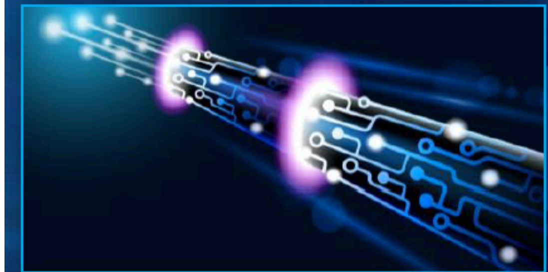
NR Overview

New Applications Stress Existing Wireless Services

LOW-POWER CONNECTED DEVICE GROWTH VIA IOT

BILLIONS of connected devices by 2020[1]



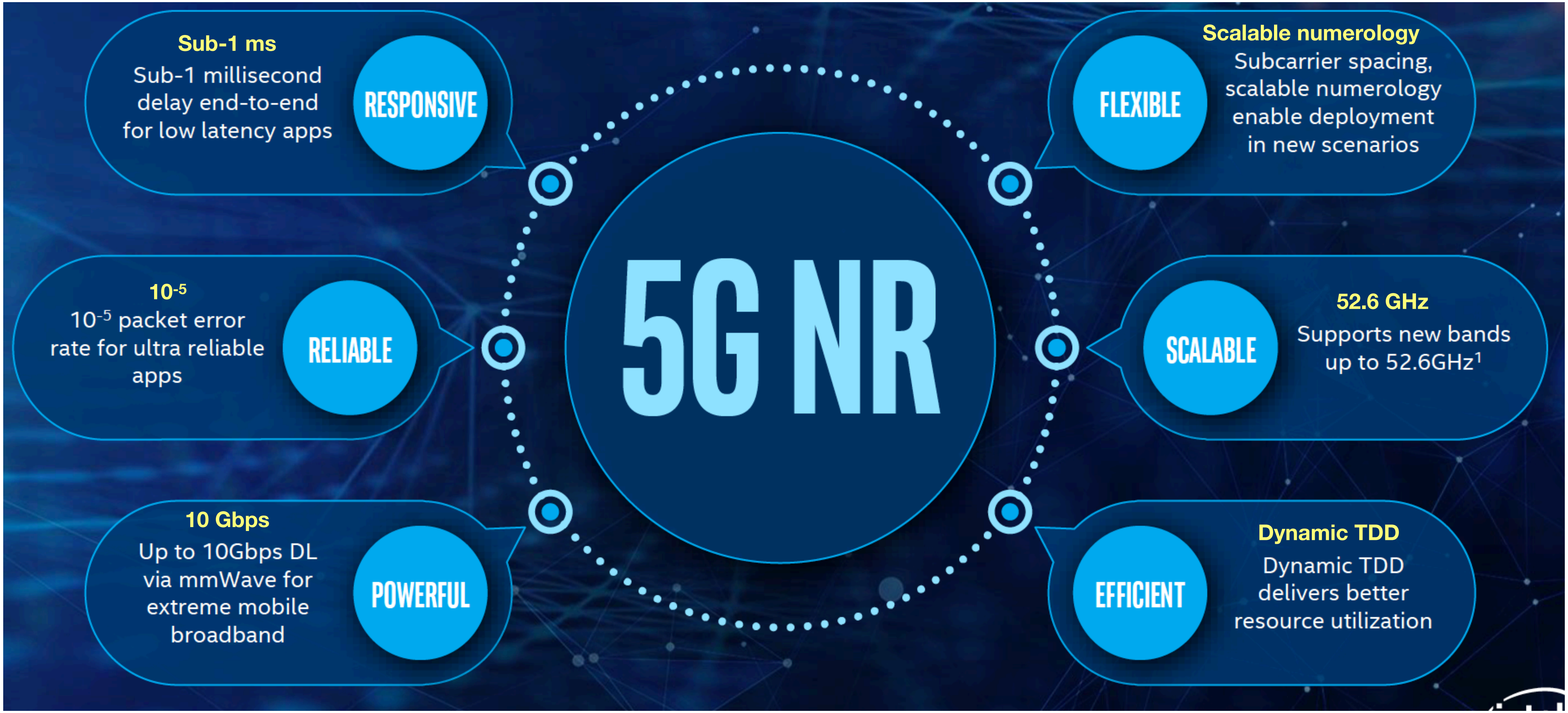
ENHANCED MOBILE BROADBAND

>1B 5G subscriptions of enhanced mobile broadband by 2023[2]

ULTRA-LOW LATENCY AND RELIABILITY

1M autonomous cars on the road by 2025; Internet apps with sub-10 millisecond latency[3]

Enter 5G NR - A Truly Unified Air Interface



Introduction

- ITU-R announced multifold design goals of 5G mobile networks known as IMT-2020

3G：IMT-2000
4G：IMT-2010
5G：IMT-2020

• 20 Gbps peak data rate	• 1 ms latency
• 100 Mbps user experienced data rate	• Mobility up to 500 km/h
• 10 Mbps/m^2 area traffic capacity	• Backward compatibility to LTE/LTE-Advanced (LTE-A)
• 10^6 devices/km^2 connection density	• Forward compatibility to potential future evolution

- Scope considered in 5G New Radio (NR) specifications
  - Standalone and non-standalone NR operations
  - Spectrum below and above 6 GHz
  - Three major use cases
    - Enhanced Mobile Broadband (eMBB)
    - Ultra-Reliable and Low Latency Communications (URLCC)
    - Massive Machine-Type Communications (mMTC)

Standalone and Non-Standalone NR Operations

- **Standalone**

  - Full <u>control plane</u> and <u>data plane</u> functions are provided in <u>NR</u>

- **Non-standalone**

  - <u>Control plane</u> functions of LTE and LTE-A are utilized as an <u>anchor</u> for NR

Spectrum Below and Above 6 GHz

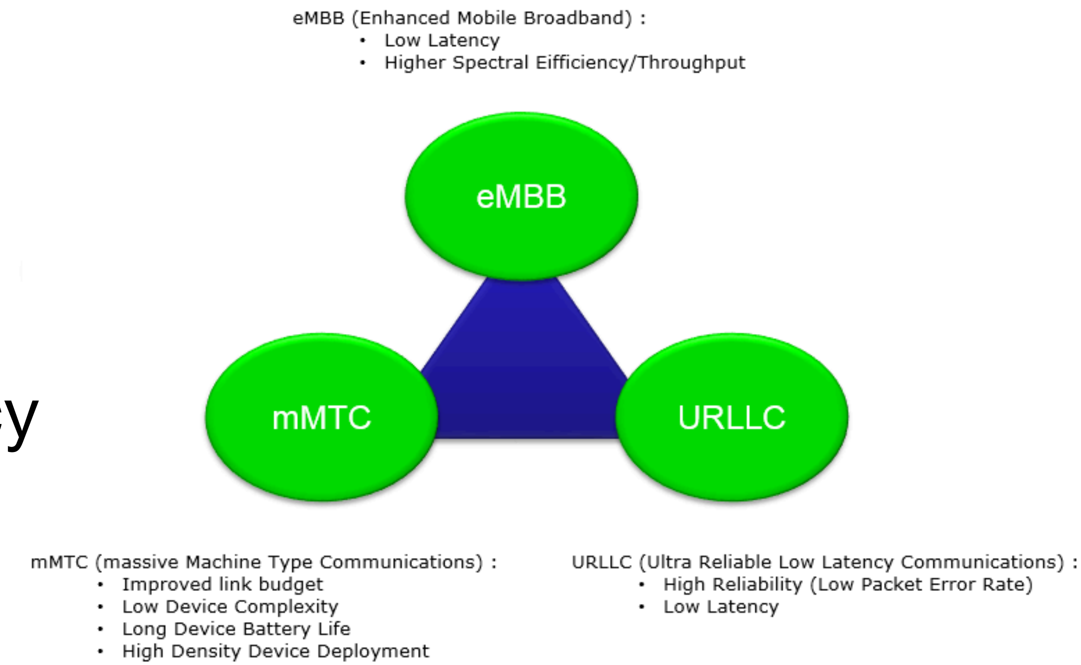
- Subject to existing fixed spectrum allocation policies, it is a challenge to obtain available spectrum with a sufficiently wide bandwidth from frequency range below 6 GHz

- Accessing the radio resources below 6 GHz is necessary to fulfill diverse deployment scenarios required by operators

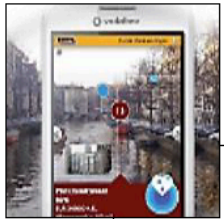
- Spectrum above 6 GHz is critical

eMBB, URLCC, mMTC

- In Release 15, three major use cases are emphasized
  - Enhanced Mobile Broadband (eMBB)
  - Ultra-Reliable and Low Latency Communications (URLCC)
  - Massive Machine-Type Communications (mMTC)



- Offering urgent data delivery with ultra low latency and massive packet transmissions are of crucial importance for NR
  - eMBB supports high capacity and high mobility (up to 500 km/h) radio access (with 4ms user plane latency)
  - URLCC provides urgent and reliable data exchange (with 0.5ms user plane latency)
  - mMTC supports infrequent, massive, and small packet transmissions (with 10s latency)



Enhanced Mobile Broadband (eMBB)

- 10-20 Gbps peak
- 100 Mbps whenever needed
- 10000x more traffic
- Macro and small cells
- Support for high mobility (500 km/h)
- Network energy saving by 100 times

Massive Machine Communication (mMTC)

- High density of devices ($2x10^5$ - $10^6/km^2$)
- Long range
- Low data rate (1 - 100 kbps)
- M2M ultra low cost
- 10 years battery
- Asynchronous access

Ultra Reliability and Low Latency (URLLC)

- Ultra responsive
  - <1 ms air interface latency
  - 5 ms E2E latency
- Ultra reliable and available (99.9999%)
- Low to medium data rates (50 kbps - 10 Mbps)
- High speed mobility

5G New Radio Topics

- Deployment scenarios
- Numerologies
- Frame structure
- New waveform
- Multiple access
- Initial/random access
- Enhanced carrier aggregation (CA)

Deployment Scenarios

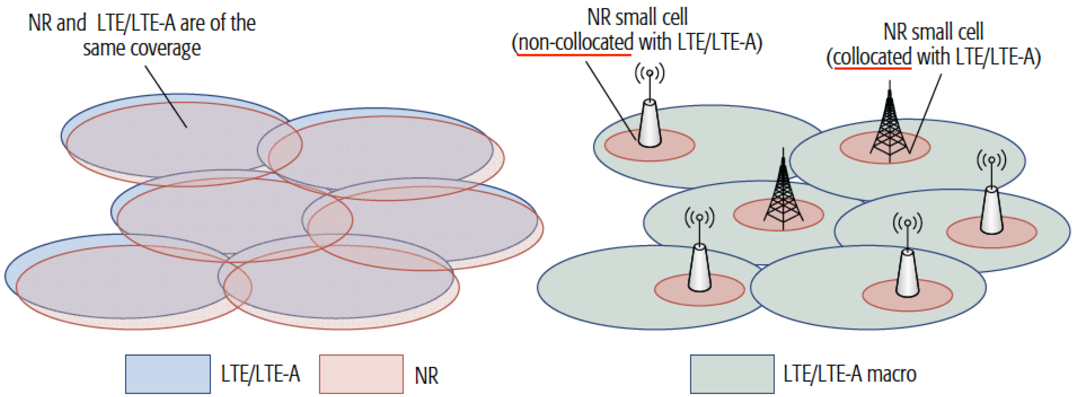
- For <u>backward compatibility</u> with LTE/LTE-A, the architecture of NR is required to closely <u>interwork with LTE/LTE-A</u>

- Cells of LTE/LTE-A and NR can have <u>different coverage</u> or the <u>same coverage</u>, and the following deployment scenarios are feasible

  - <u>LTE/LTE-A eNB</u> is a master node

  - <u>NR gNB</u> is a master node

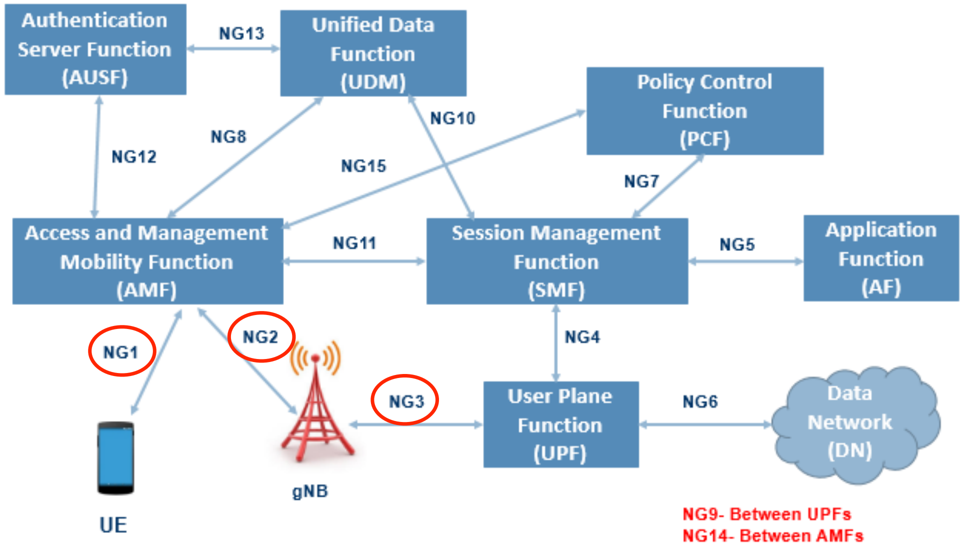
  - <u>eLTE eNB</u> is a master node

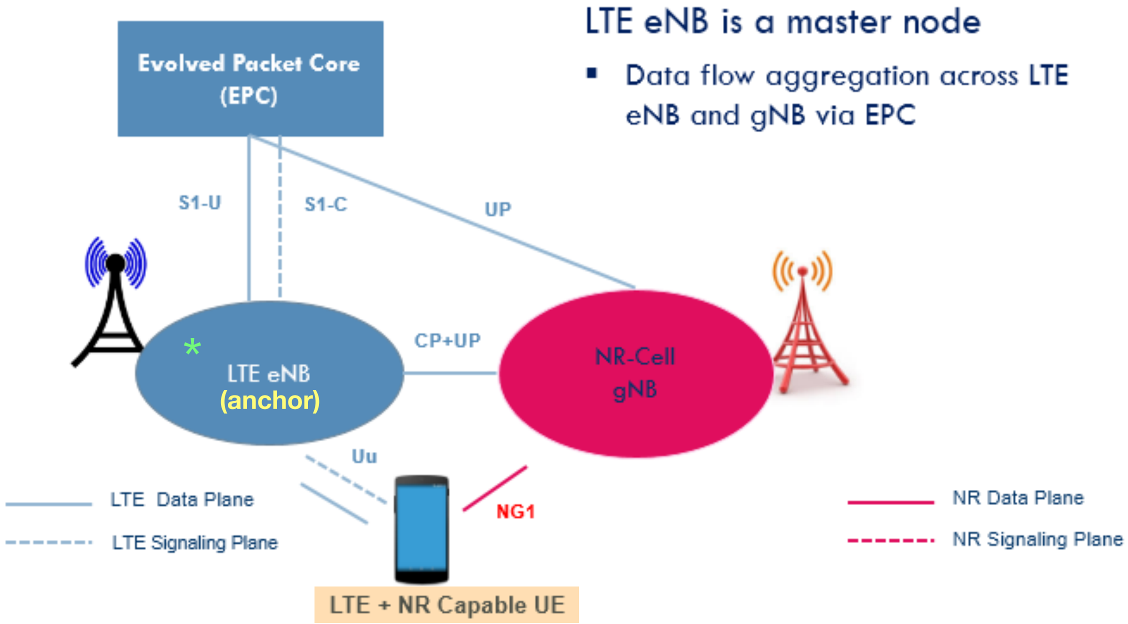


eLTE eNB

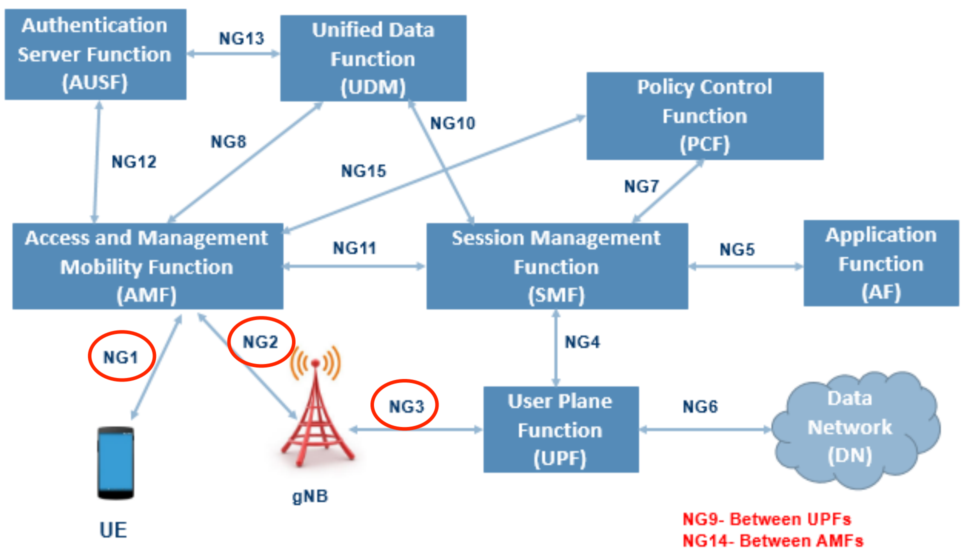
- An <u>evolved eNodeB</u> that can support connectivity to EPC as well as next-generation core network (NG-CN)
- A release 14 / release 15 LTE cell can be considered as <u>eLTE eNB</u>

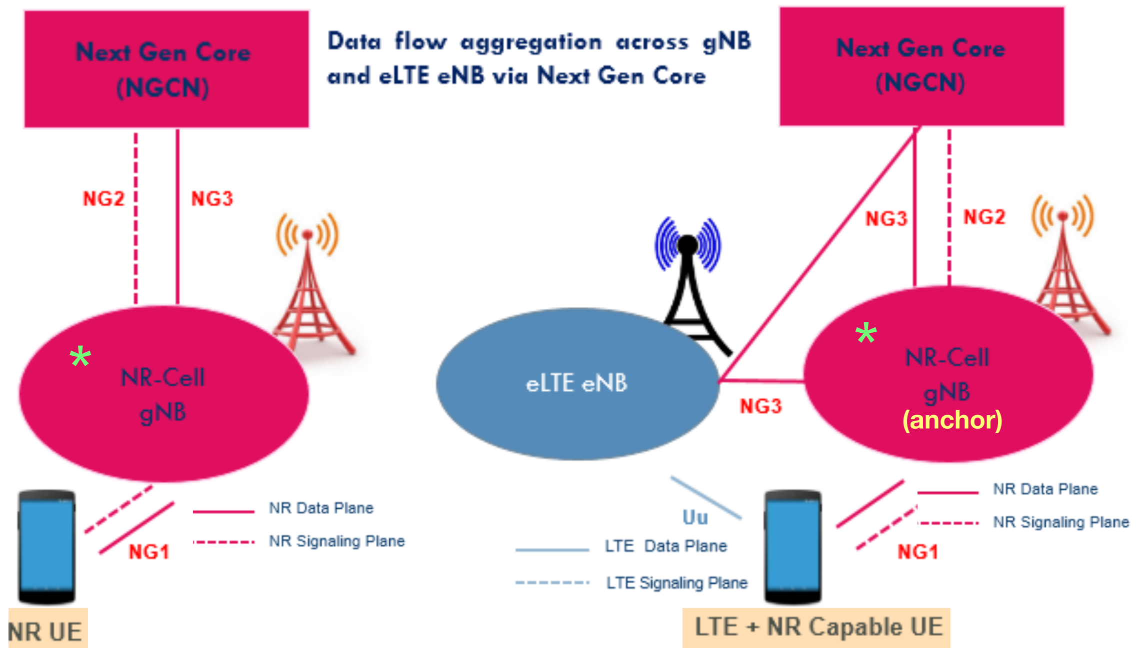
- **LTE/LTE-A eNB** is a master node
  - An LTE / LTE-A eNB offers an anchor carrier (in both control and user planes), while an NR gNB offers a booster carrier
  - All the signaling procedure shall be done at LTE / LTE-A cell
  - Data flow aggregates across an eNB and a gNB via the evolved packet core (EPC)



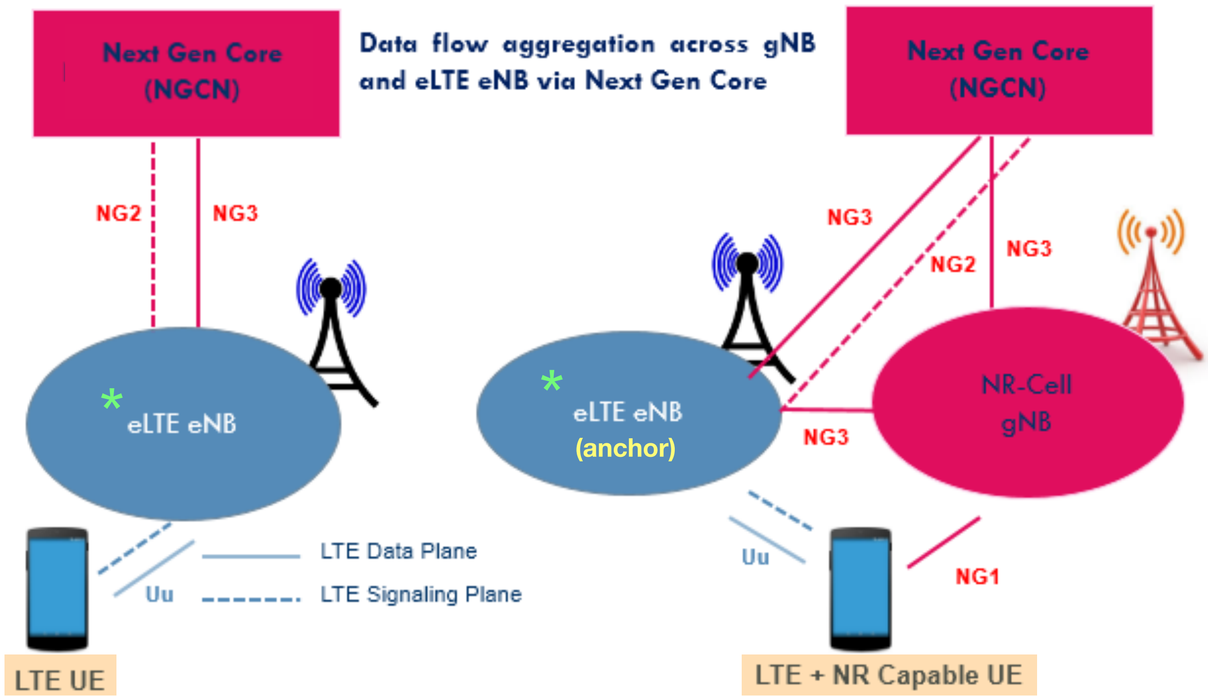


- **NR gNB** is a master node
  - A standalone NR gNB offers wireless services (in both control and user planes) via the next generation core (NG-CN)
  - A collocated enhanced LTE (eLTE) eNB is able to additionally provide booster carriers for dual connections
  - All signaling procedure shall be done at NR cell

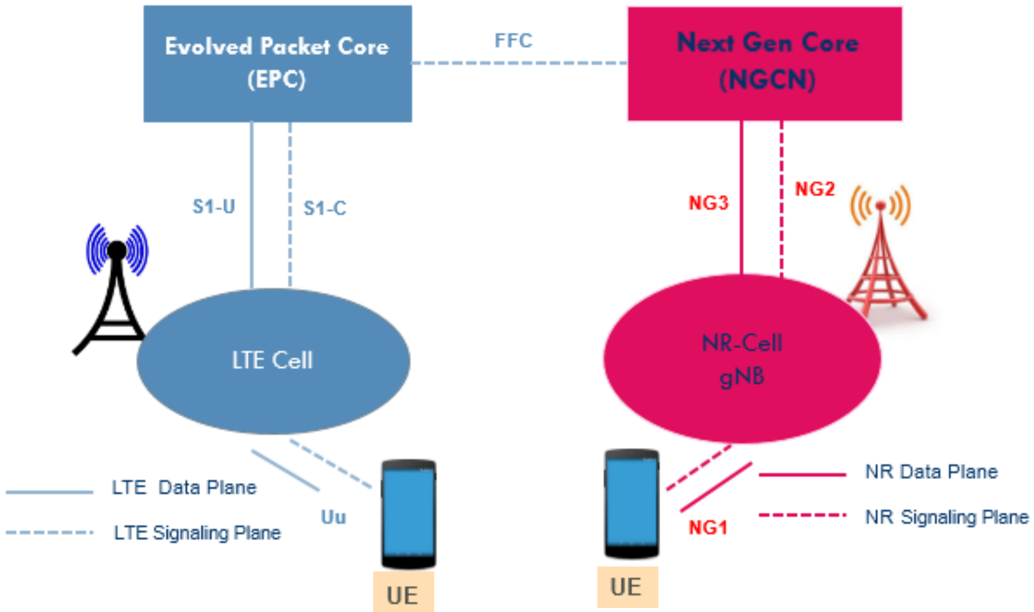




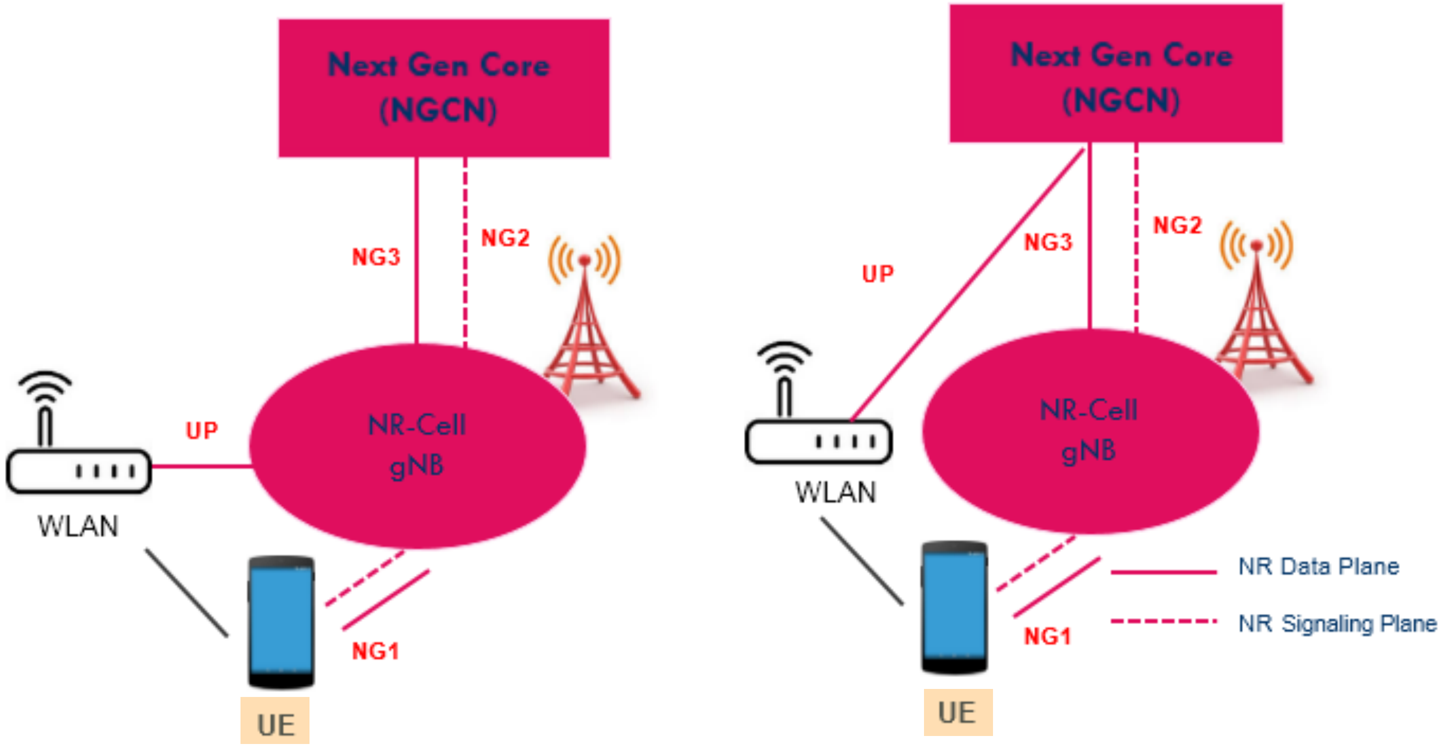
- **eLTE eNB** is a master node
  - A standalone eLTE eNB offers wireless services (in both control and user planes) via the NG-CN, or
  - A collocated NR gNB is able to provide booster carriers (eLTE eNB offers an anchor carrier)



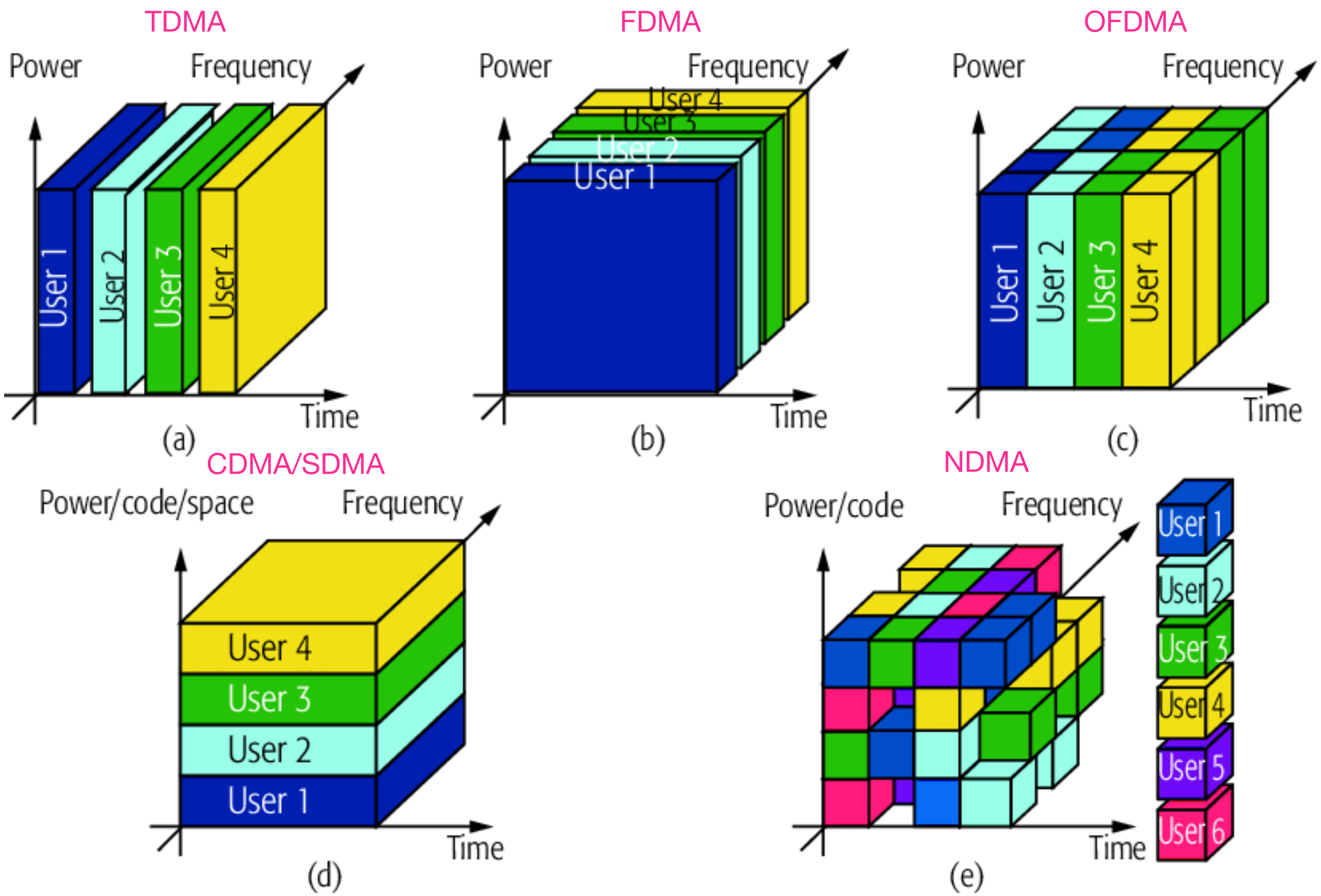
- Inter-Radio Access Technology (RAT) handover between LTE/LTE-A/eLTE eNB and NR gNB
  - An LTE/ LTE-A eNB connects to the EPC, and an NR gNB connects to the NG-CN to support handover between eNB and gNB
  - An eLTE eNB can also connect to the NG-CN, and handover between eNB and gNB can be fully managed through the NG-CN



- Inter-working with WLAN
  - When NR is capable to work as a standalone cell, it can be further enhanced to inter work with WLAN for Wi-Fi offloading and to utilize the benefits of the unpaid spectrum



OFDM Principles
(Orthogonal Frequency-Division Multiplexing)



(a) **TDMA**: each user allocated a <u>different time</u> on the channel

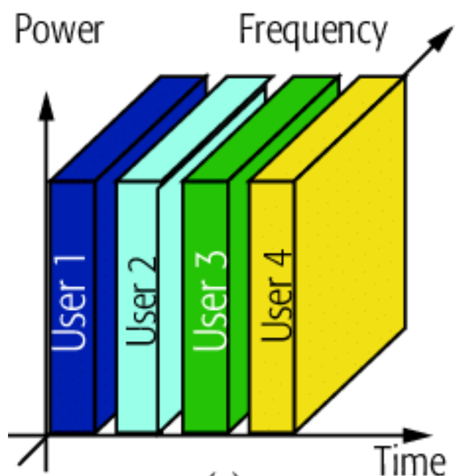
(b) **FDMA**: each user allocated a different <u>subband / channel</u>

(c) **OFDMA**: each user allocated a <u>different resource</u> which can vary in <u>time</u> and <u>frequency</u>

(d) **CDMA/SDMA**: (CDMA) each user allocated a <u>different code</u> on the channel

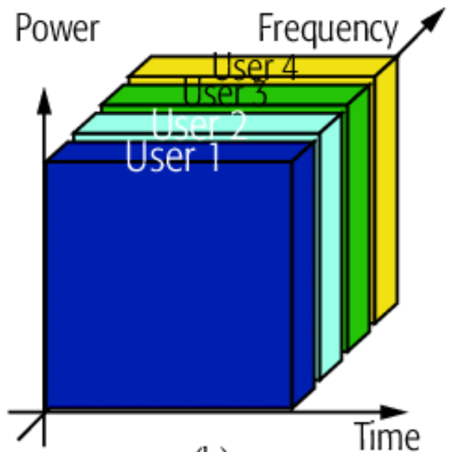
(e) **NOMA**: serve multiple users using the <u>same resource</u> in terms of <u>time</u>, <u>frequency</u>, and <u>space</u>

- **TDMA (Time Division Multiple Access)**
  - Divide the available time into slots, and each user is assigned a slot to transmit
  - Prevents collisions between users, but it can also lead to inefficient use of the spectrum if some users are not always transmitting



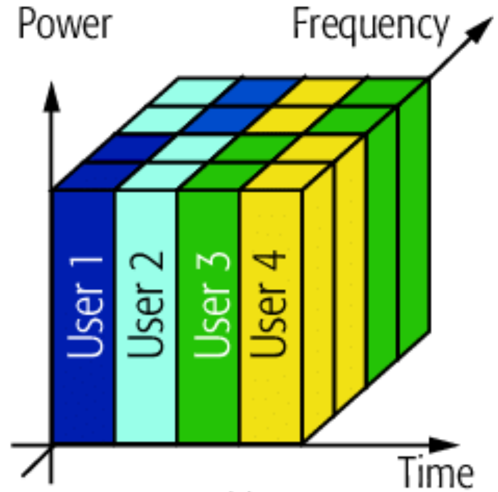
(a)

- **FDMA (Frequency Division Multiple Access)**
  - Divide the available frequency into bands, and each user is assigned a band to transmit on
  - Prevents collisions between users, but it can lead to inefficient use of the spectrum if some bands are not always being used



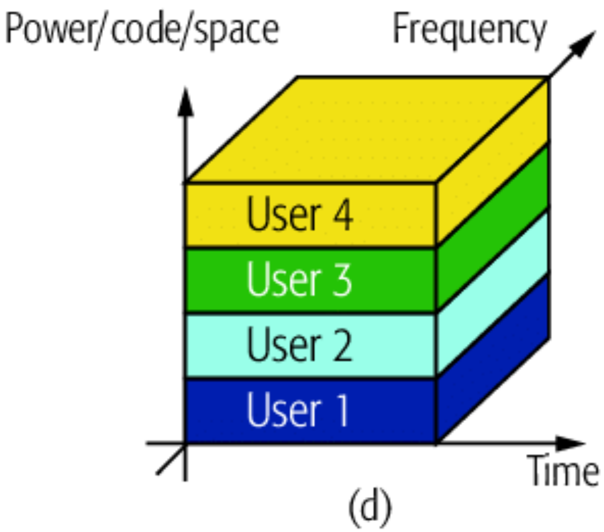
(b)

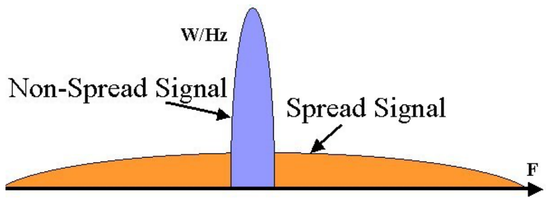
- **OFDMA (Orthogonal Frequency Division Multiple Access)**
  - A more sophisticated version of FDMA that uses orthogonal frequency bands to divide the spectrum
  - Allow for more users to share the spectrum without interfering with each other

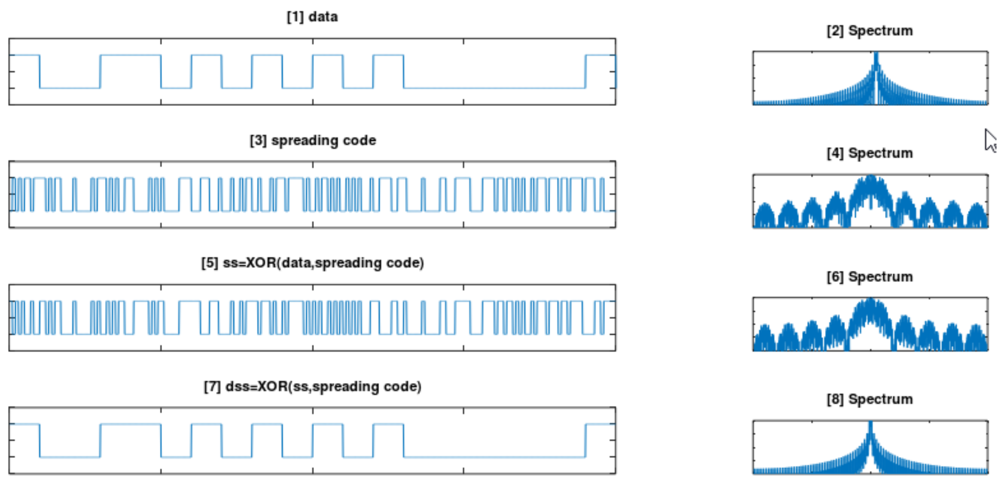


(c)

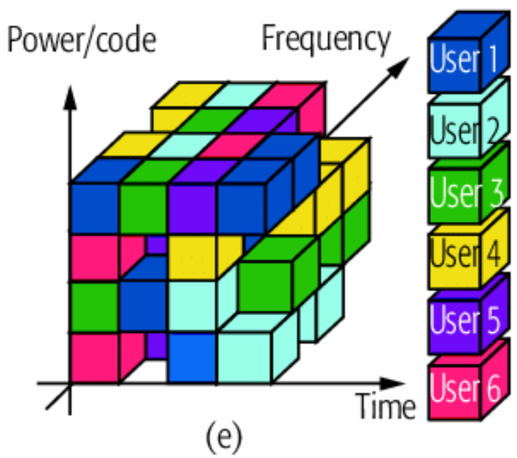
- **CDMA (Code division multiple access)**
  - Use a spreading code to spread each user's signal over a wider frequency band
  - Allow multiple users to transmit on the same frequency without interfering with each other

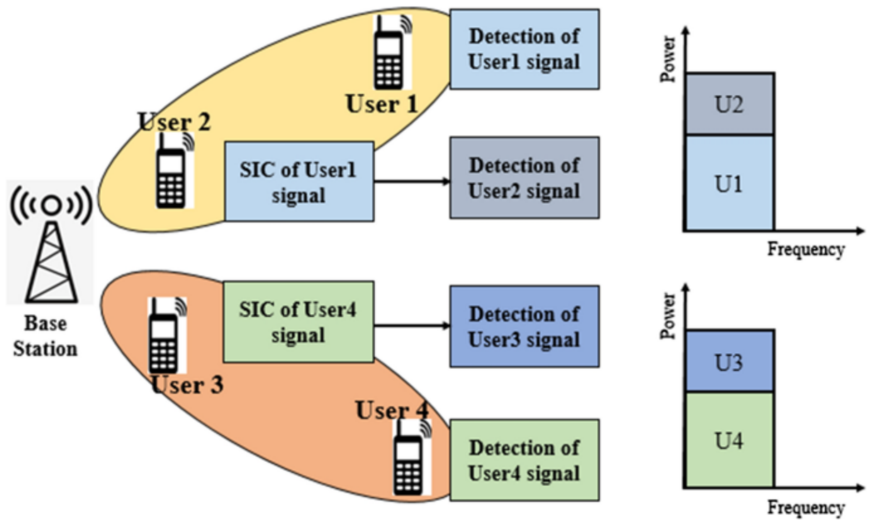




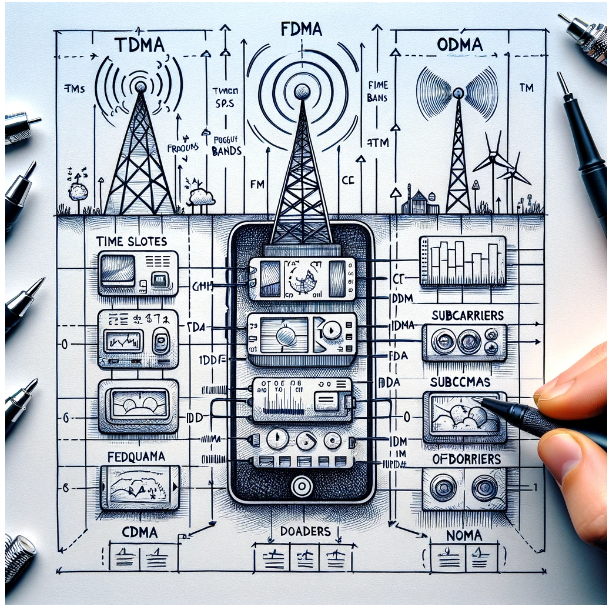


- **NoMA (Non-Orthogonal Multiple Access)**
  - Allow multiple users to transmit on the same frequency at the same time
  - Done by using successive interference cancellation (SIC) to decode the signals from multiple users





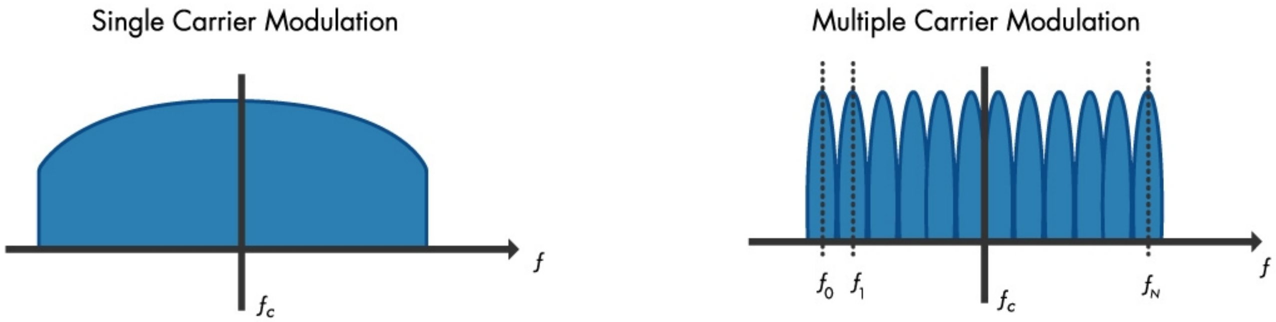
Technique	Advantages	Disadvantages
TDMA	Simple to implement	Inefficient use of spectrum if not all slots are always used
FDMA	Efficient use of spectrum	Can be difficult to implement
OFDMA	Efficient use of spectrum	More complex to implement than FDMA
CDMA	Robust to interference	Can be more complex to implement than TDMA or FDMA
NOMA	Very high spectral efficiency	More complex to implement than TDMA, FDMA, or CDMA



OFDM

- **Orthogonal Frequency Division Multiplexing (OFDM)**

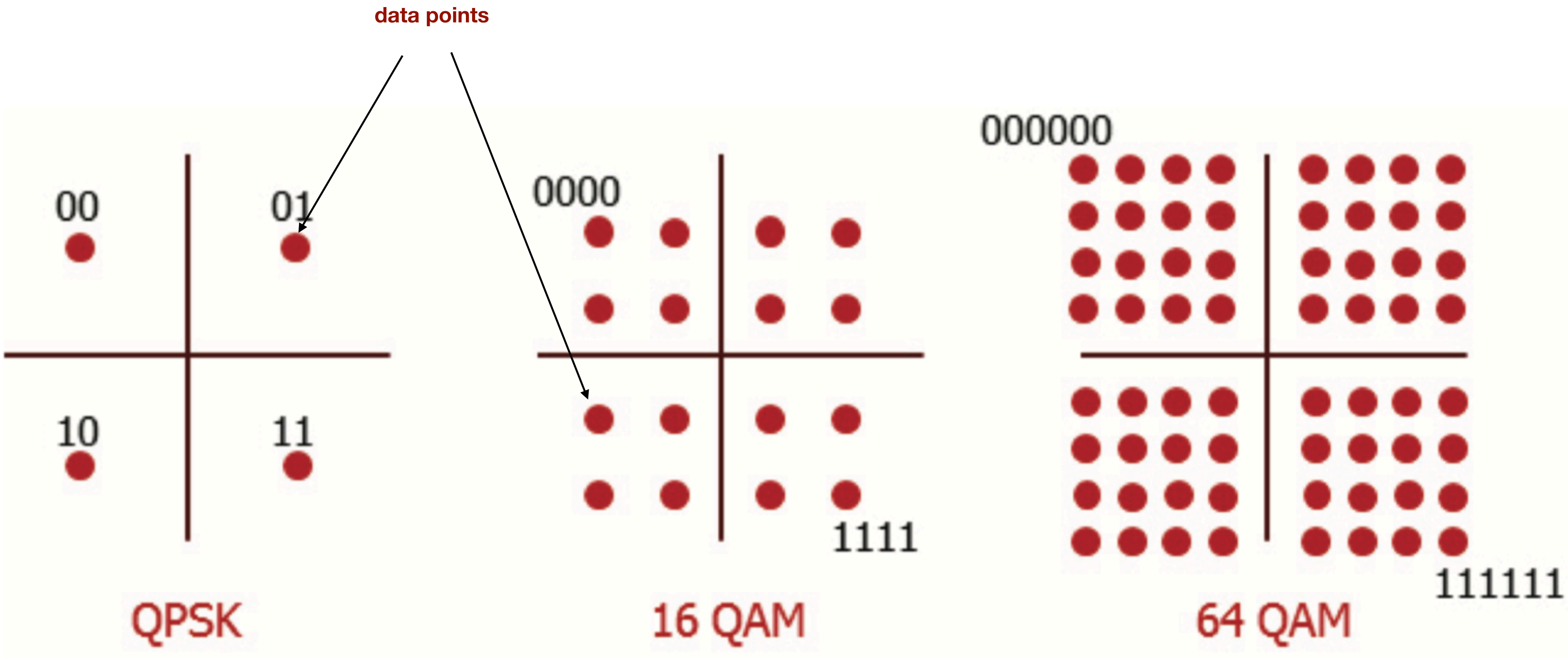
    - A digital multi-carrier modulation scheme that extends the concept of single subcarrier modulation by using multiple subcarriers within the same single channel



