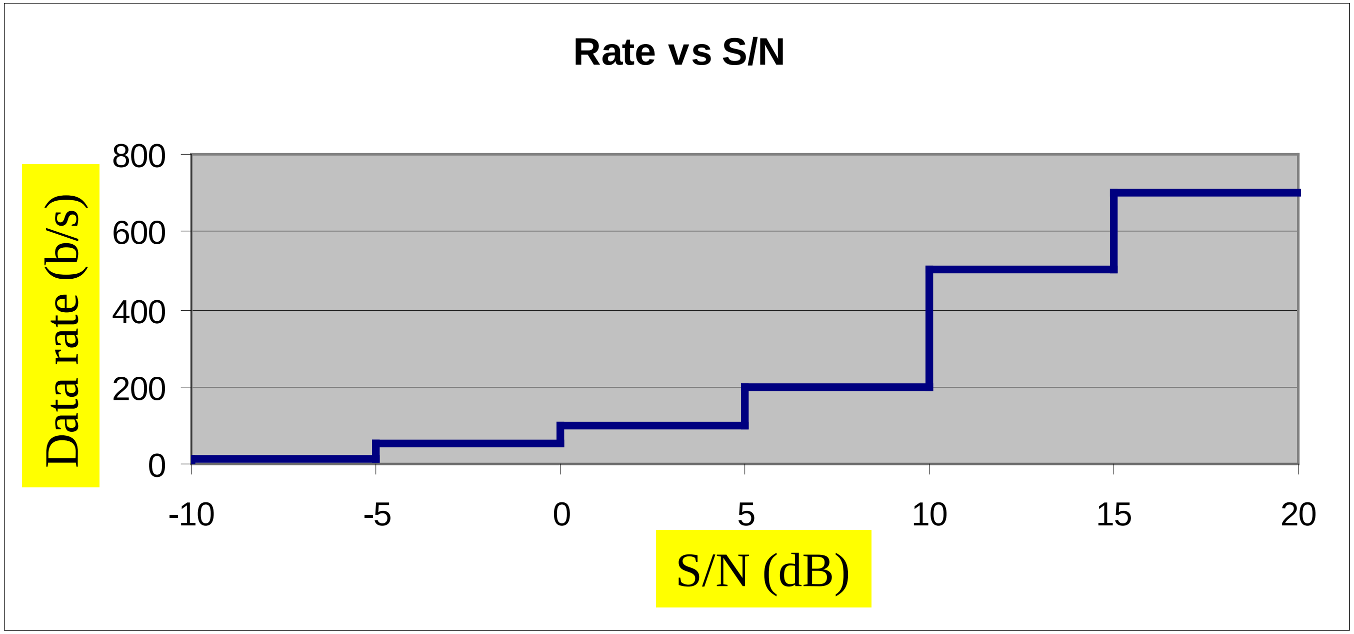
Subcarriers with high S/N carry more bits (for instance by using a modulation scheme with more bits/symbol or by using a less heavy FEC scheme)

Subcarriers with low S/N (due to frequency selective fading) carry less bits.

Note the requirement of a feedback channel.

