Mobile Wireless Networks

Chapter 3: Multiple Access in cellular systems

Prof. **Andrea Detti**
Univ. of Rome Tor Vergata
Electronic Engineering Dept.
Andrea.detti@uniroma2.it

Sources:

1. *Christopher Cox, An Introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE and 4G Mobile Communications: Second Edition, 2*

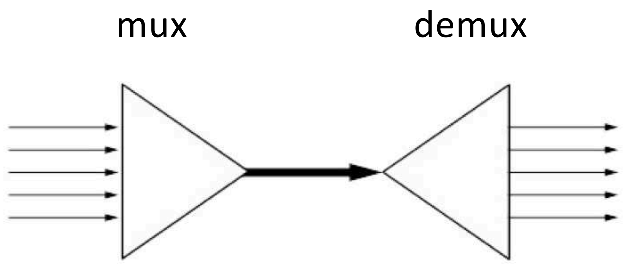
Rev 2.0

Resource sharing

- In a wireless network the radio resource is used by multiple users or, in more general terms, multiple data streams
- Resource sharing deals with the division of resource in order to create multiple physical or virtual channels for data streams
- Common resource sharing use-cases are:
  - Multiplexing
  - Multiple Access
  - Duplex

Multiplexing

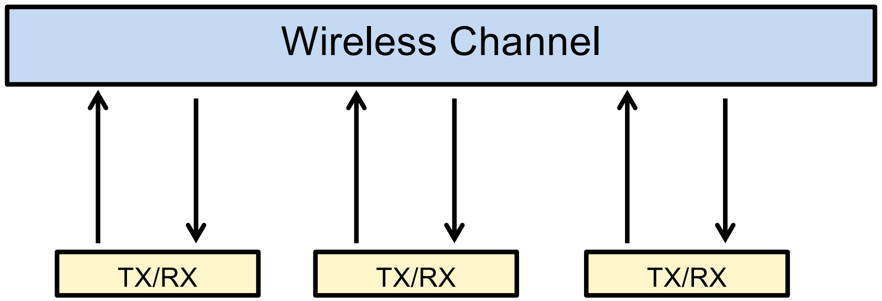
- To combine multiple streams, send them out on a shared channel towards a single end point and be able to split them again (de-multiplexing)
- Mux and demux operations are made by a single node



- Not the case of WiFi or cellular network radio interface, in which there are multiple users

Multiple Access

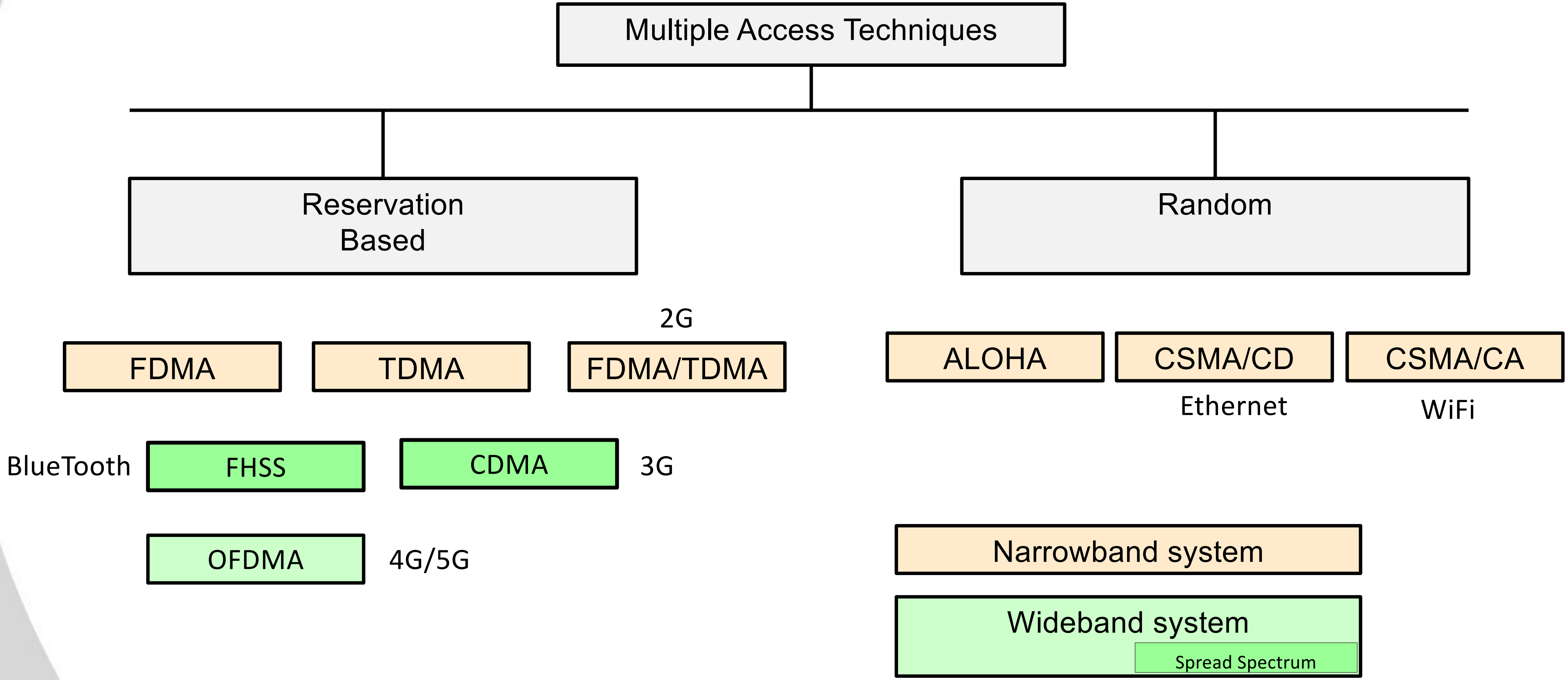
- Many transmitters and receivers that coordinate themself in a distributed manner to share a (wireless) transmission media
- This is the case of WiFi or **cellular networks**



Multiple Access Techniques

- Multiple access techniques can be classified as :
- Reservation-based multiple access (e.g., FDMA, TDMA, CDMA,OFDMA)
  - A resource is assigned for a given amount of time (a phone call, an amount of time, of bits, etc.) before to use it
  - Usually requires a centralized entity for resource allocations
  - Frequency division multiple access (FDMA), Orthogonal frequency division multiple access (OFDMA), Time division multiple access (TDMA)
  - Code division multiple access (CDMA),
- Random multiple access (e.g., ALOHA, CSMA –WiFi-)
  - Transmitters contend the resource usage, no preliminary reservation
  - No central entity
  - Collisions may occur