    - Rather than transmit a high-rate stream of data with a single subcarrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel

    - Each subcarrier is modulated with a conventional digital modulation scheme (such as QPSK, 16QAM, 64QAM etc.) at low symbol rate

Note: QPSK, 16QAM, 64QAM



QPSK：
— 2 bits/symbol
— 2 bps/Hz

(2 bits are grouped at a time)

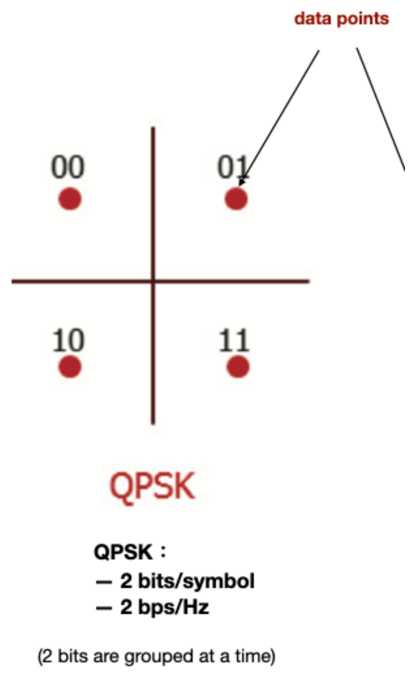
16QAM：
— 4 bits/symbol
— 4 bps/Hz

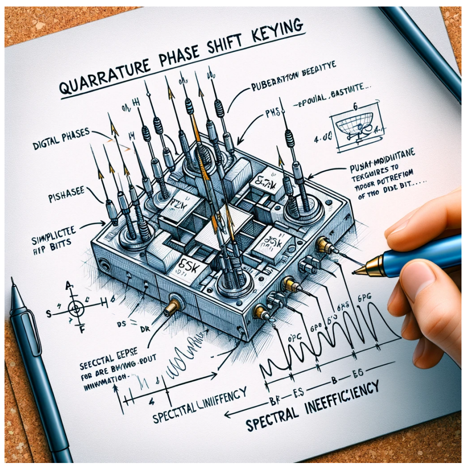
(4 bits are grouped at a time)

64QAM：
— 6 bits/symbol
— 6 bps/Hz

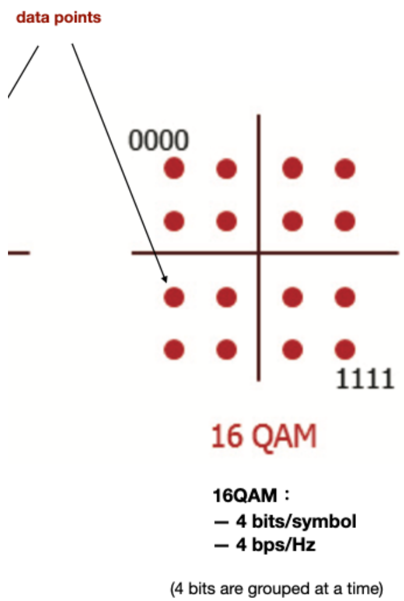
(6 bits are grouped at a time)

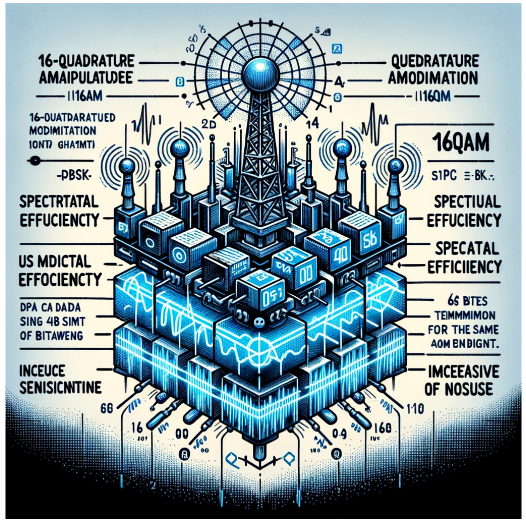
- **QPSK (Quadrature Phase Shift Keying)**
  - A type of digital modulation that uses <u>four phases</u> to encode <u>two bits</u> of info.
  - The simplest and most <u>robust</u> of the three modulation schemes, and is often used in apps where <u>reliability</u> is important, such as in <u>satellite</u> communications
  - The <u>least spectrally efficient</u> of the three modulation schemes, it <u>requires more bandwidth</u> to transmit the same amount of data
    - 2 bits/symbol
    - 2 bits/Hz



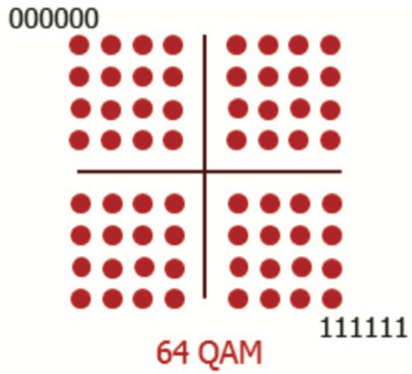


- **16QAM (16 Quadrature Amplitude Modulation)**
    - A type of digital modulation that uses 16 phases to encode four bits of info.
    - More spectrally efficient than QPSK, it can transmit more data using the same amount of bandwidth
        - 4 bits/symbol
        - 4 bits/Hz
    - More sensitive to noise and interference than QPSK



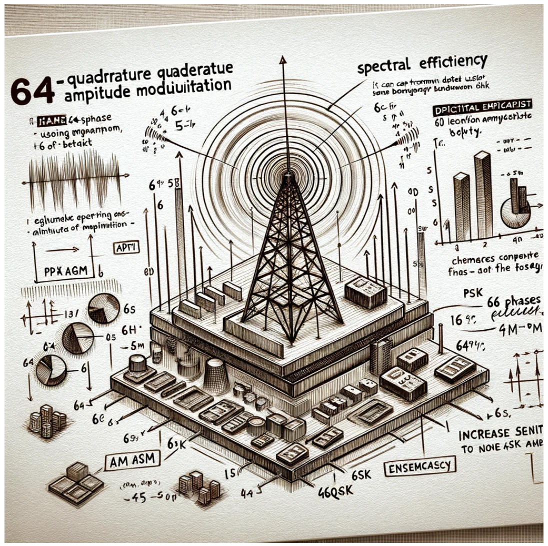


- **64QAM (64 Quadrature Amplitude Modulation)**
    - A type of digital modulation that uses 64 phases to encode six bits of info.
    - The most spectrally efficient of the three modulation schemes, it can transmit the most data using the same amount of bandwidth
        - 6 bits/symbol
        - 6 bits/Hz
    - The most sensitive to noise and interference than QPSK and 16QAM

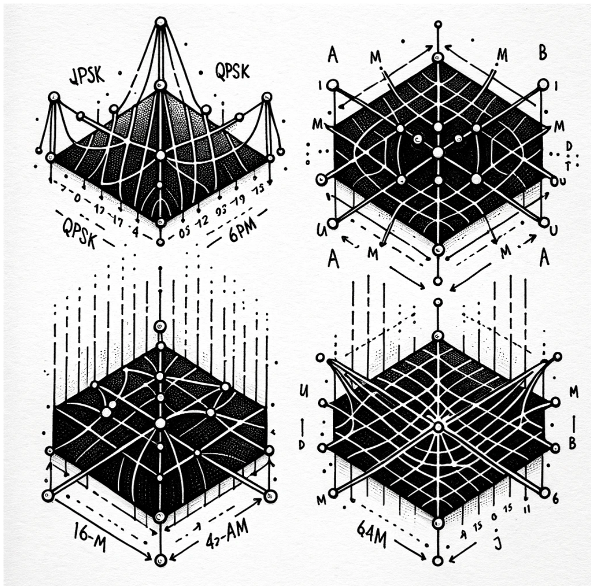


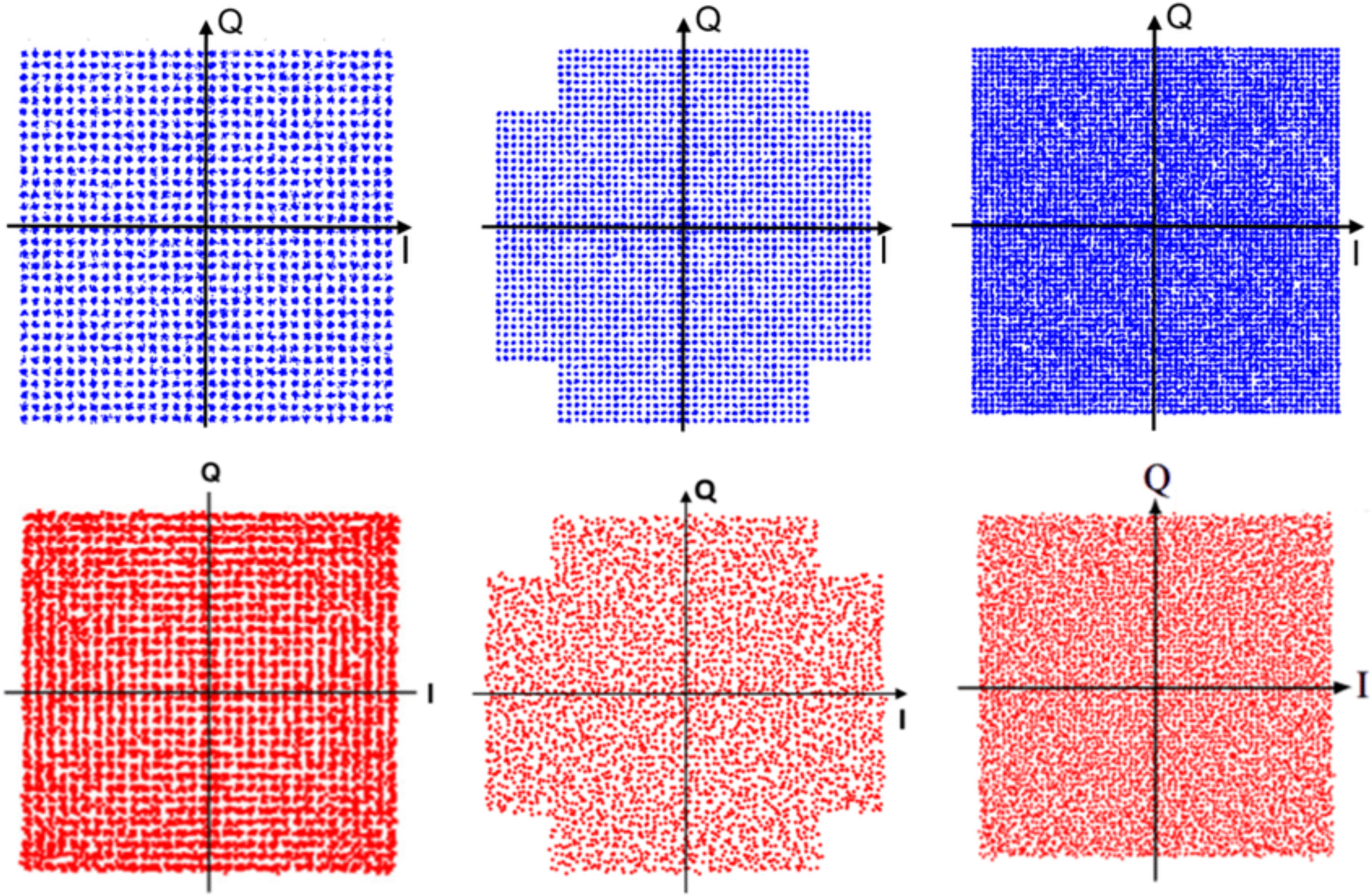
64QAM :
— 6 bits/symbol
— 6 bps/Hz

(6 bits are grouped at a time)



Modulation Scheme	Spectral Efficiency	Sensitivity to Noise/Interference	Complexity
PSK	Low	Low	Low
16QAM	Medium	Medium	Medium
64QAM	High	High	High





10 bits/symbol
10 bits/Hz
1024-QAM
OSNR=27.8 dB

11 bits/symbol
11 bits/Hz
2048-QAM
OSNR=36.5 dB

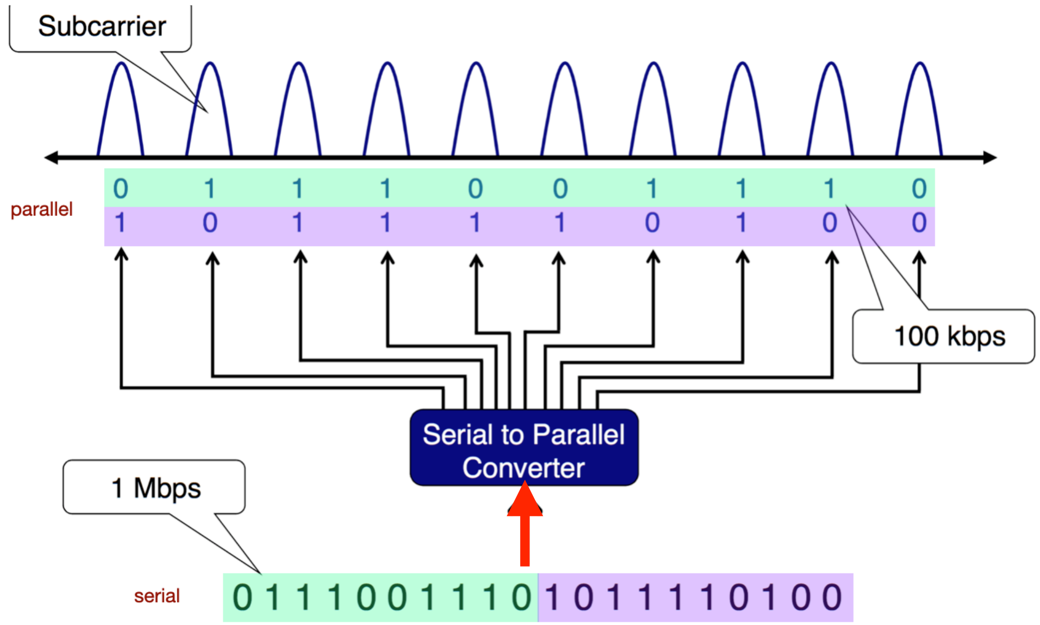
12 bits/symbol
12 bits/Hz
4096-QAM
OSNR=41 dB

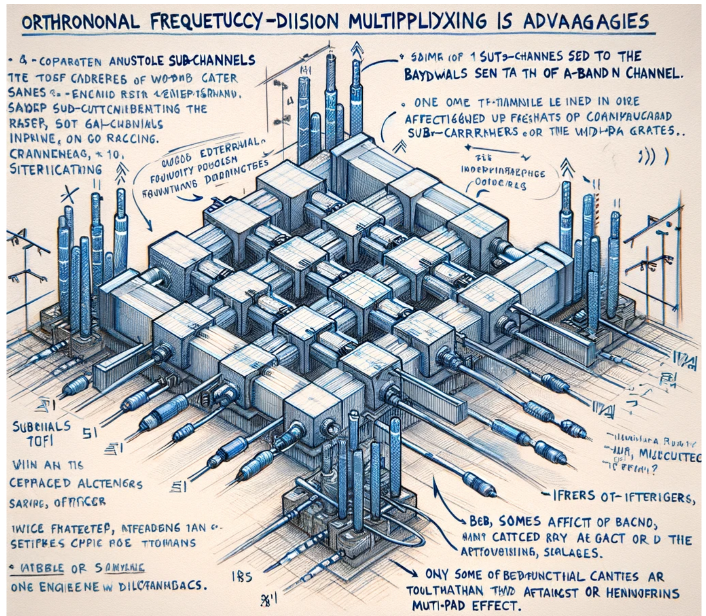
OSRR：Open Split-ring Resonator

Modulation	CNR/MER (dB)	Modulation Efficiency
No Data	<12	0
QPSK	12	2
16 QAM	15.0	4
64 QAM	21.0	6
128 QAM	24.0	7
256 QAM	27.0	8
512 QAM	30.5	9
1024 QAM	34.0	10
2048 QAM	37.0	11
4096 QAM	41.0	12
8192 QAM	46.0	13
16384 QAM	52.0	14

CNR：Carrier to Noise Ratio
MER：Modulation Error Ratio

- Why OFDM is better?
  - Multiple sub-channels (sub-carriers) carry samples sent at a lower rate
  - Almost same bandwidth with wide-band channel
  - Only some of the sub-channels are affected by interferers or multi-path effect

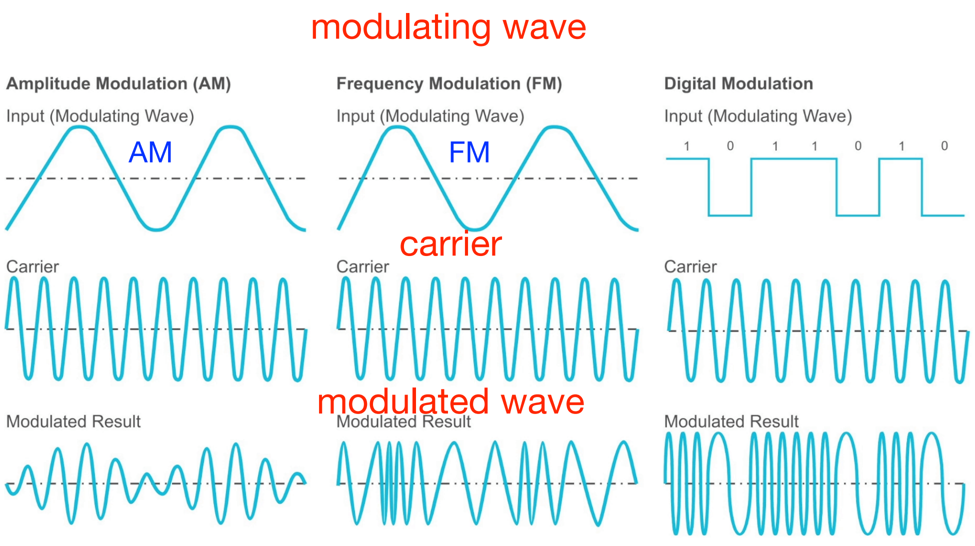




Note：Carrier Wave, Modulation

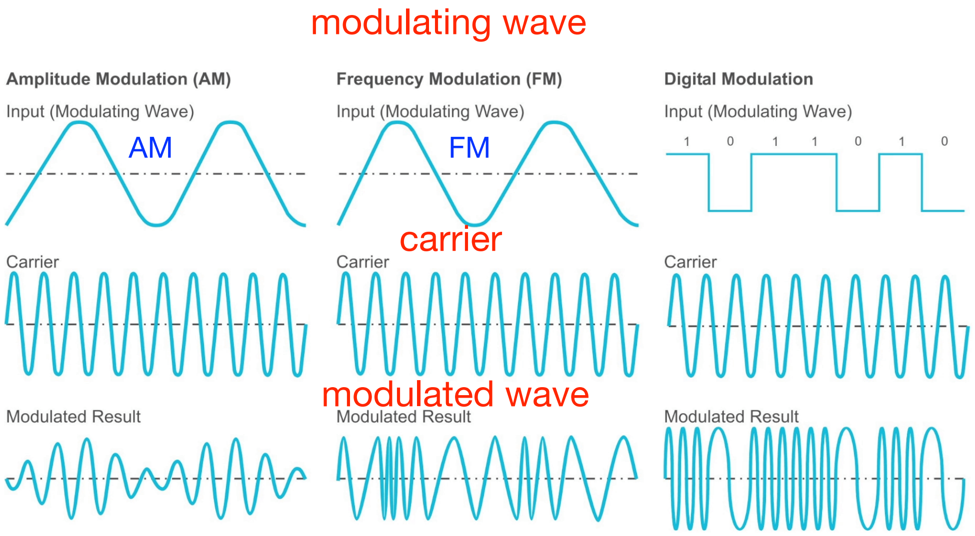
- **Modulating wave (modulating signal)**
  - The original info./message like voice, video, data
  - Low frequency, contains information
  - Modify carrier wave parameter (amplitude, frequency, phase)
- **Carrier wave**
  - A high-frequency vehicle (electromagnetic wave) for the info.
  - Higher frequency than modulating signal, effective propagation
  - Transport modulating signal, altered during modulation

input (modulating wave) + carrier = modulated wave



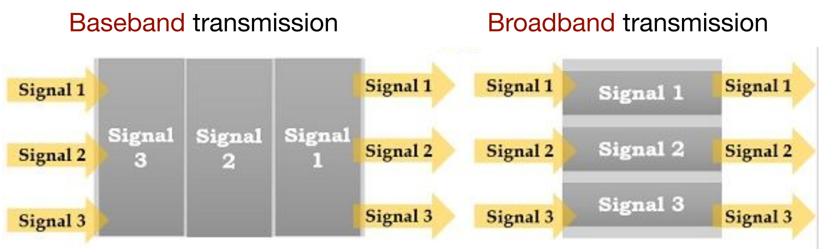
- **Modulation**
  - The process of varying one or more properties (amplitude/frequency/phase) of a periodic waveform (carrier signal), with a modulating signal
- **Modulated wave**
  - Output of modulation, mix of carrier and modulating wave, optimized for transmission
  - Carrier frequency, varied amplitude/frequency/phase
  - Transmitted wave carrying info. in suitable form

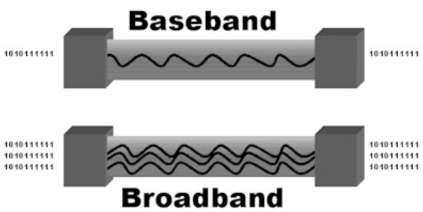
input (modulating wave) + carrier = modulated wave

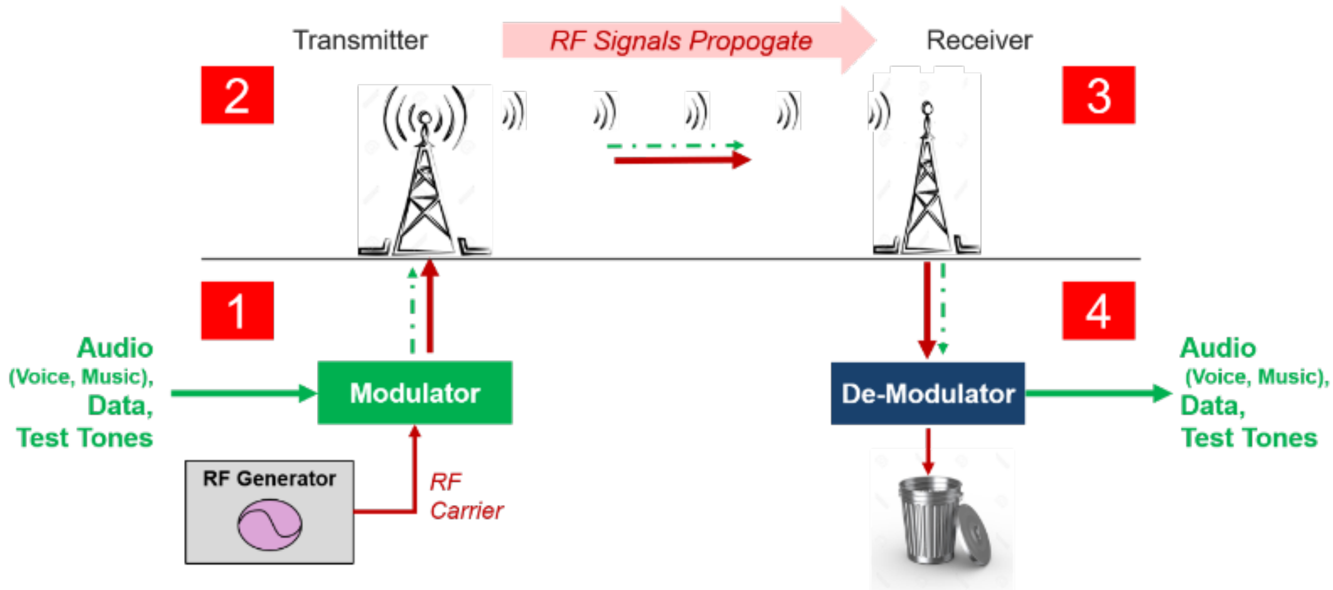


Property	Carrier Wave	Modulation
Purpose	Transport information	Encode information onto carrier wave
Representation	High-frequency electromagnetic wave	Variation of carrier wave's amplitude, frequency, or phase
Analogy	Blank canvas	Painting

- In a communication carrier system
  - **Transmitter**: a carrier wave is modulated by a baseband signal to become a modulated waveform
  - **Receiver**: the baseband info. is extracted from the incoming modulated waveform





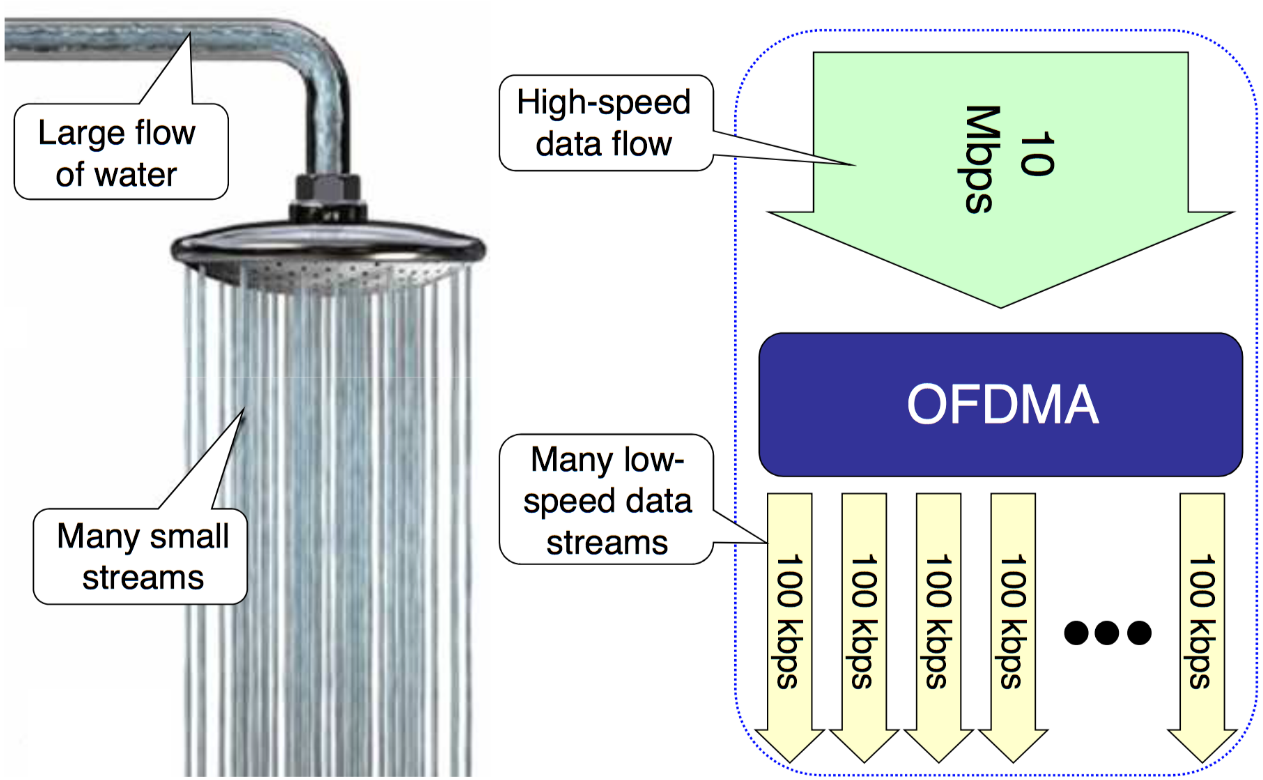


Feature	Baseband Transmission	Broadband Transmission
Signal	Unmodified	Modulated or encoded
Distance	Short	Long
Channels	Single	Multiple
Applications	Short-distance communication	Long-distance communication

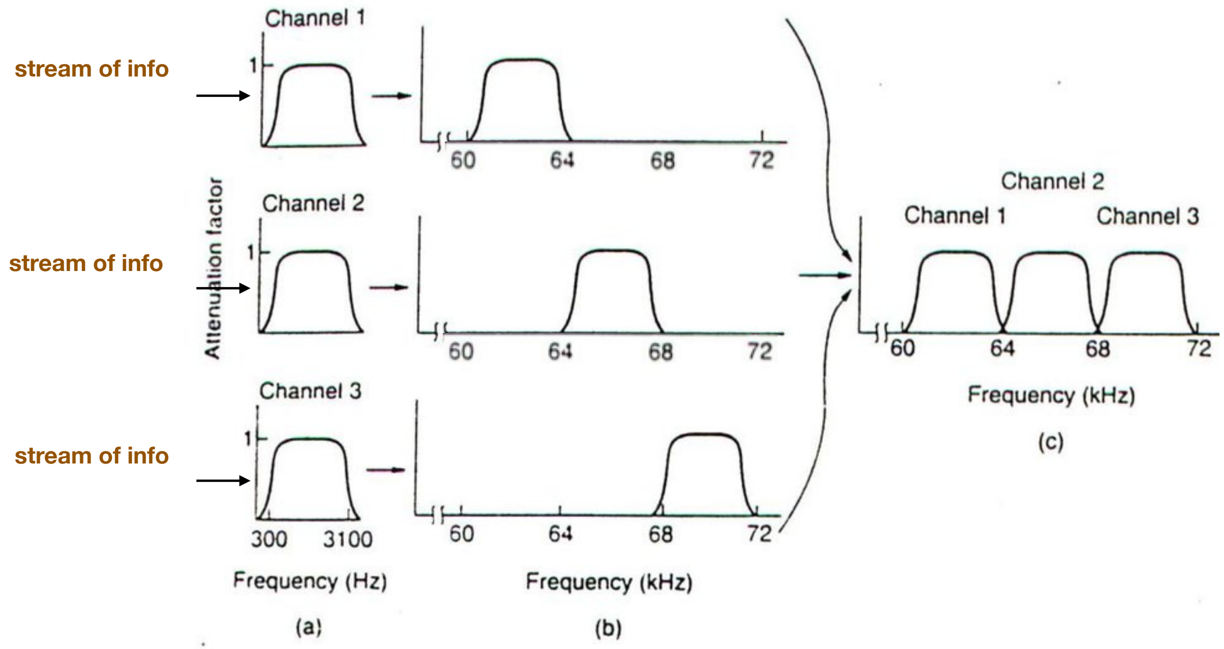
Feature	Transmitter	Receiver
Function	Encodes, amplifies, and filters information to transmit it over a channel	Detects, demodulates, amplifies, and decodes the transmitted signal to recover the original information
Input	Information	Electromagnetic signal
Output	Electromagnetic signal	Information
Direction of signal flow	From transmitter to receiver	From receiver to transmitter

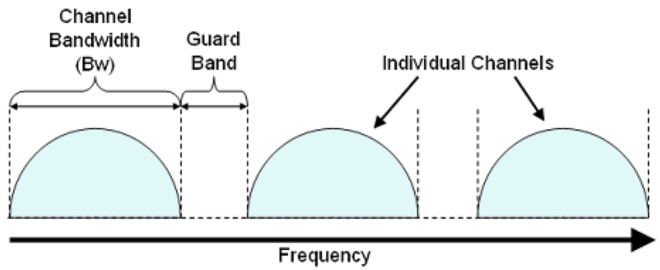
OFDM (Cont.)

- The <u>combination of many subcarriers</u> enables data rates similar to conventional single-carrier modulation schemes within <u>equivalent bandwidths</u>

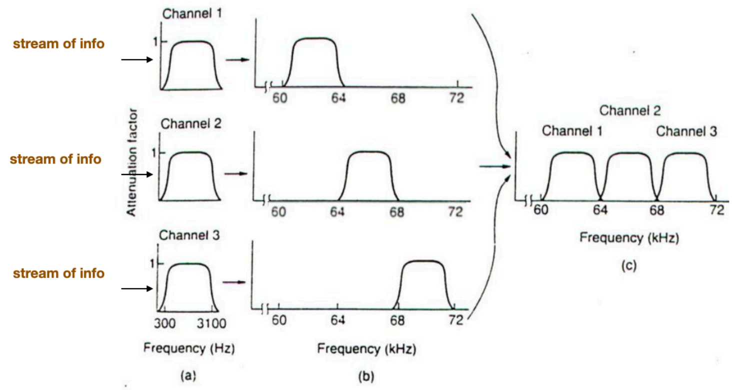


- OFDM is based on Frequency Division Multiplexing (FDM)
- Each stream of info. is allocated a specific frequency band, called a channel
- Each FDM channel is separated from the others by a frequency guard band to reduce interference between adjacent channels
- In FDM multiple info. streams are transmitted simultaneously on separate parallel frequency channels

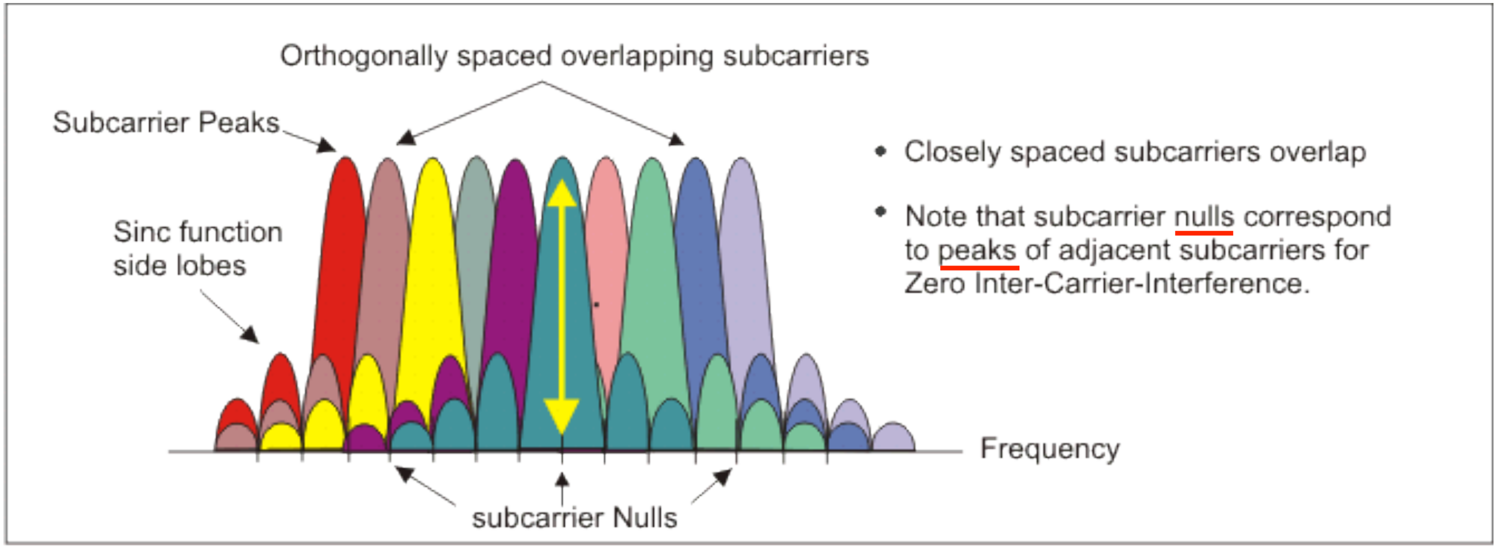




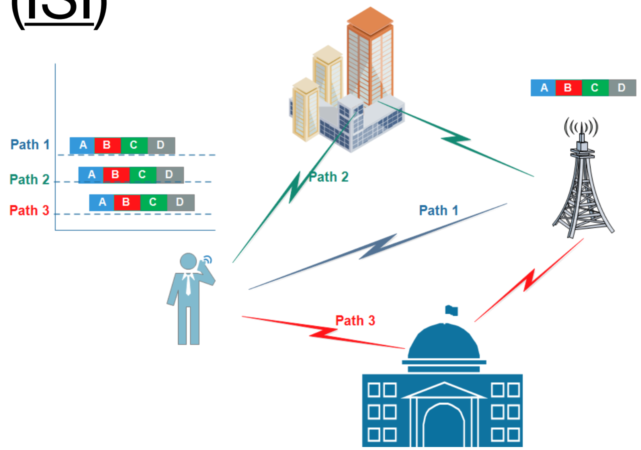
- Each channel has an attenuation factor which is ideally uniform across the channel's bandwidth but drops to zero at the channel's edges to avoid interference with adjacent channels
  - Diagram (a): Individual channels with their respective frequency bands and attenuation factors
  - Diagram (b): Each channel maintains a distinct frequency range with no overlap between the channels
  - Diagram (c): The combined frequency spectrum with three channels positioned adjacent to each other, demonstrating how FDM allocates spectrum resources among multiple data streams

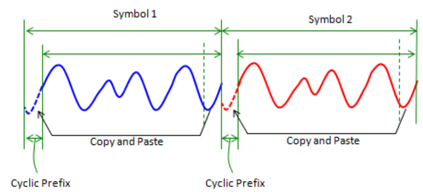


- OFDM scheme differs from traditional FDM in the following interrelated ways
  - Multiple carriers (called subcarriers) carry the info. stream
  - The subcarriers are orthogonal to each other
  - A guard interval (Cyclic Prefix) is added to each symbol to minimize the channel delay spread and intersymbol interference (ISI)

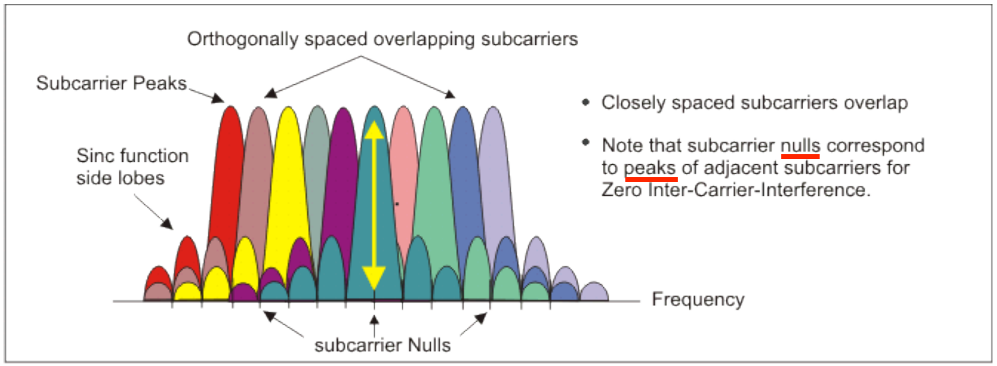


OFDM Signal Frequency Spectra





- The figure visualizes how OFDM efficiently transmits data over multiple subcarriers without interference
    - Orthogonally spaced overlapping subcarriers: Subcarriers are transmitted at different frequencies with spacing such that one's peak aligns with another's null to prevent interference
    - Subcarrier peaks: The highest signal strength points on each subcarrier where data is ideally transmitted



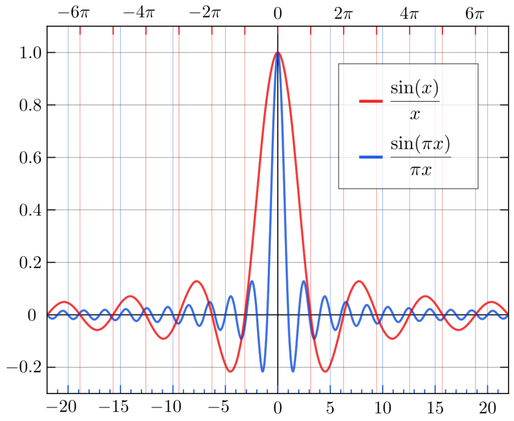
OFDM Signal Frequency Spectra

- Sinc function side lobes: The subcarrier signals exhibit side lobes (secondary peaks of a signal) that decay from the peak, characteristic of a sinc function, with some overlap due to frequency packing

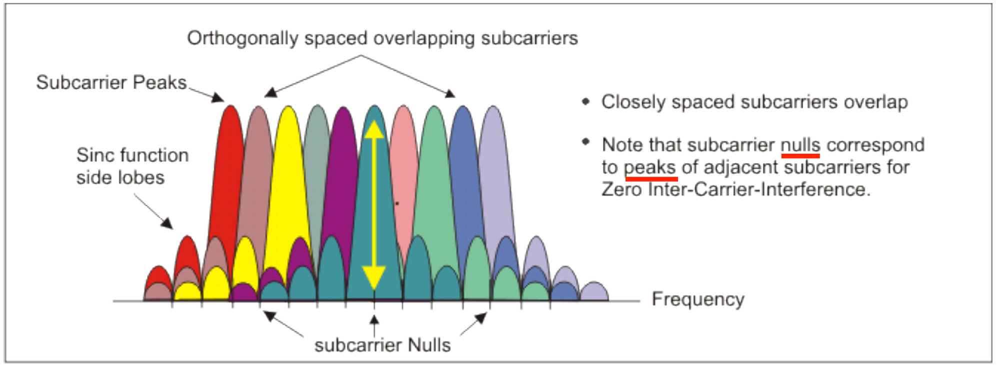
- Subcarrier nulls: Points of zero signal strength on a subcarrier, aligned with adjacent subcarrier peaks to avoid inter-carrier interference (ICI)

- Closely spaced subcarriers overlap: Despite the close proximity of subcarriers, the orthogonal design prevents interference, enabling a high data rate

- Zero inter-carrier-interference: A critical OFDM feature where subcarrier design eliminates interference for clear transmission

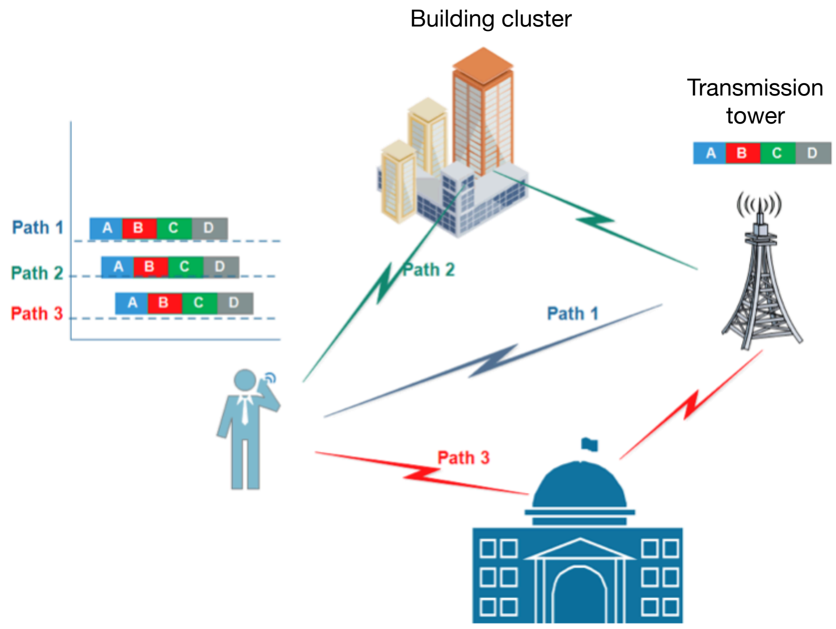


Sinc function

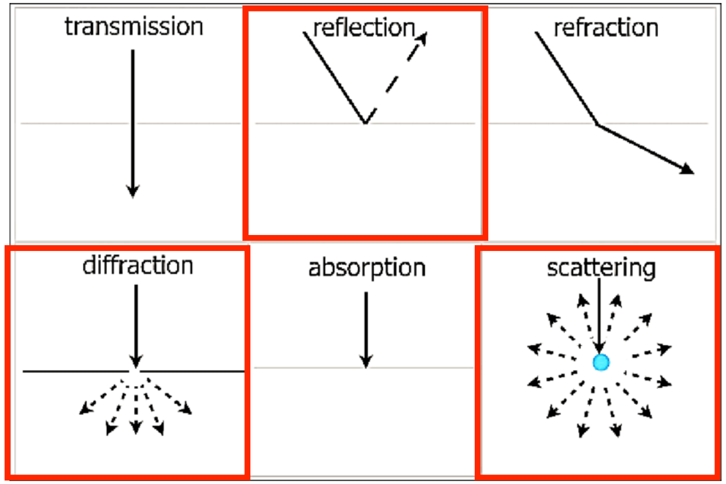


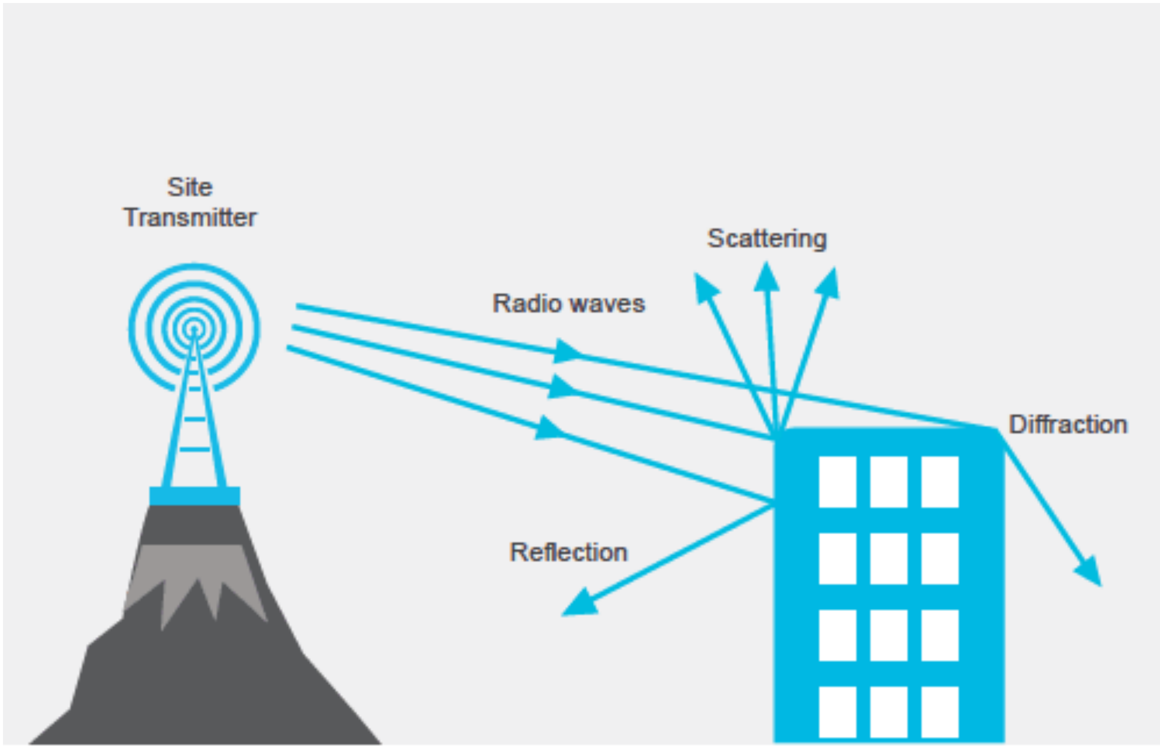
OFDM Signal Frequency Spectra

- Multipath effect
  - Transmission tower: Source <u>emitting</u> radio waves to the UE
  - UE: Receiver of the signal from the transmission tower
  - Building cluster: Obstacles that can <u>reflect</u> or <u>diffract</u> the signal
  - Path 1: Direct line-of-sight (LOS) path with the <u>least delay</u>
  - Path 2 and Path 3: Longer paths with signals <u>reflected</u> off buildings, causing <u>delays</u>
  - Signal block diagrams: Data represented by blocks A, B, C, D, showing <u>time delay</u> and <u>phase shift</u> due to path length differences