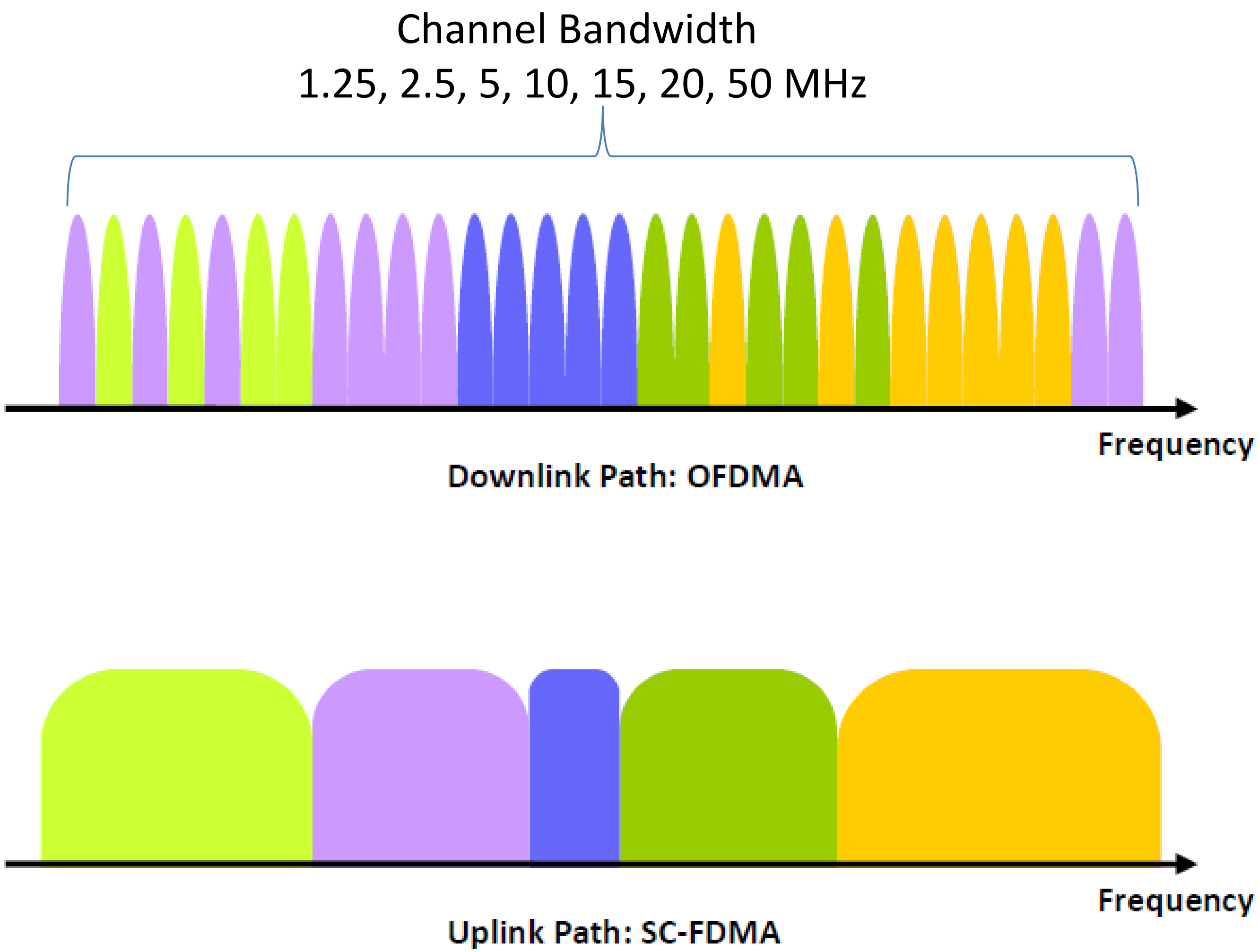
Modified from: *www.comlab.hut.fi/opetus/227/2005/9_227_2005.**ppt***

Adaptive Bit Rate



+ S/N @ the receive obtained via measurements and feedback
+ Measurement called "channel state information" (CSI)
+ Data Rate change by:
    - Modulation: from 64 QAM to QPSK
    - Number FEC bits
    - Number of time slots assigned