Multiple Access Techniques



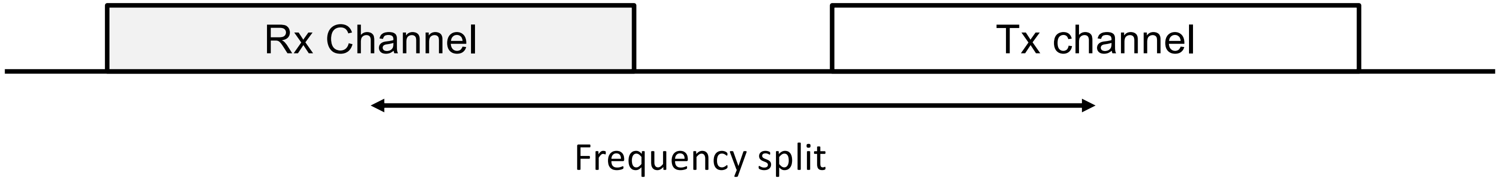
Narrow and wideband systems

- Narrowband system: the radio bandwidth provided to the user is lower than the coherence bandwidth (1/delay-spread) of the channel
  - E.g. for cellular system delay spread is lower than 10μsec, coherence bandwidth 100 kHz

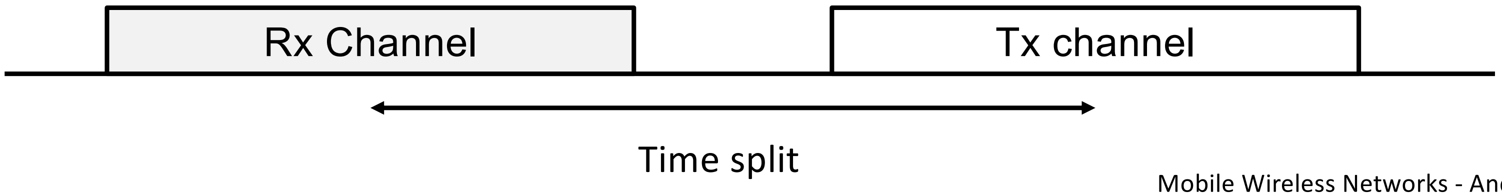
- Wideband system: to achieve high data rate the radio bandwidth provided to the user is higher than the coherence bandwidth (1/delay-spread) of the channel
  - *Spread spectrum systems* : deliberately use a wider bandwidth than "necessary" for that data rate in order to gain other advantages (CDMA).
  - Not all wideband systems are spread spectrum (OFDMA)

Duplex (FDD, TDD)

- It is the technique used to separate the wireless resources used to receive from the resources used to transmit
- Frequency Division Duplex (FDD): some frequencies reserved to transmit, others to receive

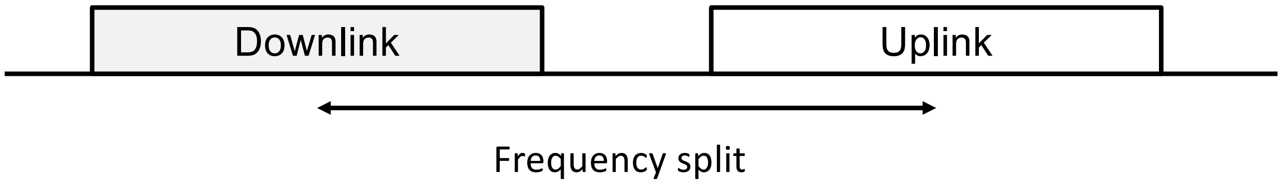


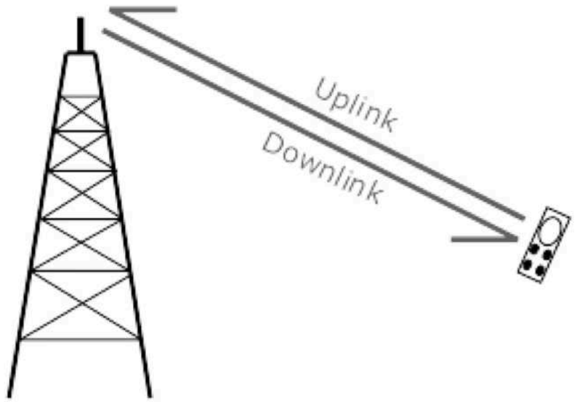
- Time Division Multiplex (TDD): the whole wireless resources are used to transmit and receive but at a different times



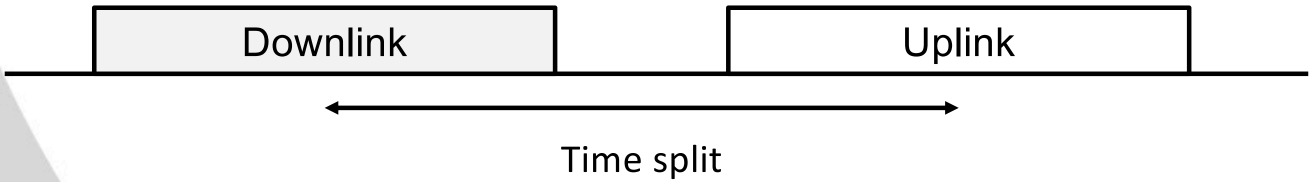
Duplex (FDD, TDD) in cellular system

- Frequency Division Duplex (FDD): some frequencies used for downlink transmissions, others for uplink transmissions





- Time Division Multiplex (TDD): the whole wireless resources is used for uplink and downlink but at a different times