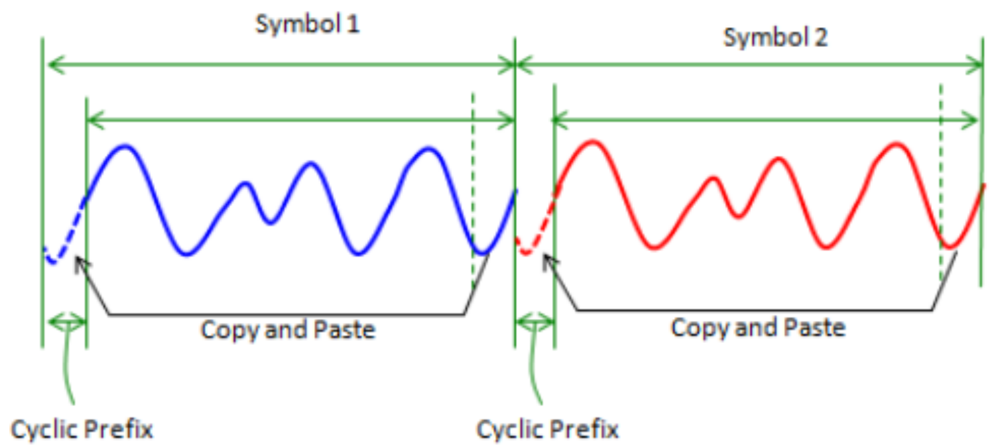


- **Multipath effect**: Signals reach the receiver via multiple paths due to reflections, diffractions, and scattering

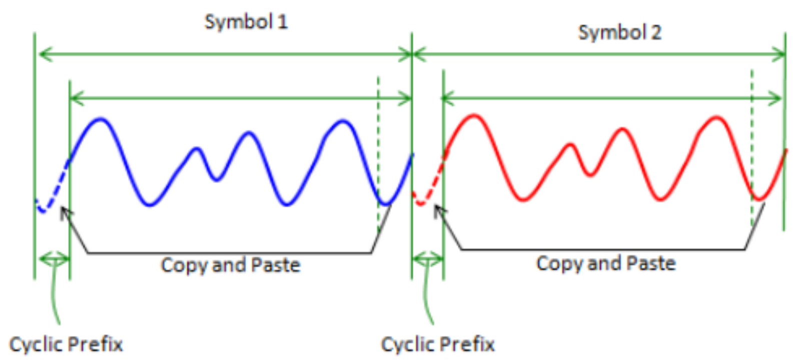




- **Intersymbol Interference (ISI)**
  - A phenomenon where signals from one symbol interfere with another, common in closely timed symbol transmissions
  - Symbols: Data blocks sent over a channel, depicted in different colors (blue for Symbol 1, red for Symbol 2) for distinction

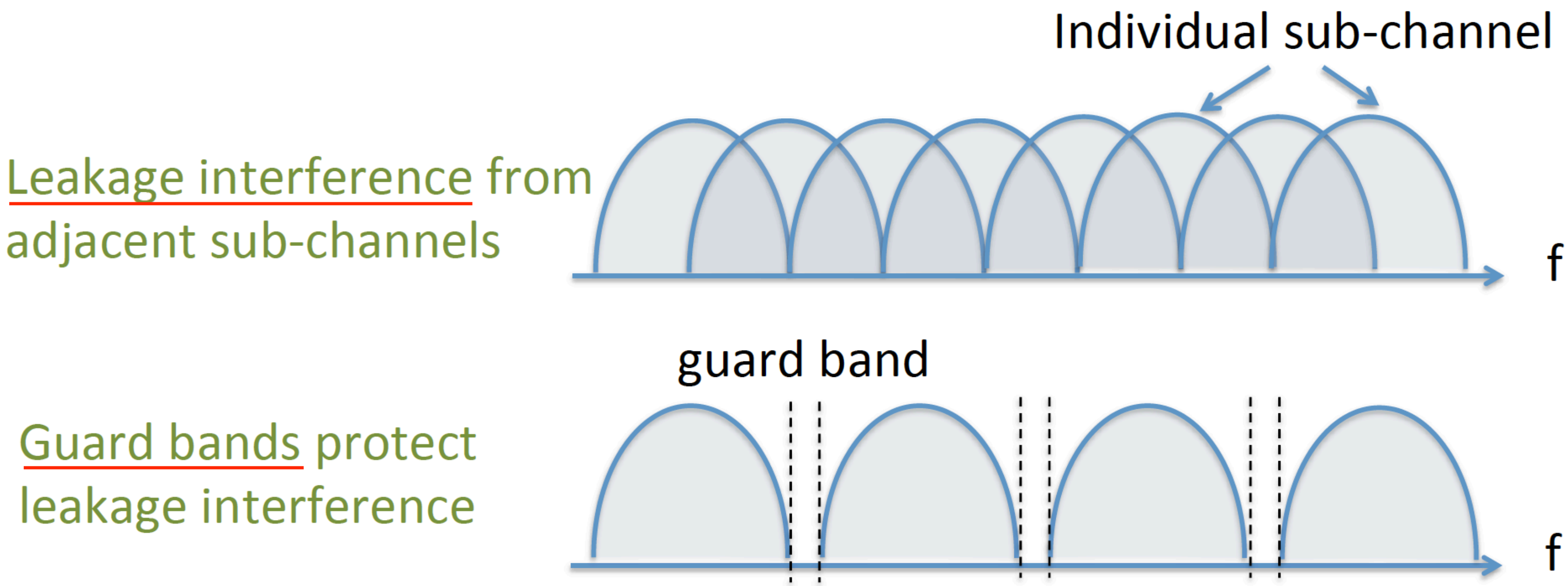


- **Cyclic Prefix (CP)**
    - A duplicated end segment of a symbol placed at its beginning to prevent ISI in OFDM systems
    - CP as a duplicated section of the symbol waveform, preventing symbol overlap
    - CP absorbs any signal spread from the previous symbol, caused by multipath propagation, to prevent interference with the current symbol
    - CP length: Selected based on the expected max multipath delay to ensure it's longer than the channel's impulse response, mitigating ISI



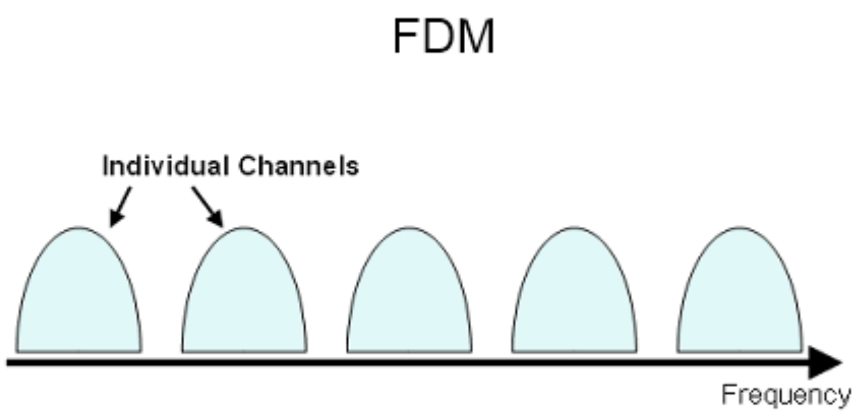
Importance of Orthogonality

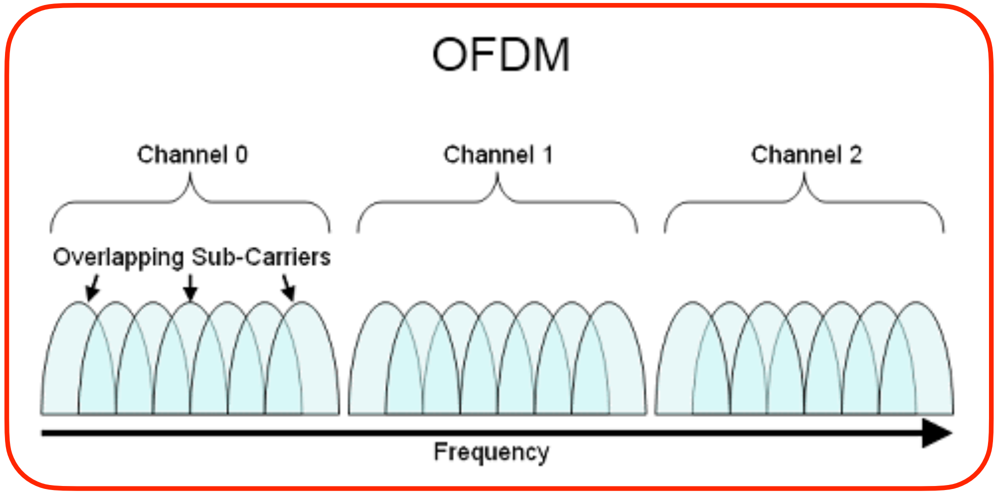
- Why not just use FDM (Frequency Division Multiplexing) → **Not orthogonal**



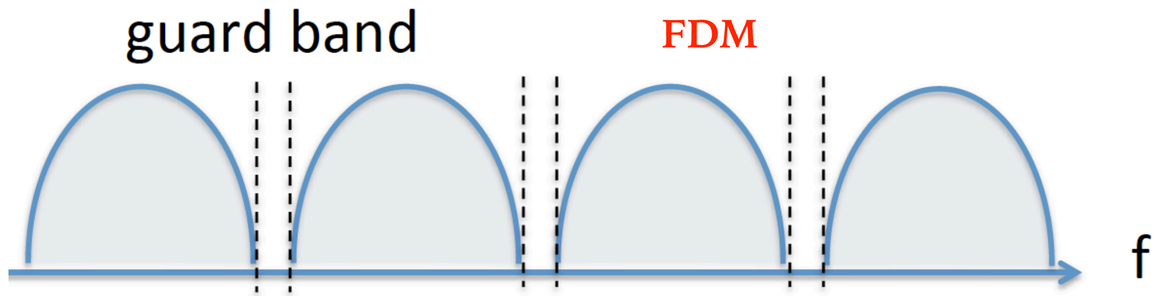
- Need <u>guard bands</u> between adjacent frequency bands → <u>extra overhead</u> and <u>lower throughput</u>

- OFDM is a modulation format that achieves
  - <u>High data throughput</u> by transmitting on hundreds or thousands of carriers simultaneously
  - <u>High spectral efficiency</u> by spacing the carriers very closely

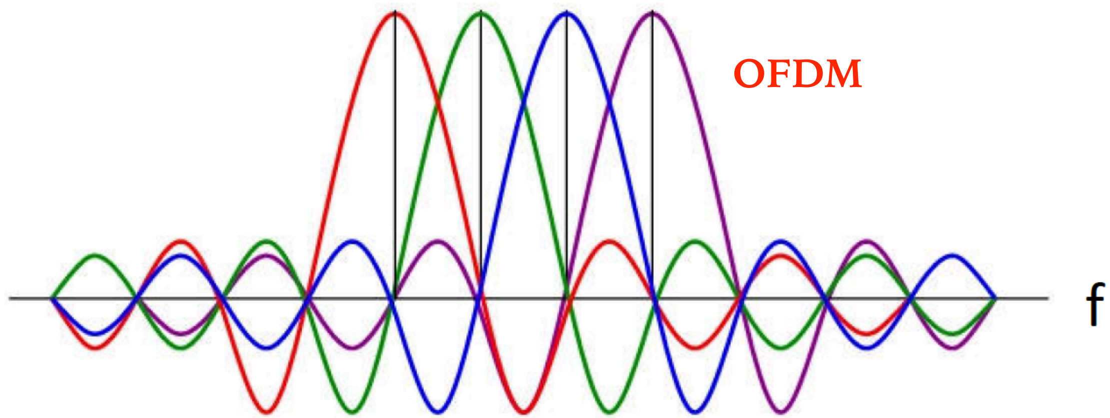




Difference between FDM and OFDM

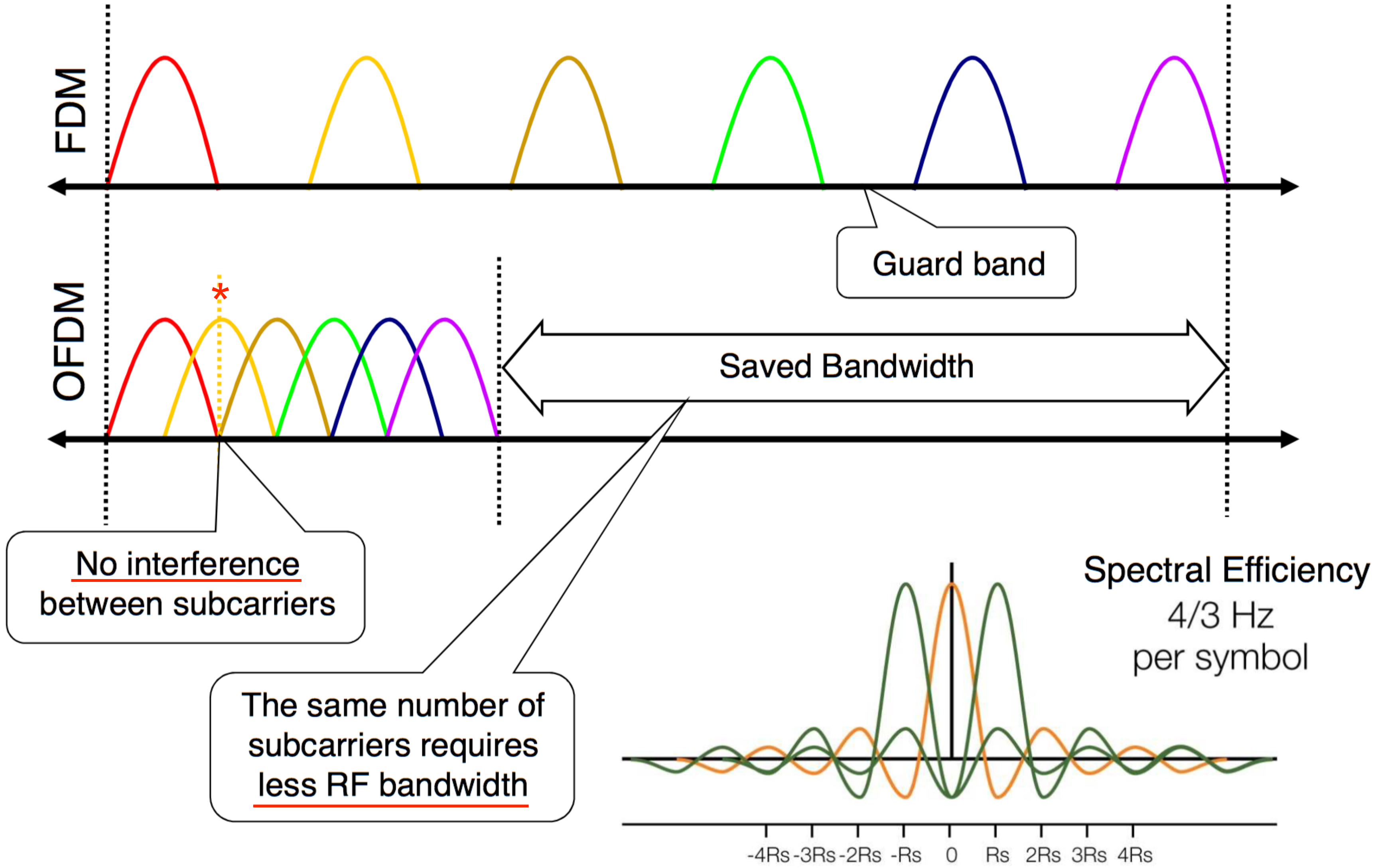


Frequency division multiplexing



Orthogonal sub-carriers in OFDM

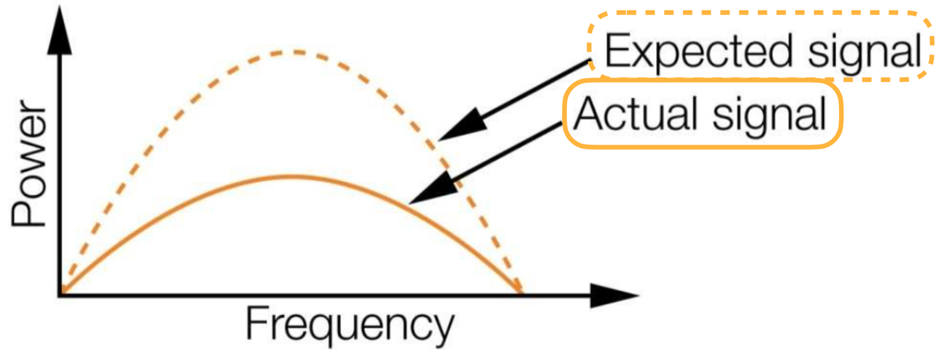
Don’t need guard bands



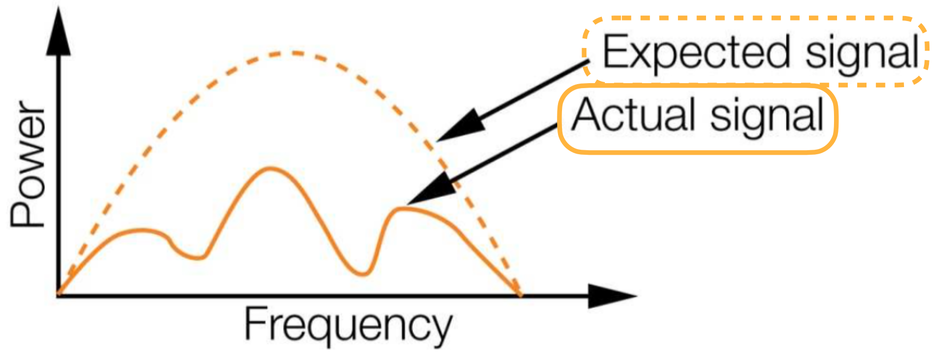
FDM
OFDM
*
Guard band
Saved Bandwidth
No interference
between subcarriers
The same number of
subcarriers requires
less RF bandwidth
Spectral Efficiency
4/3 Hz
per symbol
-4Rs -3Rs -2Rs -Rs 0 Rs 2Rs 3Rs 4Rs

Flat Fading vs. Frequency Selective Fading

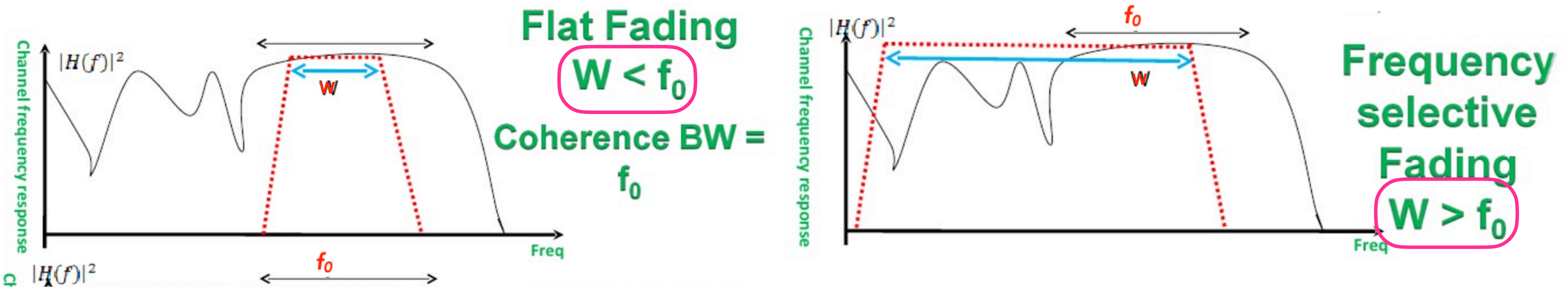
Flat Fading



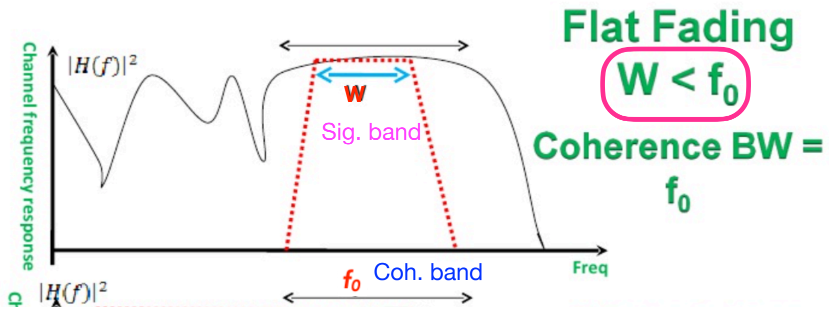
Frequency Selective Fading



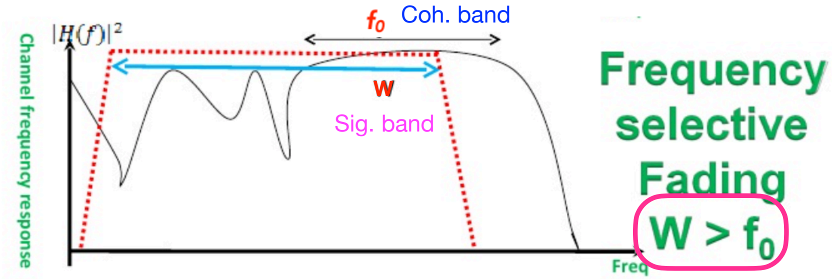
- **Coherence bandwidth**
  - A statistical measurement of the range of frequencies over which the channel can be considered “flat"
  - The approximate max bandwidth or frequency interval over which two frequencies of a signal are likely to experience comparable or correlated amplitude fading



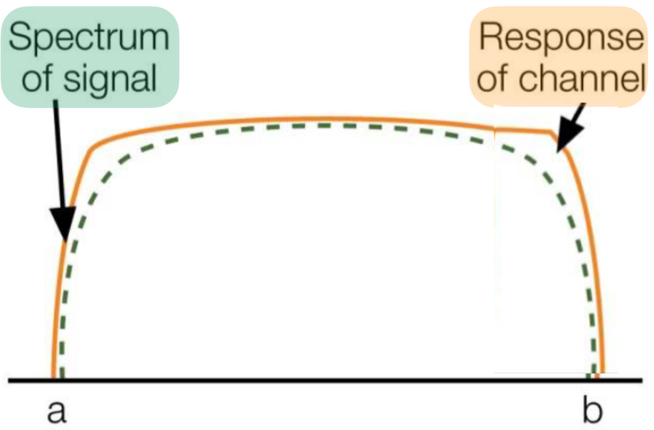
- **Flat fading**
  - The coherence bandwidth (f_0) of the channel is larger than the bandwidth of the signal (W)
  - All frequency components of the signal will experience the same magnitude of fading

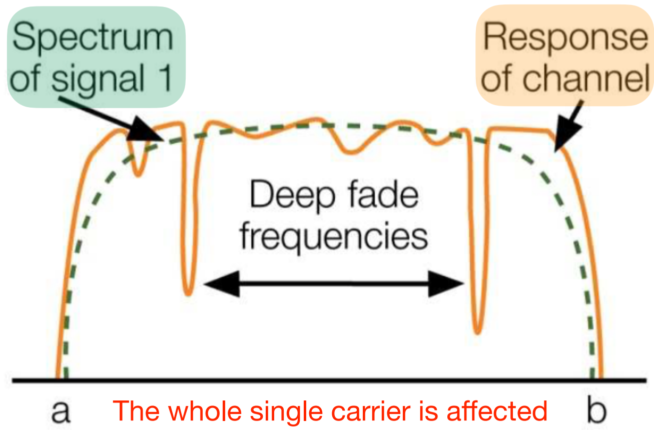


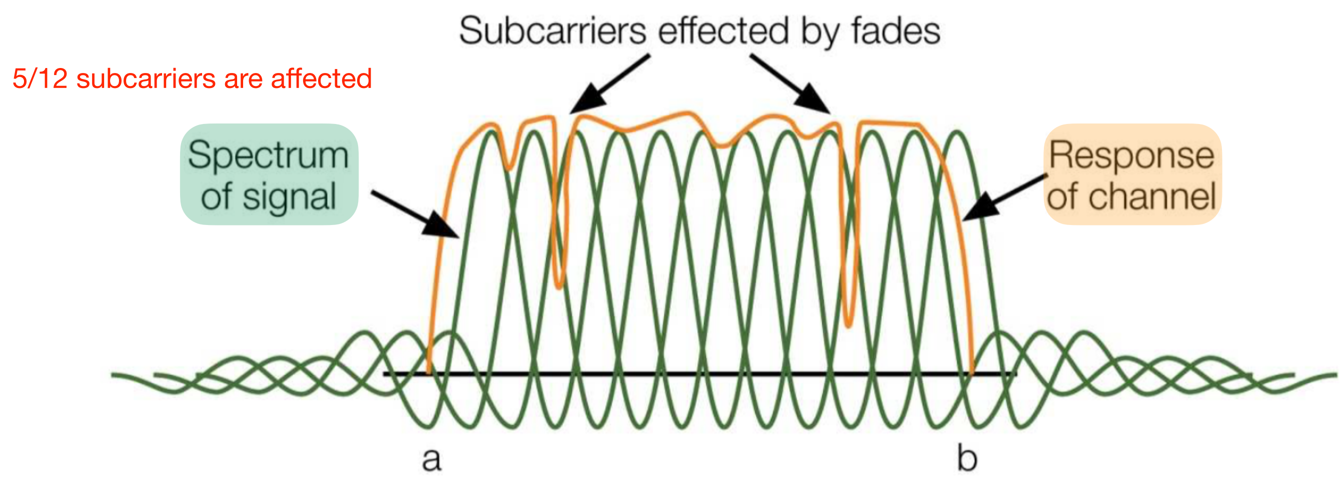
- **Frequency-selective fading**
  - The coherence bandwidth (f_0) of the channel is smaller than the bandwidth of the signal (W)
  - Different frequency components of the signal therefore experience uncorrelated fading



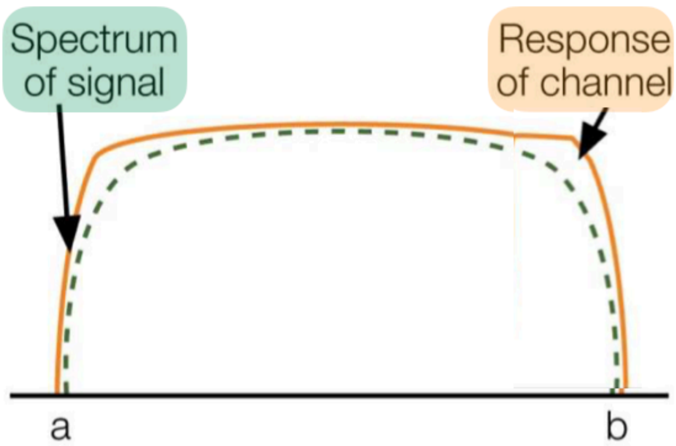
OFDM Minimizing the Impact of Multipath Induced ISI



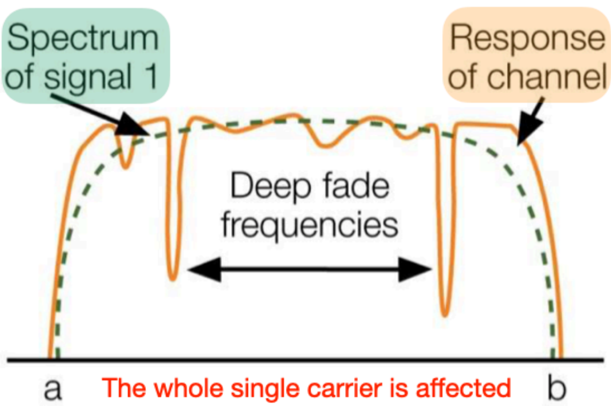


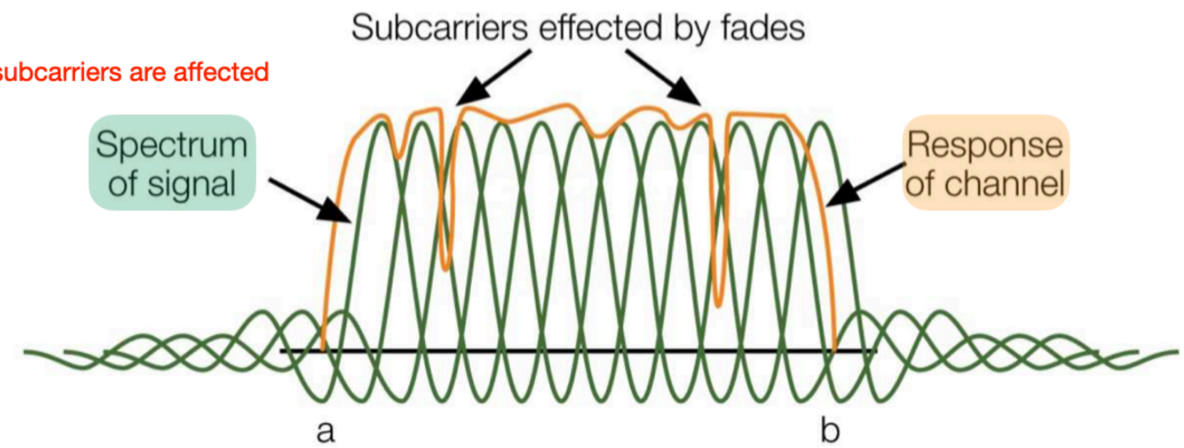


- **Single carrier system**
  - Represent frequency spectrum of a single carrier signal
  - The figure shows channel response with deep fade affecting the entire signal
  - Deep fades can lead to significant signal impact and data loss

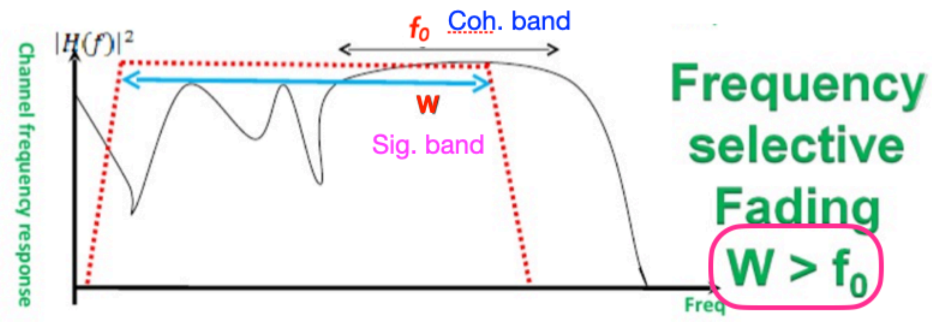


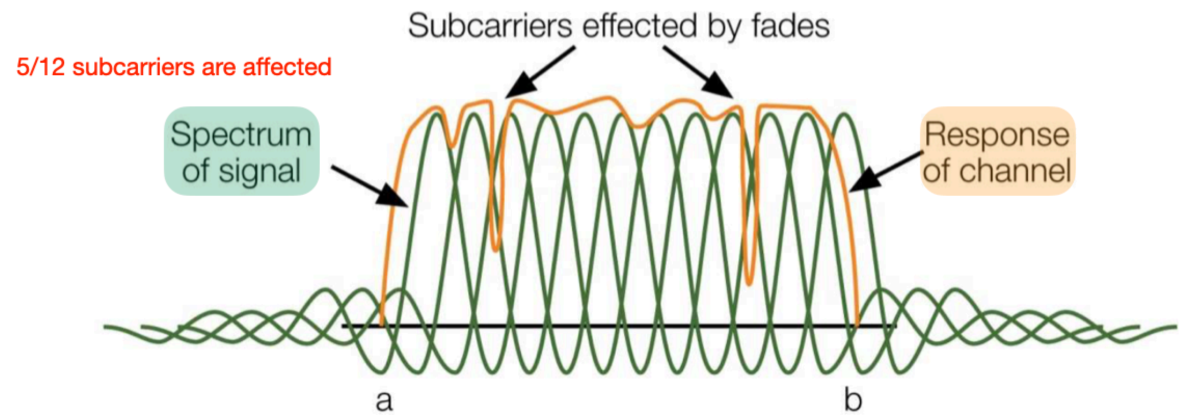
- **OFDM System**
  - Left: one subcarrier within an OFDM system
  - Right
    - Multiple subcarriers each with a narrowband spectrum
    - Channel response indicates only some subcarriers are affected by fades
    - Notes that 5 out of 12 subcarriers are affected by fading



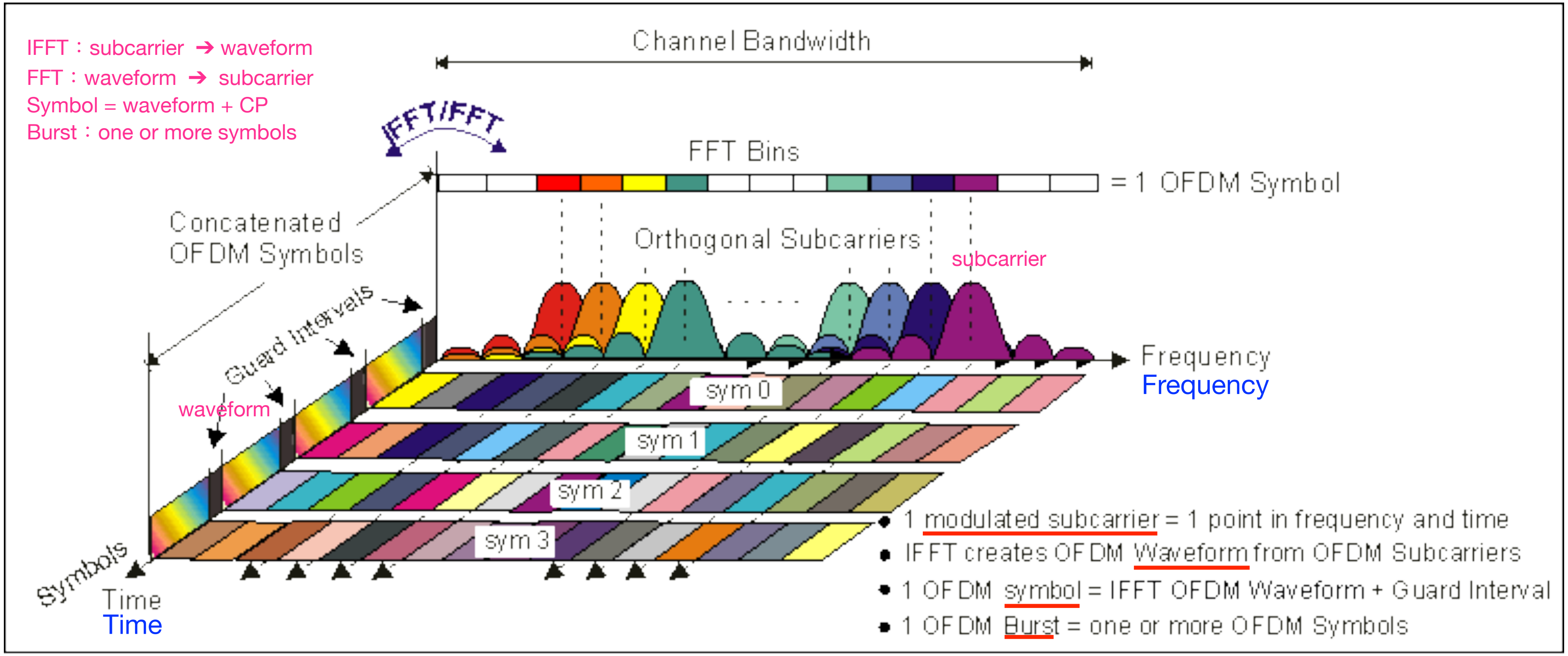


- **Advantages of OFDM**
  - More <u>robust</u> against <u>frequency-selective</u> fading
  - Allow <u>effective error correction</u> on the <u>fewer</u> affected subcarriers
  - Use <u>multiple subcarriers</u> for data reconstruction despite deep fades





OFDM Structure
(Time and Frequency Domain)



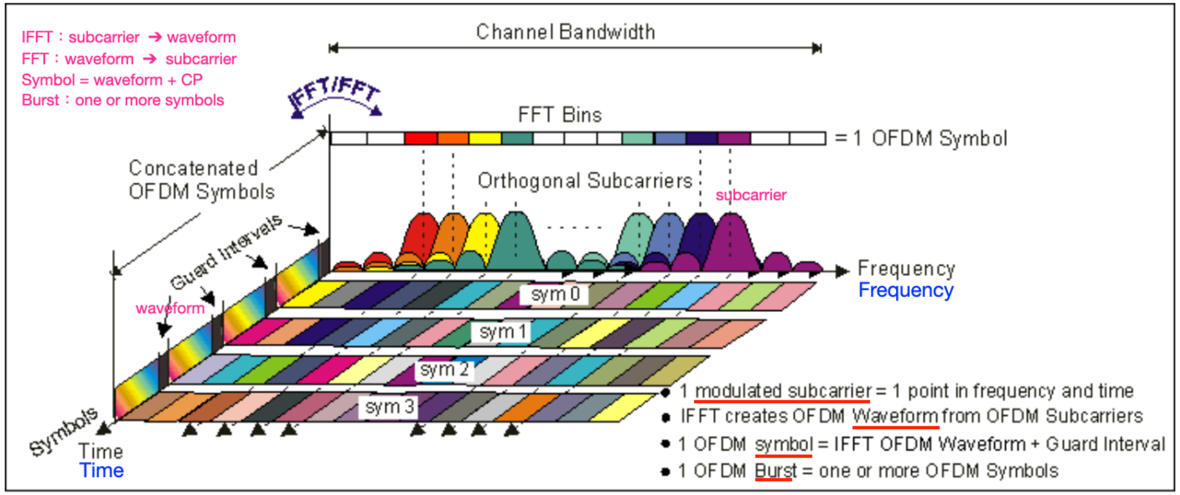
Frequency-Time Representative of an OFDM signal

IFFT：converts <u>frequency</u> domain vector signal to <u>time</u> domain vector signal

FFT：converts <u>time</u> domain vector signal to <u>frequency</u> domain vector signal

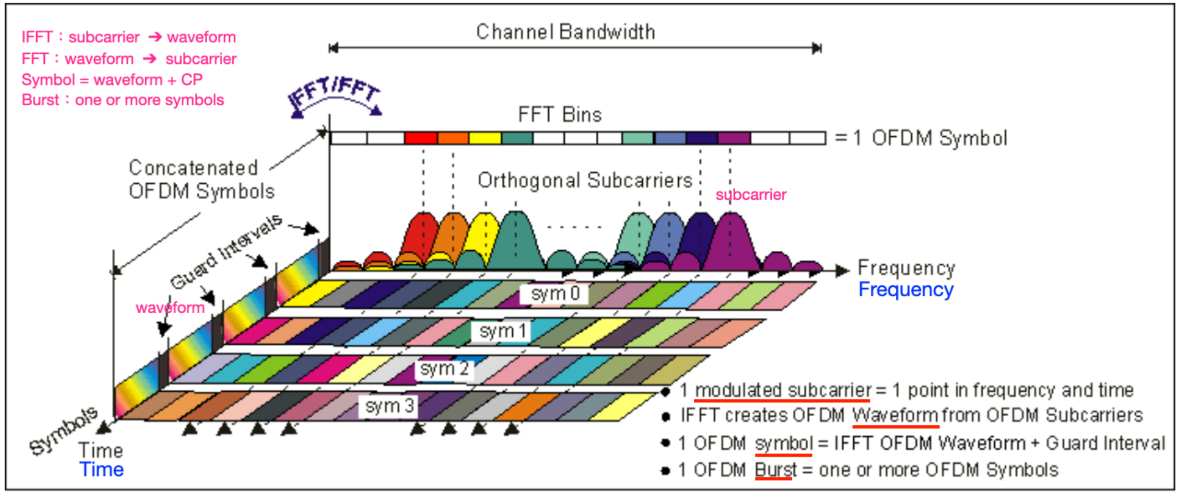
Guard Interval：Cyclic Prefix

- **Time domain (horizontal axis)**
  - Multiple OFDM symbols over time
  - Each symbol includes a waveform from IFFT on subcarriers plus a guard interval
  - Guard intervals prevent ISI due to multipath propagation
  - A burst is a sequence of one or more OFDM symbols



IFFT：converts frequency domain vector signal to time domain vector signal
FFT：converts time domain vector signal to frequency domain vector signal
Guard Interval：Cyclic Prefix

- **Frequency domain (vertical axis)**
  - The OFDM signal's structure in frequency
  - Subcarriers are independently modulated and orthogonal to prevent interference
  - "Orthogonal" means zero cross-correlation at receiver sampling points

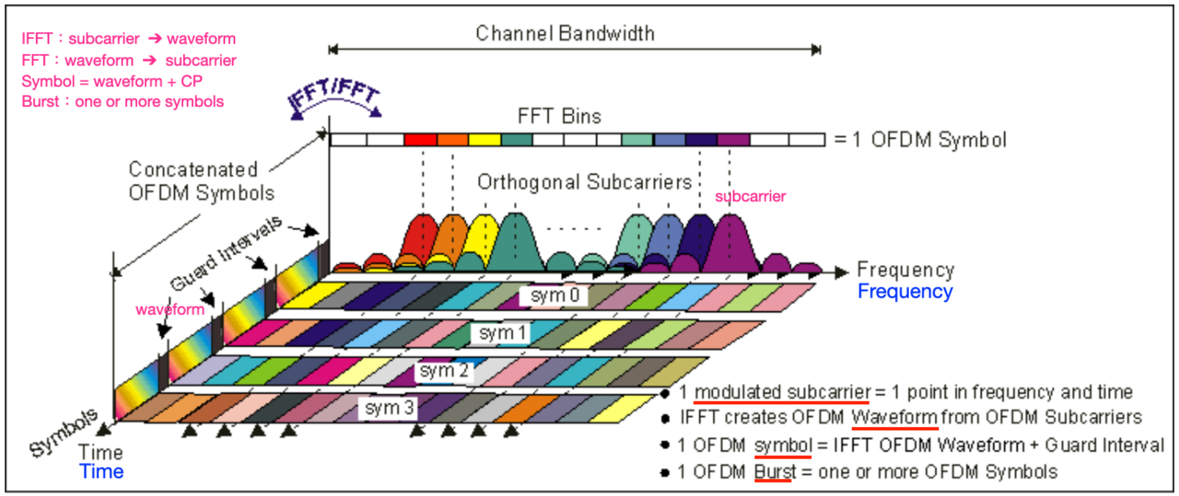


IFFT : converts frequency domain vector signal to time domain vector signal

FFT : converts time domain vector signal to frequency domain vector signal

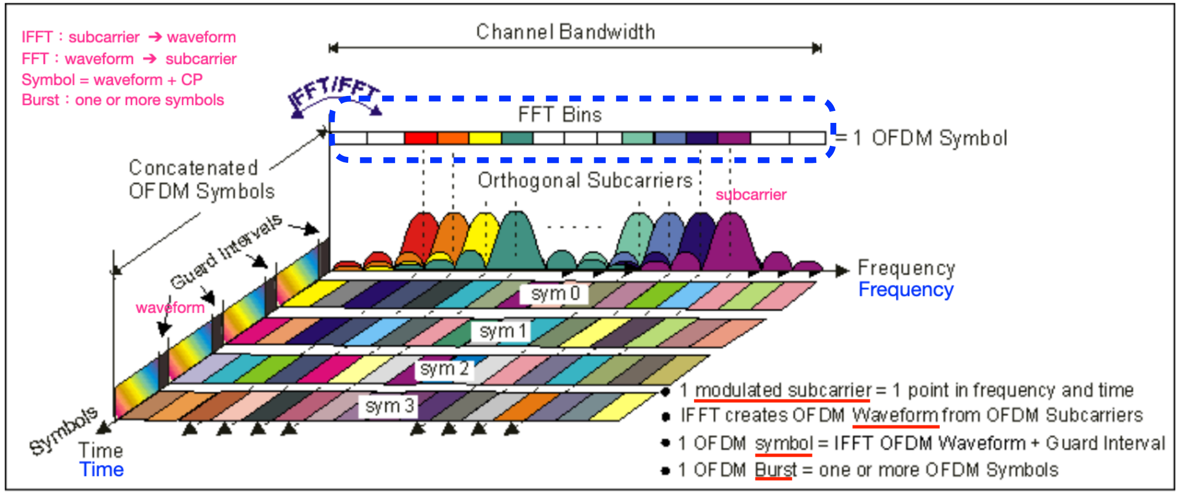
Guard Interval : Cyclic Prefix

- **Frequency-time grid**
  - <u>3D grid</u> represents time and frequency dimensions of OFDM
  - Each layer is an <u>OFDM symbol</u>; each column is a <u>modulated subcarrier</u>



IFFT：converts <u>frequency</u> domain vector signal to <u>time</u> domain vector signal
FFT：converts <u>time</u> domain vector signal to <u>frequency</u> domain vector signal
Guard Interval：Cyclic Prefix

- **FFT bins and channel bandwidth**
  - FFT bins are shown across channel bandwidth
  - Each bin corresponds to a subcarrier carrying data
  - Number of bins is determined by FFT size, which relates to bandwidth



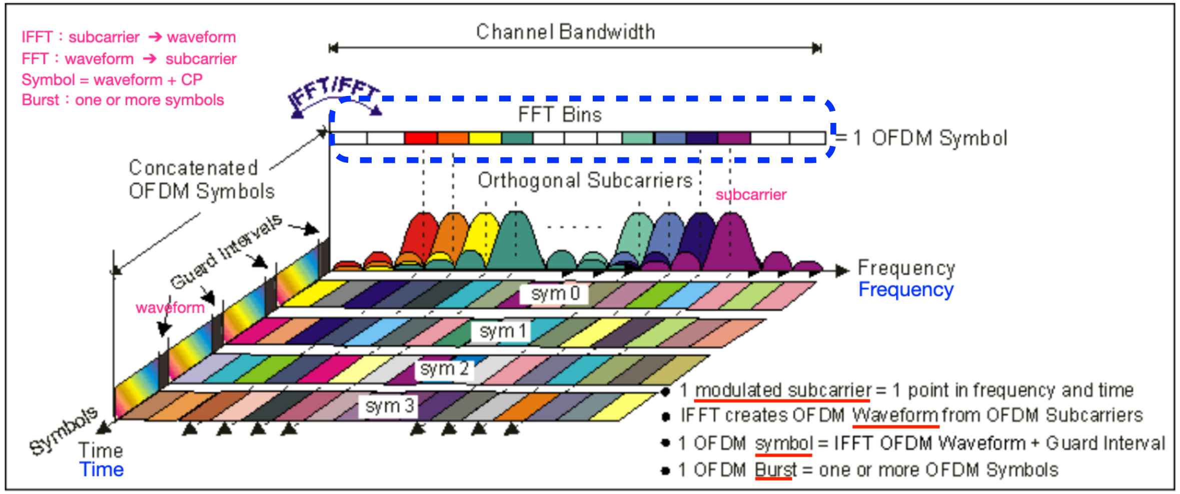
IFFT : converts frequency domain vector signal to time domain vector signal
FFT : converts time domain vector signal to frequency domain vector signal
Guard Interval : Cyclic Prefix