Putting it all together: LTE



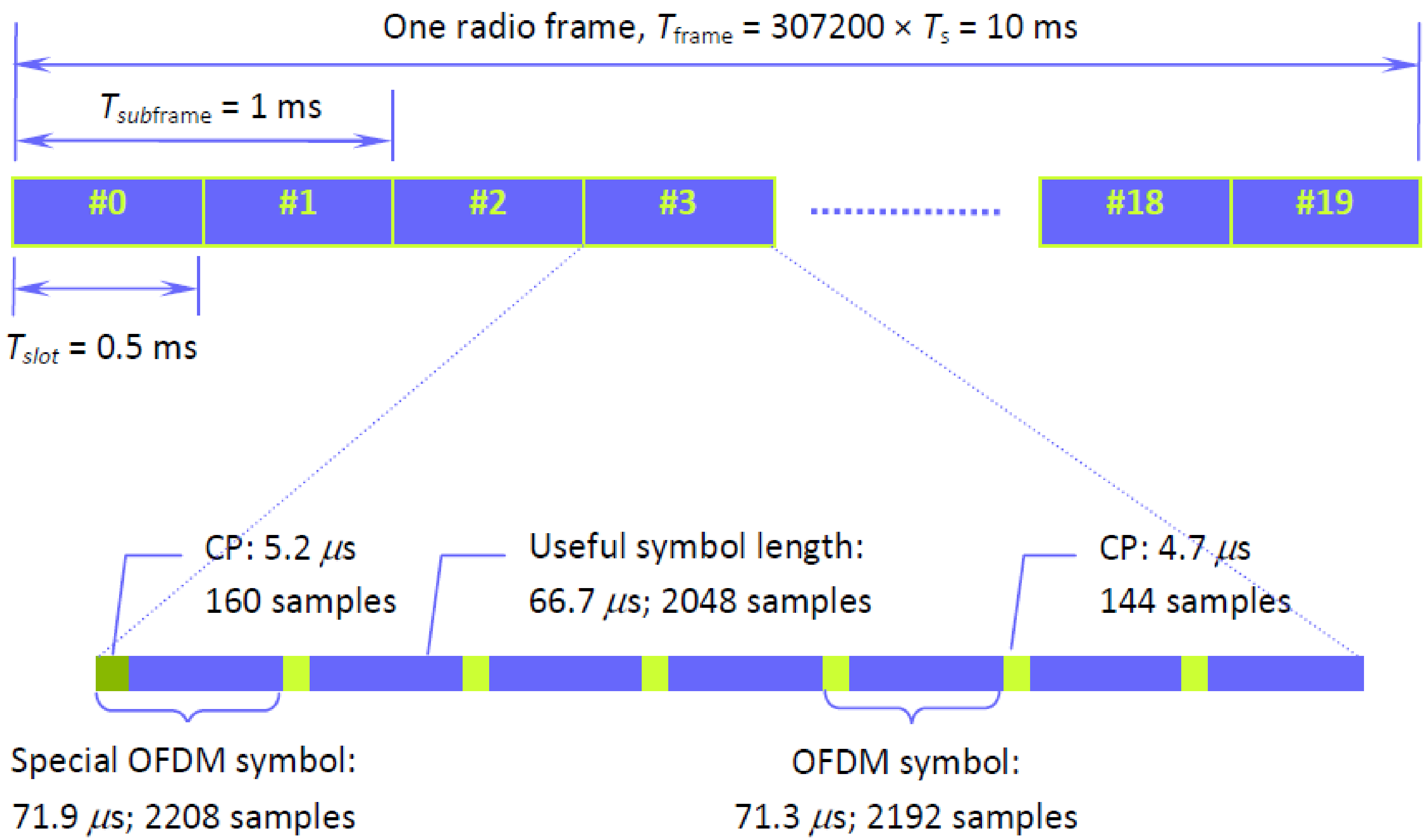
Modified from: LTE in a Nutshell: The Physical Layer, Telesystems Innovations

Putting it all together: LTE

- Time structure (TDM)
  - T_s = Base time unit = 1/30720000 sec = ~.032552us
  - T_{frame}= radio frame = 10 ms = 307200* T_s
  - $T_{subframe}$= subframe = 1 ms = 30720* T_s
  - $T_{slotsub}$= slot = $T_{subframe\ /2}$ = .5 ms = 15360* T_s
  - Normal case is one CP + 7 OFDM symbols in slot (and expended case uses longer CP + 7 OFDM symbols, what is gained and lost using a longer CP?)
  - T_u = useful symbol time 2048*T_s=~ 66.7us = 1/15kHz
  - Subcarrier spacing 15KHz
  - T_{CP} = CP time = 144*T_s= ~4.7us
  - Overhead = 4.7/(4.7+66.7)=~6.6%

Modified from: LTE in a Nutshell: The Physical Layer, Telesystems Innovations

Example LTE Time Frame Structure (on one subcarrier)