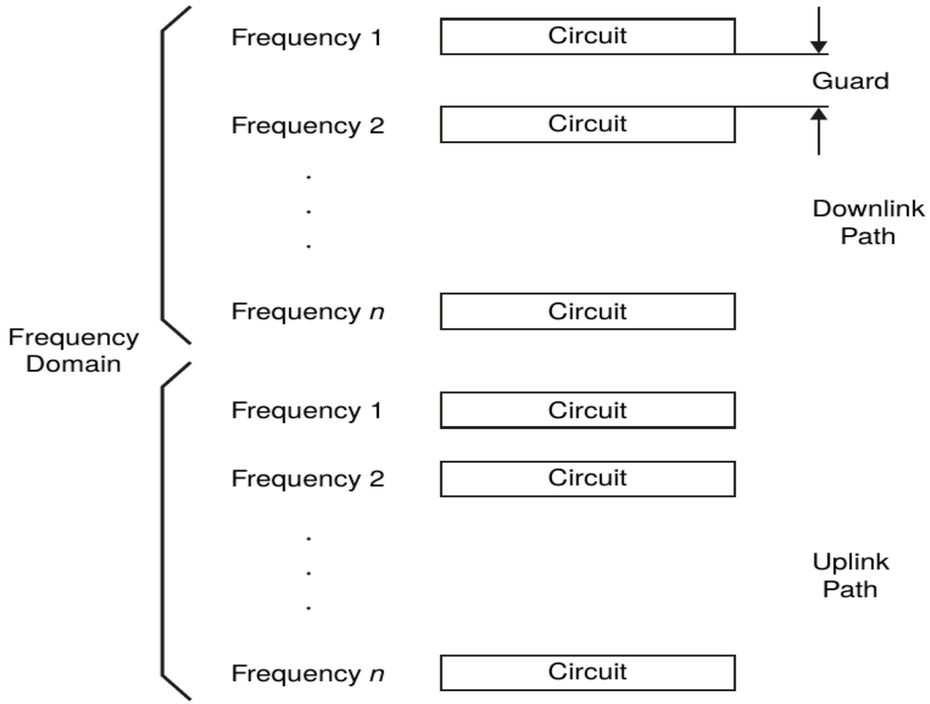
Cellular networks

RESERVATION BASED MULTIPLE ACCESS

FDMA

Frequency Division Multiple Access (FDMA)

- Simplest narrowband system
  - AM/FM radio, VHF, 1G
- Signals from various users are assigned different *narrow band channels* centered on **carrier** frequencies
- Circuit services
- Channels isolated using band-pass filters.
- Frequency guard bands minimize crosstalk between adjacent channels
- Usually associated with FDD for duplex



FDMA/FDD

Frequency Division Multiple Access (FDMA)

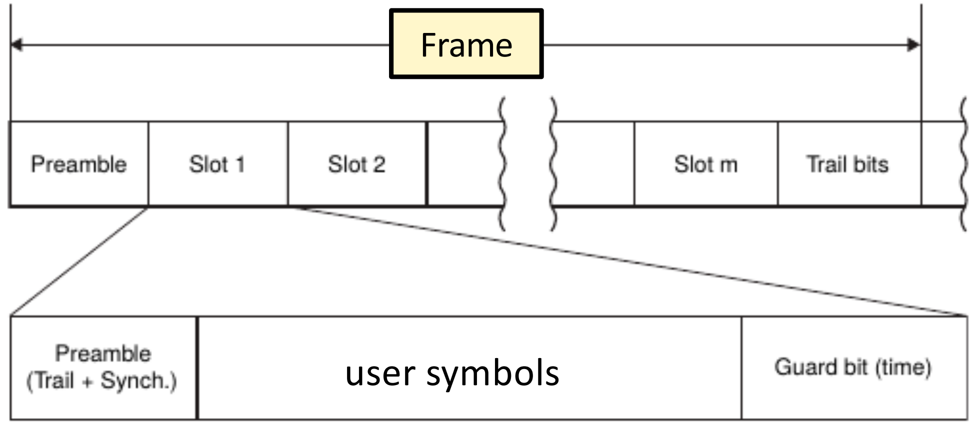
- Advantages
  - Simple technology
- Disadvantages
  - Low bitrate (narrowband)
  - **Not flexible** bit rate, bit rate per channel is fixed and related to the channel bandwidth

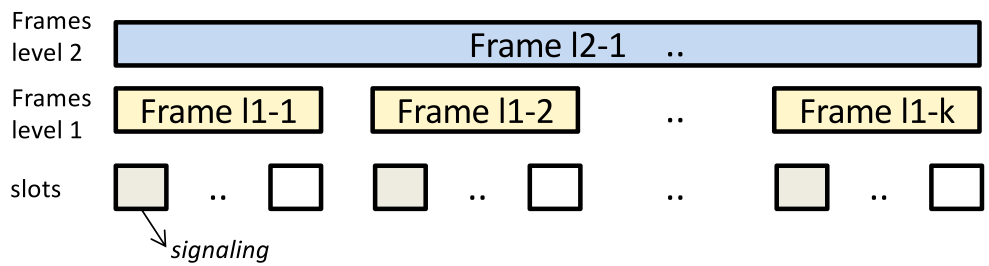
Flexibility: the ability to change or be changed easily according to the situation:

TDMA AND TDMA/FDMA

Time Division Multiple Access (TDMA)

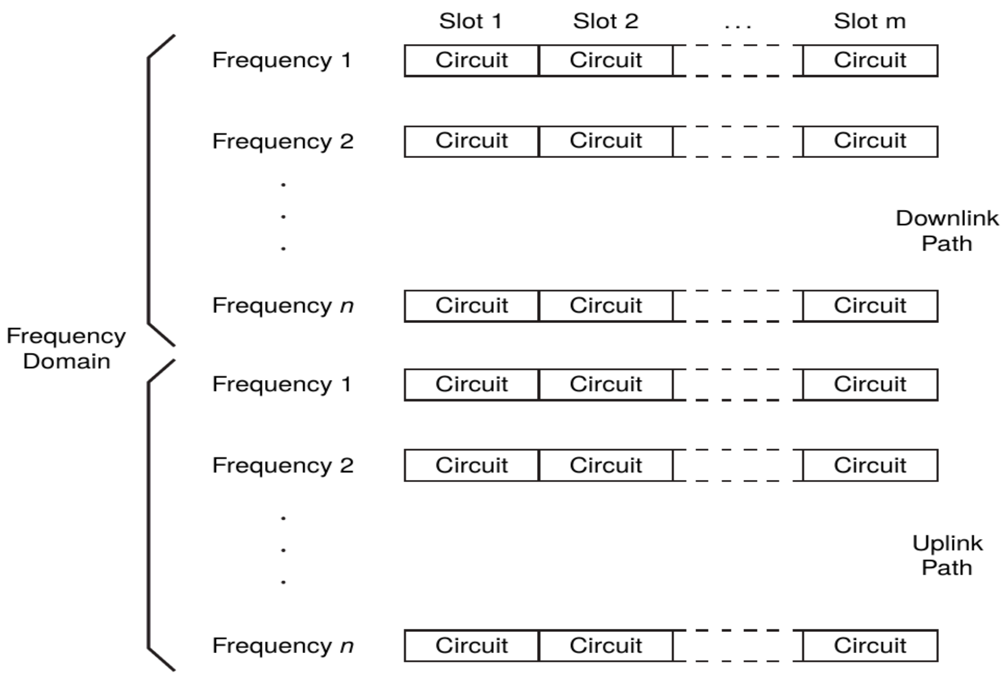
- Time organized in a sequence of periods named *slots*.
- Different slots assigned to different users to transmit in their symbols.
- A preamble and/or a middleamble and/or a trailer can be used for control purposes, e.g. channel estimation. Guard times to reduce crosstalk problems
- Several slots make up a frame (level 1), and several frames of level *x* make a frame of level *x*+1
- Framing is used to create an **hierarchical time organizations** for periodic operations (e.g. transmission of signaling, periodic assignment of slots to user, scheduling, etc.)