- **IFFT and FFT**

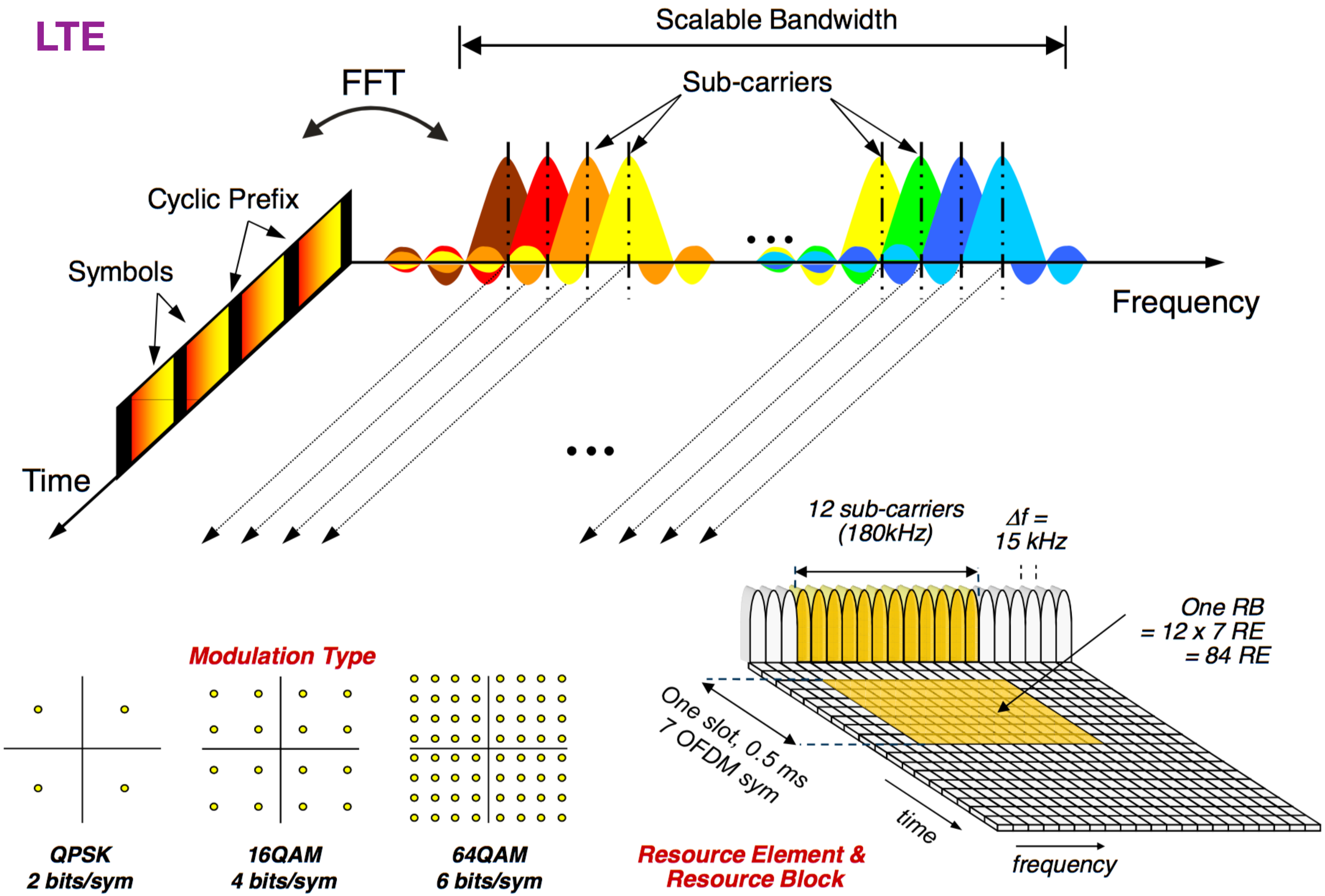
IFFT：frequency domain to time domain
FFT：time domain to frequency domain

  - IFFT (at transmitter) converts subcarriers to <u>time</u>-domain waveform

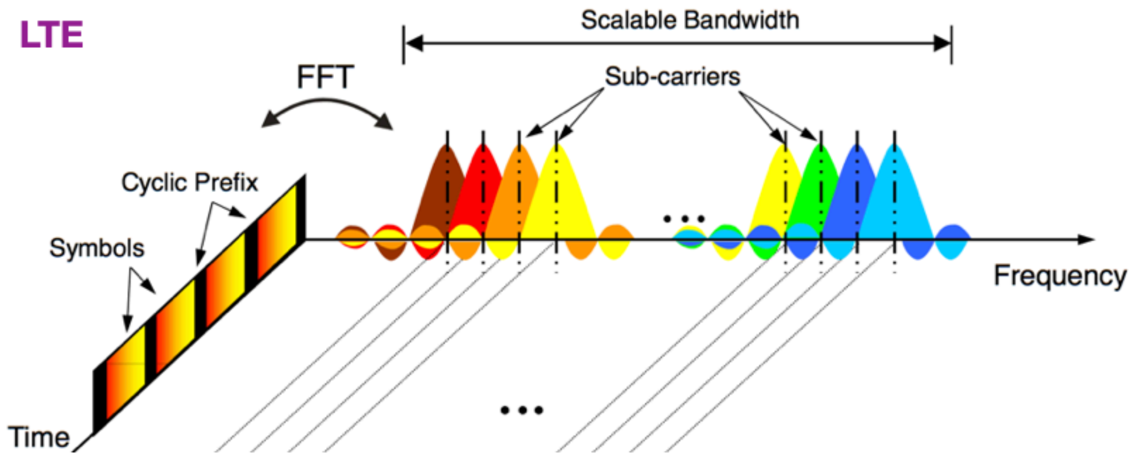
  - FFT (at receiver) converts received waveform back to subcarrier <u>frequencies</u> for <u>demodulation</u>



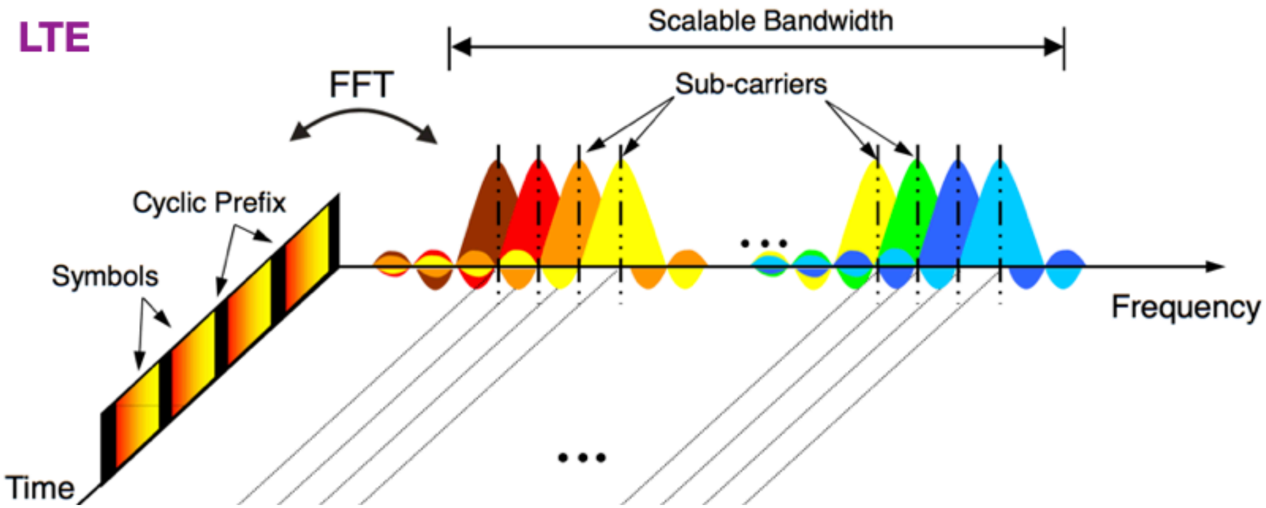
IFFT：converts <u>frequency</u> domain vector signal to <u>time</u> domain vector signal
FFT：converts <u>time</u> domain vector signal to <u>frequency</u> domain vector signal
Guard Interval：Cyclic Prefix


LTE
Scalable Bandwidth
FFT
Sub-carriers
Cyclic Prefix
Symbols
Frequency
Time
12 sub-carriers
(180kHz)
Δf =
15 kHz
One RB
= 12 x 7 RE
= 84 RE
Modulation Type
One slot, 0.5 ms
7 OFDM sym
time
frequency
QPSK
2 bits/sym
16QAM
4 bits/sym
64QAM
6 bits/sym
Resource Element &
Resource Block

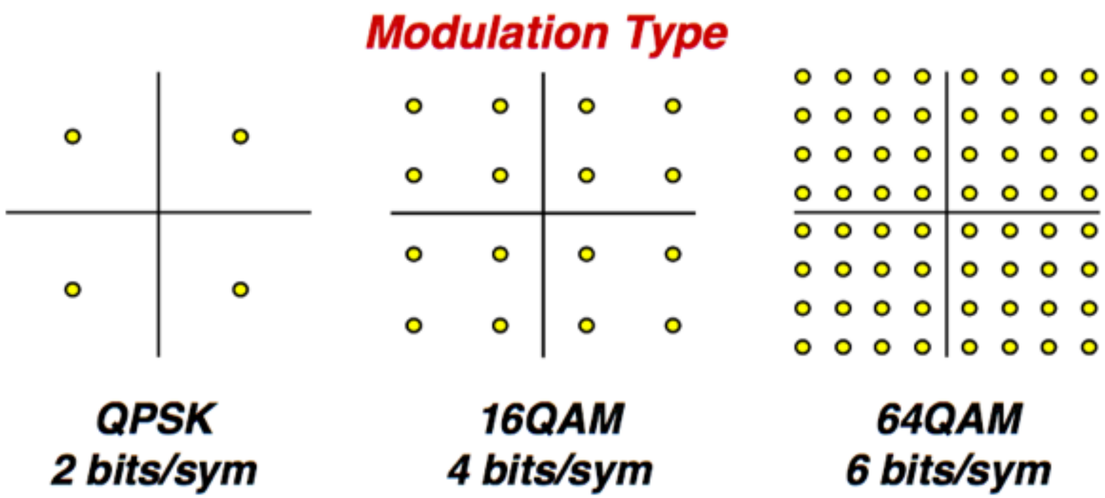
- LTE use OFDM for data transmission, resource allocation, and modulation to enhance network performance
- **Time and frequency representation**
  - The diagram shows OFDM symbols over time and frequency
  - Vertical axis is time; horizontal axis is frequency
  - Symbols consist of multiple subcarriers across the frequency spectrum
- **Scalable andwidth**
  - LTE bandwidth is scalable, with adjustable sub-carrier numbers for network needs



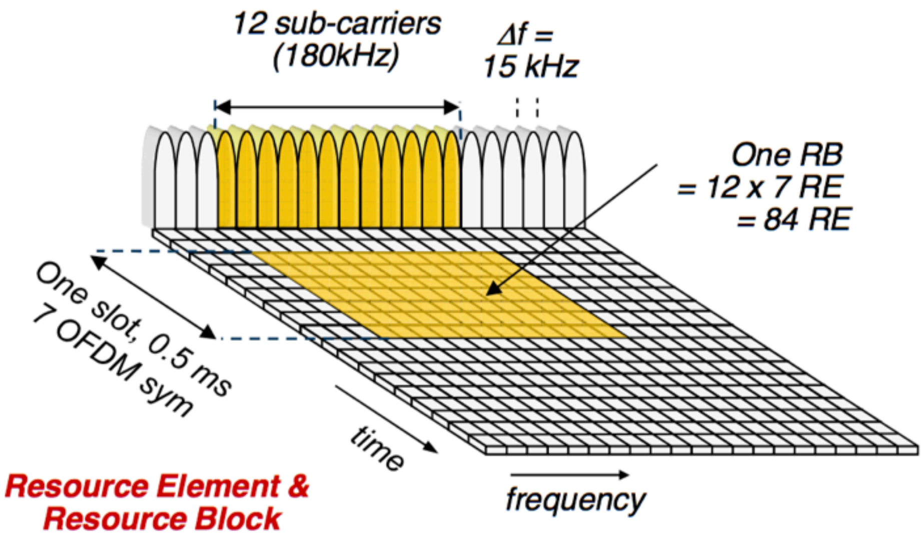
- **Cyclic Prefix (CP)**
  - OFDM symbols include a CP to mitigate multipath fading and timing errors
- **Fast Fourier Transform (FFT)**
  - Used to transform signals between time and frequency domains for transmission and reception



- Subcarriers are independently modulated
- **Modulation types**
  - Displays modulation types: QPSK, 16QAM, 64QAM.
  - Different bits per symbol for different modulation types

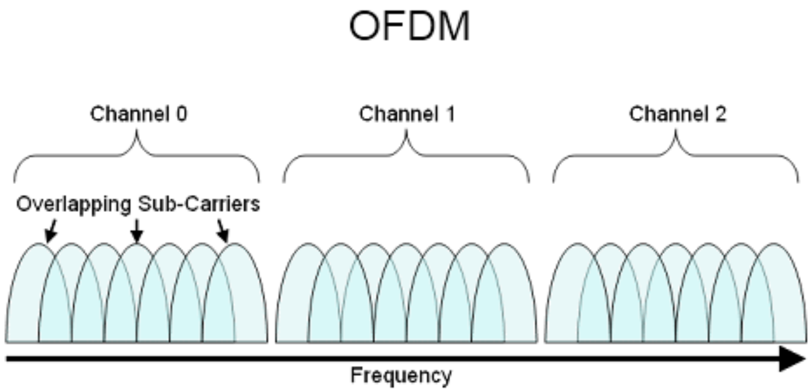


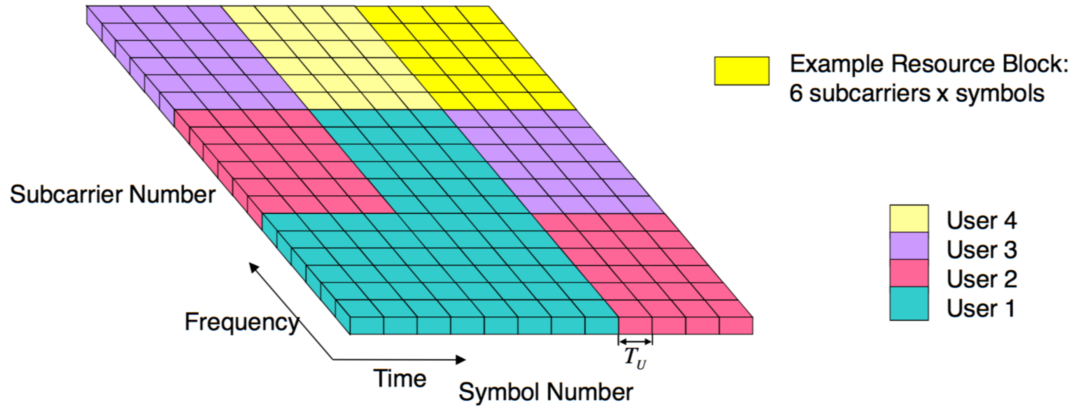
- **Resource Elements and Resource Blocks**
  - Resource grid for resource allocation
  - One Resource Block (RB) comprises 12 sub-carriers (180 kHz) and 7 OFDM symbols
  - A Resource Block contains 84 Resource Elements (RE)

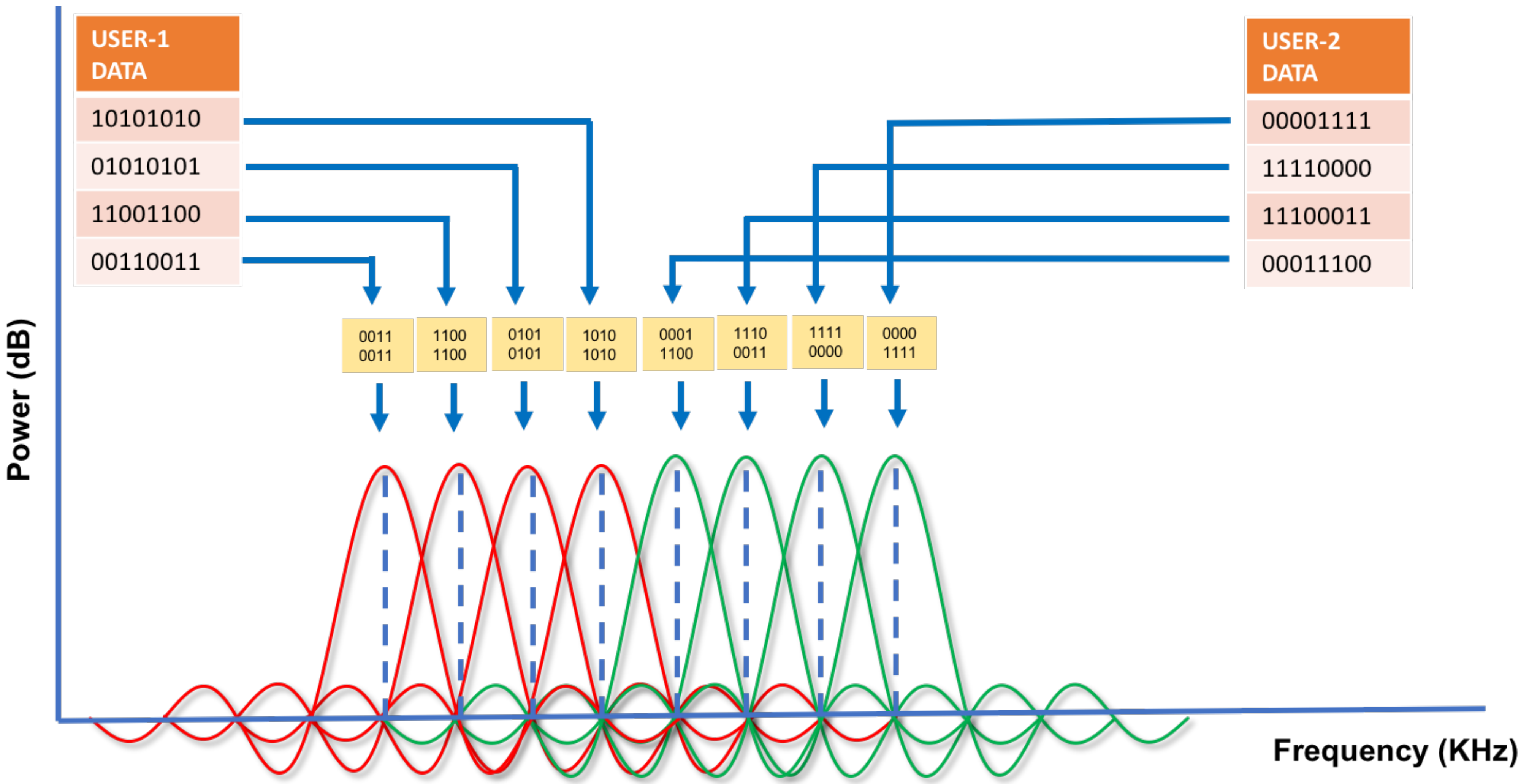


OFDMA
(LTE DOWNLINK)

- Orthogonal Frequency Division Multiple Access (OFDMA)
  - A multiple access scheme utilizing <u>OFDM</u> modulation techniques
  - Assign <u>subcarriers</u> to <u>multiple users</u> at the same time
- Resource Blocks (<u>RB</u>) define contiguous groups of subcarriers

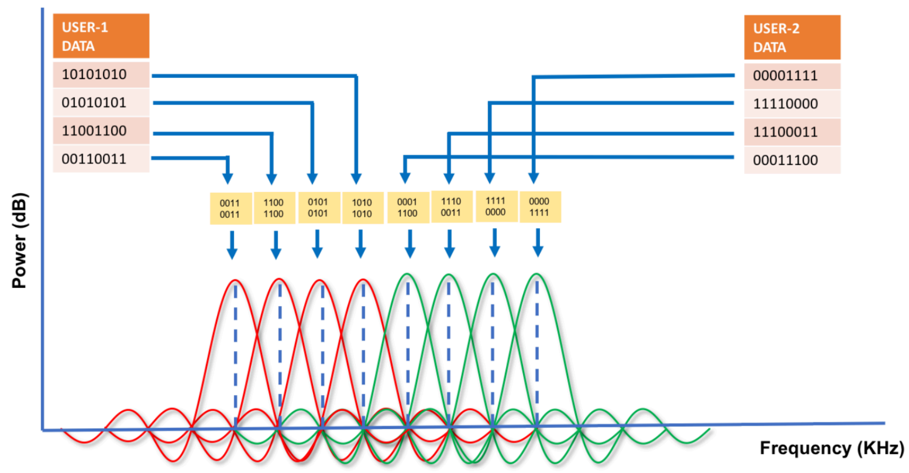






Multiplexing 2 mobile users with 4 subcarriers each

- Multiple users: User-1 and User-2, with unique data for transmission
- Data bits: Binary sequences such as 10101010 for User-1 and 00001111 for User-2
- Subcarrier assignment: Bandwidth split into <u>orthogonal subcarriers</u>, 4 per user, allowing close spacing without interference
- Modulation: Binary data mapped onto subcarriers, possibly using a scheme like QAM
- Multiplexing: OFDMA transmits data from multiple users simultaneously by allocating different subcarriers
- Frequency domain representation: <u>Sinusoidal waves</u> show subcarrier presence in frequency domain; <u>power</u> on the vertical axis, <u>frequency</u> on the horizontal

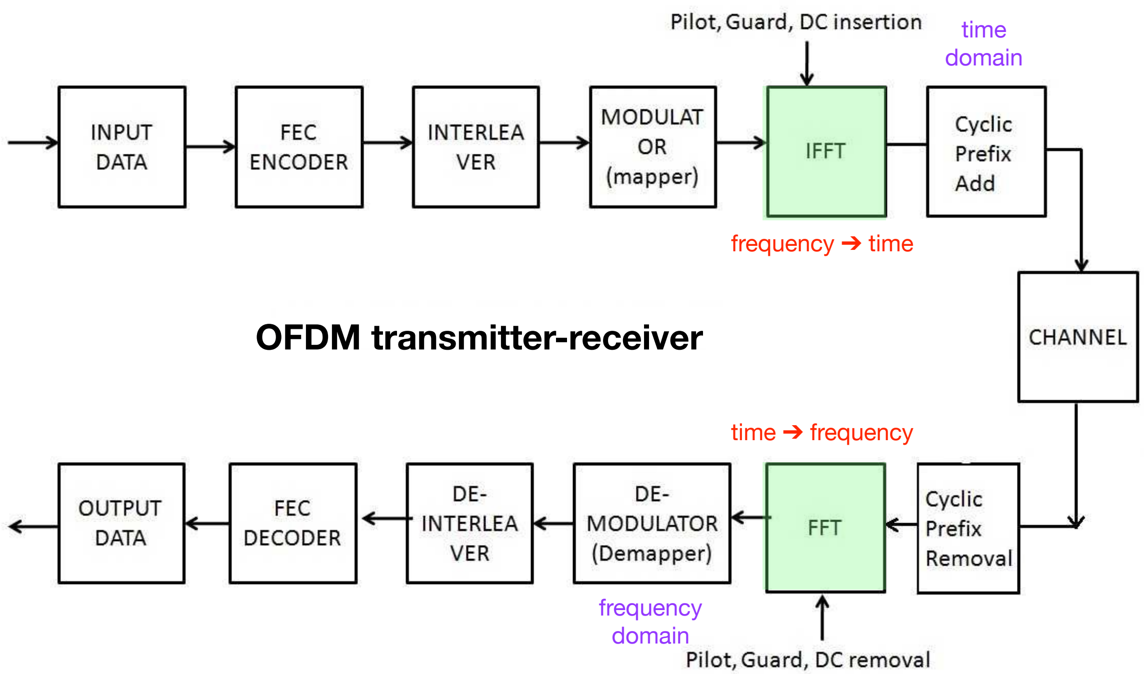


Multiplexing 2 mobile users with 4 subcarriers each

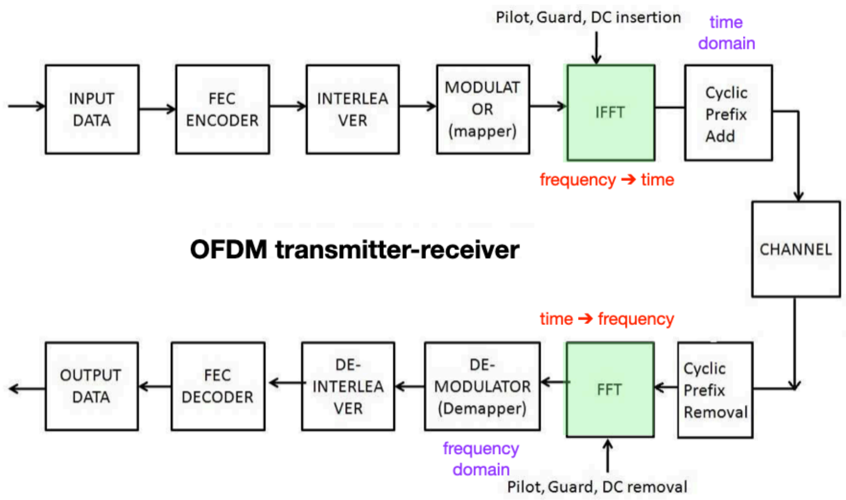
Note: OFDM Transmitter-Receiver

- **IFFT** converts frequency domain vector signal to time domain vector signal

- **FFT** converts time domain vector signal to frequency domain vector signal

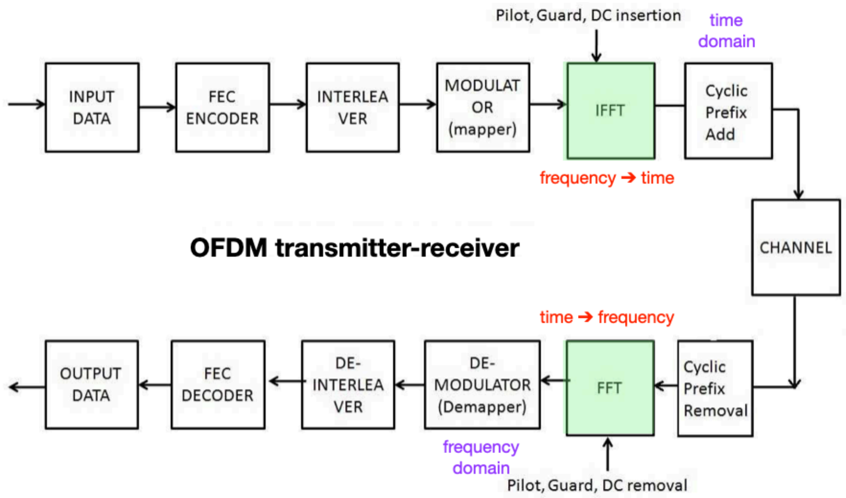


- **Transmitter**
  - Input data: Original data for transmission
  - FEC encoder: Apply error correction to the data
  - Interleaver: Rearrange bits to reduce burst errors
  - Modulator (Mapper): Map data onto subcarriers using modulation schemes
  - IFFT: Convert data from frequency to time domain for transmission
  - Cyclic Prefix add: Add a prefix to prevent intersymbol interference

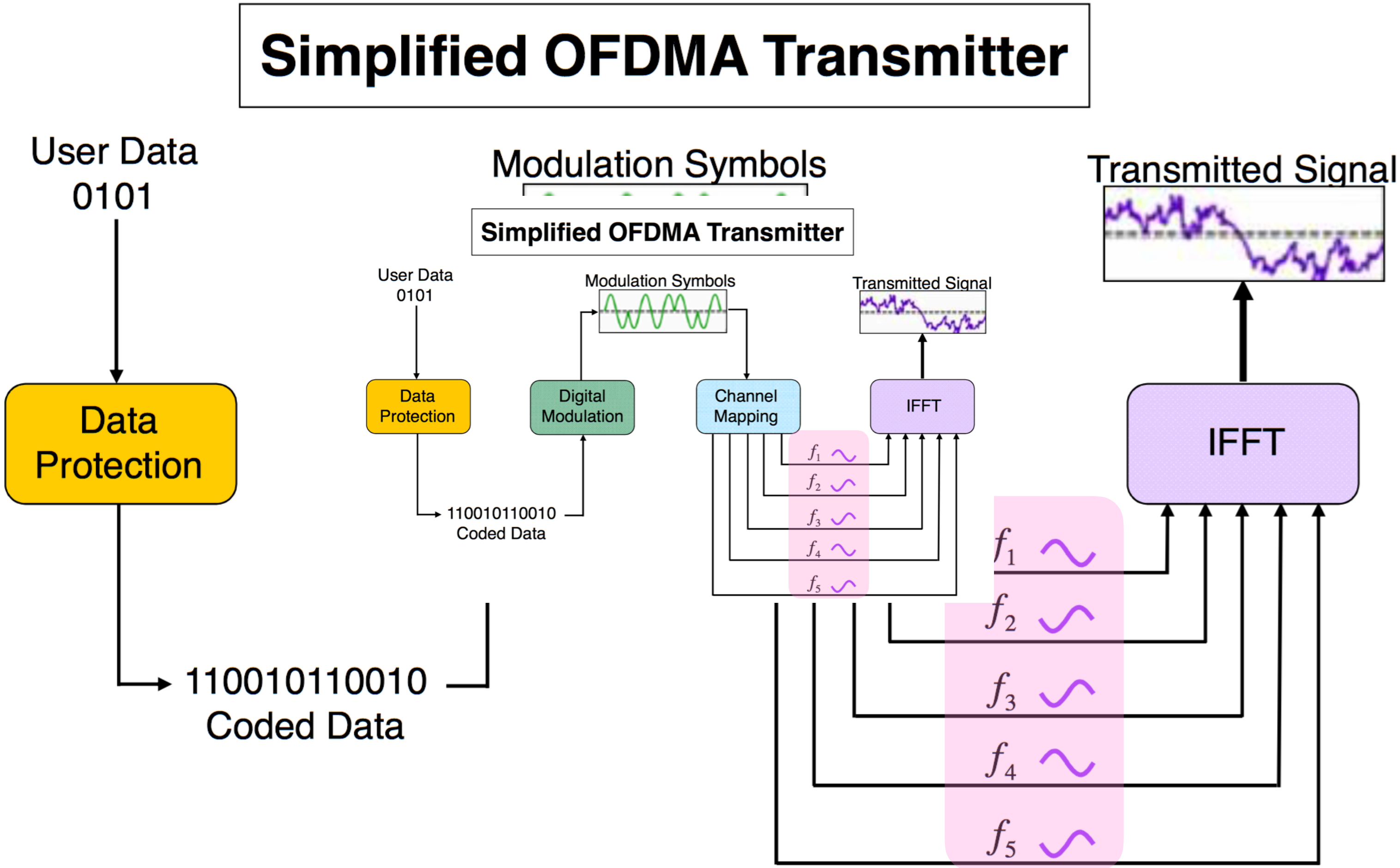


- **Channel**
  - Signal traverses the medium, affected by noise and fading

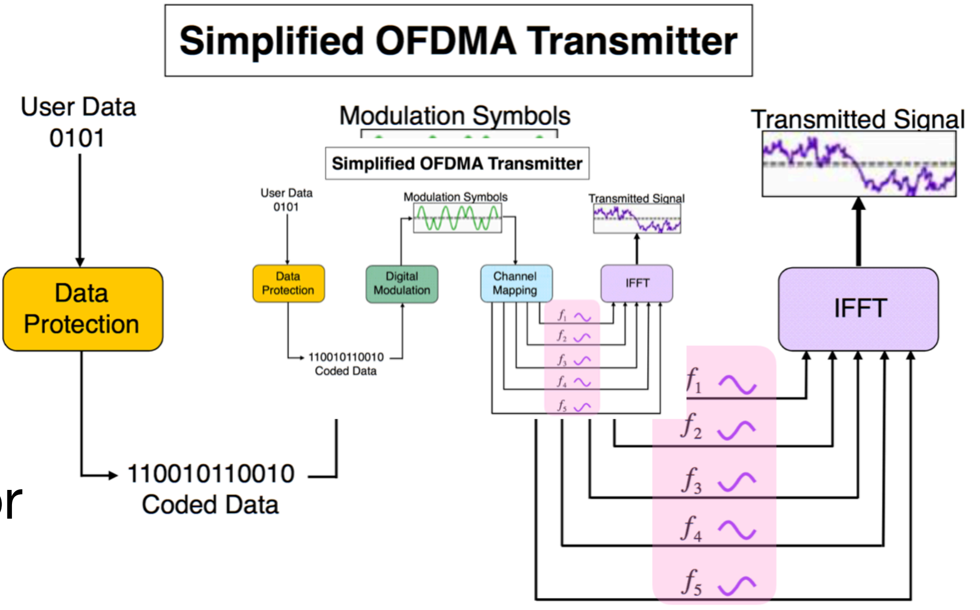
- **Receiver**
  - Cyclic Prefix removal: Remove the <u>prefix</u> added by the transmitter
  - FFT: Convert signal from <u>time</u> to <u>frequency</u> domain
  - Demodulator (Demapper): Retrieve <u>original data bits</u> from subcarriers
  - De-Interleaver: Reorder the interleaved bits to their <u>original sequence</u>
  - FEC decoder: <u>Correct</u> transmission errors using the FEC code
  - Output data: Final data output, matching the transmitter's input data

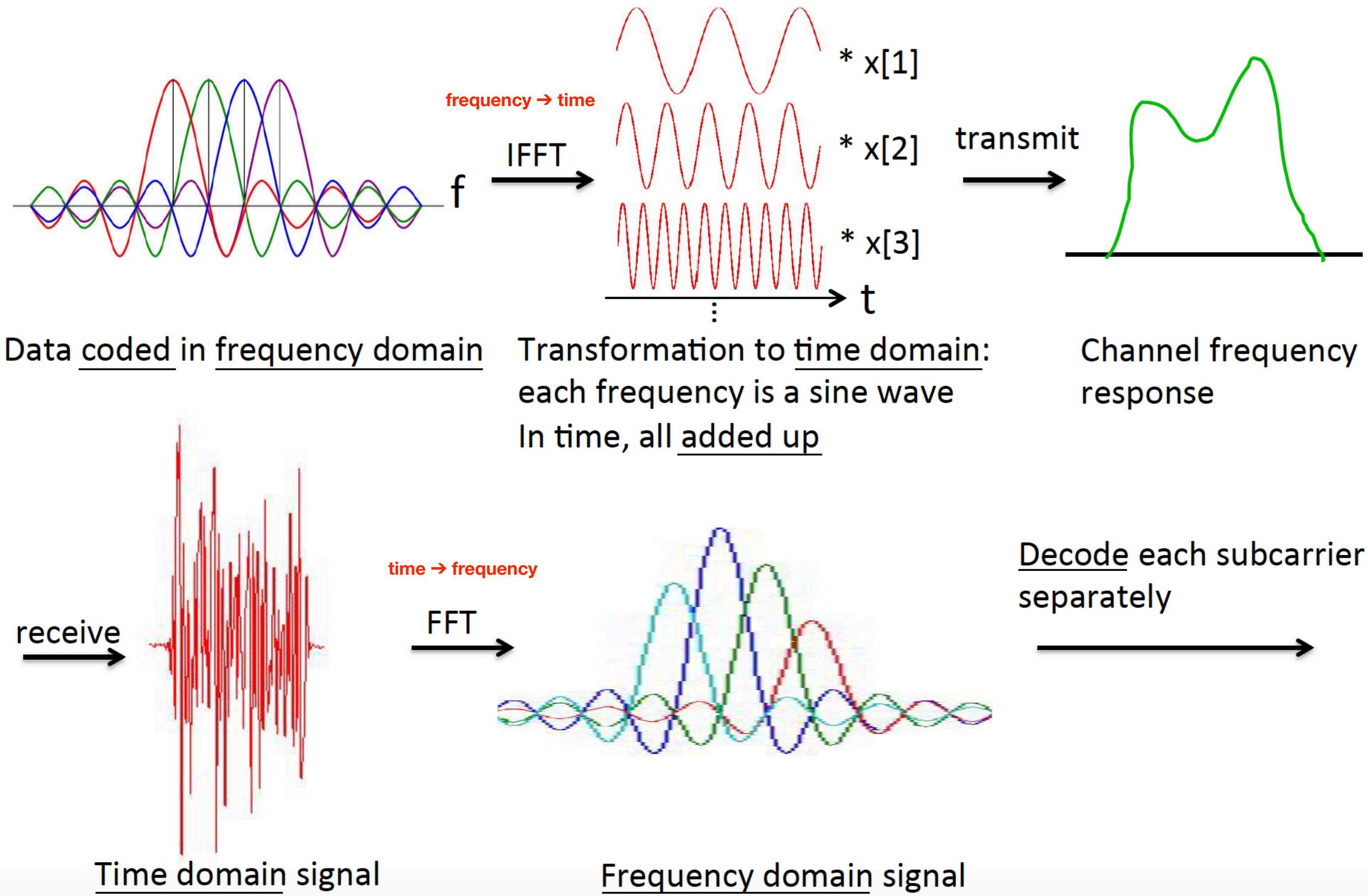


- **OFDMA data symbol** is composed by a couple of modulated independent subcarrier signals



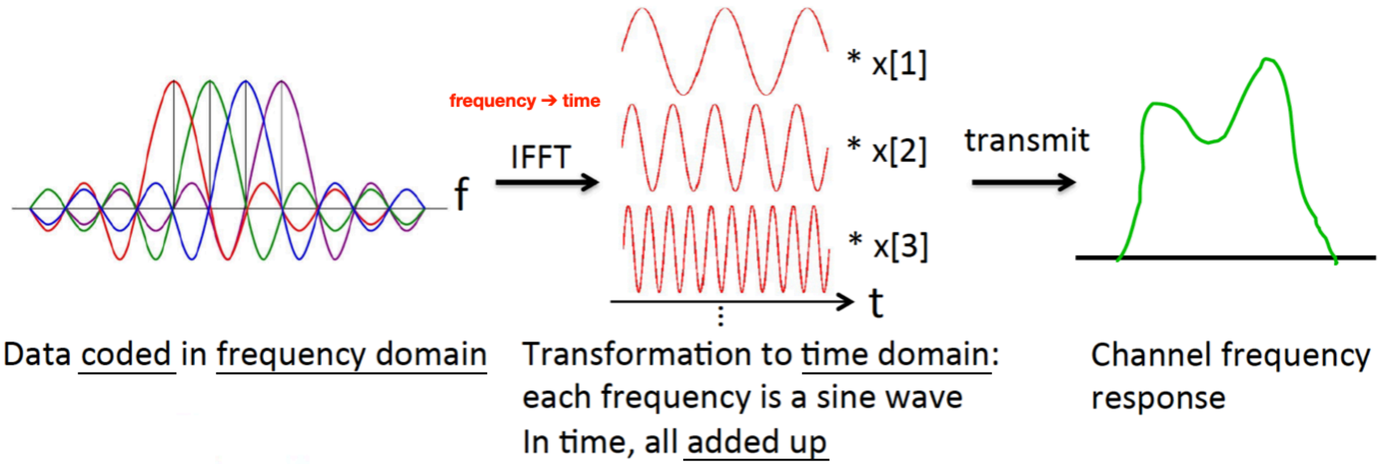
- User data: Original binary data to be transmitted
- Data protection: Encode user data for error protection
- Coded data: Error-protected data ready for modulation
- Digital modulation: Map coded data onto modulation symbols using schemes like QAM or PSK
- Channel mapping: Assign modulated symbols to specific subcarriers for each user
- IFFT: Combine subcarrier signals into one time-domain signal while maintaining orthogonality
- Transmitted signal: Broadcast the composite signal, composed of all modulated subcarriers



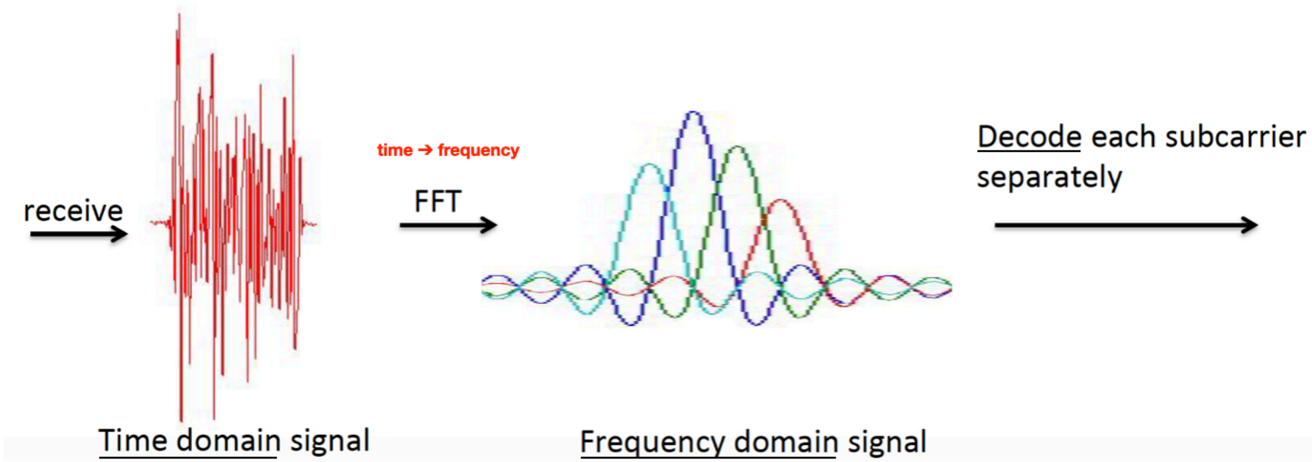


f
frequency → time
IFFT
* x[1]
* x[2]
* x[3]
t
transmit
Data coded in frequency domain
Transformation to time domain:
each frequency is a sine wave
In time, all added up
Channel frequency
response
receive
time → frequency
FFT
Decode each subcarrier
separately
Time domain signal
Frequency domain signal

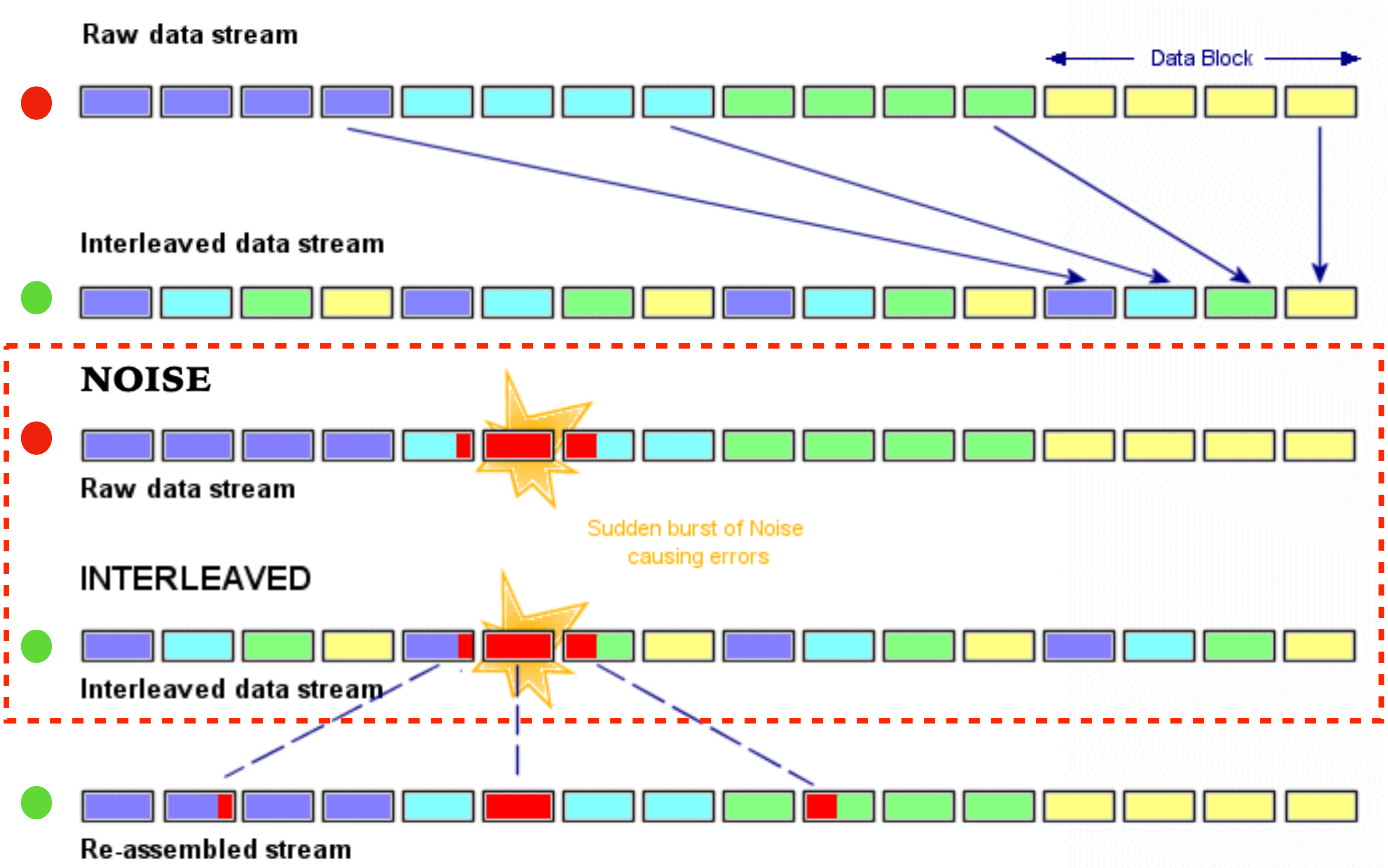
- Transmission process
  - Data coded in frequency domain: Data modulated onto multiple subcarriers
  - IFFT: Converts frequency domain subcarriers to time-domain sine waves
  - Time-domain signal: Composite signal formed by adding up all sine waves
  - Channel frequency response: Signal transmitted through a channel and affected by its response