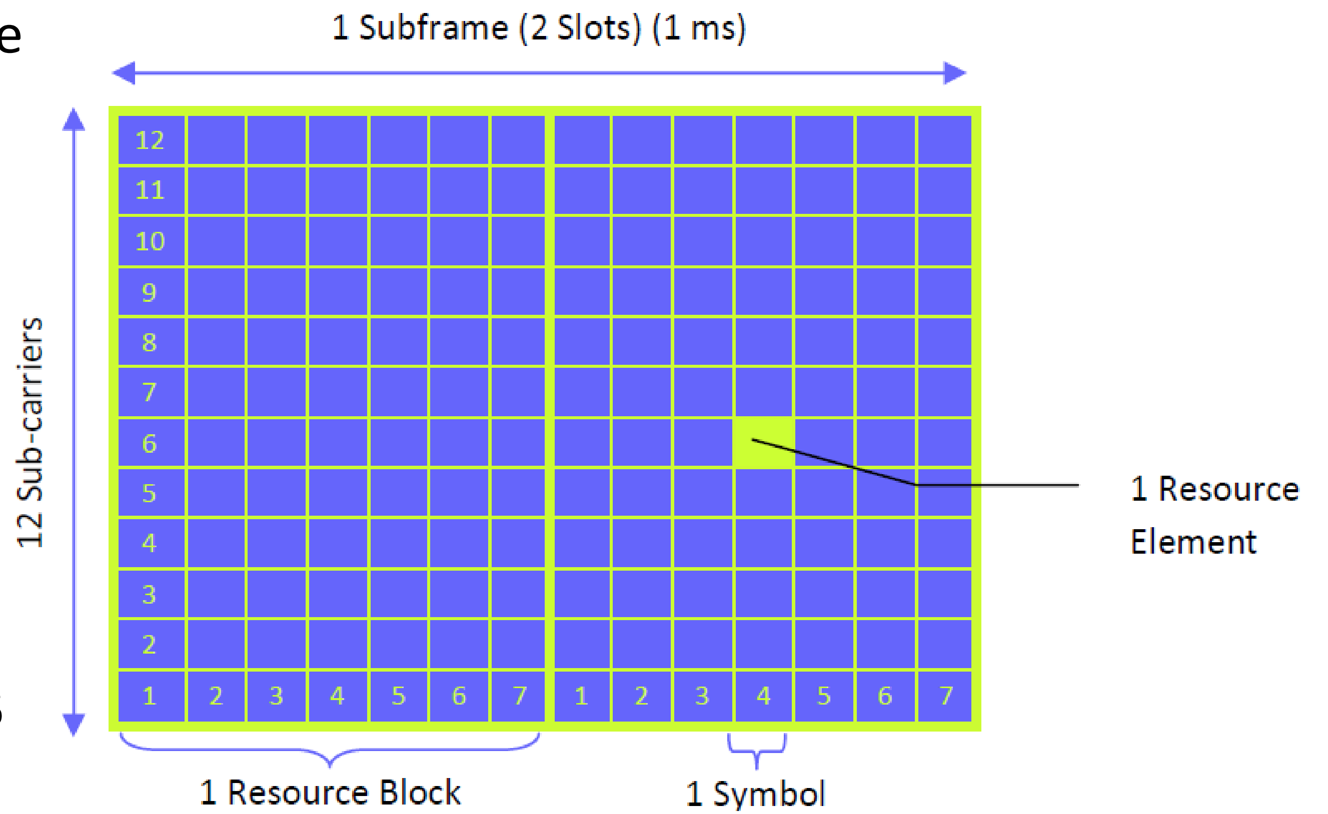
Values shown for normal CP assignment; Δf = 15 kHz