TDMA/FDMA

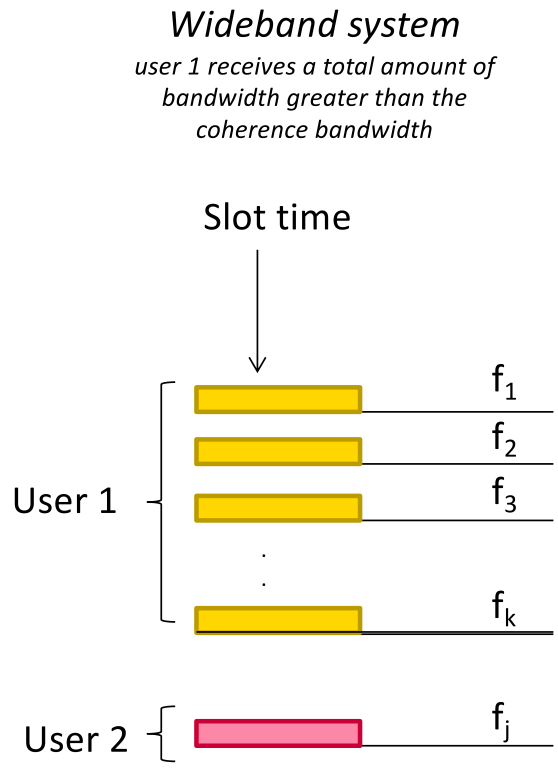
- FDMA with TDMA management of the time of each carrier frequency



Time Division Multiple Access (TDMA)

- Circuit services:
  - fixed number of time slots per frame (and per carrier in case of TDMA/FDMA)
  - Narrowband systems

- Packet services:
  - Number of time slots per user scheduled by a controller (aka **scheduler**), slot by slot or frame by frame, and according to the temporary transmission needs of users
  - Depending on the number of carriers that can be assigned to a user in a slot/frame period, FDMA/TDMA (and OFDMA too) may used to implement narrowband (GSM) or wideband systems (NR, LTE, HSDPA)

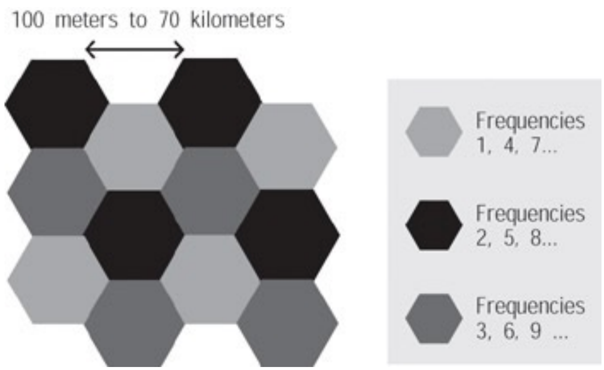


Time Division Multiple Access (TDMA)

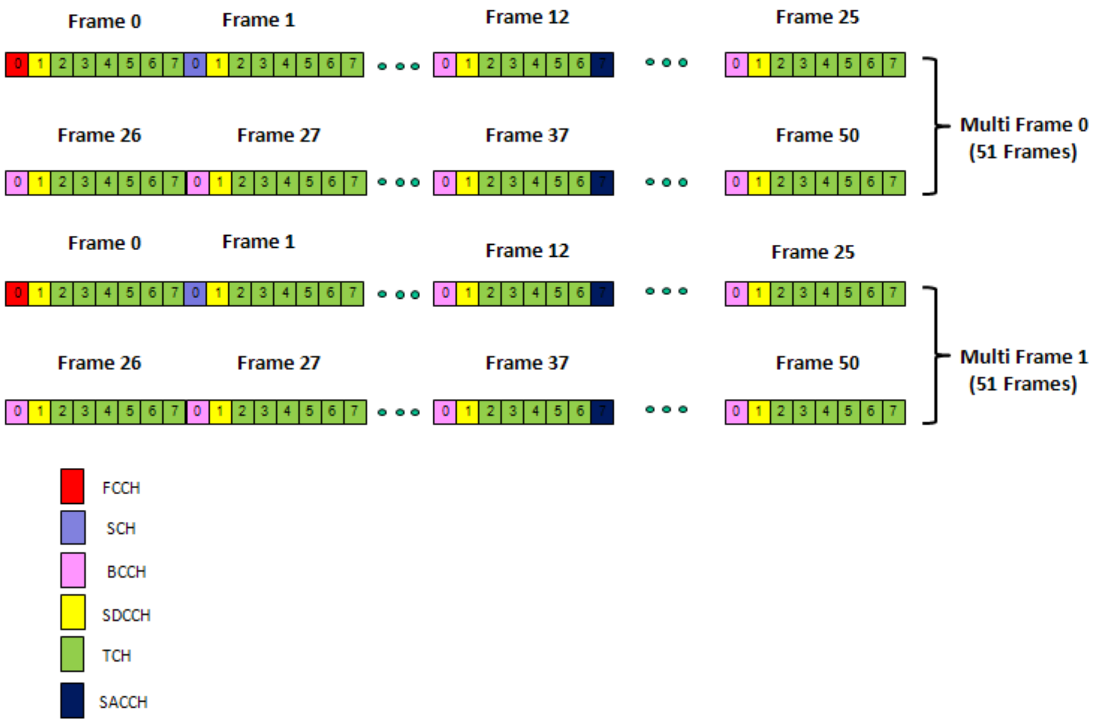
- Advantages
  - Bit rate assignment theoretically more flexible than FDMA by changing the number of assigned slot per frame
  - Packet services
  - Rather simple technology
- Disadvantages
  - If slots are not short enough, the bit rate flexibility for packet services can be limited
  - For hand-sets, the bursty TDMA transmissions requires **high peak power ratio**, shortening battery life
  - Propagation delays may cause transmission overlapping (crosstalk) at the base station if not properly handled (**Timing Advance**, guard time)

GSM TDMA/FDMA

- GSM (2G) uses TDMA/FDMA scheme for narrowband circuit (22.7 kbit/s) and packet services (GPRS/EDGE)
- Each cell uses a set of frequencies different for the one used by closer cells. Reuse factor > 1.