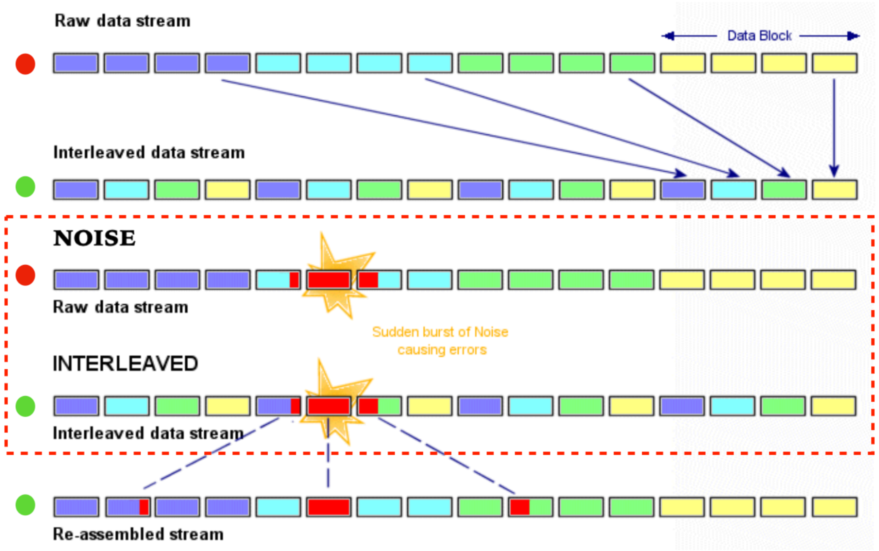
- Reception process
  - Time-domain signal: Received signal with noise and distortions
  - FFT: Received signal converted back to frequency domain
  - Frequency-domain signal: Subcarriers separated post-FFT
  - Decode subcarriers: Data decoded from each subcarrier individually



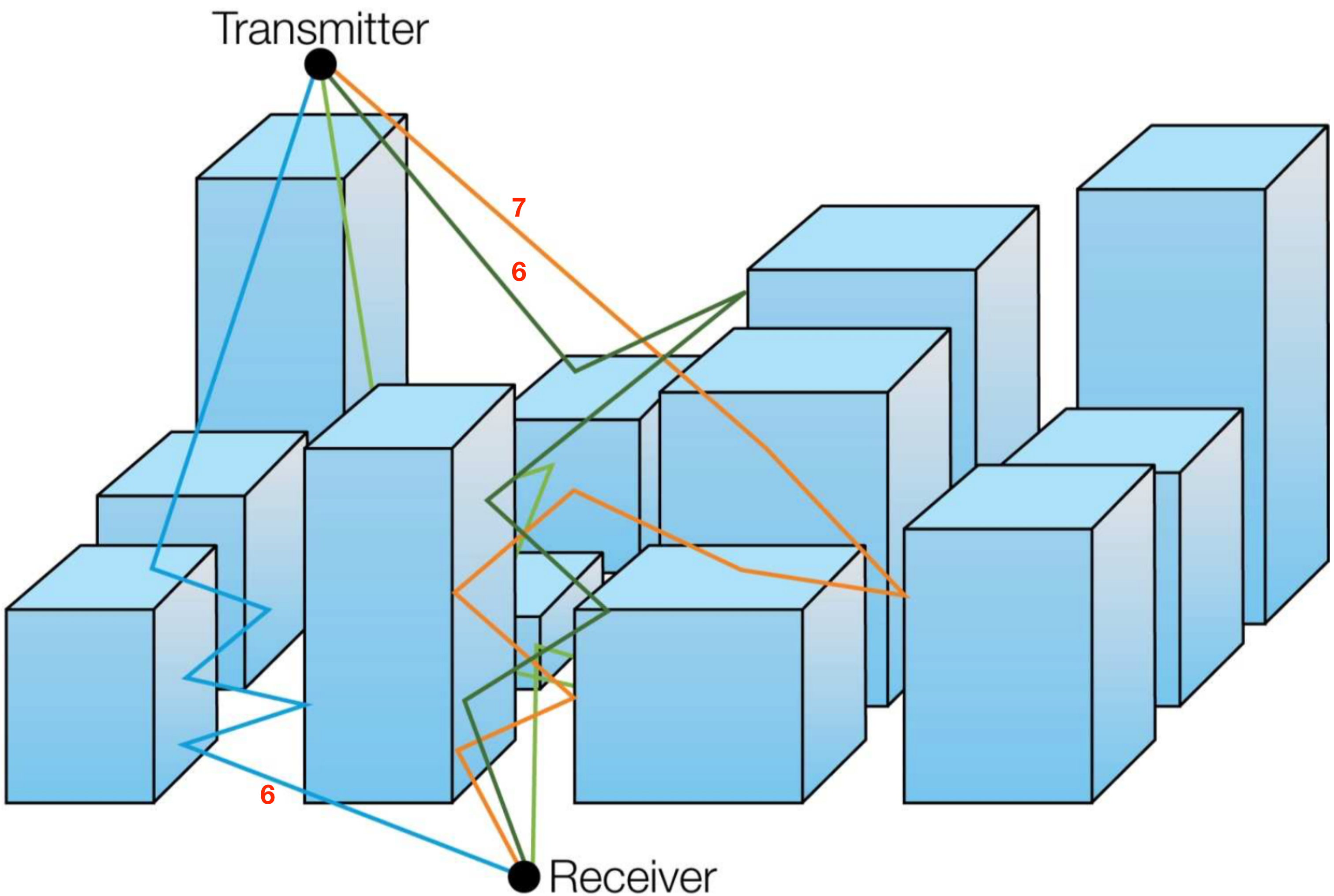
Note: Interleaving



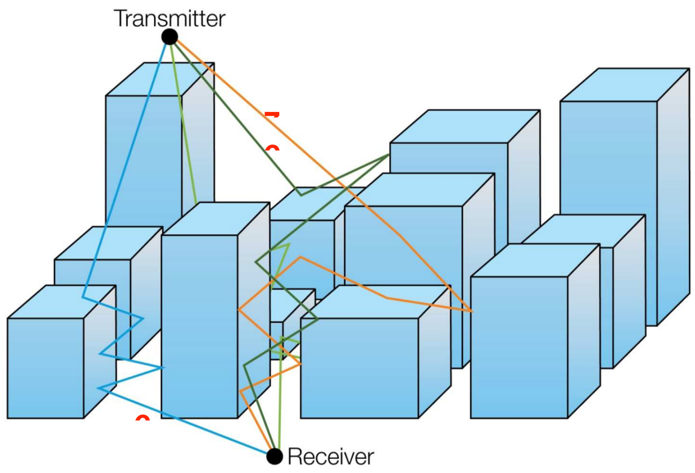
- Raw data stream: Original sequence of data before transmission
- Interleaved data stream: Data blocks rearranged in a non-sequential order to spread out adjacent blocks
- Impact of noise: Burst noise corrupts a sequence of adjacent data blocks in the raw stream, potentially causing significant data loss
- Interleaved and noise impact: The same noise affects non-adjacent blocks in an interleaved stream, minimizing the impact
- Re-assembled stream: Data blocks are reordered at the receiver, allowing error correction to effectively address the dispersed errors



Multipath Environment

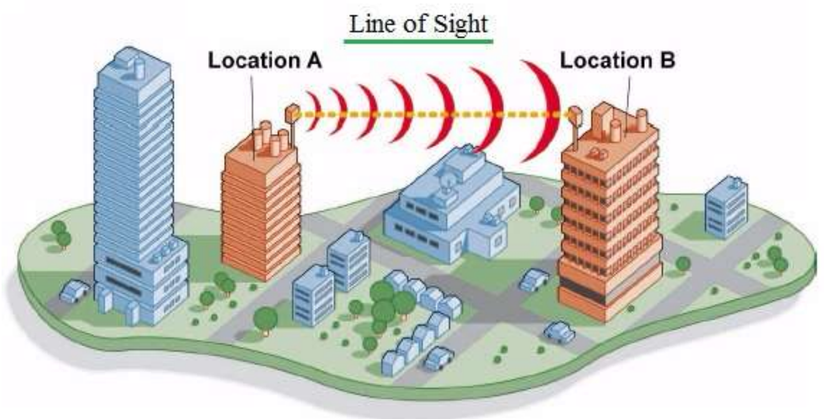


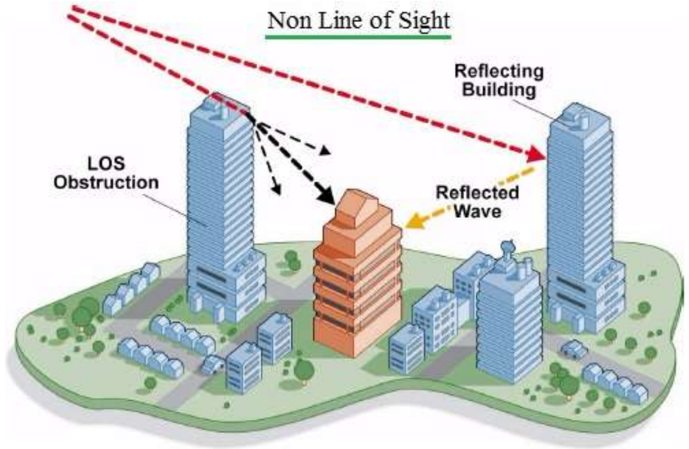
- Multipath phenomenon
  - Signals reach the receiver through multiple paths
  - Caused by reflections off objects like buildings and mountains
- Key aspects
  - Path delay: Different path lengths lead to signals arriving at different times, causing phase shifts and interference
  - Fading: Signals interfere constructively or destructively, causing signal strength fluctuations (multipath fading)
  - Doppler shift: Relative motion causes frequency shifts in signals, varying across different paths
  - Impact on communication: Lead to signal distortion and reduced data rates due to multiple signal versions arriving asynchronously



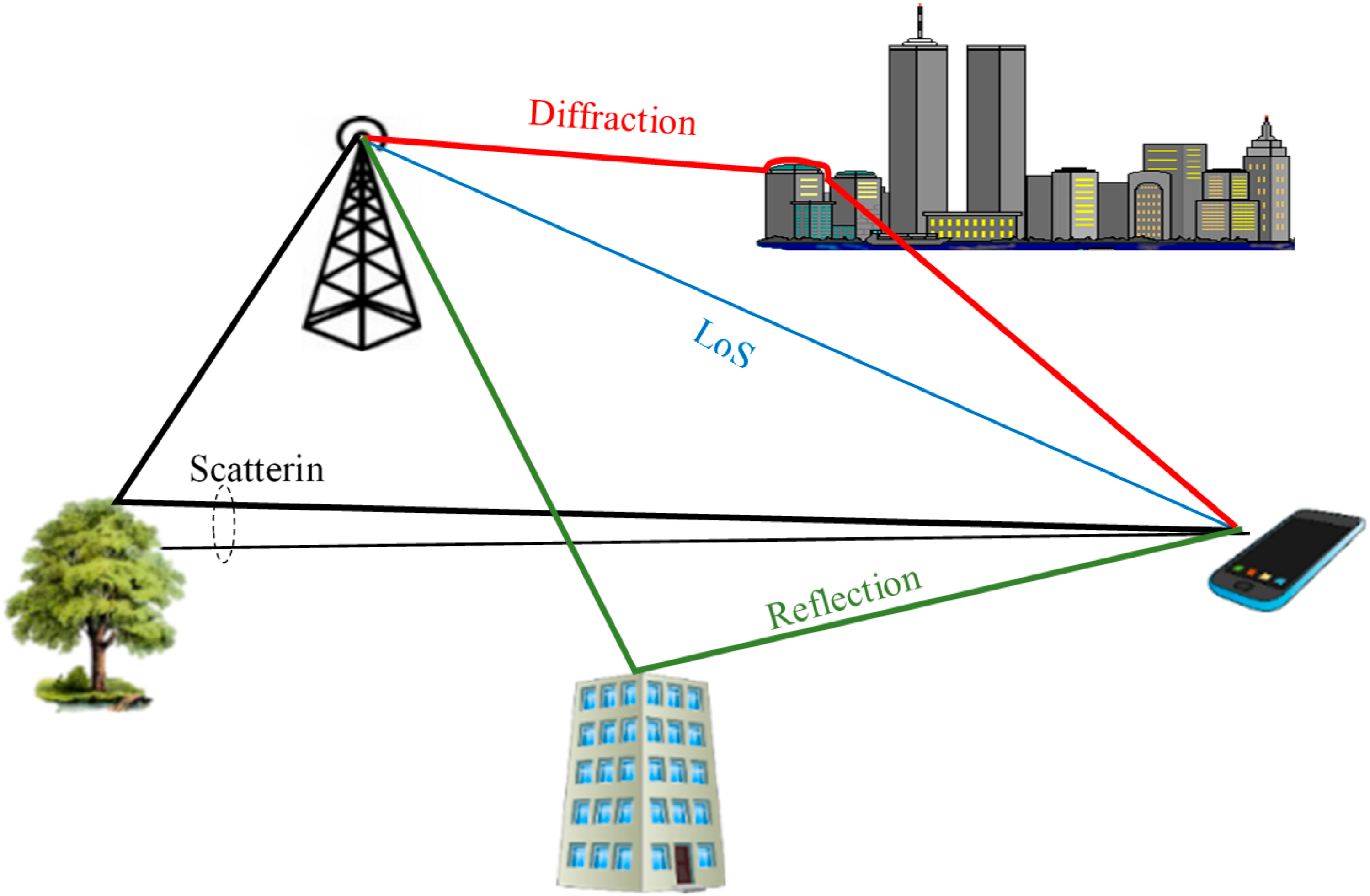
Effects of Multipath

- Signals follow several propagation paths
  - Line of Sight (LOS)
  - Non-Line of Sight (NLOS)
- Multiple copies of the signal arrive at the receiver with different <u>intensities</u>, <u>phase</u> <u>offsets</u>, and <u>delays</u>

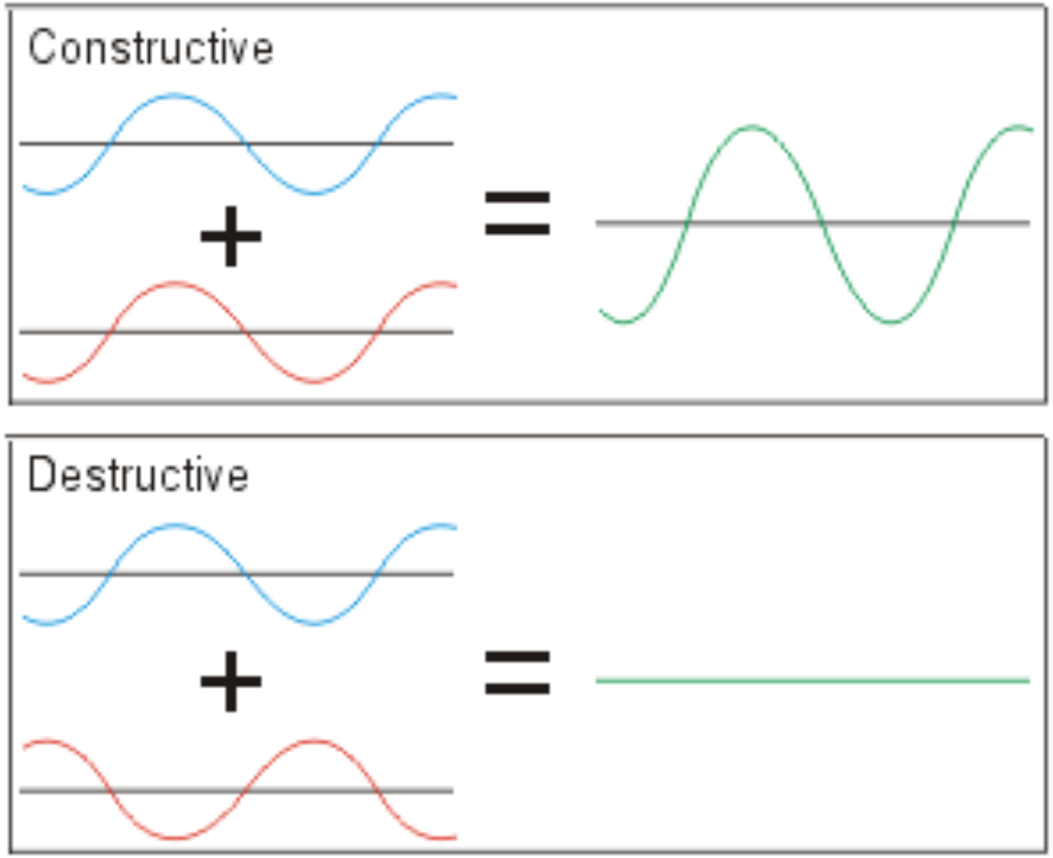




Note: Diffraction, Reflection, Scattering



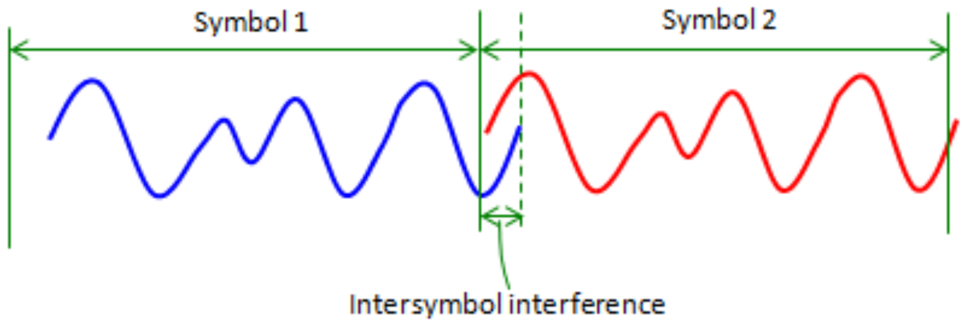
- Multiple versions of the same signal may <u>constructively</u> or <u>destructively interfere</u> with each other



Current symbol + <u>delayed</u>-version symbol ➜ signals are <u>deconstructive</u> in certain frequencies

Inter-Symbol Interference (ISI)

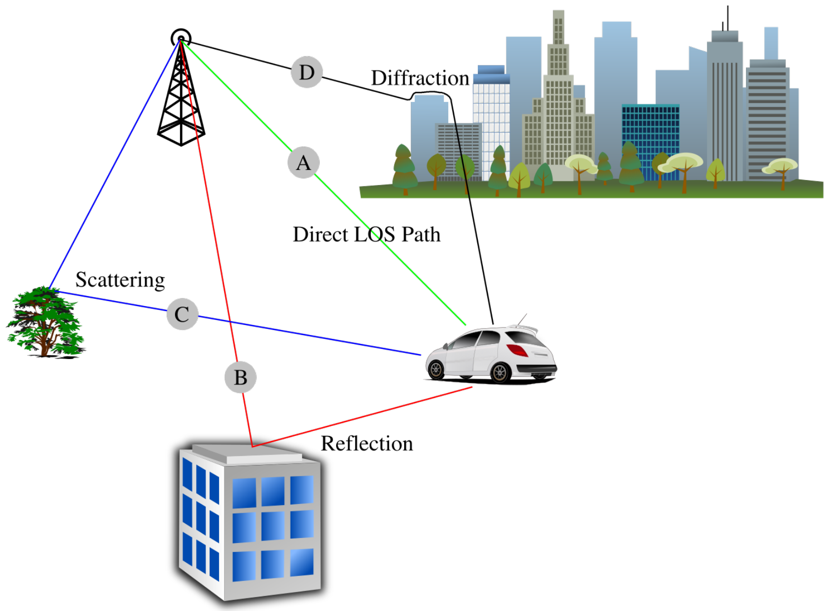
- **Inter-Symbol Interference (ISI)**
  - The delayed version of a symbol overlaps with the adjacent symbol
- ISI performance
  - Increase bit error rate (BER)
  - Reduce achievable data rate

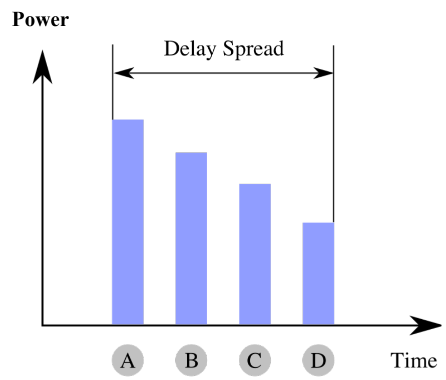


Delay Spread

- In telecommunications, the delay spread is a measure of the multipath richness of a communication channel

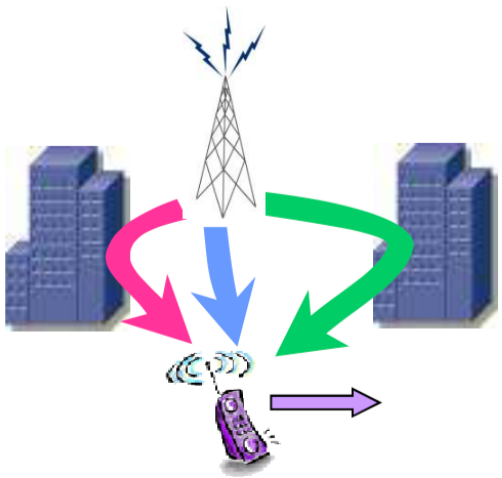
- It can be interpreted as the difference between the time of arrival of the earliest significant multipath component (typically the line-of-sight component) and the time of arrival of the latest multipath components

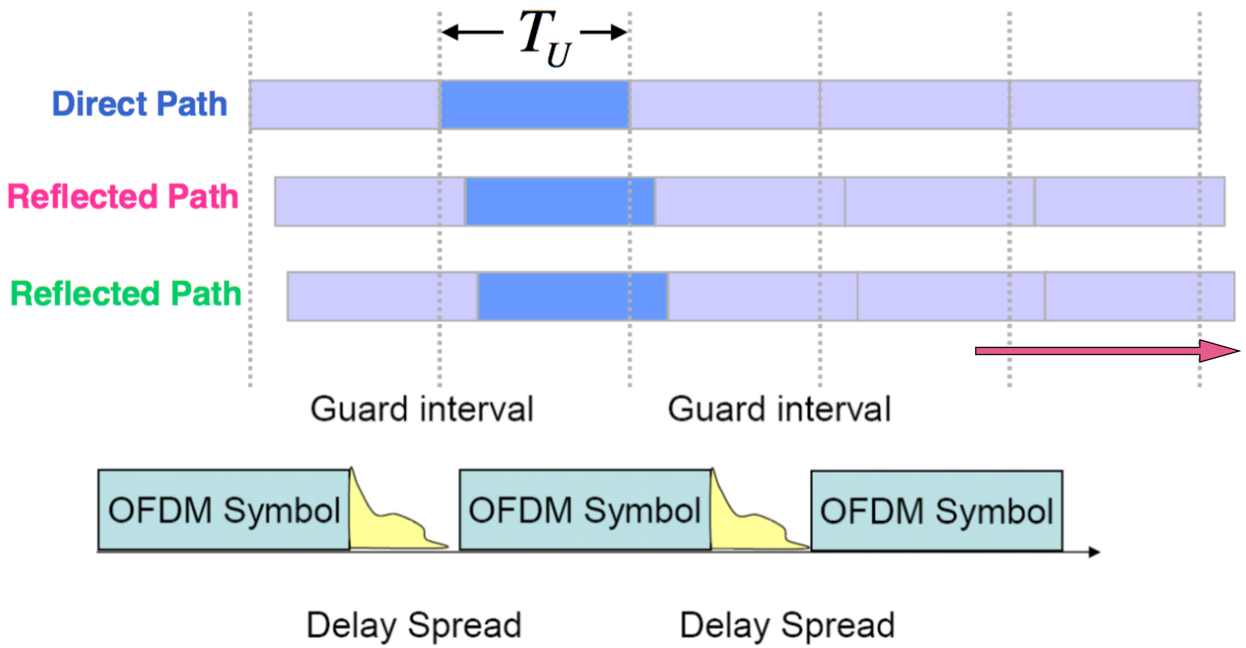




Multipath and OFDM Symbols

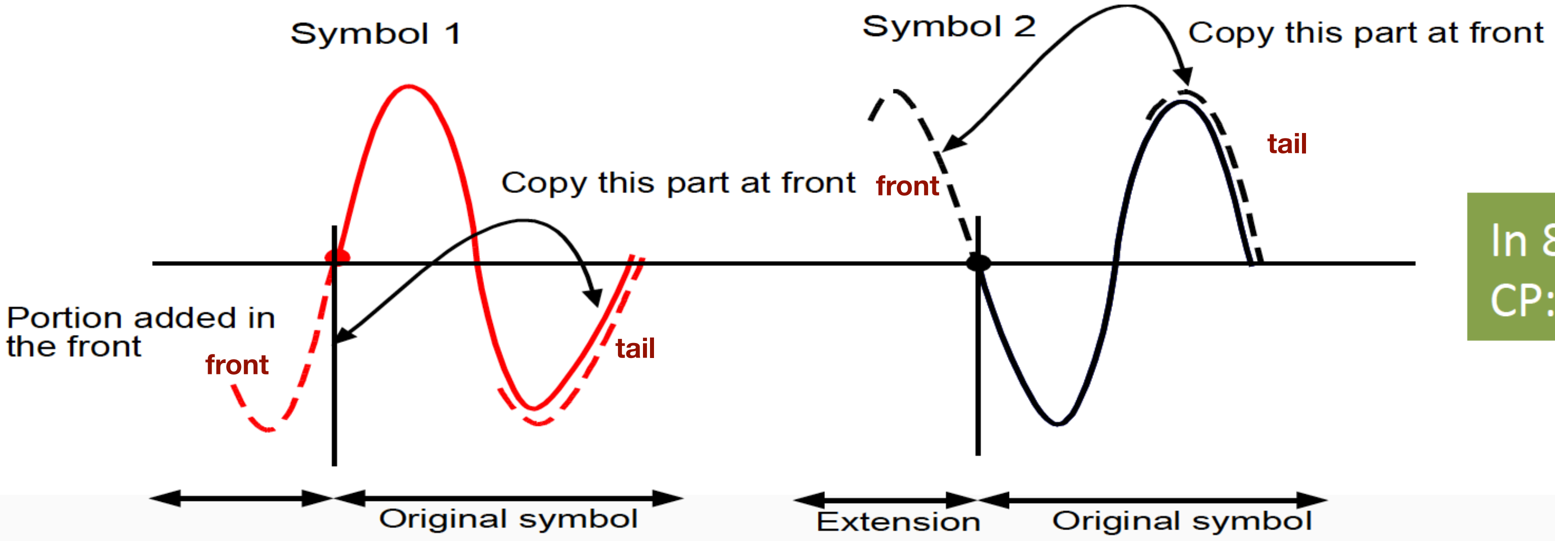
- In OFDM, multipath causes loss of orthogonality
  - Delayed paths cause overlap between symbols



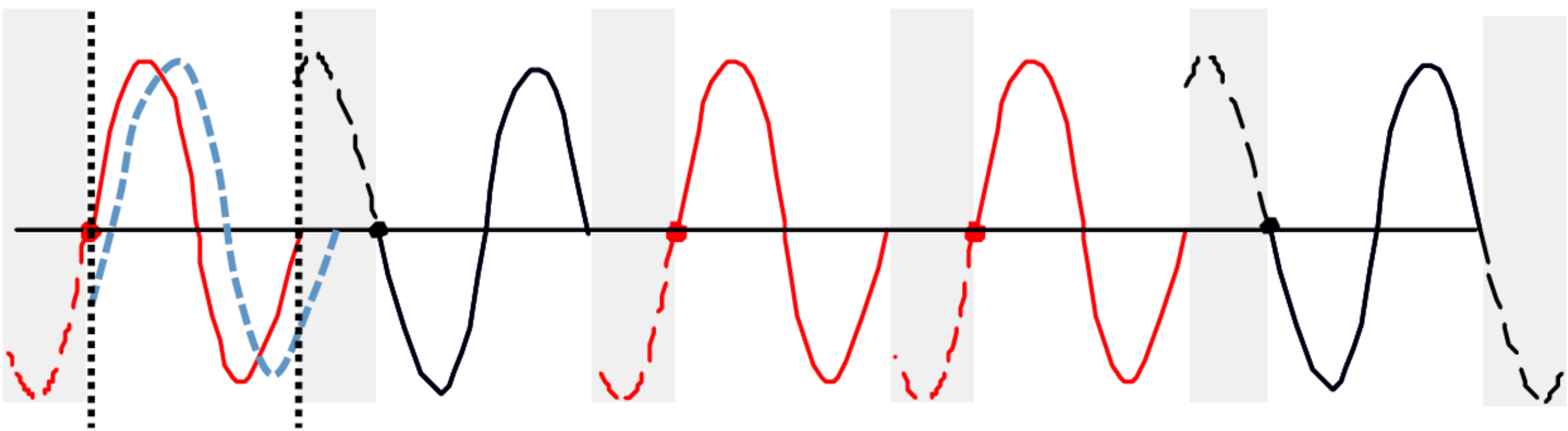


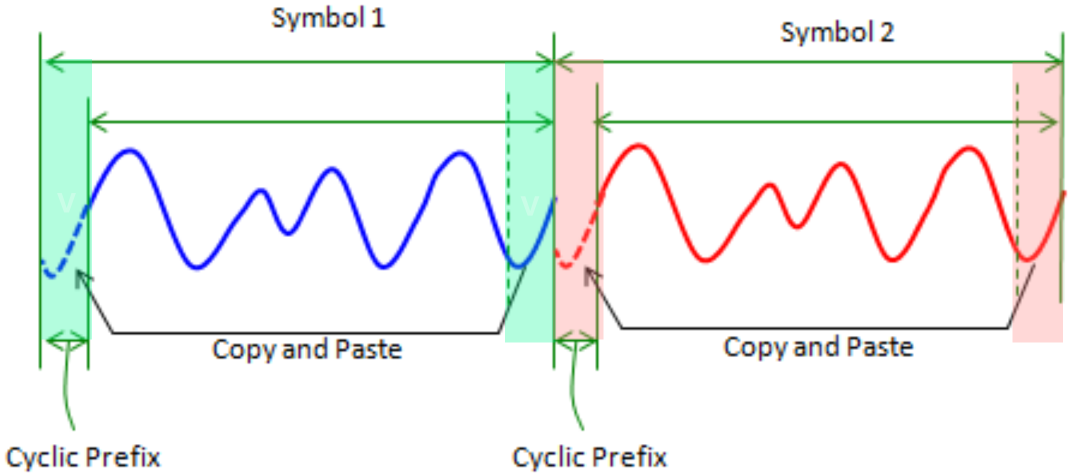
Cyclic PrefiX (CP)

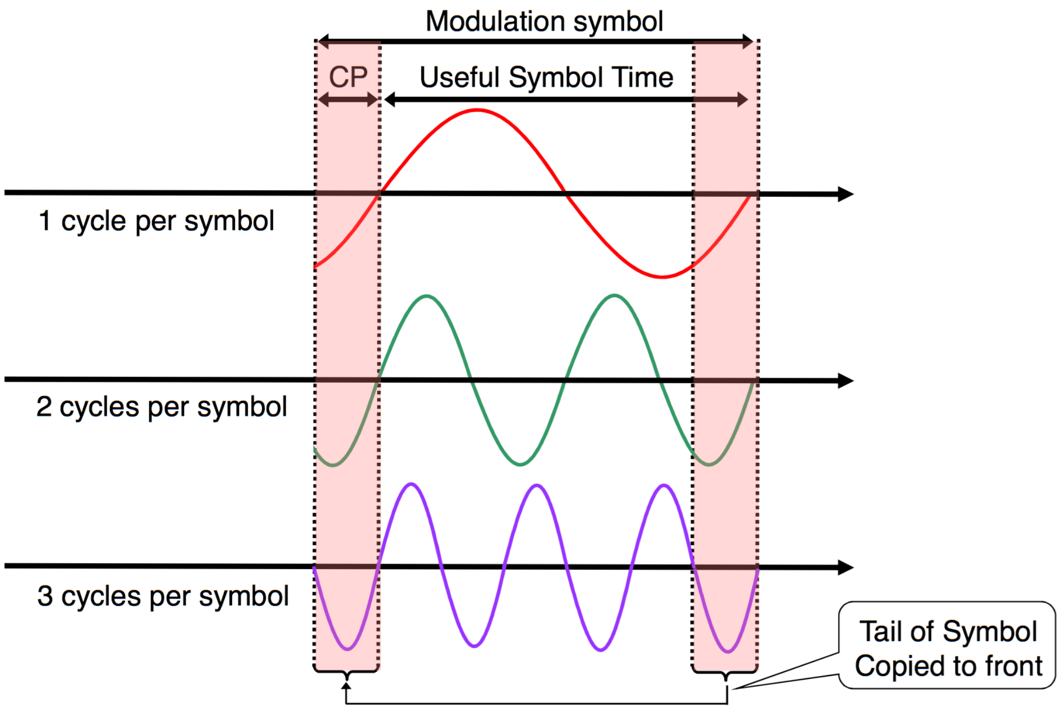
- One simple solution to avoid ISI is to introduce a guard-band
- However, we don't know the delay spread exactly
  - The hardware doesn't allow blank space because it needs to send out signals continuously
- Solution: Cyclic Prefix
  - Make the symbol period longer by copying and pasting the tail of the modulation symbol in the front
  - CP insertion helps maintain orthogonality



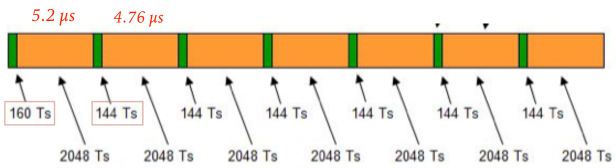
In 802.11,
CP:data = 1:4

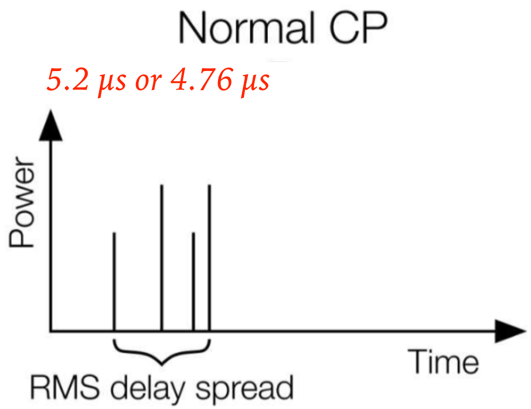


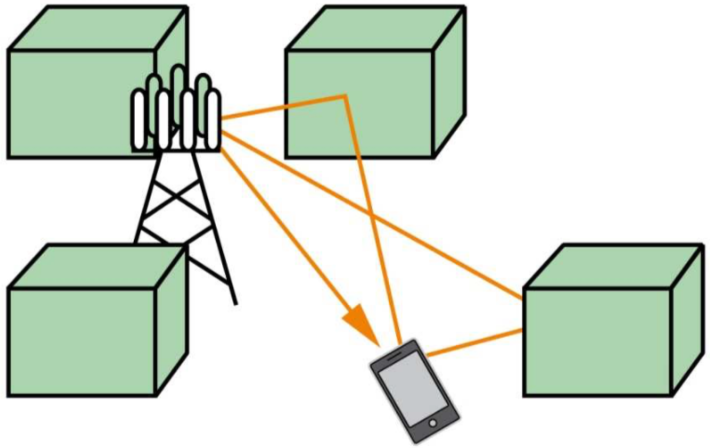

Symbol 1
Symbol 2
Copy and Paste
Copy and Paste
Cyclic Prefix
Cyclic Prefix

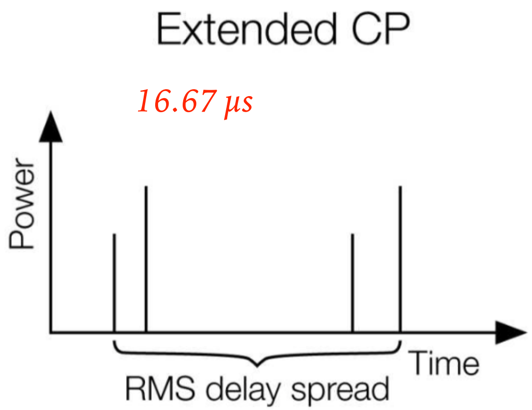

Modulation symbol
CP
Useful Symbol Time
1 cycle per symbol
2 cycles per symbol
3 cycles per symbol
Tail of Symbol
Copied to front

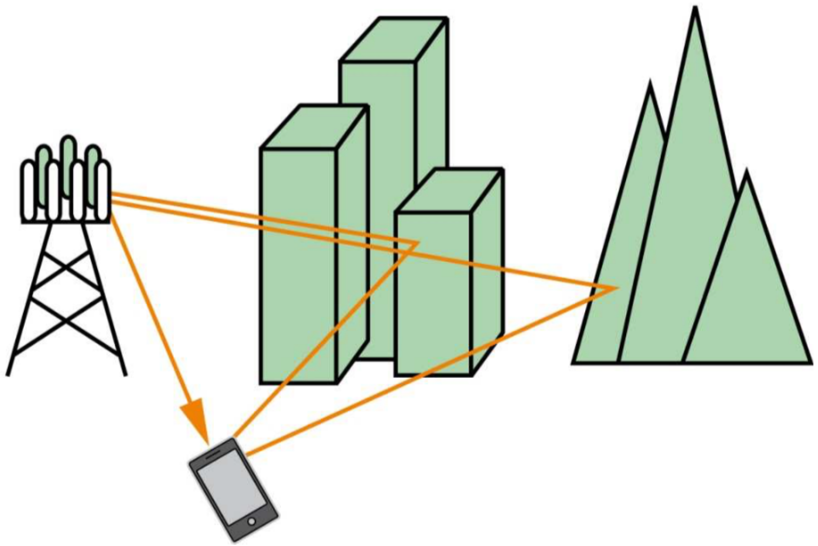
Normal and Extended CP









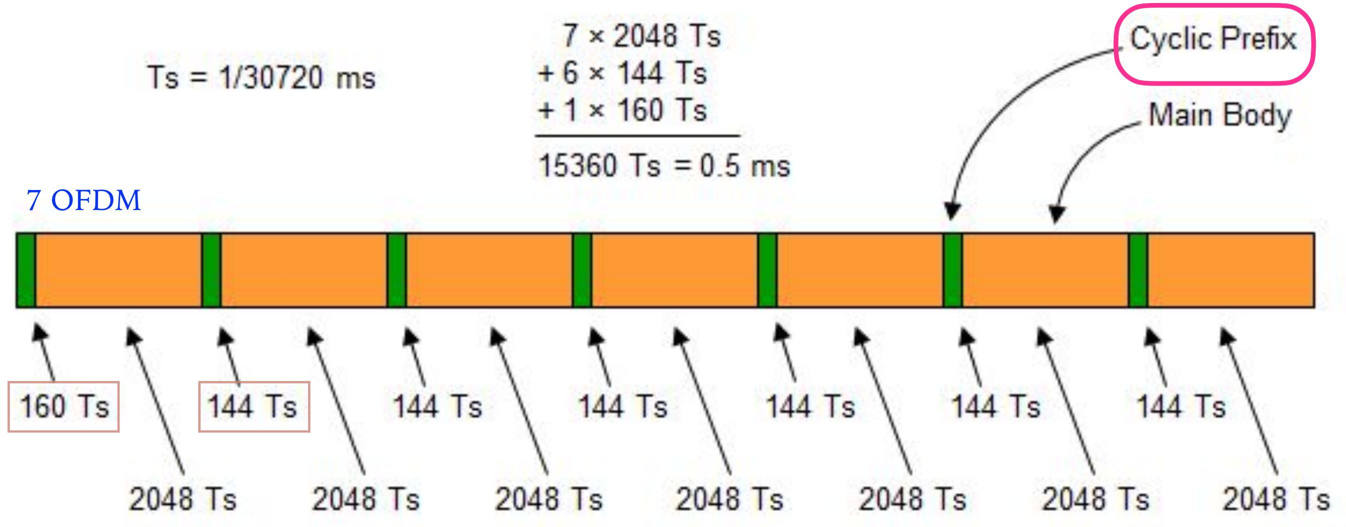


RMS : Root Mean Square

1 slot = 0.5 ms = 7 OFDM symbols (normal CP)

Normal Cyclic Prefix

5.2 μs or 4.76 μs



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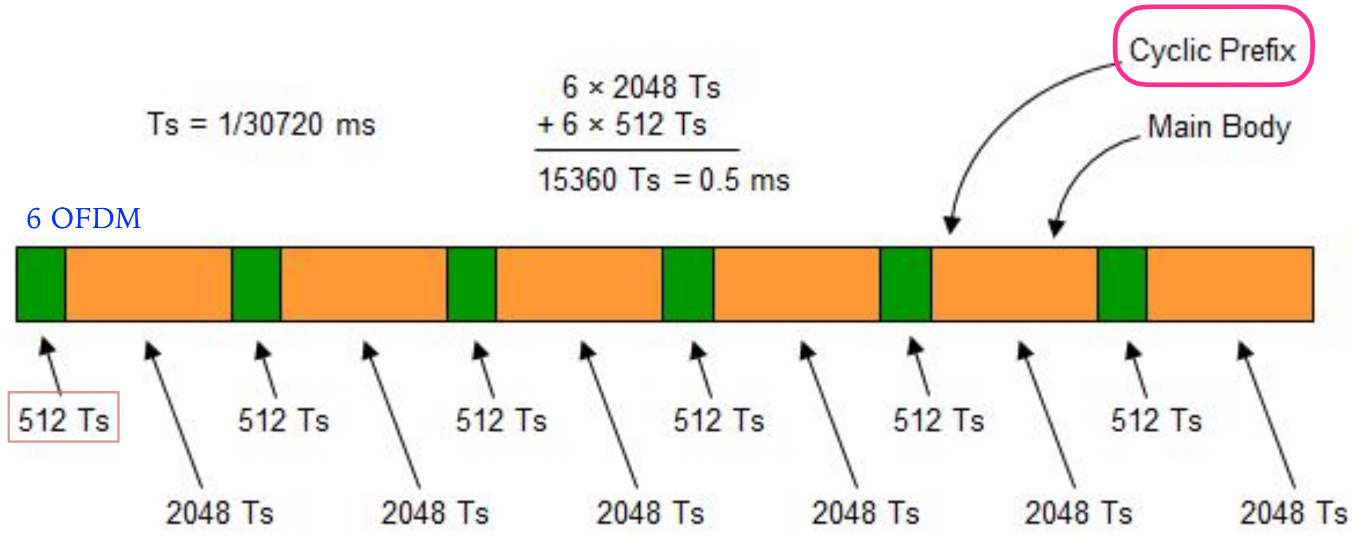
1 slot = 0.5 ms = 6 OFDM symbols (extended CP)

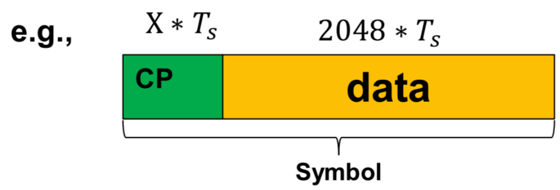
Extended Cyclic Prefix

16.67 μs



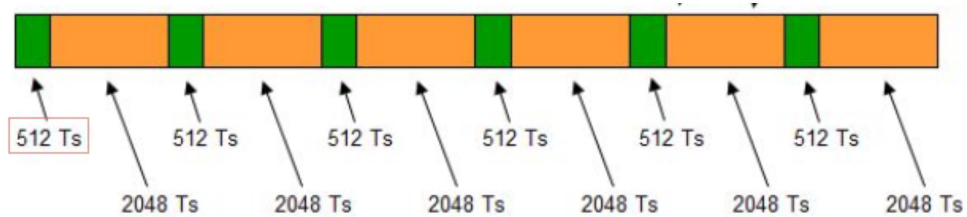
- Basic time unit： $T_s = 1/30720000$
- For the normal mode
  - The first symbol has a CP of length T_{CP} = **160** * $T_s \approx 5.2\ \mu s$
  - The remaining six symbols have a CP of length T_{CP} = **144** * $T_s \approx 4.76\ \mu s$
- For the extended mode
  - The CP is $T_{CP\text{-}e}$ = **512** * $T_s \approx 16.67\ \mu s$