Modified from: LTE in a Nutshell: The Physical Layer, Telesystems Innovations

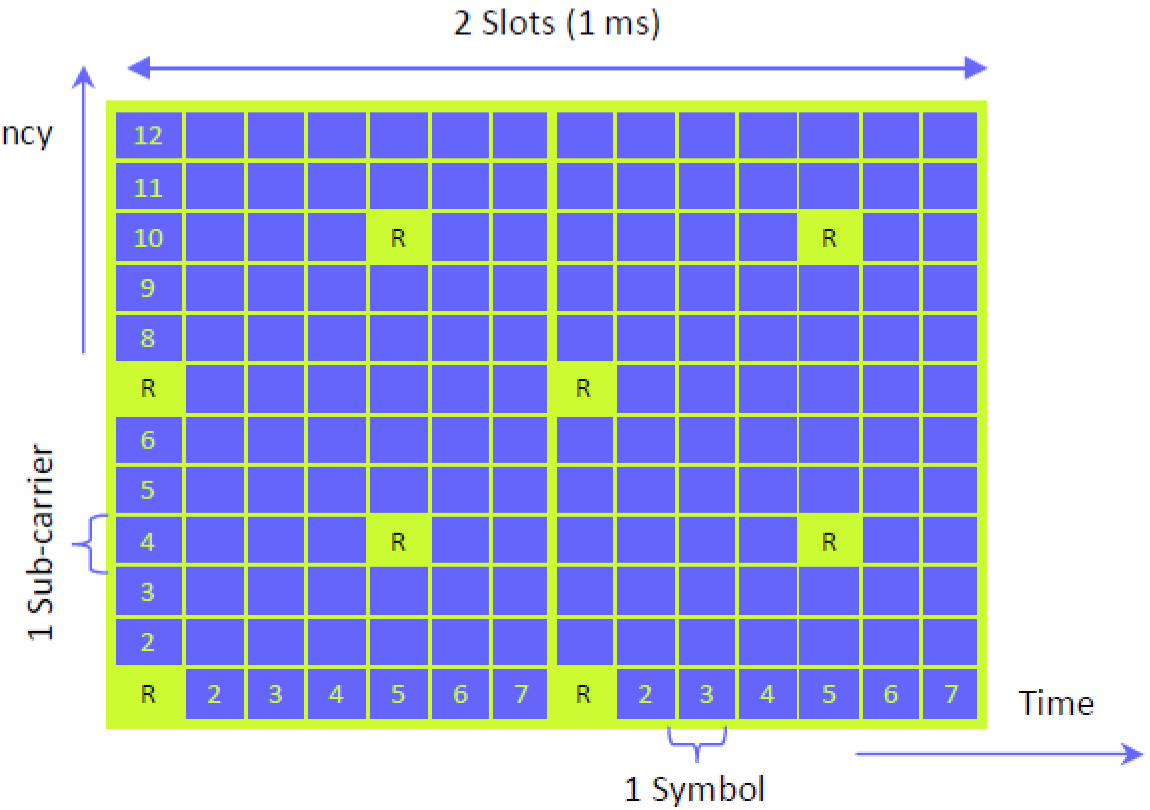
Stack subcarriers-OFDM

- Minimum Assignable resource= 1 RB
- Example: Data rate of 1 RB
  - QPSK/symbol
  - 7 symbols
  - 14 bits/subcarrier
  - 12 subcarriers/RB
  - 168 bits/RB
  - 1 RB/.5ms
  - 168bits/.5ms = 336 kb/s*