Reuse factor = 3



CDMA

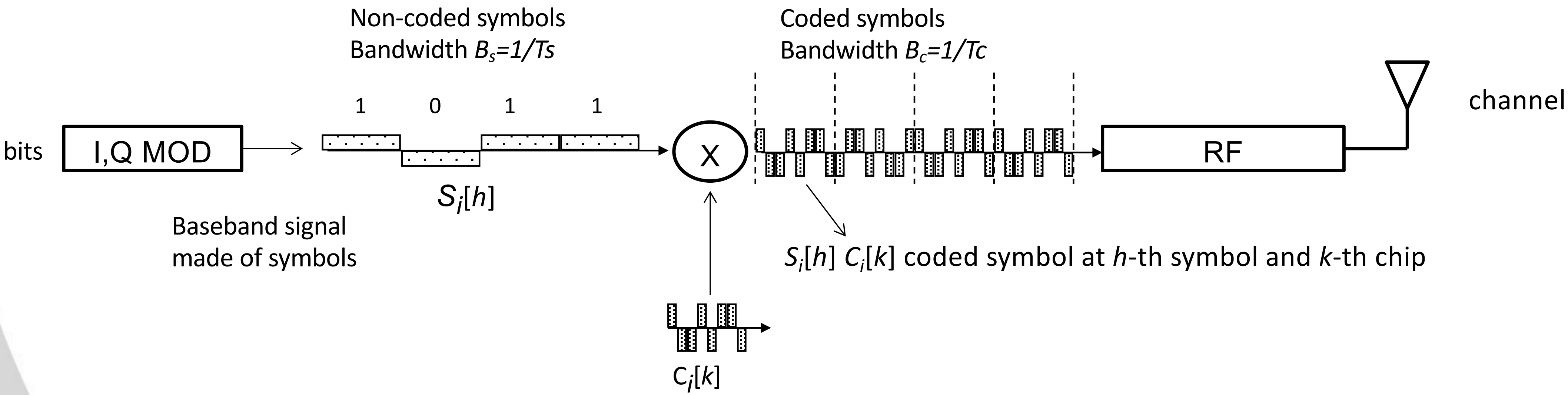
Code Division Multiple Access (CDMA)

- Spread Spectrum Wideband Systems
- Main schemes are:
  - **Direct Sequence Spread spectrum** (DSSS)
    - UMTS (3G,HSDPA)
  - Frequency Hopping Spread Spectrum (FHSS)
    - Bluetooth
- Used both to mux channels, but also as **channel coding** to improve spectral efficiency and resistance to small-scale fading
  - E.g. in 802.11, 802.11b

DIRECT SEQUENCE SPREAD SPECTRUM (DSSS)

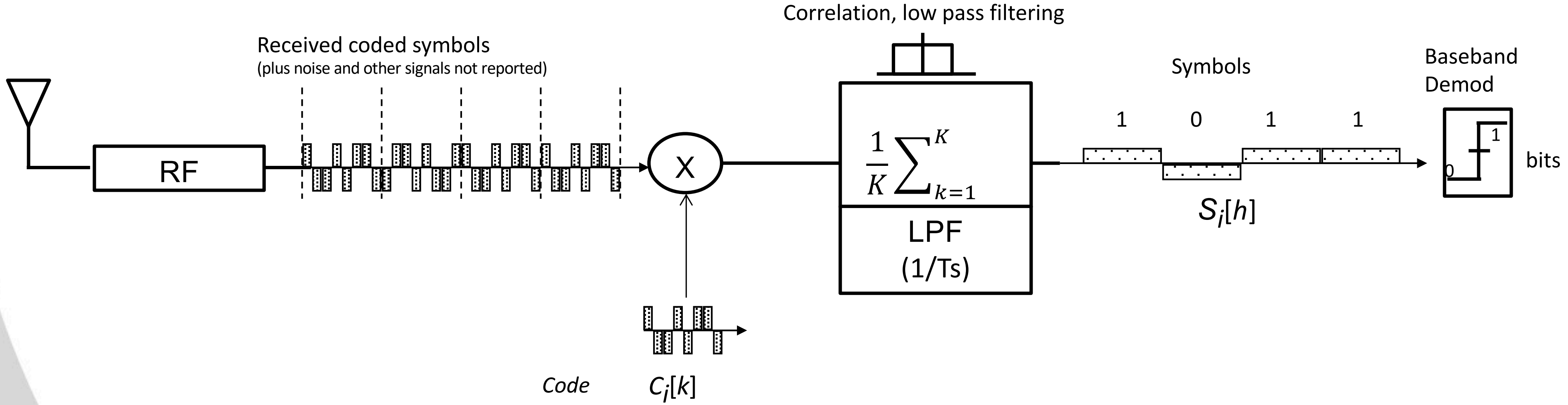
The Transmitter

- Each baseband symbol $S_i[h]$ of a user (baseband signal) is superimposed to a sequence of K binary (-1,+1) **chips** $C_i[k]$, which form the spreading code assigned to the user