- CP length

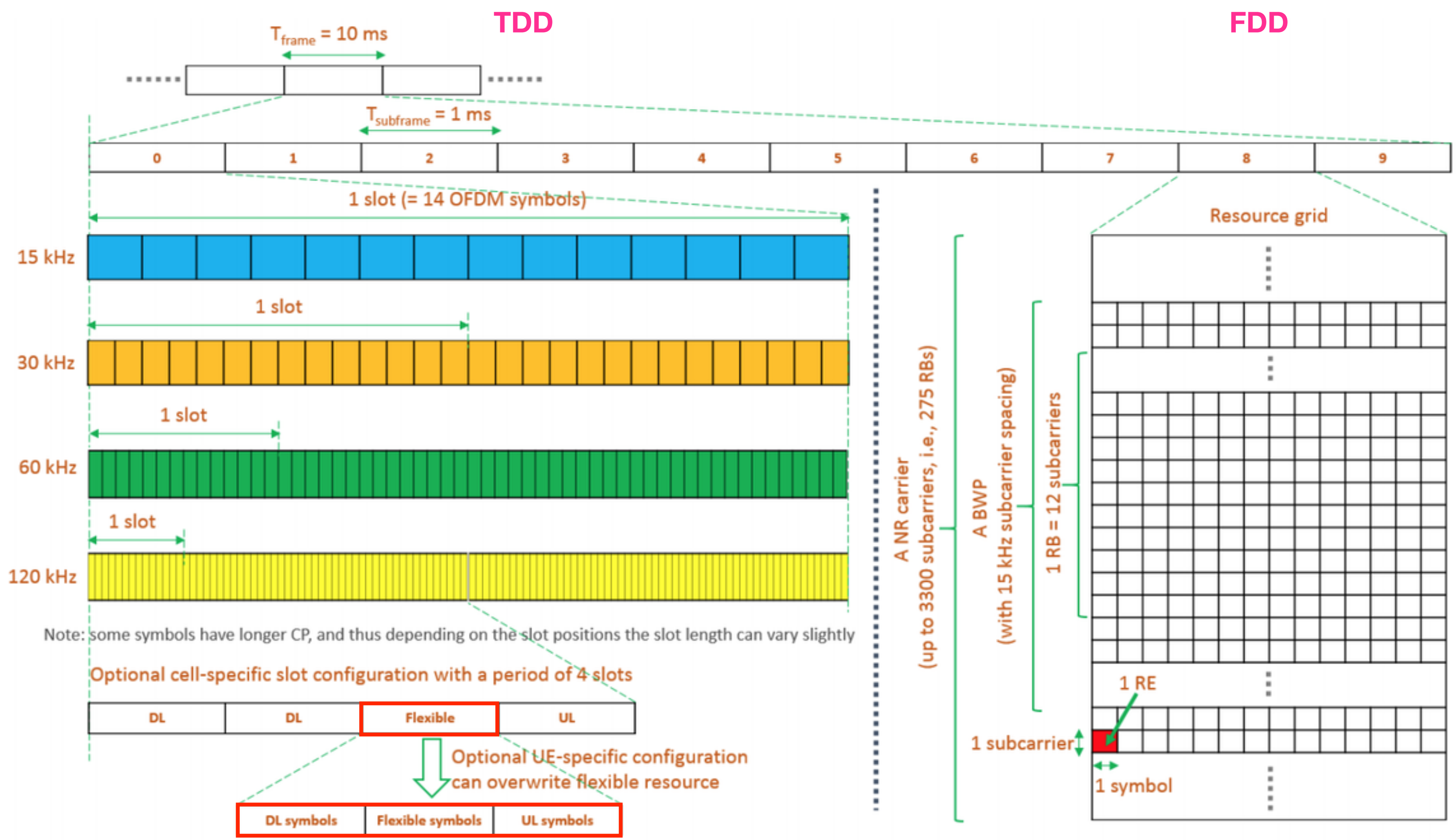


- Normal CP
  - X=160
  - X=144
- Extended CP
  - X=512

- Subcarrier spacing: 15kHz

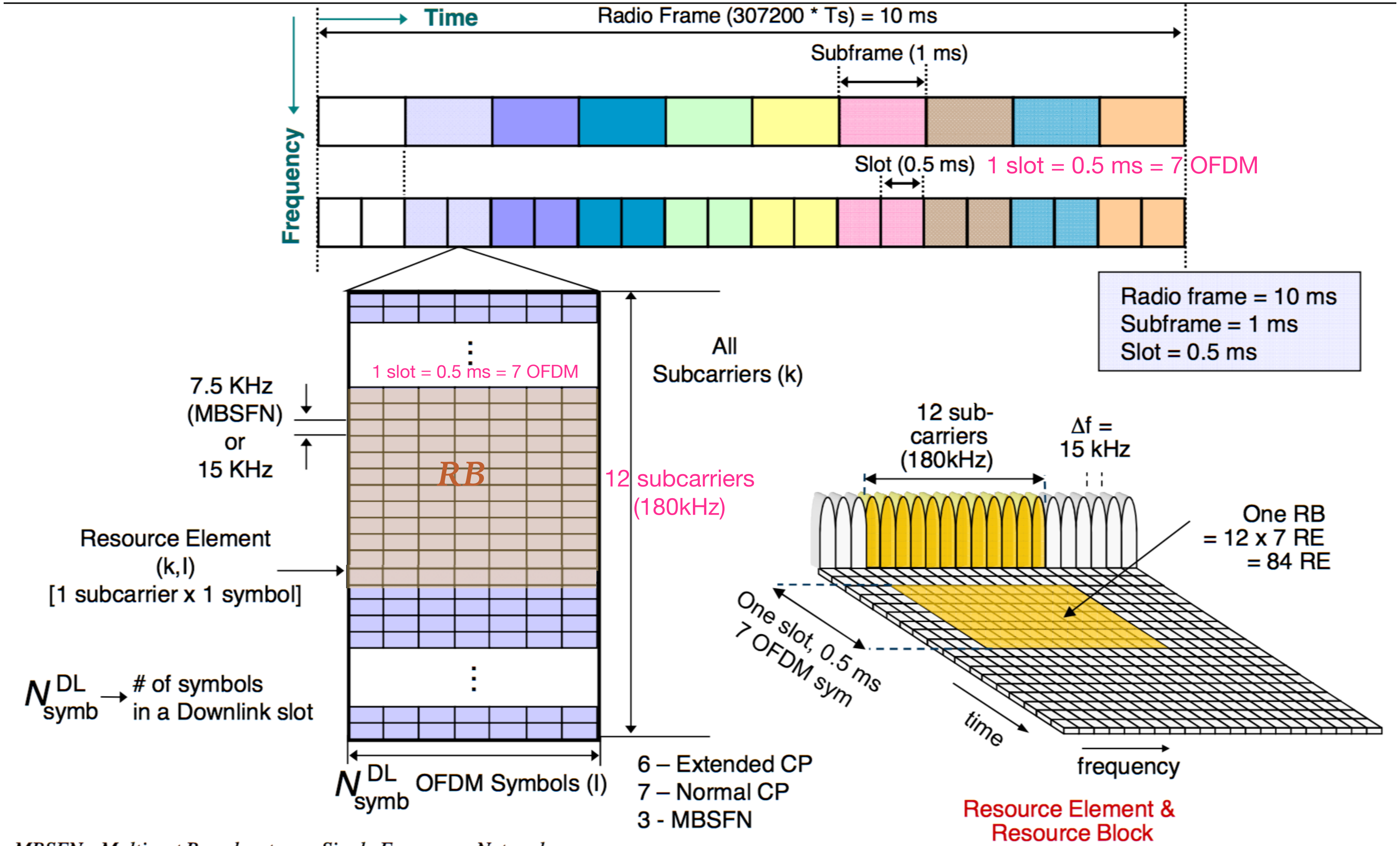


5G NR Frame Structure



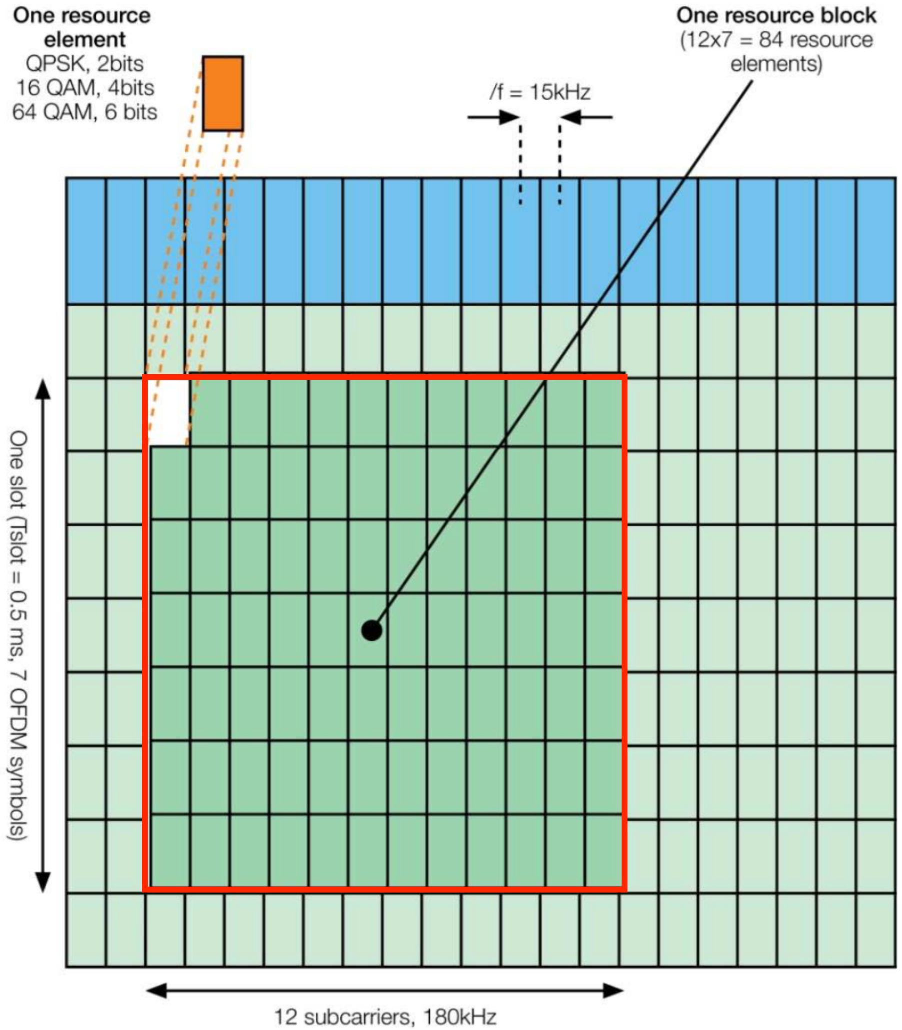
- 5G NR framework accommodates both FDD and TDD, making it versatile for various network requirements
  - FDD for the need of predictable (static) resource allocation
  - TDD for the need of dynamic, traffic-responsive allocation

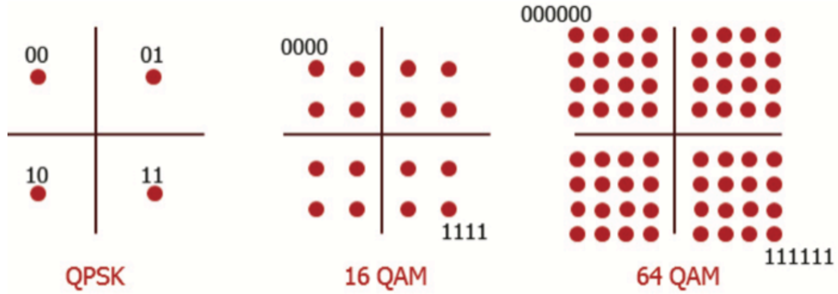
LTE FDD Frames, Subframes and Slots



MBSFN - Multicast Broadcast over Single Frequency Network

LTE OFDMA Structure





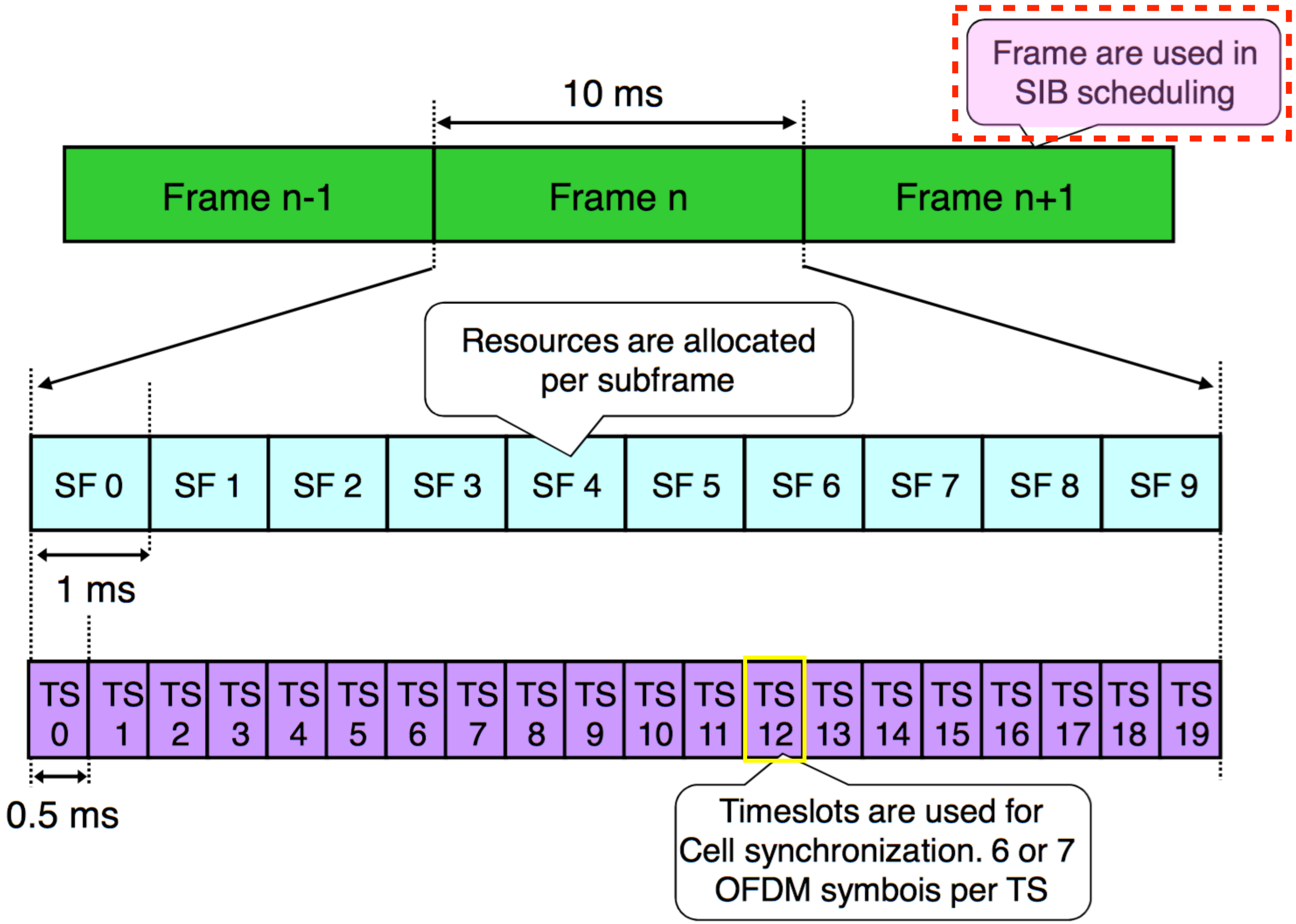
QPSK :
– 2 bits/symbol
– 2 bps/Hz

16QAM :
– 4 bits/symbol
– 4 bps/Hz

64QAM :
– 6 bits/symbol
– 6 bps/Hz

LTE FDD Frame (Type 1)

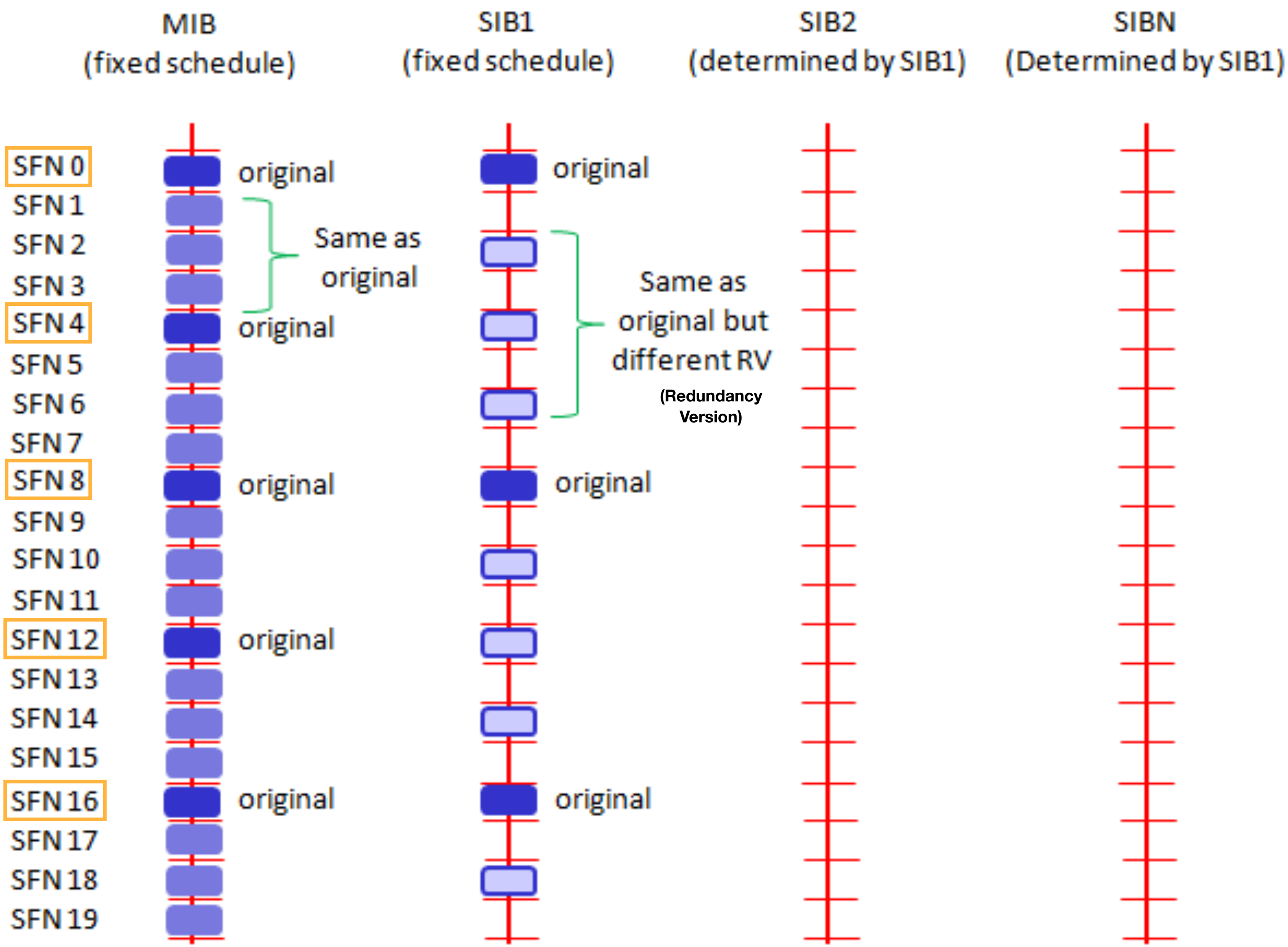
1 Frame = 10 SF = 20
1 SF = 2 TS
1 Frame =10 ms
1 SF = 1 ms
1 TS = 0.5 ms



Note: SIB Scheduling

- The radio frames are used to schedule the transmission of SIBs
- **SIB (System Information Block)** scheduling
  - In LTE, MIB, SIB1, SIB2 are mandated to be transmitted for any cells
- Overall SIB scheduling concept
  - **MIB (Master Information Block)** is transmitted at a fixed cycles (every 4 frames starting from SFN 0)
  - **SIB1** is also transmitted at the fixed cycles (every 8 frames starting from SFN 0)
  - All other SIBs are being transmitted at the cycles specified by SIB scheduling information elements in SIB1

SFN：System Frame Number


MIB
(fixed schedule)
SIB1
(fixed schedule)
SIB2
(determined by SIB1)
SIBN
(Determined by SIB1)
SFN 0
SFN 1
SFN 2
SFN 3
SFN 4
SFN 5
SFN 6
SFN 7
SFN 8
SFN 9
SFN 10
SFN 11
SFN 12
SFN 13
SFN 14
SFN 15
SFN 16
SFN 17
SFN 18
SFN 19
original
Same as original
original
original
original
original
original
Same as original but different RV
(Redundancy Version)
original
original

LTE system information blocks	Description Tracking Area Identity (TAI) = MCC (Mobile Country Code, 12 bits)+ MNC (Mobile Network Code, 8-12 bits) + TAC (Tracking Area Code, 16 bits)
MIB	Carries physical layer information of LTE cell which in turn help receive further SIs, i.e. system bandwidth **(PHICH - Physical Hybrid ARQ Indicator Channel)**
SIB1	Contains information regarding whether or not UE is allowed to access the LTE cell. It also defines the scheduling of the other SIBs. carries cell ID, MCC, MNC, TAC, SIB mapping.
SIB2	Carries common channel as well as shared channel information. It also carries RRC, uplink power control, preamble power ramping, uplink Cyclic Prefix Length, sub-frame hopping, uplink EARFCN **(RRC：Radio Resource Control)**
SIB3	carries cell re-selection information as well as Intra frequency cell re-selection information
SIB4	carries Intra Frequency Neighbors(on same frequency); carries serving cell and neighbor cell frequencies required for cell reselection as well handover between same RAT base stations(GSM BTS1 to GSM BTS2) and different RAT base stations(GSM to WCDMA or GSM to LTE or between WCDMA to LTE etc.) . Covers E-UTRA and other RATs as mentioned
SIB5	Carries Inter Frequency Neighbors(on different frequency); carries E-UTRA LTE frequencies, other neighbor cell frequencies from other RATs. The purpose is cell reselection and handover.
SIB6	carries WCDMA neighbors information i.e. carries serving UTRA and neighbor cell frequencies useful for cell re-selection
SIB7	carries GSM neighbours information i.e. Carries GERAN frequencies as well as GERAN neighbor cell frequencies. It is used for cell re-selection as well as handover purpose.
SIB8	carries CDMA-2000 EVDO frequencies, CDMA-2000 neighbor cell frequencies.
SIB9	carries HNBID (Home eNodeB Identifier)
SIB10	carries ETWS prim. notification
SIB11	carries ETWS sec. notification

LTE MIB content

Information Elements	
Downlink Channel bandwidth	
PHICH configuration	PHICH duration
	PHICH resource
System frame Number (SFN) (10 bits)	

PHICH (Physical Hybrid-ARQ Indicator Channel)
— A specially designed downlink only channel which carries ACK or NACK for the PUSCH (Physical Uplink Share Channel) received by the network
— Hybrid-ARQ (Hybrid Automatic Repeat Request): a combination of high-rate FEC (Forward Error-Correcting) coding and ARQ (ACK+timeout) error-control

System Frame number (SFN)
— Used for synchronization and timing reference. The SFN is of 10 bits in MIB so SFN numbering can be done as 0~1023 (2^{10}=1024)

LTE SIB-1 content

Tracking Area Identity (TAI) = MCC (Mobile Country Code, 12 bits)+ MNC (Mobile Network Code, 8-12 bits) + TAC (Tracking Area Code, 16 bits)

Information Elements		
Cell Access Information	PLMN Identity List (1 to 6 instances)	PLMN Identity
		Cell Reserved for Operator Use
	Tracking Area Code (TAC)	
	Cell Identity	
	Cell Barred	
	Intra-Frequency Cell Reselection Allowed	
	CSG Indication	
	CSG Identity	
Cell Selection Information	Qrxlevmin	
	Qrxlevmin	
Pmax		
Frequency Band Indicator		
Scheduling Information List (1 to 32 inst6ances)	S1 Periodicity (8, 16, 32, 64, 128, 256, 512 radio frames)	
	SIB mapping (1 to 32 instances)	SIB Type
TDD Configuration	Subframe Assignment (uplink-downlink configuration)	
	Special Subframe Pattern (Special subframe configuration)	
System Information Window Length (1, 2, 5, 10, 15, 20, 40 ms)		
System Information Value Tag		
IMS Emergency Support (rel. 9)		
Release 9 Extension	Cell Selection Information	Qqualmin
		Qqualmin Offset

CSG：Closed Subscriber Group

System Information Block Type 2 (SIB2)			
AC-Barring For Emergency	AC-Barring For MO-Signalling	ac-Barring Factor	
		ac-Barring Time	
		ac-Barring For Special AC	
	AC-Barring for MO-Data	ac-Barring Factor	
		ac-Barring Time	
		ac-Barring For Special AC	
Radio Resource Config Common	RACH Config Common	Number Of RA-Preambles	
		Size Of RA-Preambles GroupA	
		Message Size GroupA	
		Message Power Offset GroupB	
	Power Ramping Parameters	Power Ramping Step	
		Preamble Initial Received Target P.	
		Preamble Trans Max	
		RA Response Window Size	
		MAC Contention Resolution Timer	
		Max HARQ Msg3 Tx	
	BCCH Config	Modification Period Coeff	
	PCCH Config	Default Paging Cycle	
		nB	
	PRACH Config	Root Sequence Index	
		PRACH Config Info	PRACH Config Index
			High Speed Flag
			Zero Correlation Zone Cfg.
			PRACH Freq Offset
	PDSCH Config Common	Reference Signal Power	
		Pb	
	PUSCH Config Common	n-SB	
		Hopping Mode	
		PUSCH Hopping Offset	
		Enable 64QAM	
		UL Reference Signals PUSCH	Group Hopping Enabled
			Group Assignment PUSCH
			Sequence Hopping Enabled
			Cyclic Shift
	PUCCH Config Common	Delta PUCCH Shift	
		nRB CQI	
		nCS AN	
		n1PUCCH AN	
	Sounding RS UL Config Common	Setup	srs-Bandwidth Config
			ackNackSRS-Simultaneous Transmission
	Uplink Power Control Common	p0 Nominal PUSCH	
		Alpha	
		p0 Nominal PUCCH	
		DeltaF List PUCCH	DeltaF PUCCH Format1
			DeltaF PUCCH Format1b
			DeltaF PUCCH Format2
			DeltaF PUCCH Format2a
			DeltaF PUCCH Format2b
		Delta Preamble Msg3	
	UL Cyclic Prefix Length		

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LTE SIB-2 content

UE Timers and Constants	T300	
	T301	
	T310	
	N310	
	T311	
	N311	
UL Bandwidth		
Additional Spectrum Emission		
Time Alignment Timer Common		

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AC (Access Class)-Baring for Emergency Call

AC Barring for Emergency Calls (True / False)	
AC Barring for MO Signaling	Barring Factor (0 to 0.95, step 0.05)
	Barring Time (4, 8, 16, 32, 64, 128, 256, 512 seconds)
	Barring for Special AC
AC Barring for MO Data	Barring Factor (0 to 0.95, step 0.05)
	Barring Time (4, 8, 16, 32, 64, 128, 256, 512 seconds)
	Barring for Special AC
SSAC Barring for MMTEL Voice (rel. 9)	Barring Factor (0 to 0.95, step 0.05)
	Barring Time (4, 8, 16, 32, 64, 128, 256, 512 seconds)
	Barring for Special AC
SSAC Barring for MMTEL Video (rel. 9)	Barring Factor (0 to 0.95, step 0.05)
	Barring Time (4, 8, 16, 32, 64, 128, 256, 512 seconds)
	Barring for Special AC
AC Barring for CS Fallback (rel. 10)	Barring Factor (0 to 0.95, step 0.05)
	Barring Time (4, 8, 16, 32, 64, 128, 256, 512 seconds)
	Barring for Special AC

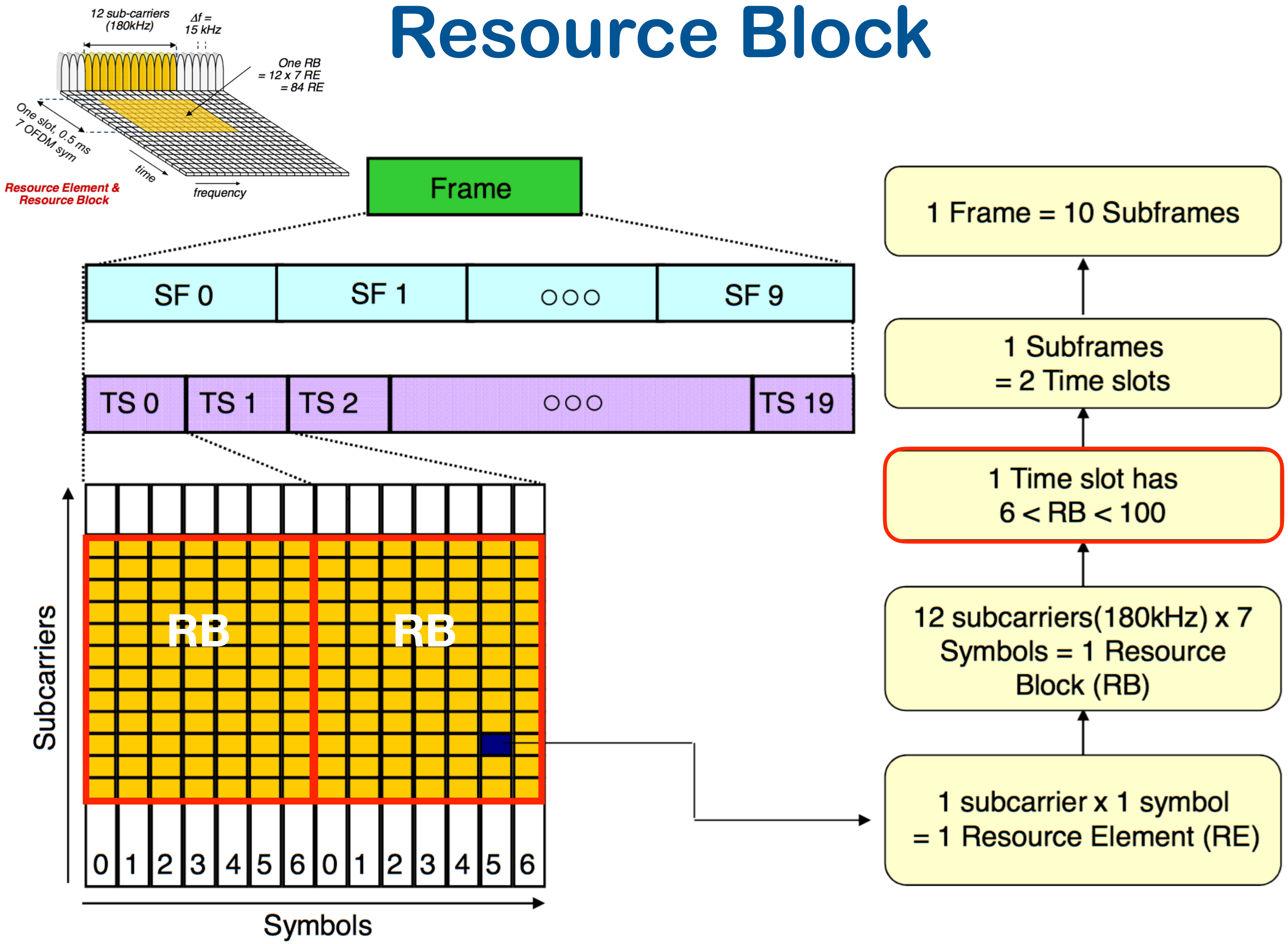
The Difference between SIBs in 4G and 5G

System Information Block

SIB	4G	5G
MIB	Carries physical layer information of LTE cell which in turn help receive further SIs, i.e. system bandwidth	SFN, critical information for the reception of SIB1, Cell barred flag, Intra frequency reselection allowed flag
SIB1	Cell Access Related Information - PLMN Identity List, PLMN Identity, TA Code, Cell identity & Cell Status	Cell selection/barring, radio resource config, scheduling of other SIBs
SIB2	Access Barring Information - Access Probability factor, Access Class Baring List, Access Class Baring Time, Random Access Parameter, PRACH Configuration	Cell reselection (intra freq, inter freq, IRAT) common
SIB3	Cell-reselection parameters for INTRA-Frequency, INTER-Frequency and Inter-RAT	Information about the serving frequency and intra-frequency neighbouring cells relevant for cell re-selection
SIB4	Cell-reselection parameters for Neighbouring INTRA-Frequency	Information about Inter-frequencies neighbouring cells relevant for cell re-selection
SIB5	Cell-reselection parameters for INTER-Frequency	Information about E-UTRA frequencies and E-UTRA neighbouring cells relevant for cell re- selection
SIB6	Cell-reselection parameters INTER RAT Frequency	ETWS primary notification, ETWS: Earthquake and Tsunami Warning System
SIB7	Cell-reselection parameters INTER RAT Frequency (GERAN)	ETWS secondary notification, ETWS: Earthquake and Tsunami Warning System
SIB8	Information for reselection to CDMA2000 systems	CMAS warning notification, CMAS: Commercial Mobile Alert System
SIB9	Home eNodeB name – for future LTE femtocell applications	Information related to GPS time and Coordinated Universal Time (UTC)

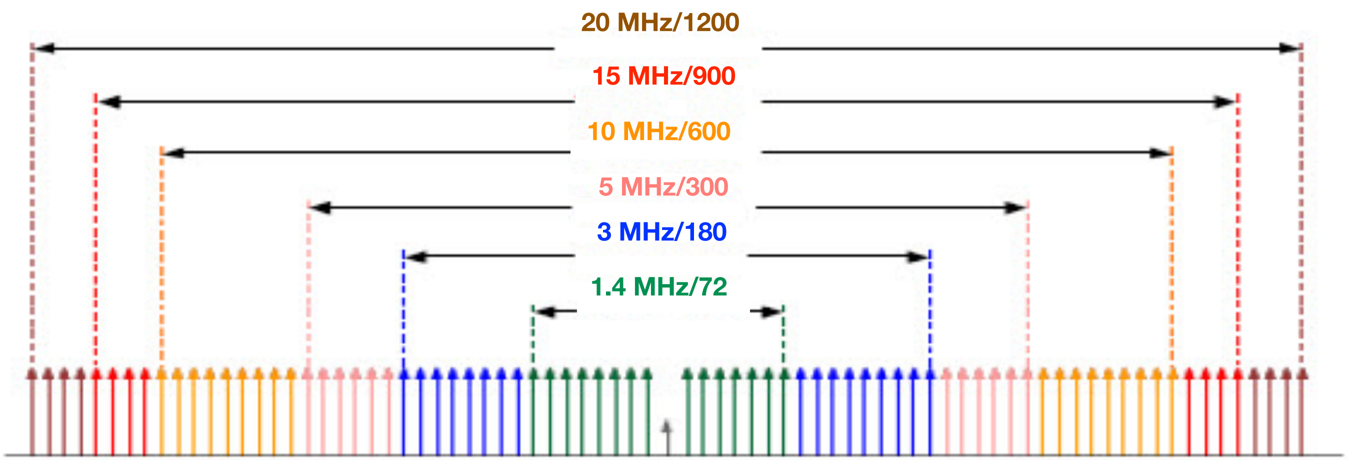
Resource Block

1 Frame = 10 SF = 20 TS
1 SF = 2 TS
1 Frame =10 ms
1 SF = 1 ms
1 TS = 0.5 ms



LTE Bandwidth / Resource Configuration

Channel bandwidth [MHz]	1.4	3	5	10	15	20
Number of resource blocks (N_{RB})	6	15	25	50	75	100
Number of occupied subcarriers	x12 72	180	300	600	900	1200



Channel bandwidths
(bandwidth/data subcarriers)

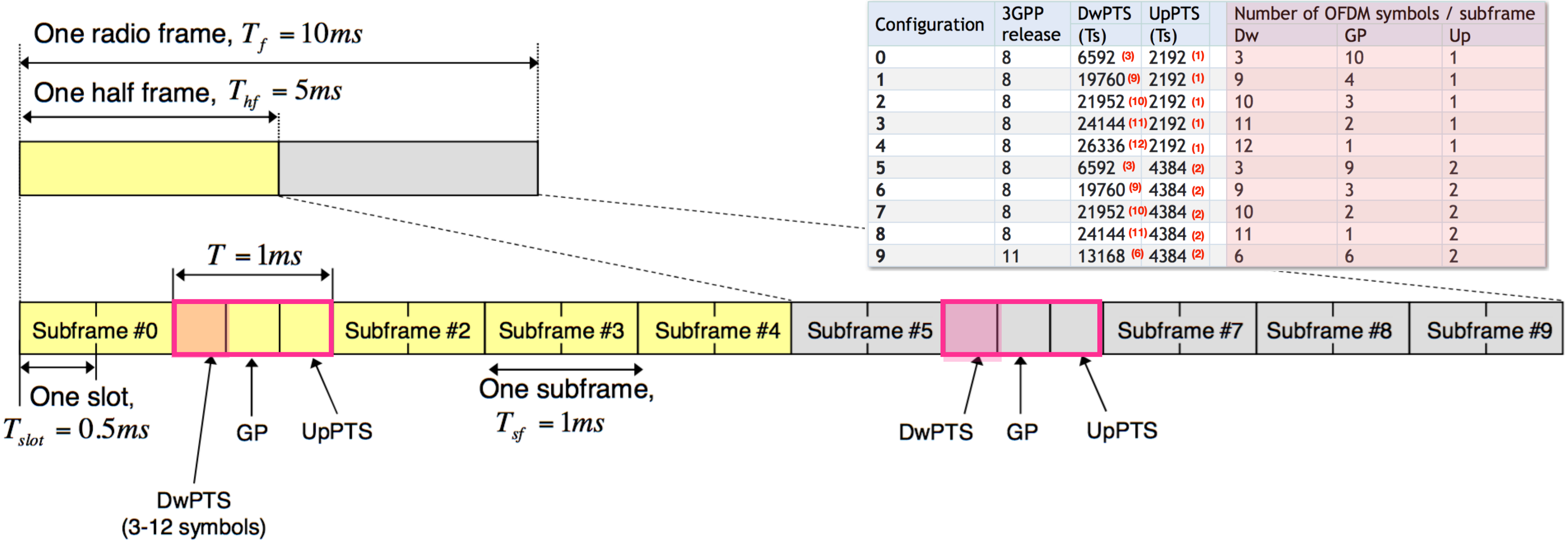
LTE TDD Frame (Type 2)

(Dw/GP/Up)

Configuration	3GPP release	DwPTS (Ts)	UpPTS (Ts)	Number of OFDM symbols / subframe: Dw	GP	Up
0	8	6592 (3)	2192 (1)	3	10	1
1	8	19760 (9)	2192 (1)	9	4	1
2	8	21952 (10)	2192 (1)	10	3	1
3	8	24144 (11)	2192 (1)	11	2	1
4	8	26336 (12)	2192 (1)	12	1	1
5	8	6592 (3)	4384 (2)	3	9	2
6	8	19760 (9)	4384 (2)	9	3	2
7	8	21952 (10)	4384 (2)	10	2	2
8	8	24144 (11)	4384 (2)	11	1	2
9	11	13168 (6)	4384 (2)	6	6	2

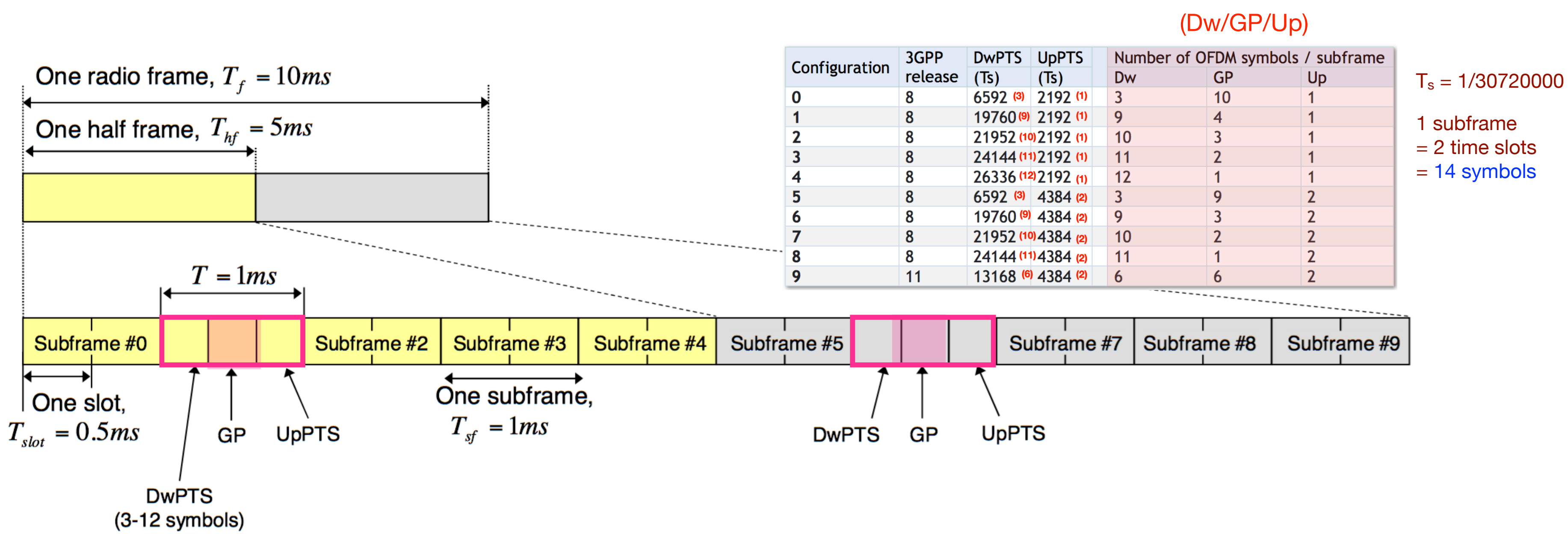
$T_s = 1/30720000$

1 subframe
= 2 time slots
= 14 symbols



DwPTS (Downlink Pilot Time Slot)

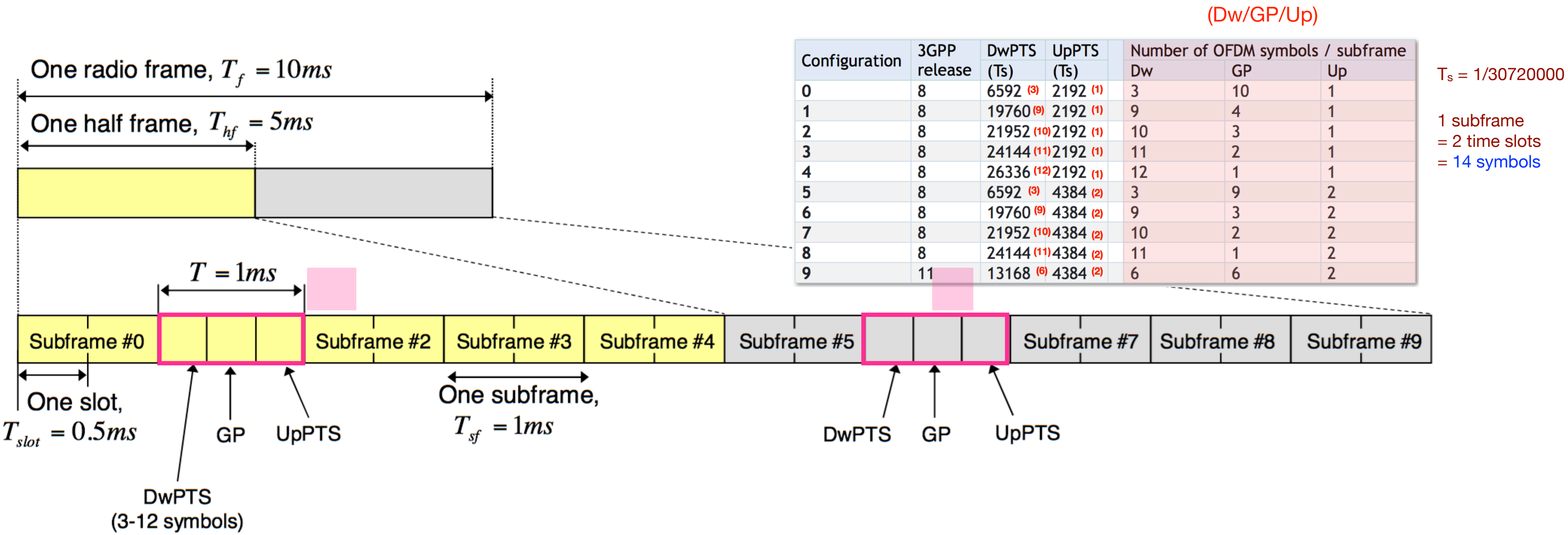
- The subframe allocated for DL transmission from BS to UE
- Include time for sending reference signals, known as pilots, which are used by the devices to estimate the channel quality



Configuration	3GPP release	DwPTS (Ts)	UpPTS (Ts)	Number of OFDM symbols / subframe Dw	GP	Up
0	8	6592 (3)	2192 (1)	3	10	1
1	8	19760 (9)	2192 (1)	9	4	1
2	8	21952 (10)	2192 (1)	10	3	1
3	8	24144 (11)	2192 (1)	11	2	1
4	8	26336 (12)	2192 (1)	12	1	1
5	8	6592 (3)	4384 (2)	3	9	2
6	8	19760 (9)	4384 (2)	9	3	2
7	8	21952 (10)	4384 (2)	10	2	2
8	8	24144 (11)	4384 (2)	11	1	2
9	11	13168 (6)	4384 (2)	6	6	2

GP (Guard Period)

- A small amount of time inserted between DL and UL transmissions to <u>prevent interference</u>
- This is necessary because of the time taken by the radio waves to <u>travel</u> between the BS and the UE, ensuring that DL transmissions do not <u>overlap</u> with UL transmissions



Configuration	3GPP release	DwPTS (Ts)	UpPTS (Ts)	Number of OFDM symbols / subframe: Dw	GP	Up
0	8	6592 (3)	2192 (1)	3	10	1
1	8	19760 (9)	2192 (1)	9	4	1
2	8	21952 (10)	2192 (1)	10	3	1
3	8	24144 (11)	2192 (1)	11	2	1
4	8	26336 (12)	2192 (1)	12	1	1
5	8	6592 (3)	4384 (2)	3	9	2
6	8	19760 (9)	4384 (2)	9	3	2
7	8	21952 (10)	4384 (2)	10	2	2
8	8	24144 (11)	4384 (2)	11	1	2
9	11	13168 (6)	4384 (2)	6	6	2

UpPTS (Uplink Pilot Time Slot)

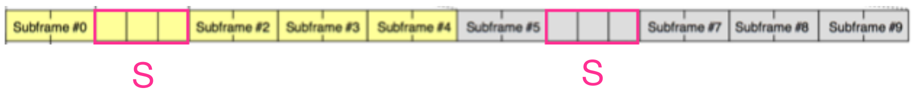
- The <u>subframe</u> allocated for <u>UL</u> transmission, where the Ue sends <u>pilot signals</u> to the BS
- This helps BS to estimate the uplink <u>channel quality</u>

LTE TDD Subframe Allocation

DL/UL switch every
5ms / 10ms

1 frame = 10 subframes = 10 ms

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



D : a subframe for <u>downlink</u> transmission

S : a "special" subframe used for a <u>guard time</u> (<u>Dw/GP/Up</u>)

U : a subframe for <u>uplink</u> transmission

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

- **UL-DL configuration**
  - The different configurations that determine how the UL (U) and DL (D) subframes are distributed across a 10 ms radio frame
  - The radio frame is typically made up of 10 subframes, each 1 ms in length

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

- **DL-to-UL switch-point periodicity**
    - This indicates how often the switch from DL to UL occurs
    - The switch can happen every 5 ms, and in others, every 10 ms
    - This periodicity is important for synchronizing the transmission and reception within the network

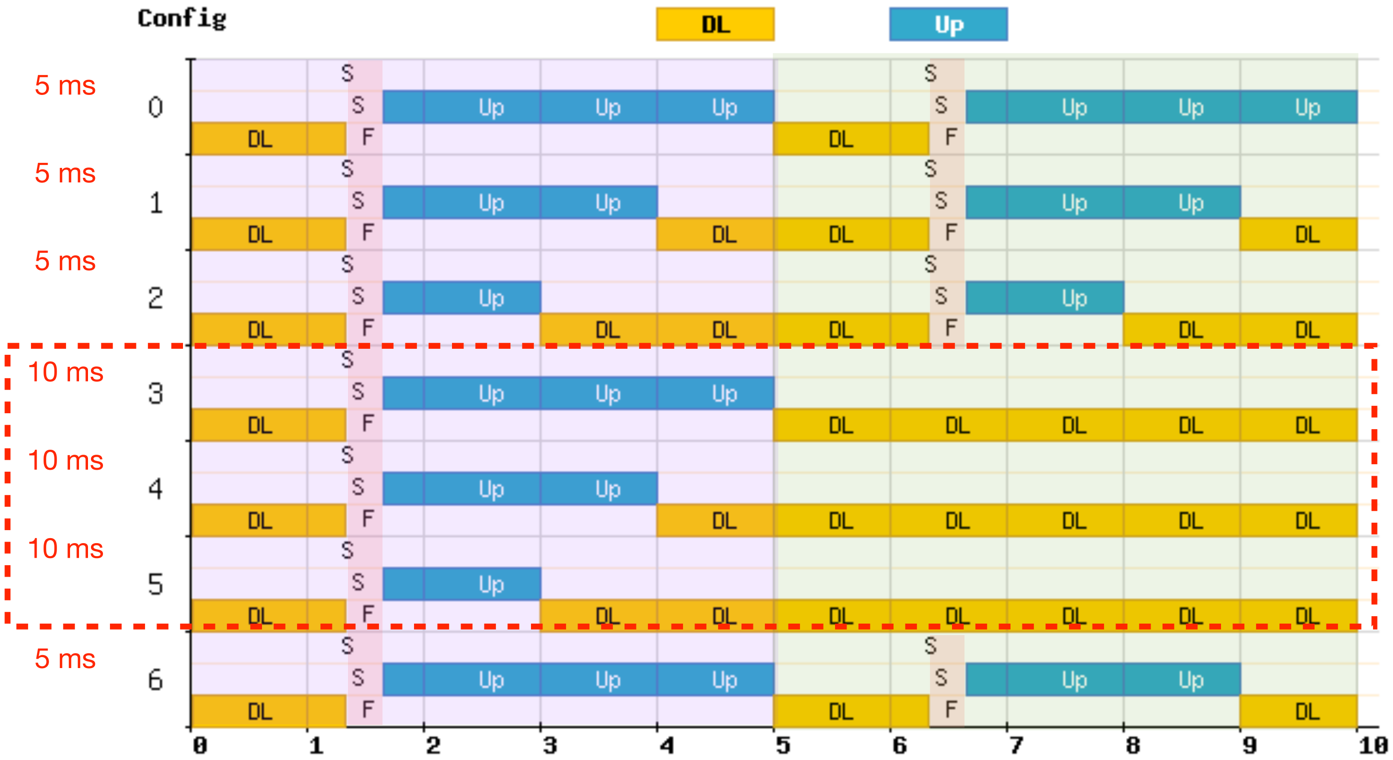
Uplink-Downlink Configuration	Downlink-to-Uplink Switch-point Periodicity	Subframe Number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U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