  *Assuming no overhead, e.g. pilots



Pilots



R=Reference Symbols, i.e., pilots & overhead

Modified from: LTE in a Nutshell: The Physical Layer, Telesystems Innovations

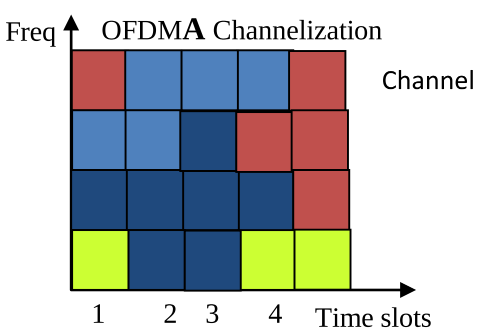
LTE Downlink Physical Layer Parameters

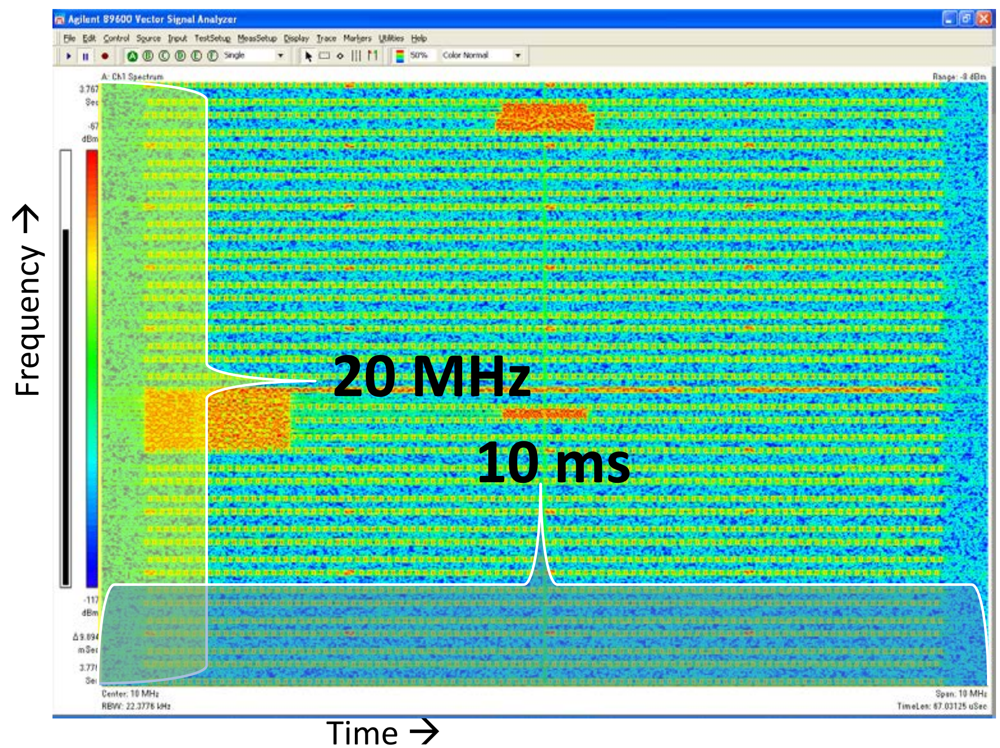
Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1.140	2.265	4.515	9.015	13.515	18.015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP Length (Short CP) (μs)	5.2 (first symbol) / 4.69 (six following symbols)					
CP Length (Long CP) (μs)	16.67					

Modified from: LTE in a Nutshell: The Physical Layer, Telesystems Innovations

Spectrogram of Downlink Physical Channel for Long Term Evolution (LTE)

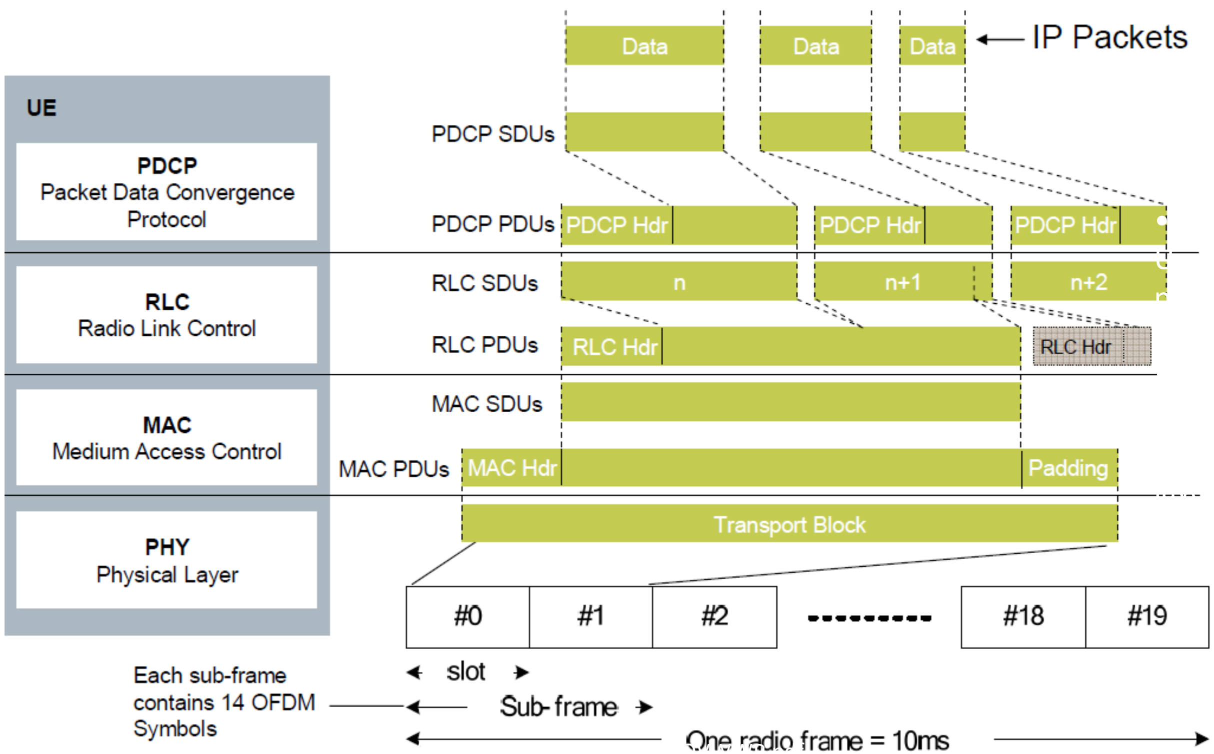
Subcarrier BW=15kHz
Resource Block=
12 subcarriers (180kHz)
Time Slot = 0.5 ms