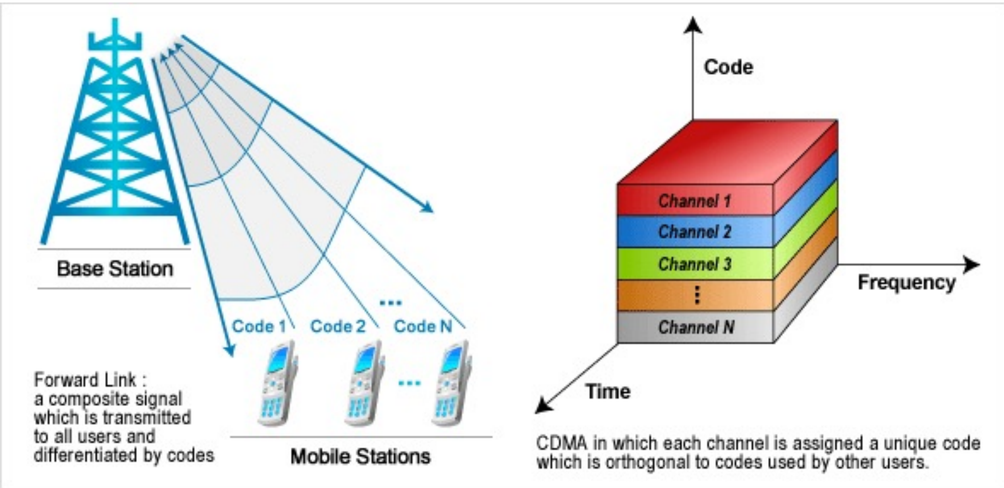
The Receiver

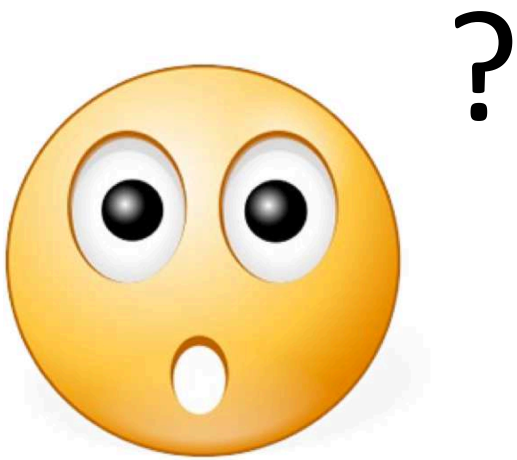
- On the receiving side, to extract the symbol of a user from a received mux of coded symbols, the receiver multiply the mux signal for the user spreading code then sum over a symbol time (i.e. *K* chips)
- Sum approximates a Low Pass Filtering (LPF)….



Multiplexing

- Multiplexing: Different users, different spreading codes, but same time and frequency.
- Same time and frequency! Why interference does not destroy everything





Demultiplexing: the math

- Spreading codes are **orthogonal** or nearly orthogonal (**Pseudo Noise**) each other, over the whole sequence of chips used for a symbol

$$\frac{1}{K}\sum_{k=1}^{K} C_i[k]C_j[k] \approx 0 \ \text{ for } i \neq j$$

$$\frac{1}{K}\sum_{k=1}^{K} C_i[k]C_i[k] = 1$$

- Multiplying a multiplex signal formed by *M* sources for a code we mainly extract only the multiplexed source associated to the code

Multiplex signal at *h*-th symbol and *k*-th chip

$$\sum_{j=1}^{M} S_j[h]C_j[k]$$

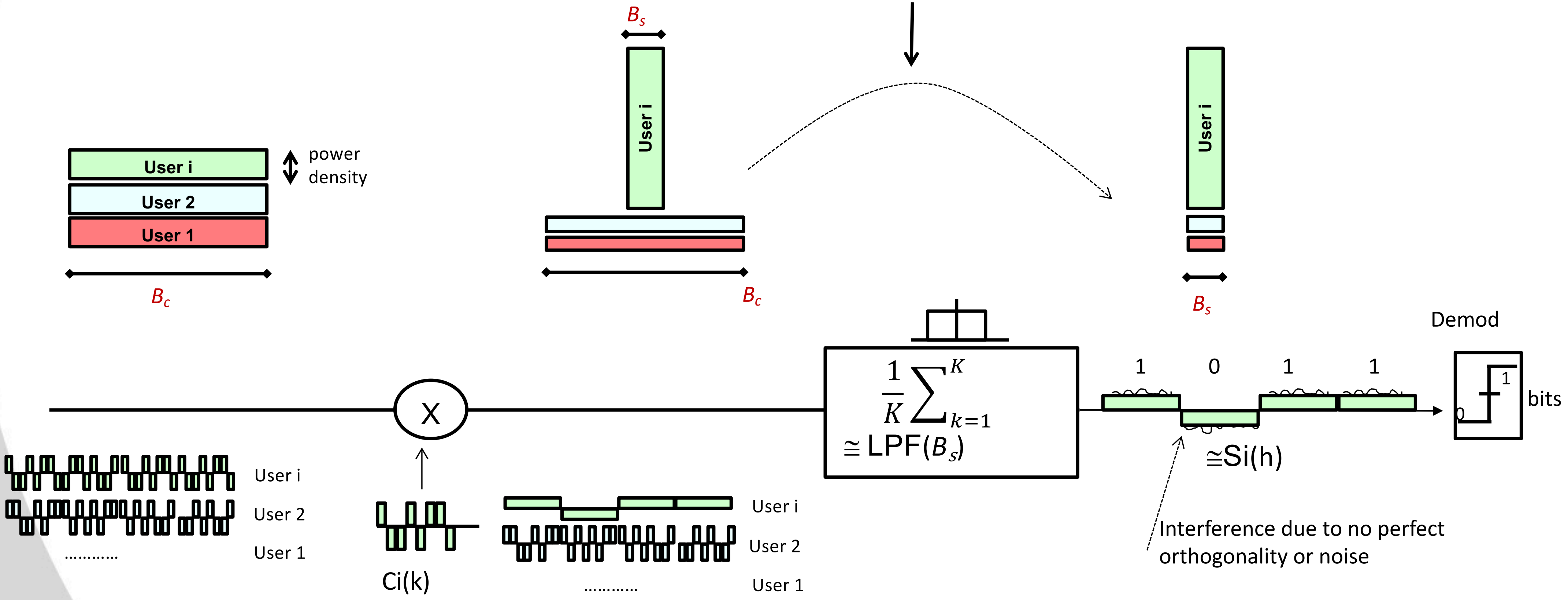
Sum operation in the receiver

$$\frac{1}{K}\sum_{k=1}^{K}\left(C_i[k]\sum_{j=1}^{M} S_j[h]C_j\,[k]\right) \approx S_i[h]$$