- **Subframe number**
  - The subframe numbers within a 10 ms LTE radio frame
  - Each subframe can be designated as a DL (D), UL (U), or special (S) subframe

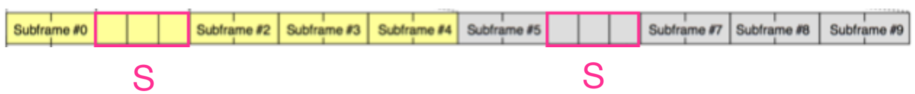
Uplink-Downlink Configuration	Downlink-to-Uplink Switch-point Periodicity	Subframe Number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U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

- D (DL subframe): The subframes for DL transmission from BS to UE
- U (UL subframe): The subframes for UL transmission from UE to BS
- S (Special subframe): This subframe contains three fields: DwPTS, GP, and UpPTS, which are necessary for the transition between DL and UL transmissions within the same frequency band

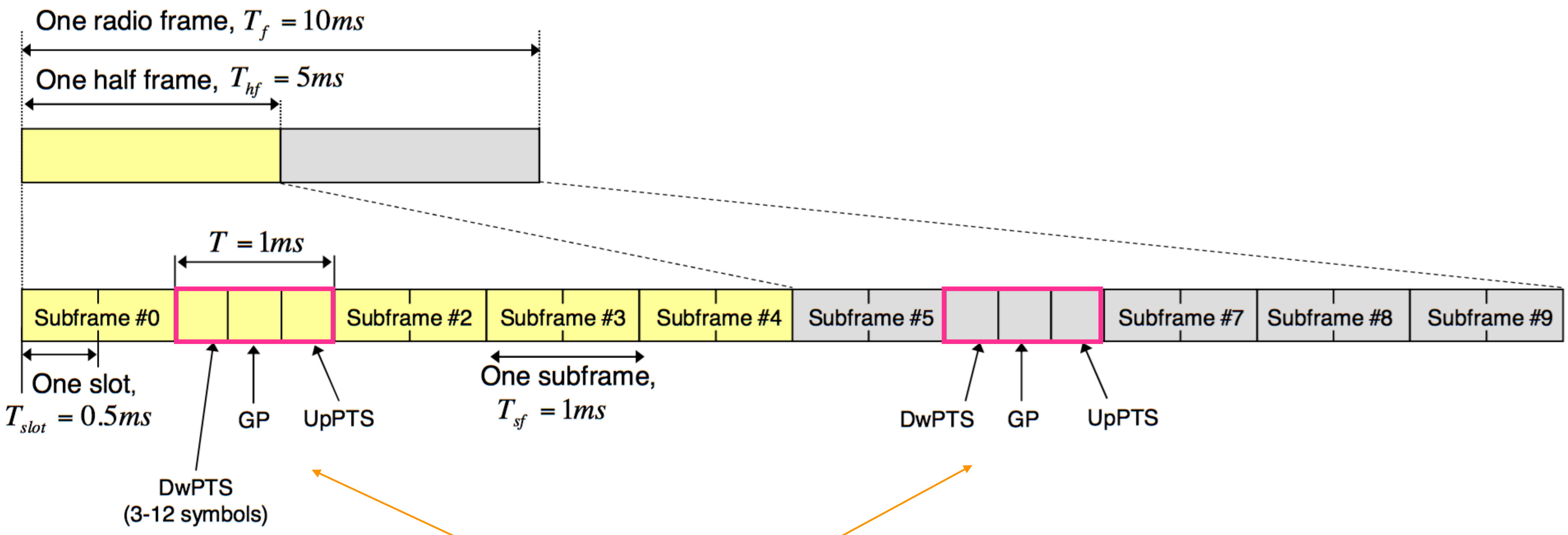
Graphical view of one TDD frame (10ms)



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



LTE DL/UL Switching Options



Special Subframes

- Facilitate DL-to-UL switch
- Two in the case of 5 ms DL-to-UL switch-point periodicity
- One in the case of 10 ms DL-to-UL switch-point periodicity

SSF Special SubFrame, normal CP (Dw / GP / Up)

Configuration	3GPP release	DwPTS (Ts)	UpPTS (Ts)	Number of OFDM symbols / subframe		
				Dw	GP	Up
0	8	6592 (3)	2192 (1)	3	10	1
1	8	19760 (9)	2192 (1)	9	4	1
2	8	21952 (10)	2192 (1)	10	3	1
3	8	24144 (11)	2192 (1)	11	2	1
4	8	26336 (12)	2192 (1)	12	1	1
5	8	6592 (3)	4384 (2)	3	9	2
6	8	19760 (9)	4384 (2)	9	3	2
7	8	21952 (10)	4384 (2)	10	2	2
8	8	24144 (11)	4384 (2)	11	1	2
9	11	13168 (6)	4384 (2)	6	6	2

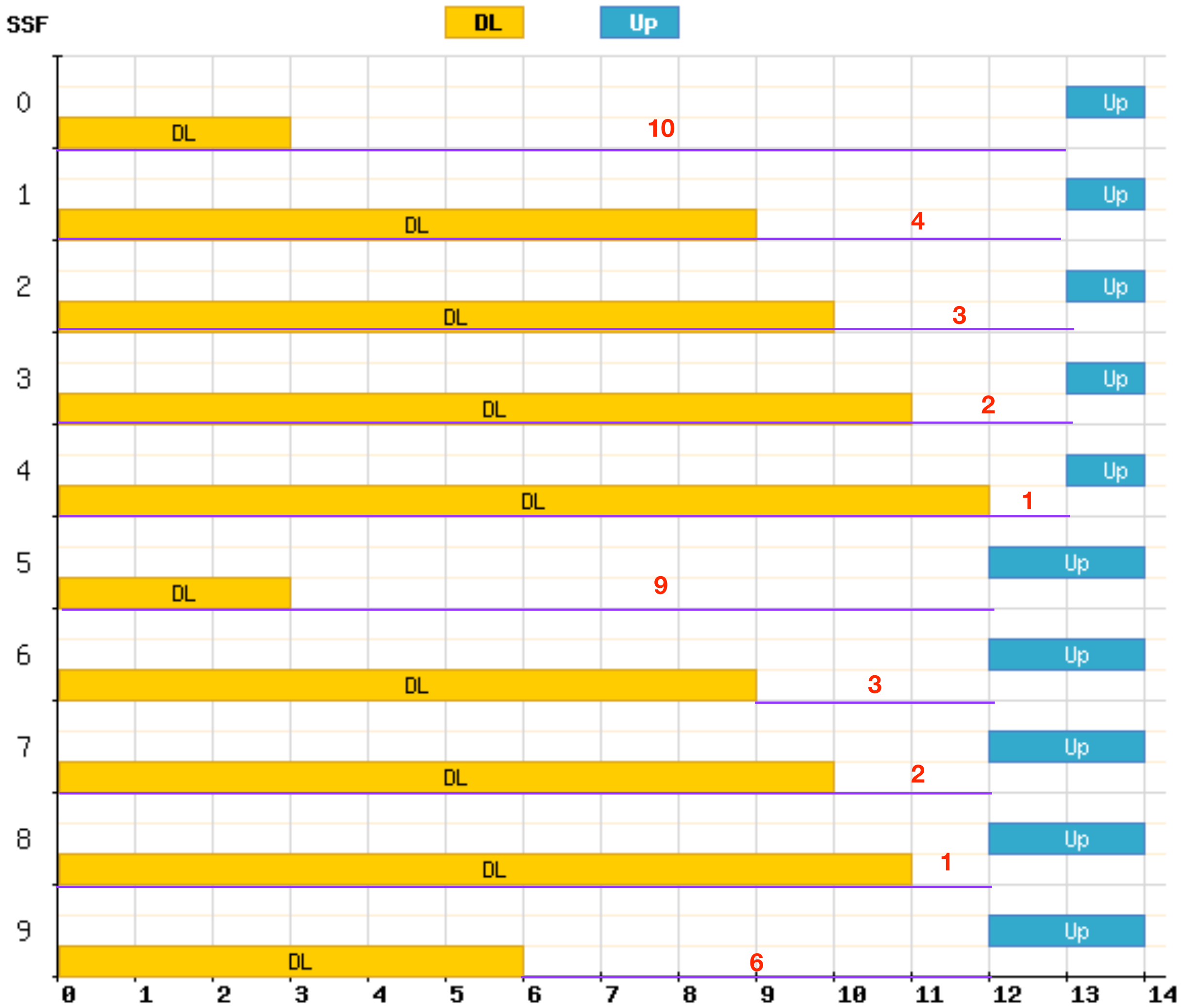
Increasing SSF configuration $T_s = 1/30720000$ seconds

DwPTS Downlink Pilot Time Slot

UpPTS Uplink Pilot Time Slot

GP Guard period

Graphical view of a Special SubFrame (1ms)



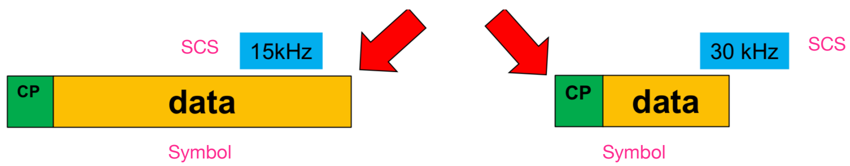
Number of OFDM symbols / subframe		
Dw	GP	Up
3	10	1
9	4	1
10	3	1
11	2	1
12	1	1
3	9	2
9	3	2
10	2	2
11	1	2
6	6	2

LTE vs. 5G NR

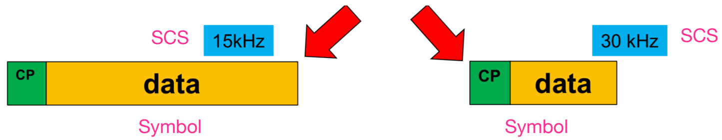
	LTE	5G NR
Radio Frame	10 ms	10 ms
Half Frame	FDD: N/A, TDD: 5 ms	5 ms
Subframe	1 ms	1 ms
Slot size	0.5 ms	Δf=1/2^{μ} ms μ = 0, 1, 2, 3, 4, 5, 6 1, 0.5, 0.25, 0.125, 0.0625, 0.03125, 0.015625
Slot description	7 OFDM symbols with Normal CP and 6 symbols with Extended CP	14 OFDM symbols with Normal CP and 12 symbols with Extended CP
Mini Slot size	N/A	2, 4 or 7 OFDM symbols
Subcarrier Spacing (SCS)	15 KHz or 7.5 KHz in case of eMBMS (evolved Multimedia Broadcast Multicast Service)	Δf=2^{μ} * 15kHz μ = -2, -1, 0, 1, 2, 3, 4, 5, 6 3.75, 7.5, 15, 30, 60, 120, 240, 480, 960
Bandwidth	1.4, 3, 5, 10, 15 or 20 MHz UE is aware about total bandwidth (Broadcasted in MIB)	5; 10; 15; 25; 30; 40; 50; 60; 80 and 100 MHz for frame range 1 (below 6 GHz) 50; 100; 200 and 400 MHz for frame range 2 (Above 24.25 GHz)

Numerologies of NR

- Multiple combinations of physical transmission parameters in NR
  - **Subcarrier spacing (SCS) (Hz)**
    - Frequency separation between adjacent subcarriers in an OFDM signal
    - Larger SCS supports shorter Transmission Time Interval (TTI), aiding low latency, and less susceptible to Doppler shifts, beneficial for high-frequency (mmWave) operations
  - **OFDM symbol duration (*μs*)**
    - Time duration of one OFDM symbol
    - Inversely proportional to the SCS
    - Higher SCS leads to shorter symbols for faster transmission but increased sensitivity to channel delay spread



- **CP duration (μs)**
  - Serves as a buffer to mitigate ISI from multipath delays
  - Duration inversely related to SCS (larger SCS shortens CP)
  - Normal CP is used for typical cellular environments; extended CP is for greater delay spread protection, suitable for broadcasting or large cell radius scenarios
- **OFDM symbol including CP**



Parameter / Numerlogy (u)	0	1	2	3	4	
* Subcarrier Spacing (Khz)	15	30	60	120	240	(a)
OFDM Symbol Duration (us)	66.67	33.33	16.67	8.33	4.17	
Cyclic Prefix Duration (us)	4.69	2.34	1.17	0.57	0.29	
* OFDM Symbol including CP (us)	71.35	35.68	17.84	8.92	4.46	(b)

Subcarrier spacing (a) x OFDM symbol including CP (b) ≃ 1

- NR supports scalable numerology to address different spectrum, bandwidth, deployment and services

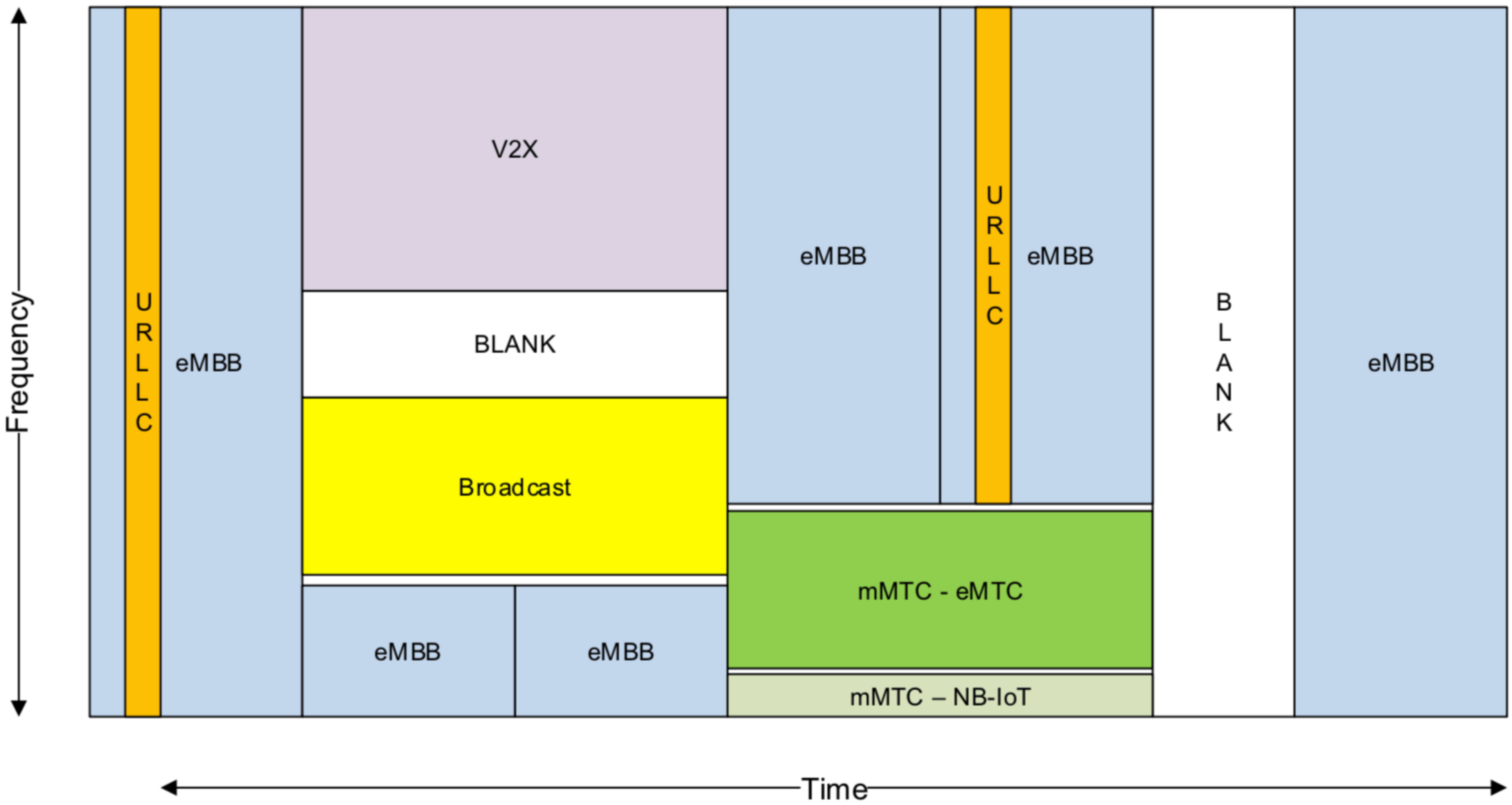
Flexible NR Framework

- NR provides flexible framework to support different services and QoS requirements
  - Scalable slot duration, mini-slot and slot aggregation
  - Self-contained slot structure
  - Traffic preemption for URLLC
  - Support for different numerologies for different services
- NR transmission is well-contained in time and frequency
  - Future feature can be easily accommodated

slot size

$\Delta f = 1/2^{\mu}$ ms $\mu = 0, 1, 2, 3, 4$

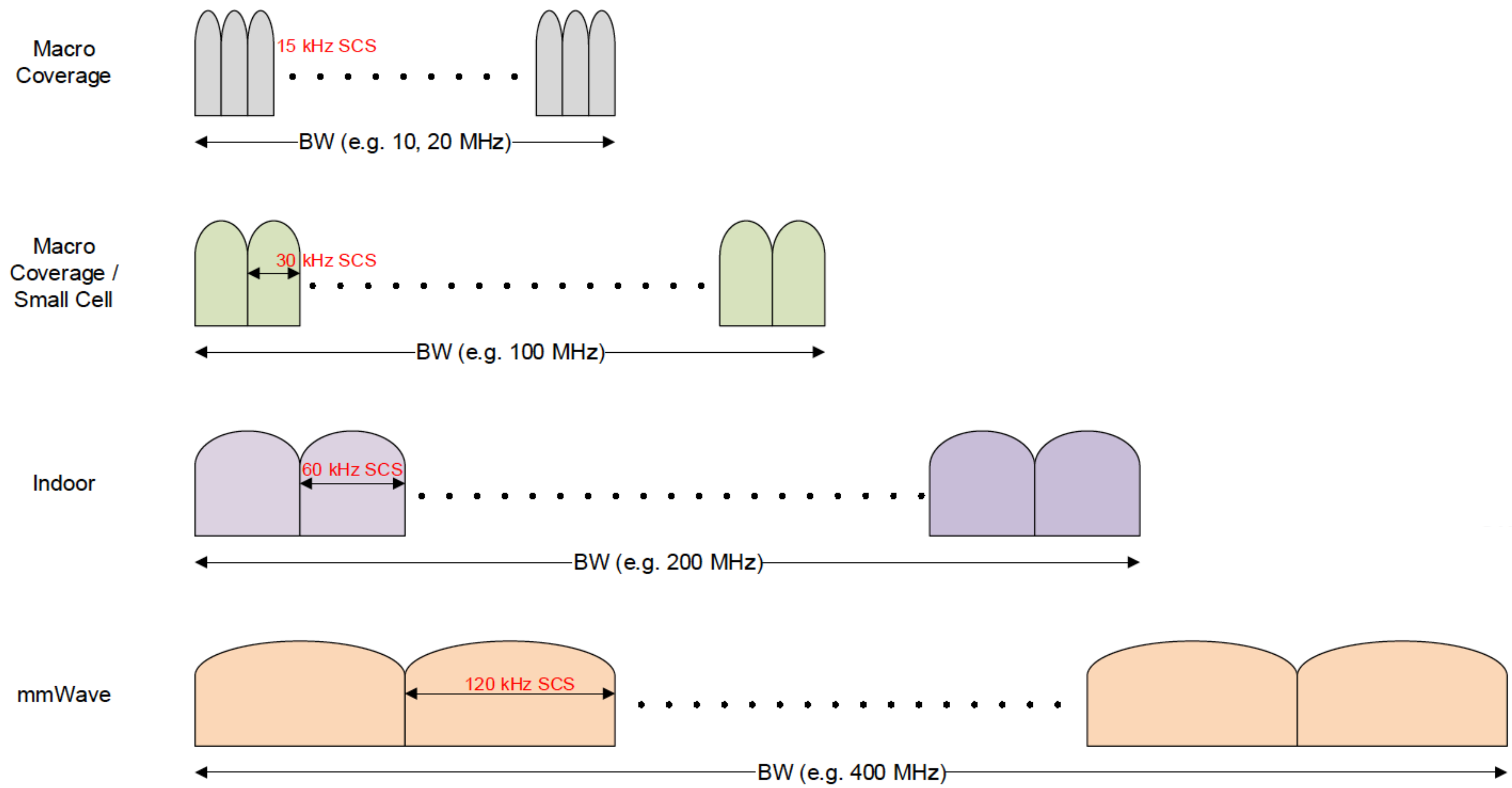
1, 0.5, 0.25, 0.125 or 0.0625

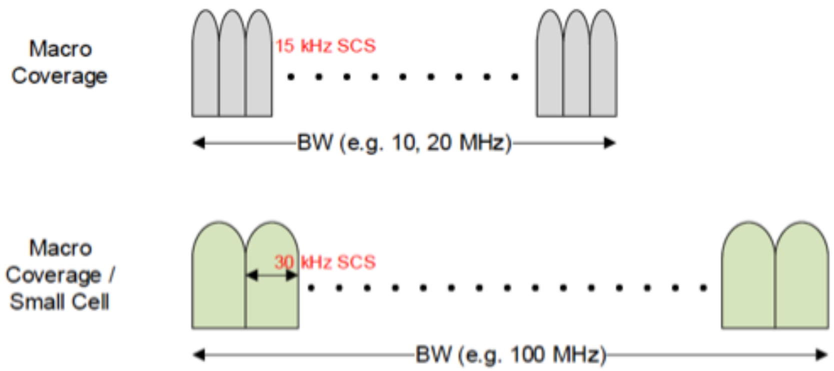


NR transmission is well-contained in time and frequency

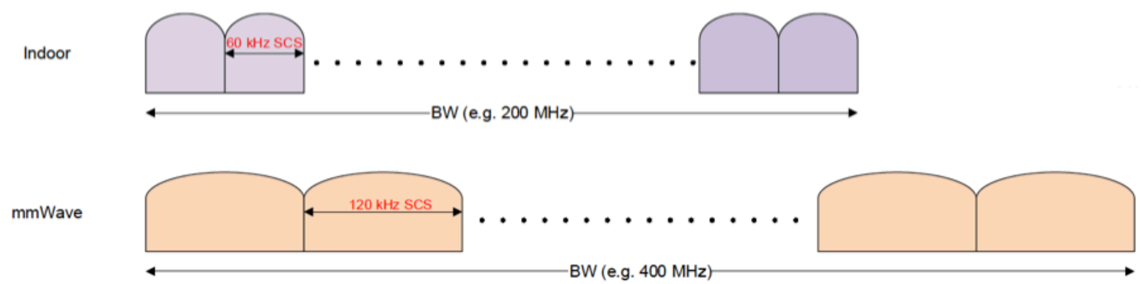
Scalable NR Slot Duration

- **Sub-carrier spacing (SCS)** of 15, 30, 60, 120, 240, 480, 960 kHz is supported for <u>data</u> channels

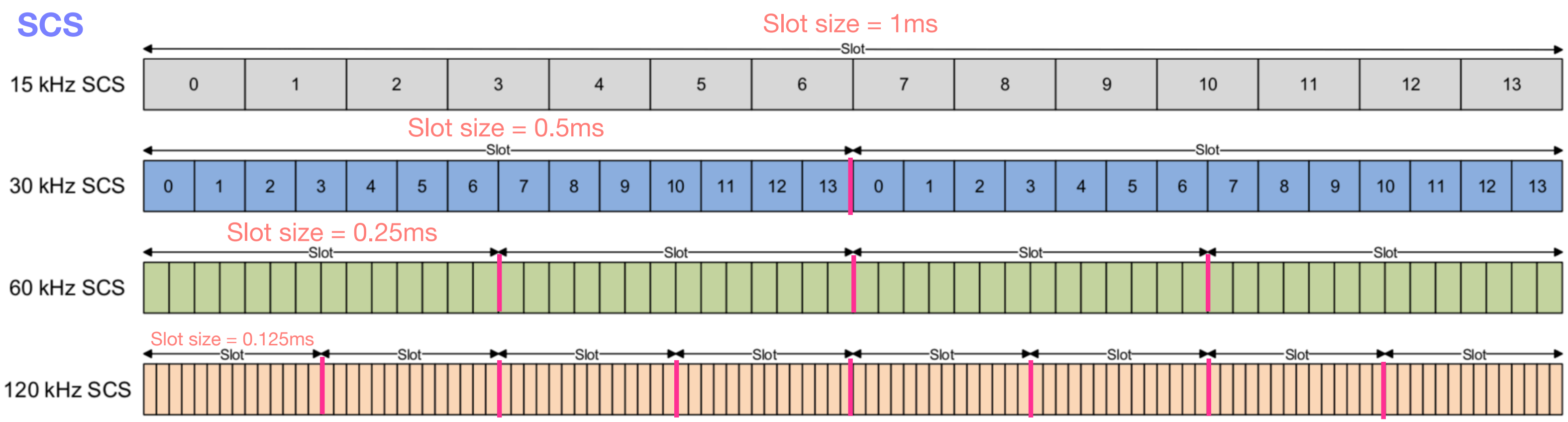




- Macro coverage
  - Use 15 kHz SCS for <u>wide-area</u> coverage
  - <u>Larger CP</u> to handle delay spread in large cells
  - Bandwidths like 10, 20 MHz for <u>broad coverage</u>, not focused on high throughput
- Macro coverage / small cell
  - Employ 30 kHz SCS, suitable for <u>urban areas</u> and <u>small cells</u>
  - Balances coverage and capacity with <u>moderate bandwidths</u>, e.g., 100 MHz.
  - Enables <u>denser cell deployment</u> and <u>moderate throughput</u>



- Indoor
  - Utilizes 60 kHz SCS for indoor settings
  - Less delay spread allows for wider bandwidths, e.g., 200 MHz
  - Targets higher throughput in dense areas like offices and malls
- mmWave
  - Adopts 120 kHz SCS for mmWave frequency use
  - Handles high Doppler shifts, with bandwidths around 400 MHz
  - Supports very high data rates over short distances, ideal for urban hotspots



Subcarrier spacing x OFDM symbol including CP ≃ 1

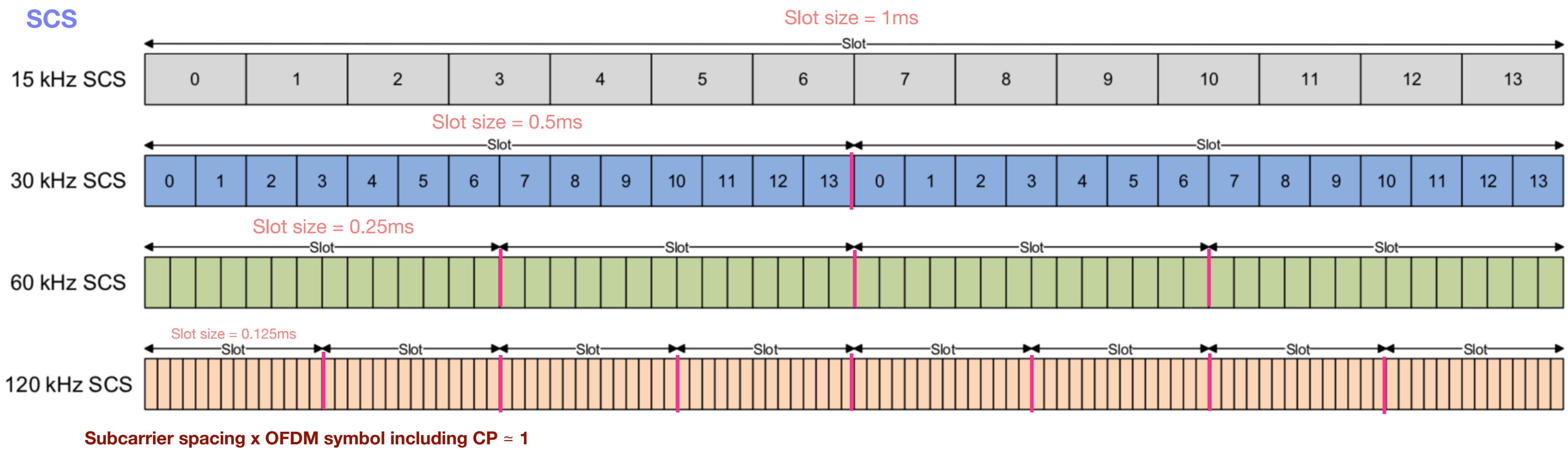
- One slot is comprised of 14 symbols (normal CP)
  - Slot length depends on SCS (slot length x SCS = 15)
    - 1ms for 15kHz SCS
    - 0.5ms for 30kHz SCS
    - 0.25ms for 60kHz SCS
    - 0.125ms for 120kHz SCS
    - ……
- Mini-slot (2,4, or 7 symbols) can be allocated for shorter transmissions
- Slot aggregation: slots can also be aggregated for longer transmissions

Slot size $\Delta f = 1/2^{\mu}$ ms μ = 0, 1, 2, 3, 4, 5, 6

1, 0.5, 0.25, 0.125, 0.0625, 0.03125, 0.015625

SCS $\Delta f = 2^{\mu} * 15$kHz μ = 0, 1, 2, 3, 4, 5, 6

15, 30, 60, 120, 240, 480, 960



- As the SCS increases, the slot size decreases allowing the 5G NR to be flexible and adaptable to various use cases, from wide-area coverage with longer transmission times to dense urban areas requiring high throughput and low latency

- The number of slots within a fixed time frame increases with SCS, which allows for more frequent transmission opportunities and the ability to respond quicker to changing network conditions

- There can be <u>multiple combinations</u> of <u>physical transmission parameters</u> in NR, and these physical transmission <u>parameters</u> are collectively referred to as <u>numerologies</u> in NR
  - Subcarrier spacing (i.e. 2^{μ} * 15 kHz with varied μ)
  - CP lengths (i.e. Normal / Extended)

SCS

$\Delta f = 2^{\mu} * 15\text{kHz}$ μ = 0, 1, 2, 3, 4, 5, 6

15, 30, 60, 120, 240, 480, 960

SCS

	μ	$\Delta f = 2^{\mu} \cdot 15$ kHz	Cyclic Prefix	
Sync < 6 GHz	0	15 kHz	Normal	Data < 6 GHz
	1	30 kHz	Normal	
	2	60 kHz	Normal, Extended	Data > 6 GHz
Sync > 6 GHz	3	120 kHz	Normal	
	4	240 kHz	Normal	
	5	480 kHz	Normal	

- Numerology and supported channels

Data Sync

Numerology	Subcarrier Spacing (kHz)	CP type	Supported for Data (PDSCH, PUSCH etc)	Supported for Sync (PSS,SSS,PBCH)	PRACH
N/A	1.25		No	No	Long Preamble
N/A	5		No	No	Long Preamble
0	15	Normal	Yes	Yes	Short Preamble
1	30	Normal	Yes	Yes	Short Preamble
2	60	Normal,Extended	Yes	No	Short Preamble
3	120	Normal	Yes	Yes	Short Preamble
4	240	Normal	No	Yes	
5	480				
6	960				

Preamble：

- UE tells eNodeB that there is a random access request
- Enable eNodeB to estimate the transmission delay between it and UE
- eNodeB can thus calibrate the UL timing and inform UE of the calibration info. through timing advance command

Note：Physical Downlink Channels and Signals

- **Downlink physical channels**
  - Physical Broadcast CHannel (PBCH)
  - Physical Downlink Control CHannel (PDCCH)
  - Physical Downlink Shared CHannel (PDSCH)
- **Downlink physical signals**
  - Primary Synchronization Signal (PSS)
  - Secondary Synchronization Signal (SSS)
  - Channel State Information Reference Signal (CSI-RS)
  - Tracking Reference Signal (TRS)

Data Supported for Data (PDSCH, PUSCH etc)	Sync Supported for Sync (PSS,SSS,PBCH)
No	No
No	No
Yes	Yes
Yes	Yes
Yes	No
Yes	Yes
No	Yes

Note：Physical Uplink Channels and Signals

- Uplink physical channels
  - Physical Uplink Control Channel (PUCCH)
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Random Access Channel (PRACH)
- Uplink physical signals
  - Sounding Reference Signal (SRS)

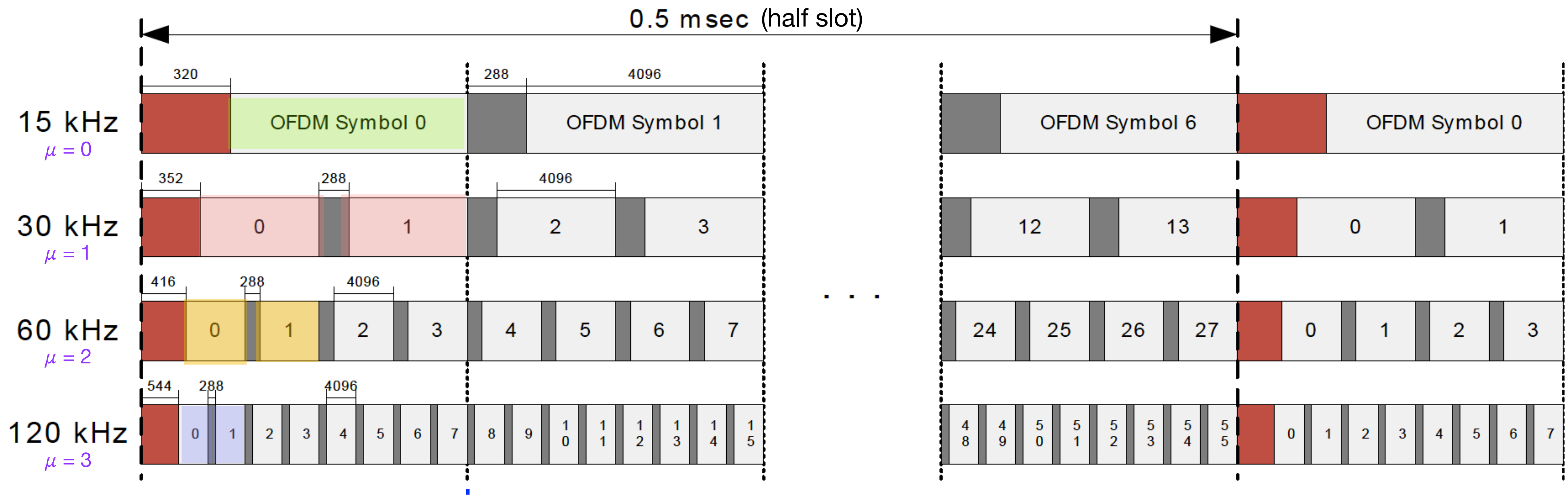
Data Supported for Data (PDSCH, PUSCH etc)	Sync Supported for Sync (PSS,SSS,PBCH)	PRACH
No	No	Long Preamble
No	No	Long Preamble
Yes	Yes	Short Preamble
Yes	Yes	Short Preamble
Yes	No	Short Preamble
Yes	Yes	Short Preamble
No	Yes	

Note：Initial Access — Physical Channels and Signals

- Downlink
  - Primary Synchronization Signal (PSS)
  - Secondary Synchronization Signal (SSS)
  - Physical Broadcast Channel (PBCH)
- Uplink
  - Physical Random Access Channel (PRACH)
- PSS, SSS and PBCH are the only always-on signals in NR

Data	Sync	
Supported for Data (PDSCH, PUSCH etc)	Supported for Sync (PSS,SSS,PBCH)	PRACH
No	No	Long Preamble
No	No	Long Preamble
Yes	Yes	Short Preamble
Yes	Yes	Short Preamble
Yes	No	Short Preamble
Yes	Yes	Short Preamble
No	Yes	

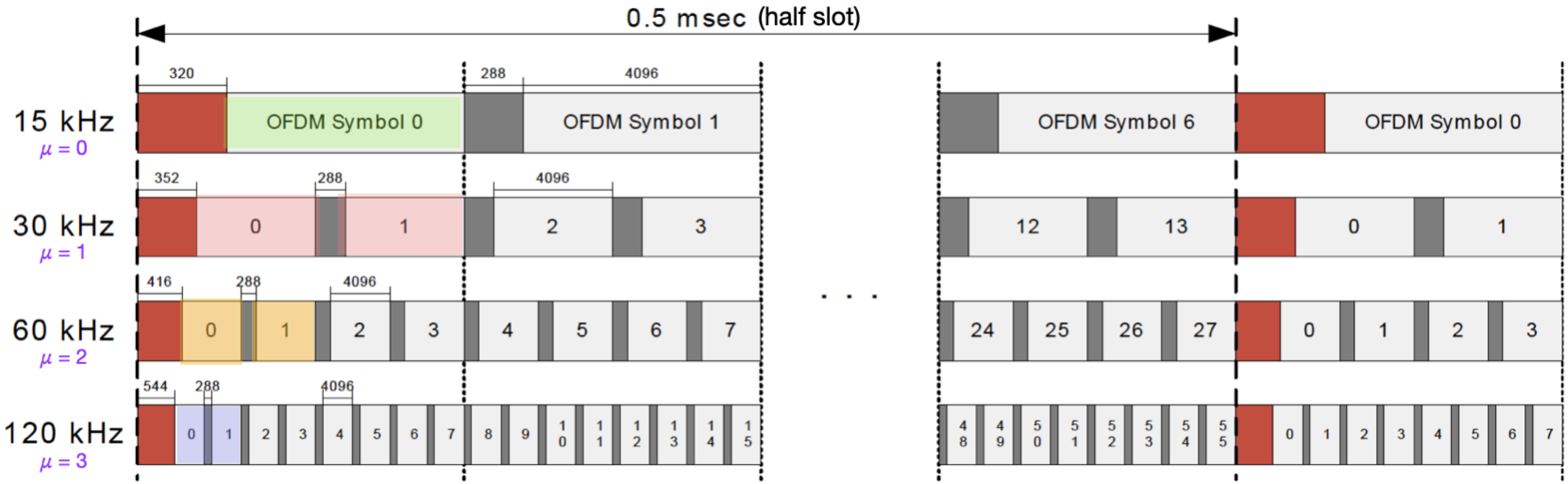
- Numerology example



- Each symbol length (including CP) of **15 kHz** equals the sum of the corresponding **2**$^{\mu}$ symbols of **2**$^{\mu}$ *** 15 kHz** (μ = 0,1,2,3)

  (1 symb/5KHz, 2 symb/30KHz, 4 symb/60KHz, 8 symb/120KHz)

- Other than the <u>first</u> OFDM symbol in every 0.5 ms, all symbols within 0.5 ms have the <u>same length</u>



- In NR, transmitters and receivers may enjoy a <u>wider bandwidth</u> at <u>high frequency bands</u>

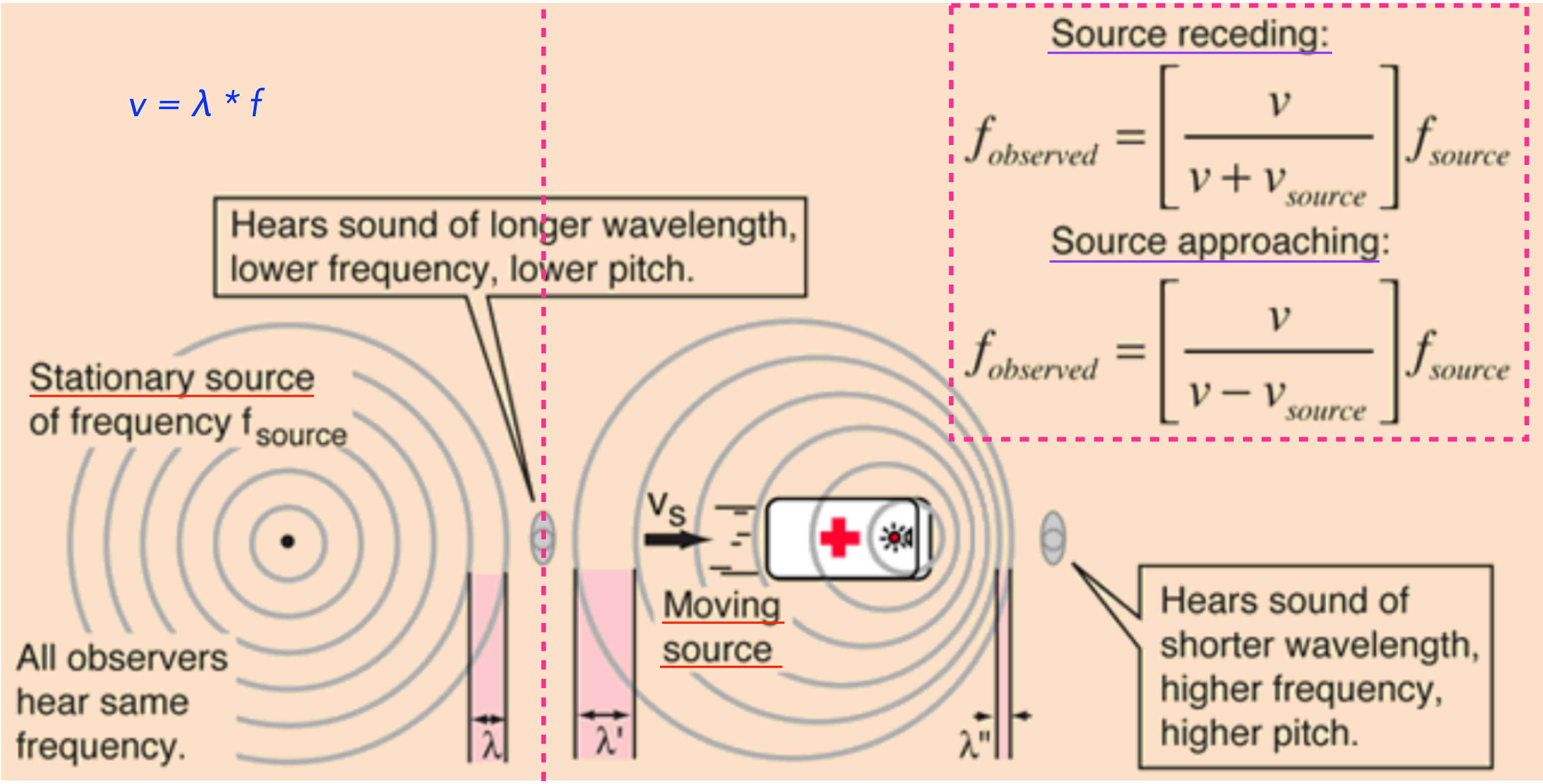
- In this case, the <u>SCS</u> can be <u>extended</u> (larger than 15 kHz as adopted by LTE/LTE-A, and potentially up to <u>960 kHz</u> (μ = 6))

- A <u>large SCS</u> may facilitate <u>inter-carrier interference (ICI) mitigation</u>

- High carrier frequencies are vulnerable to the Doppler effect
    - Doppler effect refers to the change in frequency or wavelength of a wave in relation to an observer who is moving relative to the wave source
    - Doppler effect occurs when there is relative motion between the transmitter and receiver, causing the frequency of the signal received to differ from the frequency that was transmitted

Note：Doppler Effect

- The <u>high pitch</u> of the siren of the <u>approaching</u> ambulance
- The <u>pitch drops</u> suddenly as the ambulance <u>passes</u> you



- NR should also support a small SCS, such as 3.75 kHz as supported by NB-IoT, to enjoy better power efficiency at low frequency bands

- SCSs in NR are scalable as a subset (3.75 kHz = 1/4 × 15 kHz) or superset (960 kHz = 64 × 15 kHz) of 15 kHz

- Scalable SCSs can be *$2^{\mu} \times 15$ kHz*, where μ can be a positive / negative integer or zero

$$\boxed{\Delta f = 2^{\mu} \cdot 15\, kHz}$$

μ = -2, -1, 0, 1, 2, 3, 4, 5, 6

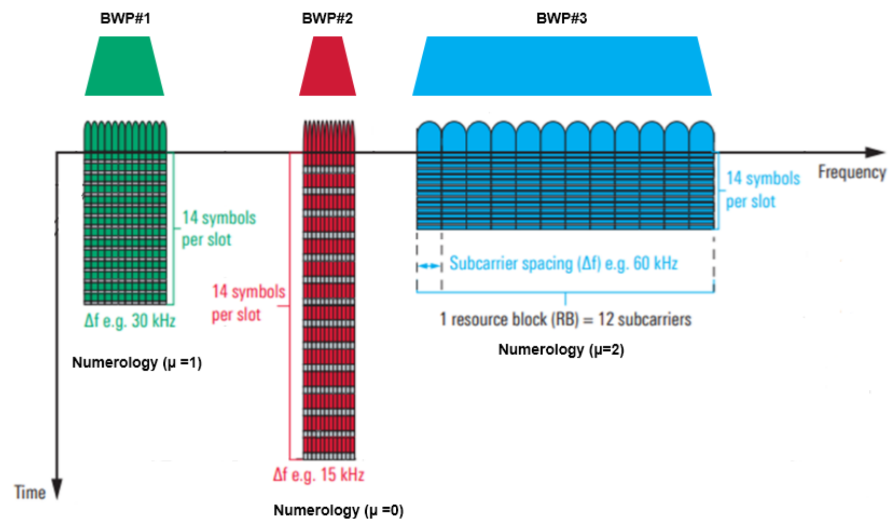
Δf = 3.75, 7.5, 15, 30, 60, 120, 240, 480, 960

- For each SCS value
  - Multiple CP lengths can be inserted to adapt to different levels of ISI at different carrier frequencies and mobility

- <u>Multiple OFDM numerologies</u> are supported as given by the following table where *μ* and <u>CP</u> for a bandwidth part (<u>BWP</u>) are given by the higher-layer parameters
  - DL-BWP-*mu* (*μ*) and DL-BWP-cp for <u>DL</u>
  - UL-BWP-*mu* (*μ*) and UL-BWP-*cp* for <u>UL</u>

μ	$\Delta f = 2^{\mu} \cdot 15 [\text{kHz}]$	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal
5	480	
6	960	

Supported transmission numerologies



BWP: A bandwidth part is a <u>subset</u> of <u>contiguous common resource blocks</u> for a given numerology (*μ*) on a given carrier

Note：DL-BWP-mu / cp, UL-BWP-mu / cp

- **DL-BWP-*mu* (*μ*)**
  - The numerology of DL BWP configuration is applied to at least PDCCH, PDSCH & corresponding DMRS (Demodulation Reference Signal)
- **DL-BWP-*cp***
  - Configure the CP for the bandwidth part
  - Support CPs, where normal CP is for all numerologies and slot formats, extended CP is for 60 kHz numerology