From: Peter Cain, Using Wireless Signal Decoding to Verify LTE Radio signals, Agilent Technologies, July 2011

Example: LTE Protocol Stack Showing how bits get to the PHY Layer



FDD & TDD

- Downlink, e.g. , base station → smartphone
- Uplink, e.g., smartphone → base station
- Frequency-division duplexing (FDD)
  - Downlink on frequency carrier 1, f1
  - Uplink on frequency carrier 2, f2
- Time-division Duplexing (TDD)
  - Downlink is time slots 1, k
  - Uplink in time slots k+1, M

LTE Operating Bands: 15 use FDD and 8 use TDD

Table 4. EUTRA operating bands (TS 36.101 [6] Table 5.5-1)

E-UTRA operating band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex mode
	$F_{UL\_low} - F_{UL\_high}$	$F_{DL\_low} - F_{DL\_high}$	
1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
2	1850 – 1910 MHz	1930 – 1990 MHz	FDD
3	1710 – 1785 MHz	1805 – 1880 MHz	FDD
4	1710 – 1755 MHz	2110 – 2155 MHz	FDD
5	824 – 849 MHz	869 – 894 MHz	FDD
6	830 – 840 MHz	875 – 885 MHz	FDD
7	2500 – 2570 MHz	2620 – 2690 MHz	FDD
8	880 – 915 MHz	925 – 960 MHz	FDD
9	1749.9 – 1784.9 MHz	1844.9 – 1879.9 MHz	FDD
10	1710 – 1770 MHz	2110 – 2170 MHz	FDD
11	1427.9 – 1452.9 MHz	1475.9 – 1500.9 MHz	FDD
12	698 – 716 MHz	728 – 746 MHz	FDD
13	777 – 787 MHz	746 – 756 MHz	FDD
14	788 – 798 MHz	758 – 768 MHz	FDD
...			
17	704 – 716 MHz	734 – 746 MHz	FDD
...			
33	1900 – 1920 MHz	1900 – 1920 MHz	TDD
34	2010 – 2025 MHz	2010 – 2025 MHz	TDD
35	1850 – 1910 MHz	1850 – 1910 MHz	TDD
36	1930 – 1990 MHz	1930 – 1990 MHz	TDD
37	1910 – 1930 MHz	1910 – 1930 MHz	TDD
38	2570 – 2620 MHz	2570 – 2620 MHz	TDD
39	1880 – 1920 MHz	1880 – 1920 MHz	TDD
40	2300 – 2400 MHz	2300 – 2400 MHz	TDD