Demultiplexing: from spectrum prospective

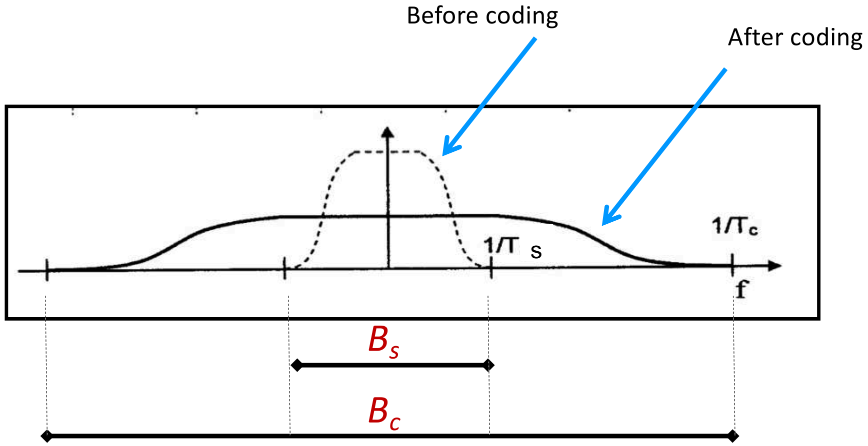
Processing Gain

After LPF, Interference (and noise) power is reduced by a factor B_c/B_s



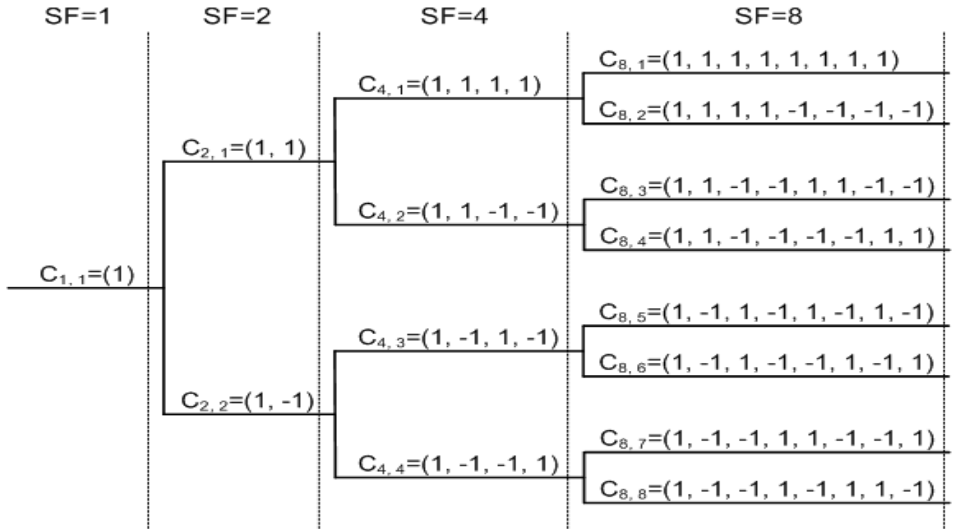
Spreading Factor and Processing Gain

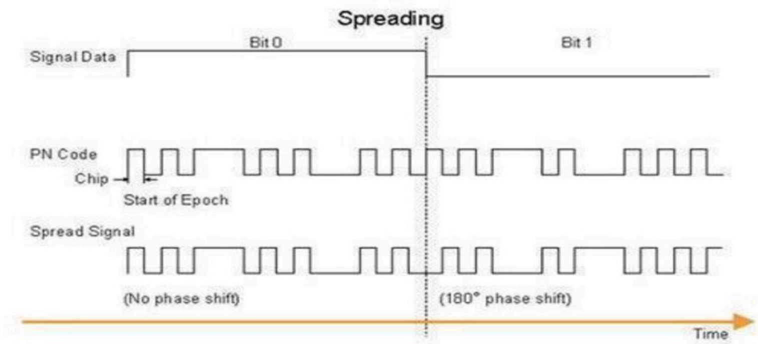
- Many chips for a single symbol
- The chip rate is much larger than symbol rate
- Symbol duration T_s, Chip duration T_c, $T_c << T_s$
- Symbol rate R_s, Chip rate R_c, $R_c >> R_s$
- Spreading factor = R_c / R_s
- Processing Gain $G_p = B_c / B_s$
- Processing Gain ≅ Spreading Factor



Codes

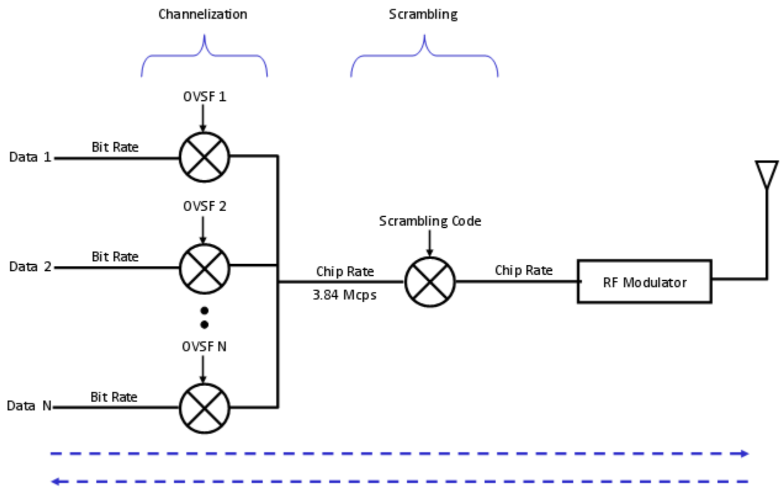
- Walsh-Hadamard codes: Orthogonal Variable Spreading Factor (OVSF)
  - Tree of “short” codes
  - Same word code per symbol
  - Assigning a code prevents the possibility of assigning any other child in the three
  - Each point of the tree we use or prevent to be used is a kind of resource we consume. Shorter codes consume more resources
  - With strong time synchronization among multiplex sources provides **zero interference** (perfect cancel), otherwise mutual interference is strong
- Pseudo Noise
  - sequences of random -1 +1
  - Each code a different sequence
  - Do not need synchronization to provide good performance orthogonality with long sequences , but a small mutual interference is always present

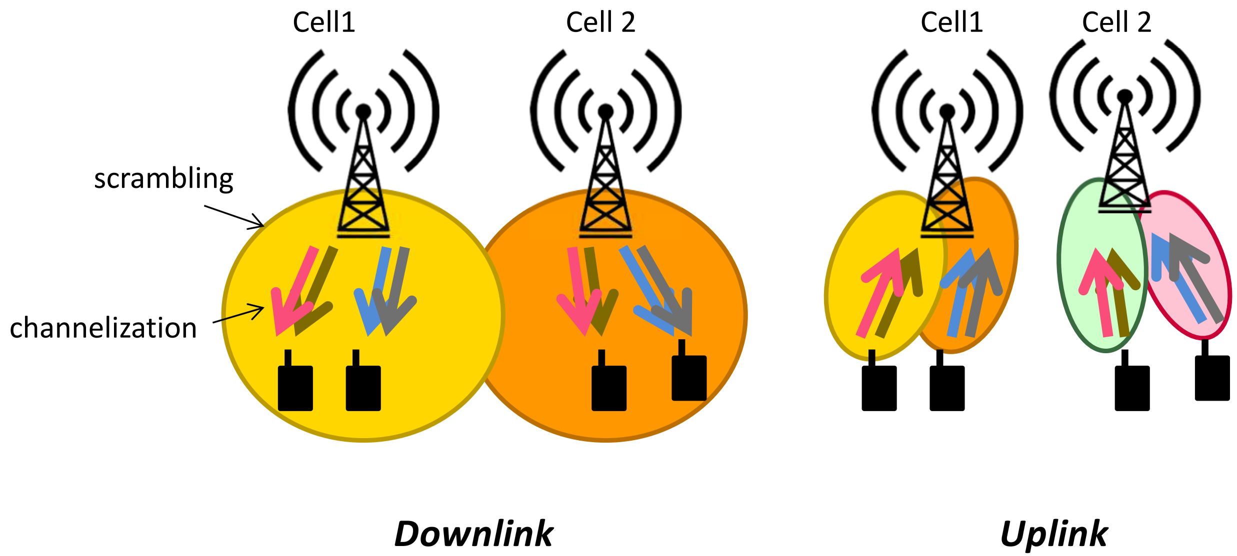




UMTS codes

- OVSF and PN.
- OVSF = channelization code; PN = scrambling code
- Channelization used to separate perfectly different channels, since they are generated by the same transmitter (base station, mobile phone) – perfect time sync
- Scrambling used to: (Downlink) differentiate cells (base stations are not synchronized), (Uplink) differentiate users (mobile phones are not synchronized)