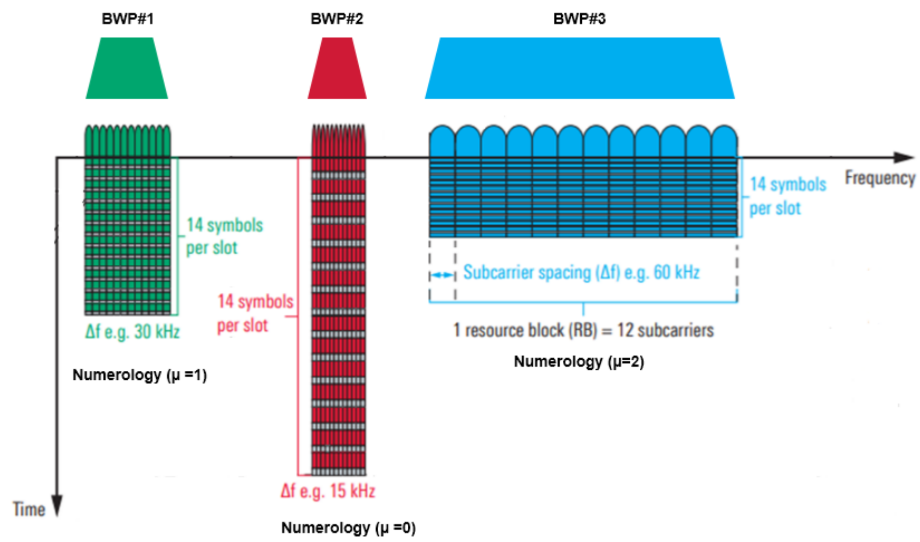
Numerology	Subcarrier Spacing (kHz)	CP type	Supported for Data (PDSCH, PUSCH etc)	Supported for Sync (PSS,SSS,PBCH)	PRACH
N/A	1.25		No	No	Long Preamble
N/A	5		No	No	Long Preamble
0	15	Normal	Yes	Yes	Short Preamble
1	30	Normal	Yes	Yes	Short Preamble
2	60	Normal,Extended	Yes	No	Short Preamble
3	120	Normal	Yes	Yes	Short Preamble
4	240	Normal	No	Yes	
5	480				
6	960				

- **UL-BWP-*mu* (*μ*)**
  - The numerology of UL BWP configuration is applied to at least PUCCH, PUSCH & corresponding DMRS
- **UL-BWP-*cp***
  - Configure the CP for the bandwidth part
  - Support CPs, where normal CP is for all numerologies and slot formats, extended CP is for 60 kHz numerology

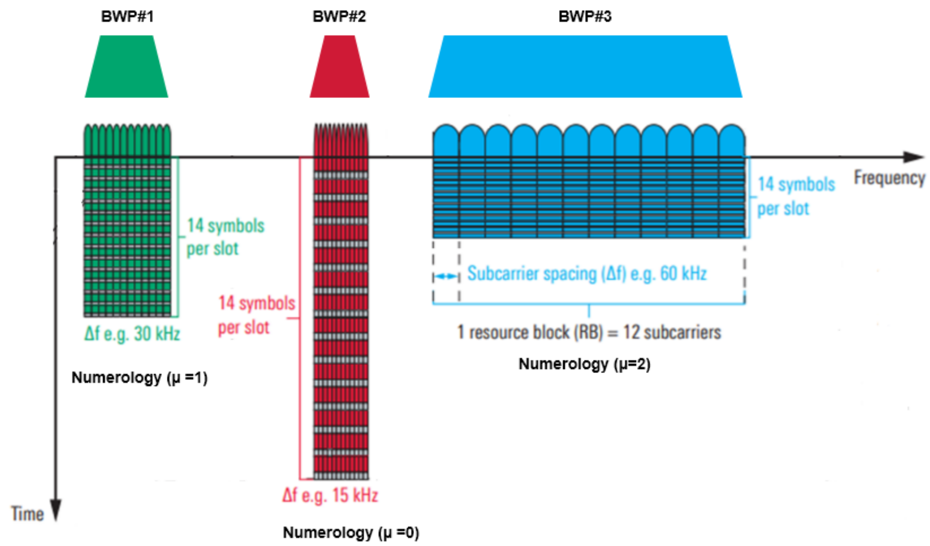
Numerology	Subcarrier Spacing (kHz)	CP type	Supported for Data (PDSCH, PUSCH etc)	Supported for Sync (PSS,SSS,PBCH)	PRACH
N/A	1.25		No	No	Long Preamble
N/A	5		No	No	Long Preamble
0	15	Normal	Yes	Yes	Short Preamble
1	30	Normal	Yes	Yes	Short Preamble
2	60	Normal,Extended	Yes	No	Short Preamble
3	120	Normal	Yes	Yes	Short Preamble
4	240	Normal	No	Yes	
5	480				
6	960				

Bandwidth Part (BWP)

- A Bandwidth Part is a contiguous set of PRBs (Physical Resource Blocks) on a given carrier
  - These RBs are selected from a contiguous subset of the common resource blocks for a given numerology (***μ***), denoted by BWP
  - Each BWP defined for a numerology can have the following three different parameters
    - Subcarrier spacing
    - Symbol duration
    - Cyclic prefix (CP) length

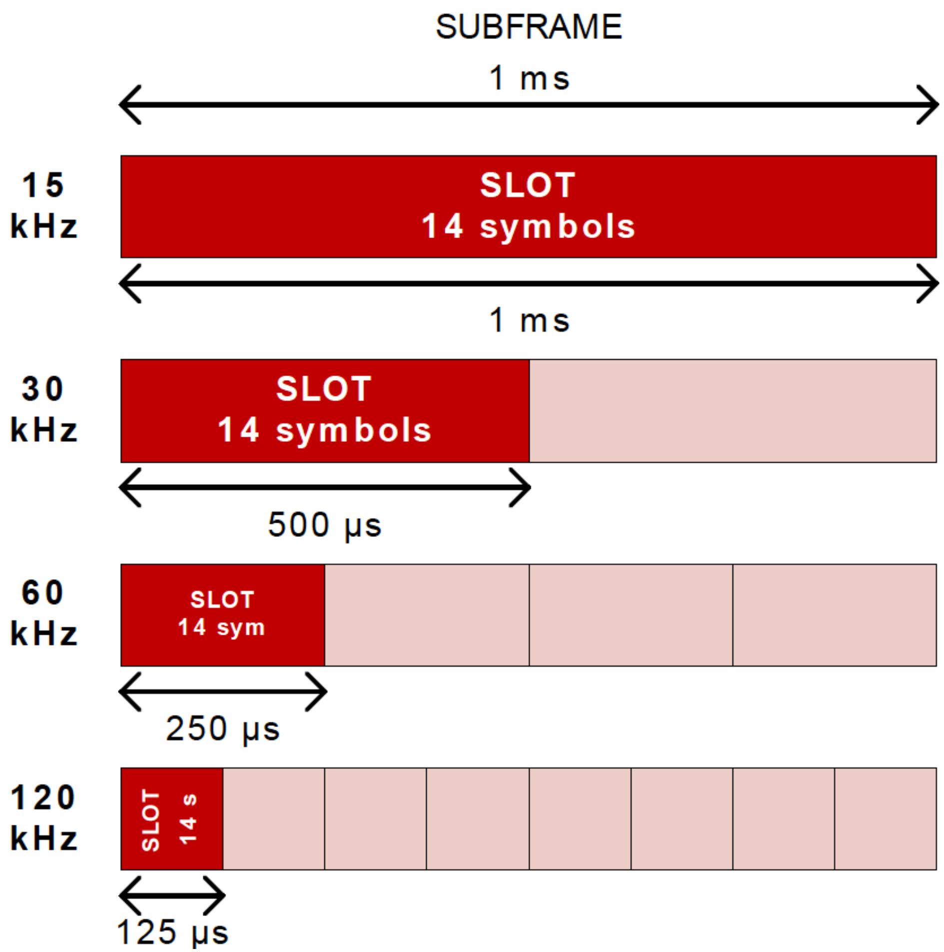


- BWP configuration properties
  - UE can be configured with
    - Max 4 BWP for DL and UL, but
    - At a given point of time only one BWP is active for DL and one for UL
  - BWP concept
    - Enable UEs to operate in narrow bandwidth
    - When user demands more data (bursty traffic) it can inform gNB to enable wider bandwidth



Frame Structure of NR

- In the time domain (dynamic TDD)
  - **Frame**: 10 ms
  - **Subframe**: reference period of 1 ms
  - **Slot** (slot based scheduling)
    - 14 OFDM symbols
    - One possible scheduling unit
    - Slot aggregation allowed
    - Slot length scales with the SCS
      - Slot length = **1**ms **/ 2**$^{\mu}$ (μ = 0, 1, 2, 3, 4, 5, 6) (1 ms, 0.5 ms, 0.25 ms, 0.125 ms, 0.0625 ms, 0.03125 ms, 0.015625 ms)

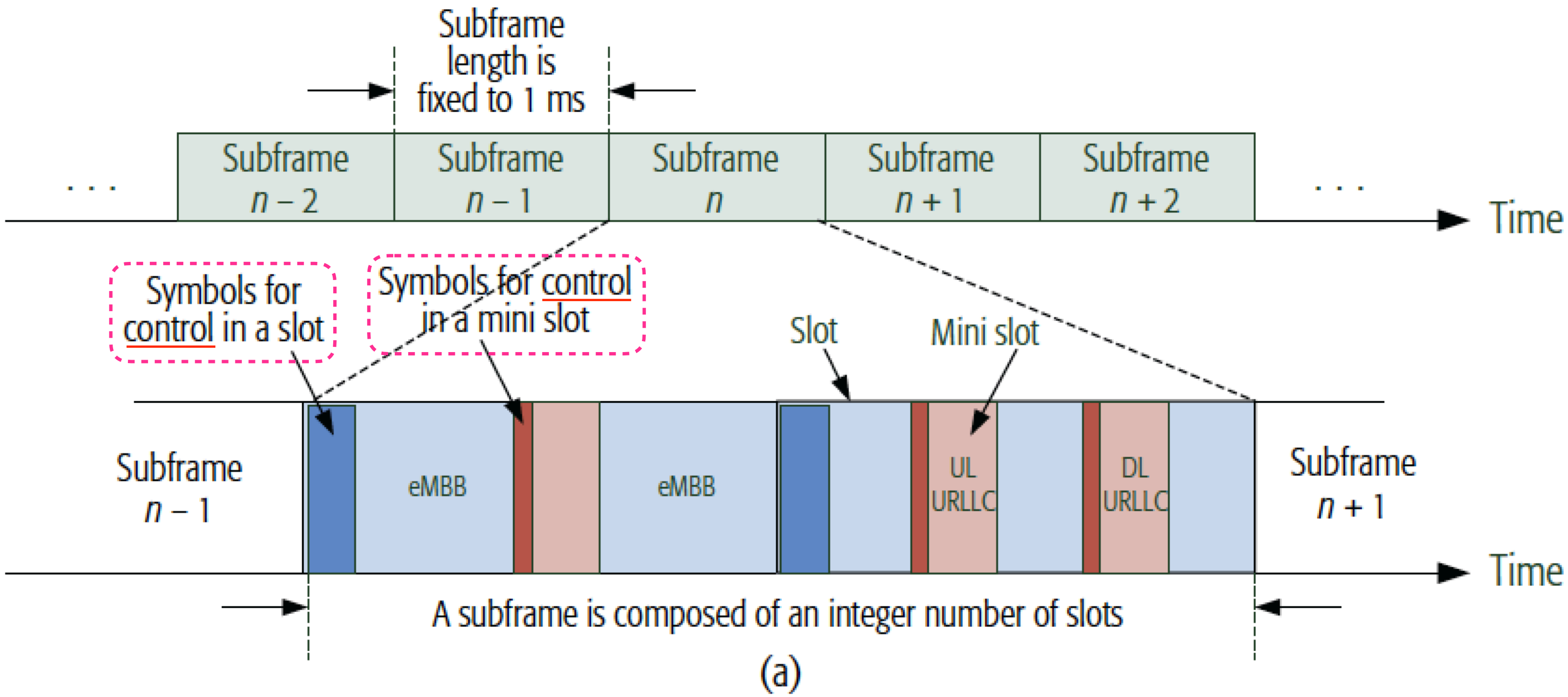


Subcarrier spacing x OFDM symbol including CP ≃ 1

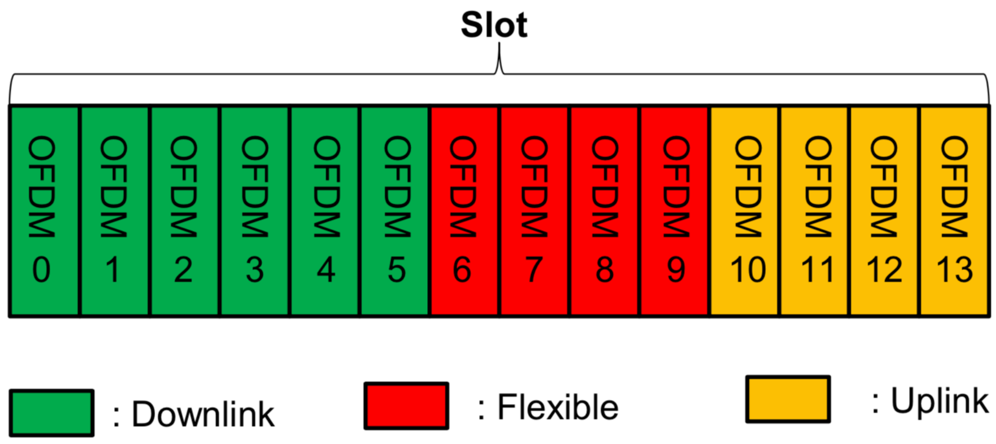
- **Mini-slot** (non-slot based scheduling)
  - 2, 4 or 7 OFDM symbols
  - Min scheduling unit

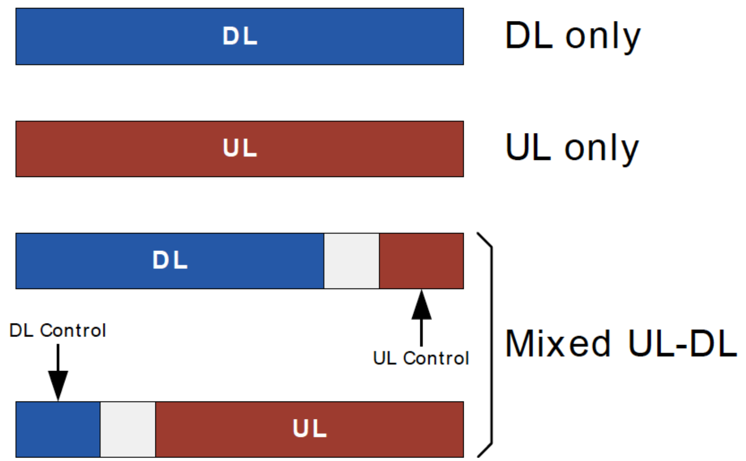
- Each slot can carry control signals/channels at the beginning and/or ending OFDM symbol(s)

- This design enables a gNB to immediately allocate resources for URLLC when urgent data arrives



- OFDM symbols in a slot are able to be
  - All DL
  - All UL
  - At least one DL part and at least one UL part (mixed) (static, semi-static or dynamic)





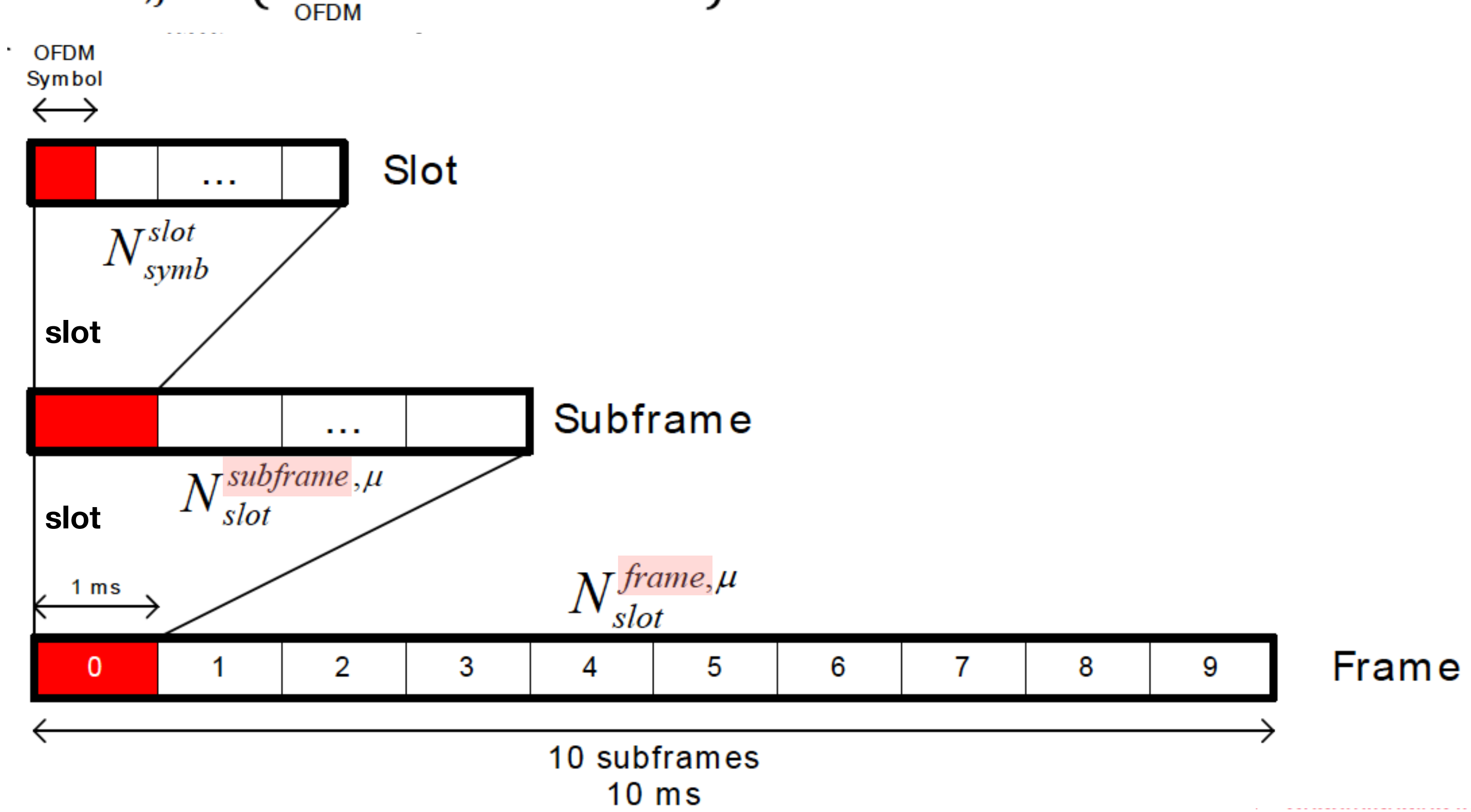
- Slot aggregation is supported
  - Data transmission can be scheduled to span one or multiple slots
- Time-Division Multiplexing (TDM) scheme in NR is more flexible than that in LTE

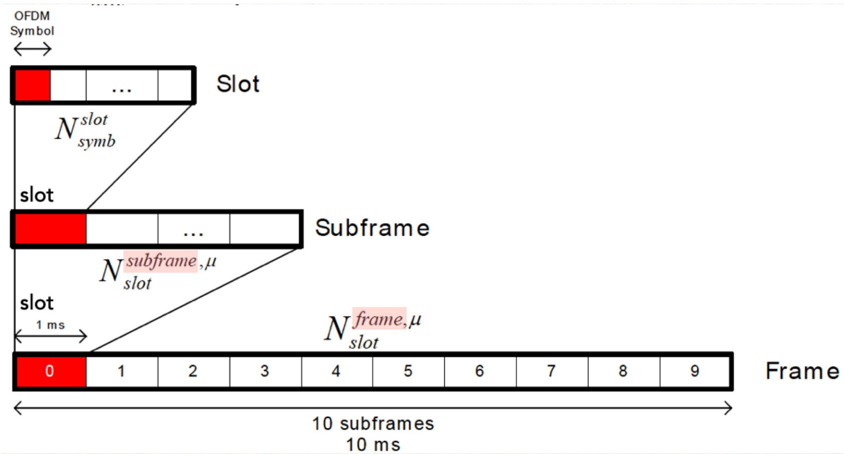
- **Slot Format Indication (SFI)**
  - SFI informs the UE whether an OFDM symbol is DL, UL or Flexible
  - SFI can indicate link direction over one or many slots (configured through RRC - Radio Resource Control)
  - The SFI carries an index to pre-configured UE-specific table (configured through RRC)
  - SFI can be either
    - Dynamic
      - UE assumes there is no conflict between dynamic SFI and DCI (Downlink Control Information) DL/UL assignment
    - Static or semi-static (i.e. through RRC)

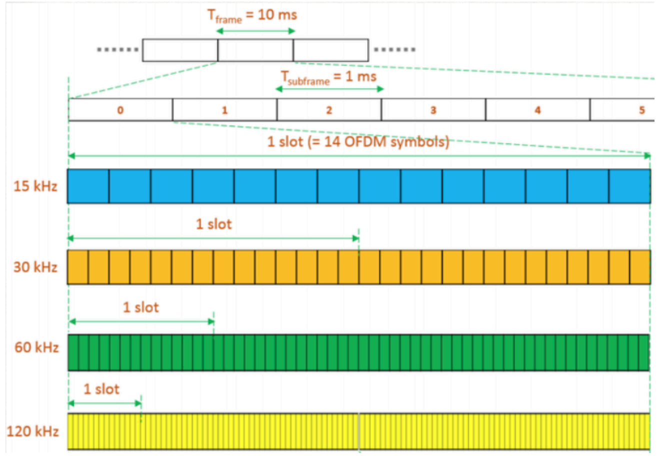
- Mini-slot use cases
  - Support of very low latency (i.e. part of URLLC)
  - Support of finer TDM granularity scheduling for the same/different UEs within a slot
    - Especially if TRxP (Transmission Reception Point) uses beam-sweeping (e.g. above 6GHz)
  - NR-LTE co-existence (e.g. using LTE MBSFN subframes for NR)
  - Forward compatibility towards unlicensed spectrum operation

Beam Sweeping：a technique to transmit the beams in all predefined directions in a burst in a regular interval
MBSFN：Multimedia Broadcast Single Frequency Network

- Slots are numbered
  - $n_s^\mu \in \left\{0, \dots, N_{slot}^{subframe,\mu} - 1\right\}$ within a subframe
  - $n_{s,f}^\mu \in \left\{0, \dots, N_{slot}^{frame,\mu} - 1\right\}$ within a frame





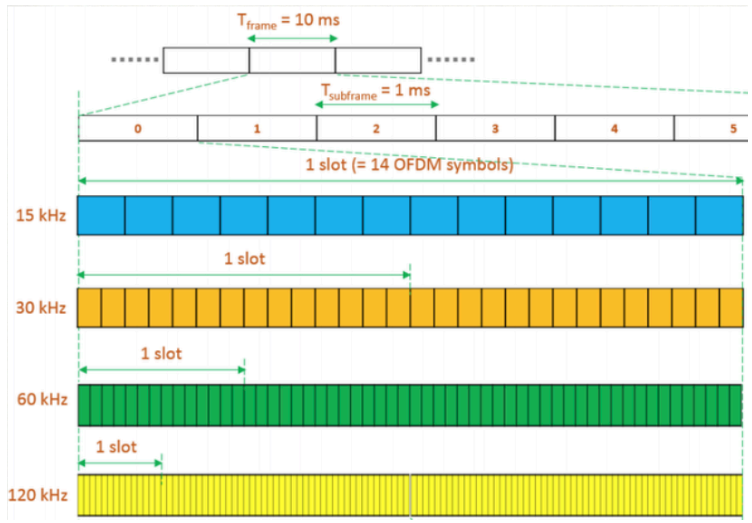


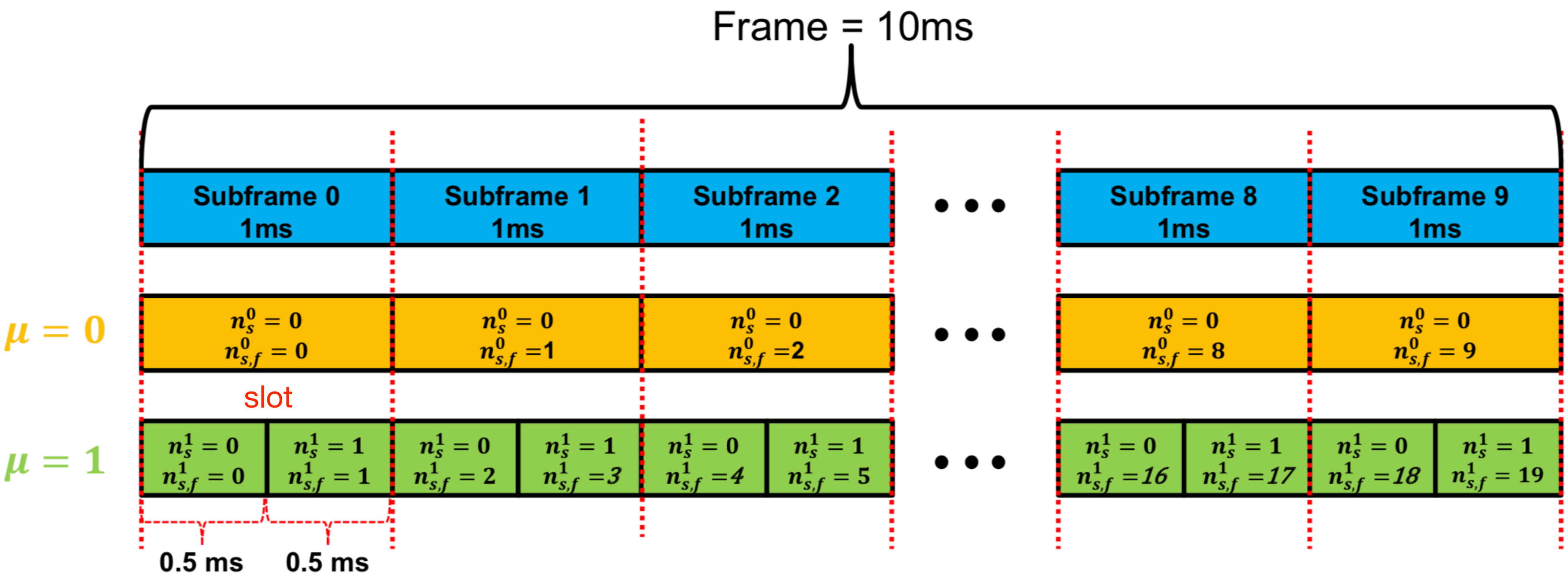
Subcarrier Spacing (μ)	Number of OFDM Symbols per Slot (N^{slot}_{symb})	Number of Slots per Subframe ($N^{subframe,\mu}_{slot}$)	Number of Slots per Frame ($N^{frame,\mu}_{slot}$)
0 *15 kHz*	14 ***1 ms***	2^0 1 *1 slot x 1 ms =* ***1 ms*** x 10 =	10 ***10 ms***
1 *30 kHz*	14 ***500 μs***	2^1 2 *2 slots x 500 μs =* ***1 ms*** x 10 =	20 ***10 ms***
2 *60 kHz (normal CP)*	14 ***250 μs***	2^2 4 *4 slots x 250 μs =* ***1 ms*** x 10 =	40 ***10 ms***
2 *60 kHz (extended CP)*	12 ***250 μs***	2^2 4 *4 slots x 250 μs =* ***1 ms*** x 10 =	40 ***10 ms***
3 *120 kHz*	14 ***125 μs***	2^3 8 *8 slots x 125 μs =* ***1 ms*** x 10 =	80 ***10 ms***
4 *240 kHz*	14 ***62.5 μs***	2^4 16 *16 slots x 62.5 μs =* ***1 ms*** x 10 =	160 ***10 ms***
5 *480 kHz*	14 ***31.25 μs***	2^5 32 *32 slots x 31.25 μs =* ***1 ms*** x 10 =	320 ***10 ms***

Number of OFDM symbols per slot, slots per subframe, and slots per frame for **normal cyclic** / **extended prefix**

- $n_s^\mu \in \left\{0, \dots, N_{slot}^{subframe,\mu} - 1\right\}$ within a subframe
- $n_{s,f}^\mu \in \left\{0, \dots, N_{slot}^{frame,\mu} - 1\right\}$ within a frame

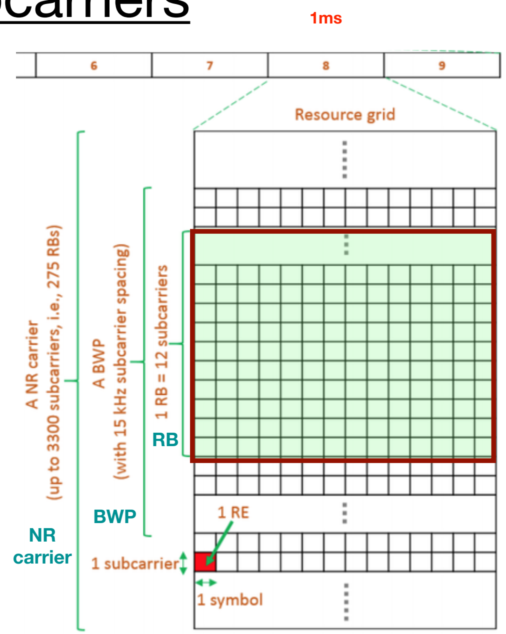
OFDM





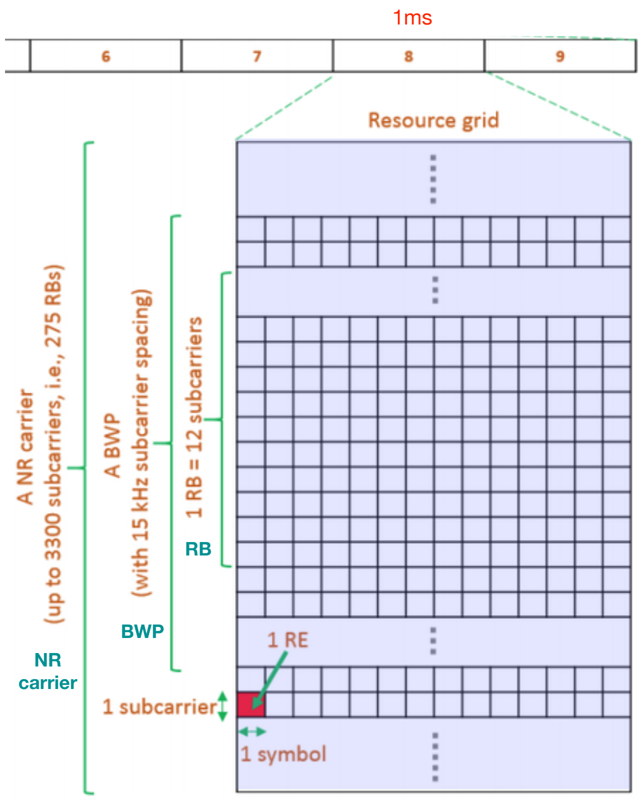
- In the frequency domain (FDD)
  - The basic scheduling unit (grouped Resource Elements) in NR is a physical resource block (PRB), which is composed of 12 subcarriers

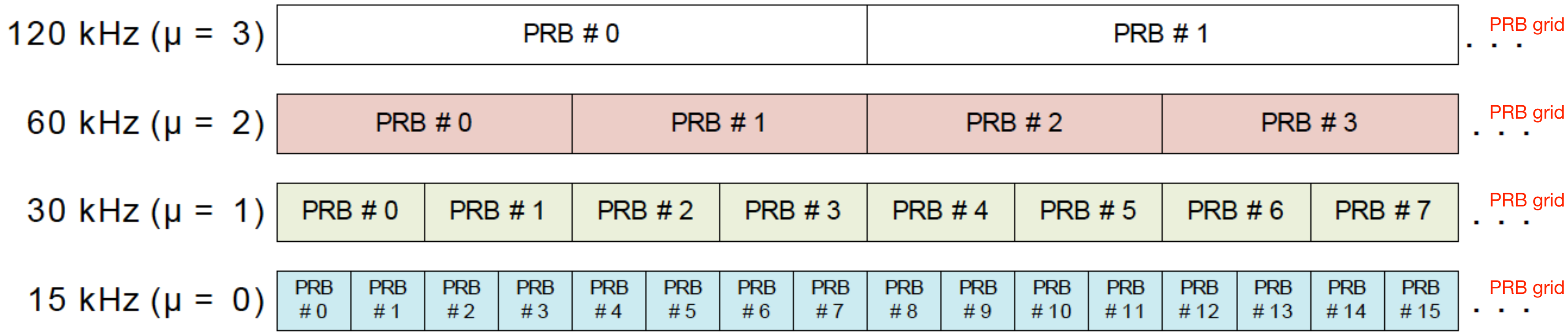
μ	Δf	Min N_{RB} $N_{RB}^{min,\mu}$	Max N_{RB} $N_{RB}^{max,\mu}$
0	15 kHz	20	275
1	30 kHz	20	275
2	60 kHz	20	275
3	120 kHz	20	275
4	240 kHz	20	138
5	480 kHz	20	69



  - All subcarriers within a PRB are of the same spacing and CP overhead
  - Since NR should support multiple SCSs, NR supports PRBs of different bandwidth ranges

- <u>Multiple PRBs</u> of the <u>same bandwidth</u> forms a <u>PRB grid</u>, which is formed by subcarriers with spacing ***15kHz × 2***$^{\mu}$, where μ is a positive (resp. negative) integer





Bandwidth Part (BWP)

- A Bandwidth Part is a contiguous set of PRBs (Physical Resource Blocks) on a given carrier
  - These RBs are selected from a contiguous subset of the common resource blocks for a given numerology (***μ***), denoted by BWP
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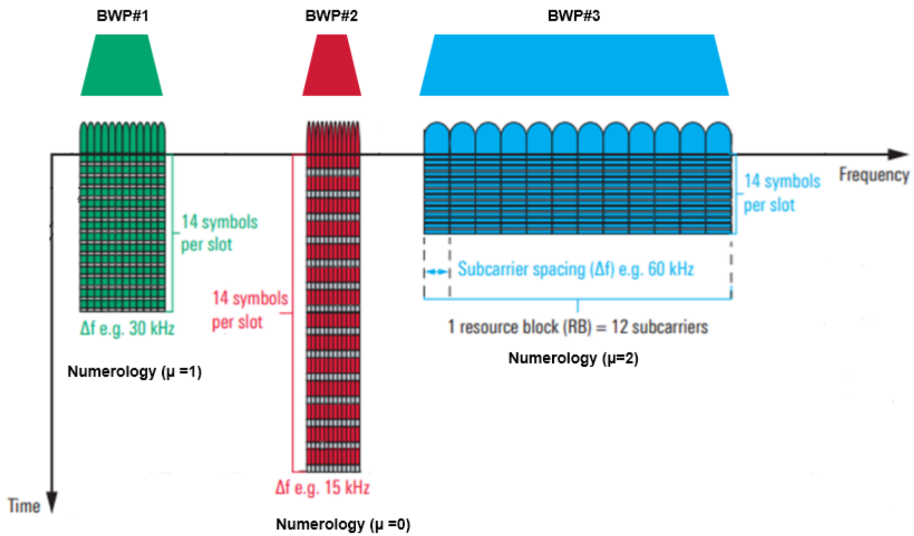
    - Subcarrier spacing
    - Symbol duration
    - Cyclic prefix (CP) length



- BWP configuration properties
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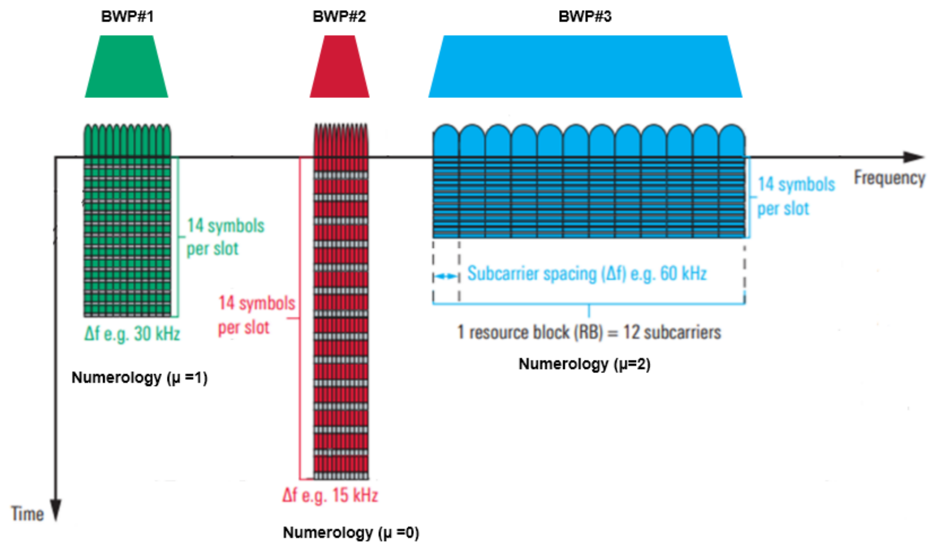
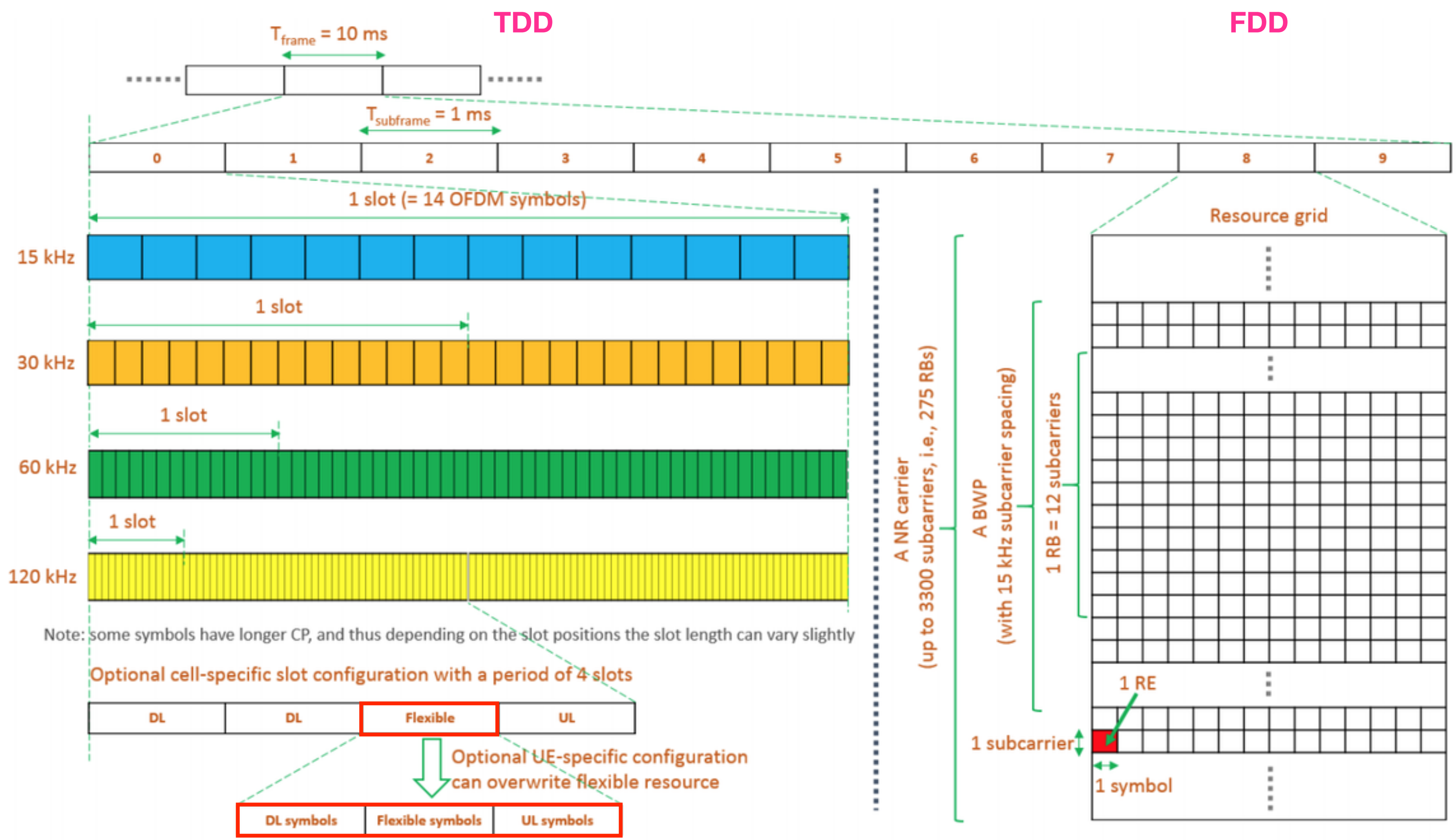
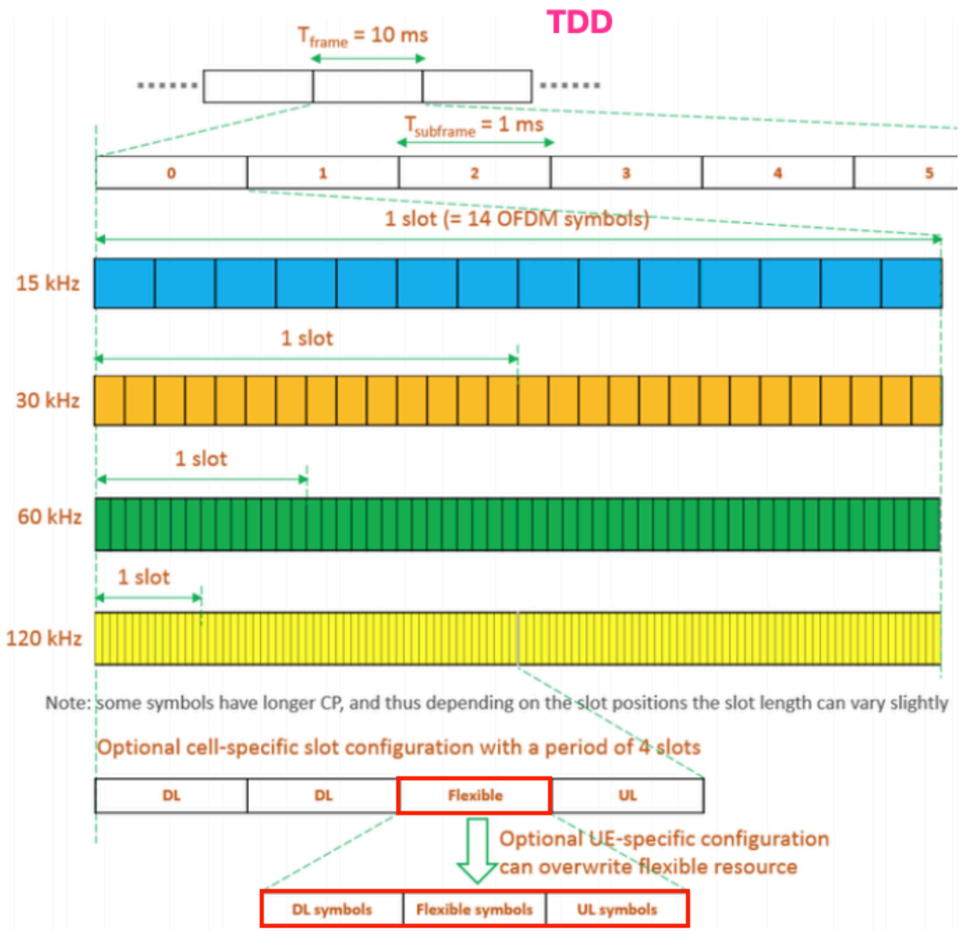


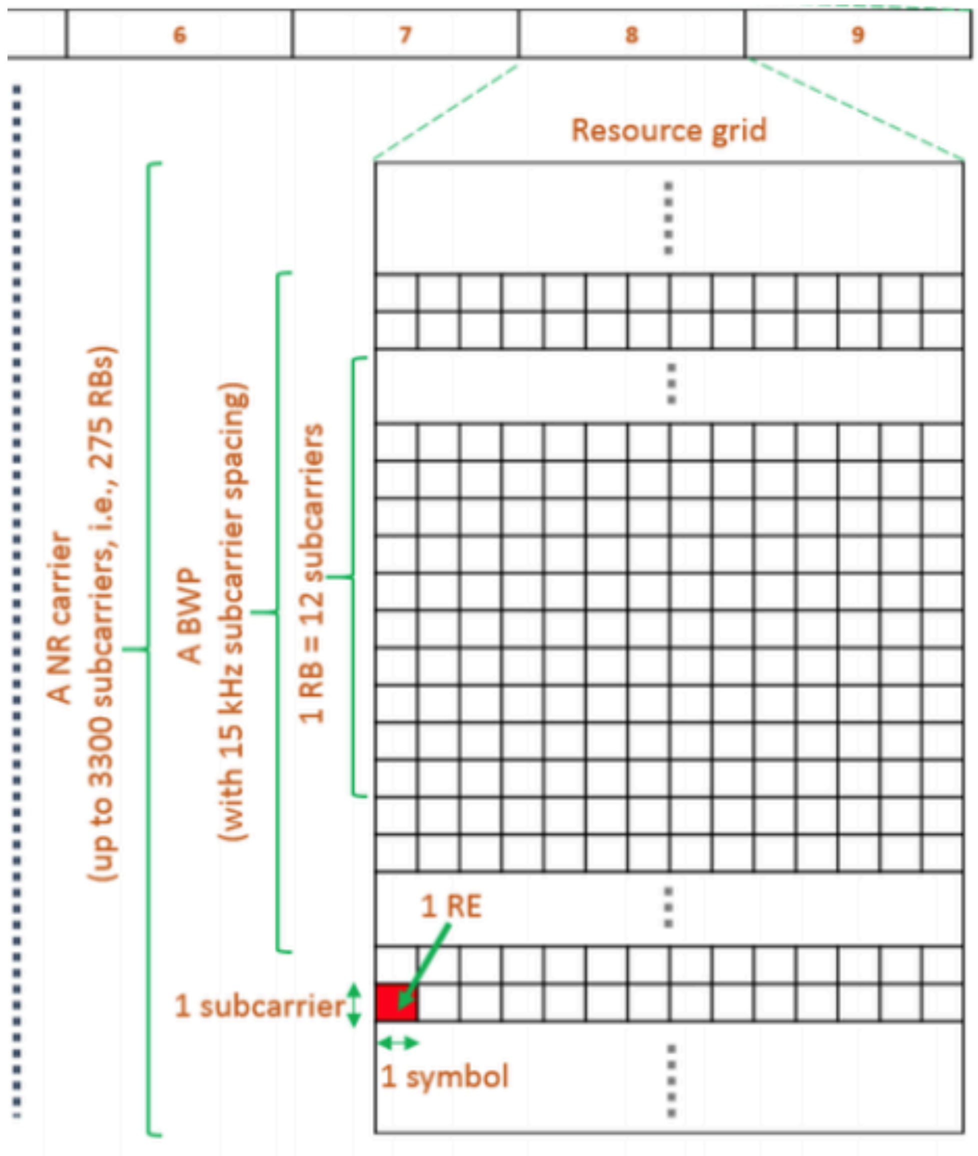
5G NR Frame Structure



- **TDD frame in 5G NR**
  - Flexible configuration: Subframes can be configured for UL, DL, or a combination of both within a 10 ms frame
  - Dynamic allocation: Allow for dynamic switching between UL and DL to adapt to varying traffic demands
  - Slot-based scheduling: Slots, which include several OFDM symbols, can be dynamically designated as UL, DL, or flexible. This allocation can change every 1 ms
  - Resource efficiency: This adaptability makes TDD efficient for asymmetric traffic patterns



- **FDD frame in 5G NR**
  - Static allocation: The resource grid is consistent, with fixed allocations for UL and DL that do not change over time
  - Symmetry and predictability: FDD is suited for scenarios requiring balanced UL and DL traffic



- **5G NR design implications**
  - 5G NR framework accommodates both FDD and TDD, making it versatile for various network requirements
  - Support scenarios that need either predictable (static) resource allocation of FDD or dynamic, traffic-responsive allocation of TDD