TDD: Same Band for: BS→UE & UE → BS

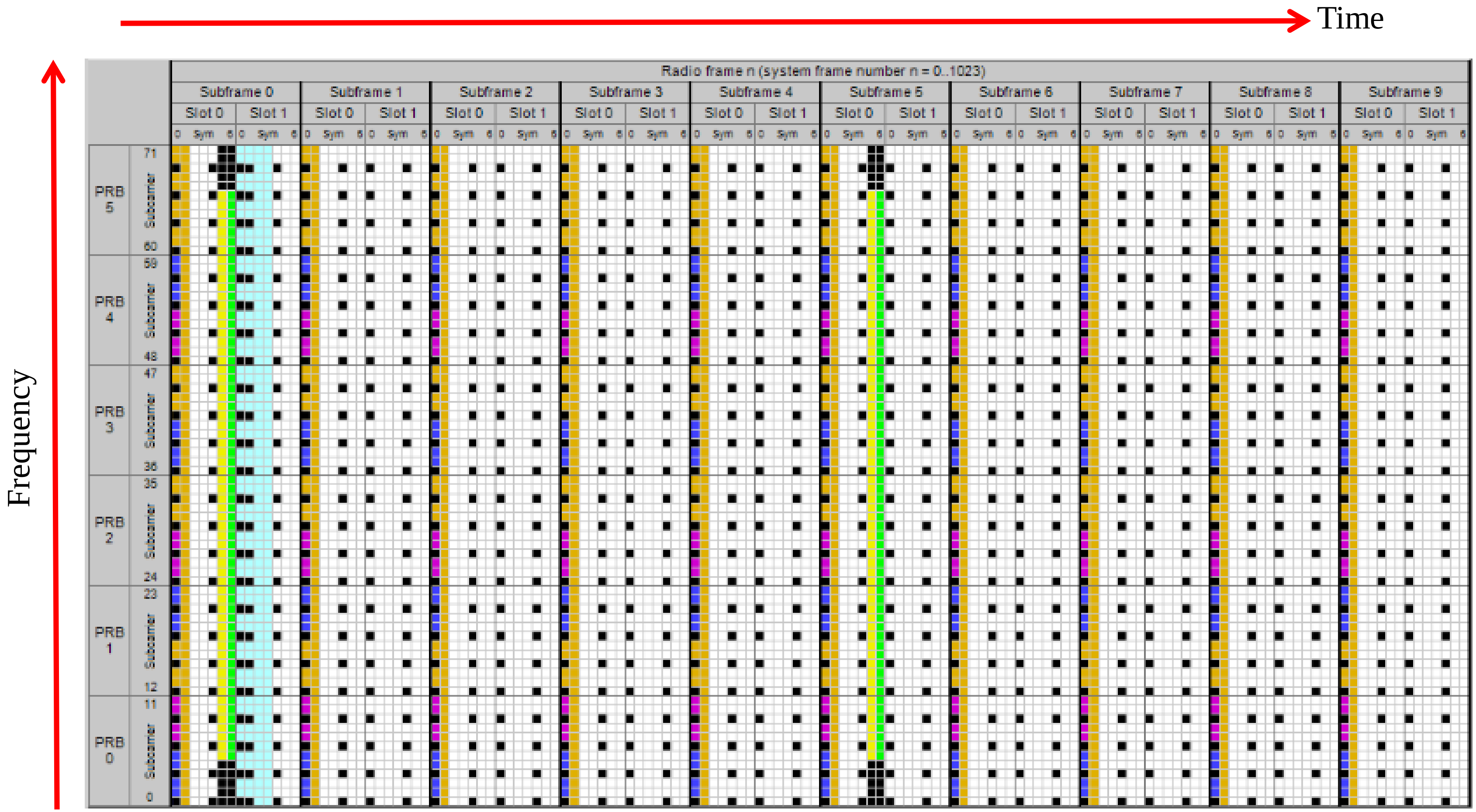
LTE definitions

UE = User Equipment, e.g., smartphone

eNB = Evolved NodeB = Base station

From: Agilent, 3GPP Long Term Evolution:
System Overview, Product Development, and Test Challenges, Application Note

LTE Resource Grid



- PSCH (Primary Synchronization Channel)
- SSCH (Secondary Synchronization Channel)
- PBCH (Physical Broadcast Channel)
- RS (cell-specific Reference Signal) for selected Tx antenna port
- PCFICH (Physical Control Format Indicator Channel)
- PHICH (Physical Hybrid ARQ (Automatic Repeat reQuest) Indicator Channel)
- PDCCH (Physical Downlink Control Channel)
- Available for PDSCH (Physical Downlink Shared Channel)
- Reserved

See http://dhagle.in/LTE

PRB=Physical Resource Block

Uplink: SC-FDMA

- SC-FDMA= single carrier FDMA
  - aka DFT spread OFDM (DFTS-OFDM)
- SC-FDMA closely related to OFDM
- When multiple carriers with arbitrary phases are added together, we no longer have a constant envelope signal, resulting in high Peak-to-Average Power Ratio (PAR)
- Power efficient RF amplifiers need constant envelope signal
- OFDM has high Peak-to-Average Power Ratio (PAR) is bad for power efficient transmission needed for UE's.
- SC-FDMA has a better PAR