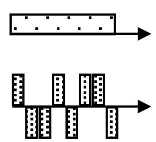


Multi-rate services with codes

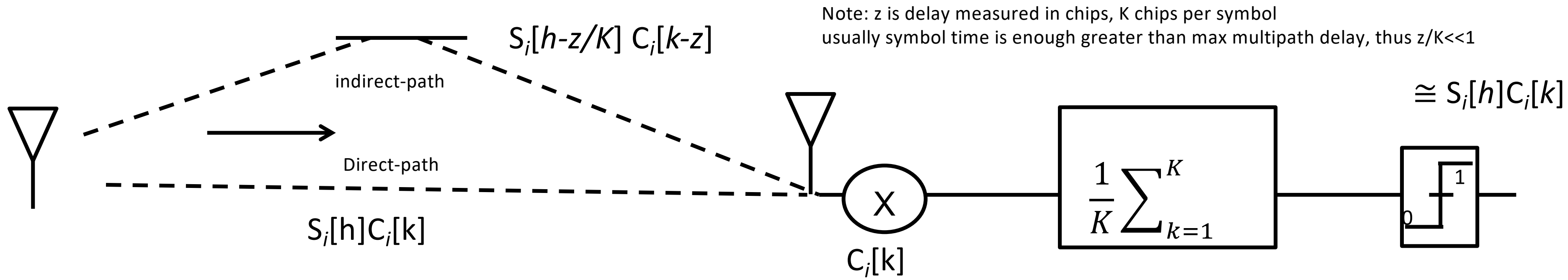
- DSSS devices use a fixed chip rate Bc (UMTS 3.84 Mcps)
  - Chip rate fixed, symbol-rate variable
  - A symbol = A codeword
  - **Symbol-rate = Chip-rate / codeword length**
  - Longer codeword, lower symbol rate
  - Changing the codeword length it is possible to control the symbol rate, i.e. bitrate
  - Remind: the shorter codeword is, the higher is the amount of consumed resources in the code domain
  - E.g chip-rate = 2 Mcps, code word length 2 --> symbol rate = 2 Mcps/2 = 1 Msps

A symbol — symbol rate, variable

A codeword — chip rate, fixed



DSSS - Pro



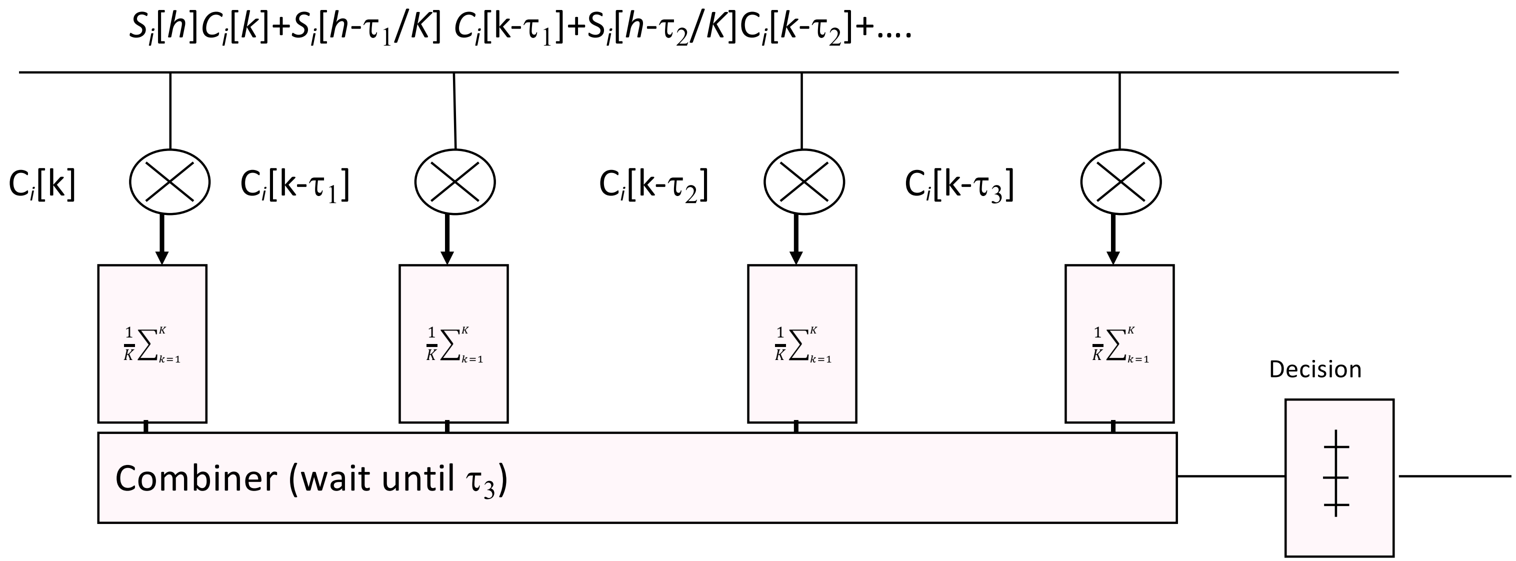
- Resistance to Interference and Anti-jamming Effects
  - Intentional or unintentional interference and jamming signals are rejected by because they do not contain the spread-spectrum "key".
- Resistance to multipath
  - Auto correlation of a code is close to 0 for delay values different from 0
  - So good as DSSS also used only for channel coding (WiFi 11b)

$$\frac{1}{K}\sum_{k=1}^{K} C_i[k]C_i[k-z] \cong 0 \text{ for } z \neq 0$$ (z is delay measured in chips)

- No frequency planning for cellular system, i.e. the need to decide which frequency band is used in a cell and which other in the adjacent ones

RAKE Receiver – the intelligence receiver to exploit multipath

- Multipath can be even exploited
- A channel estimator derive the multi-path delays τ_ι or fixed delay “fingers” are used 0, τ, 2τ, 3τ

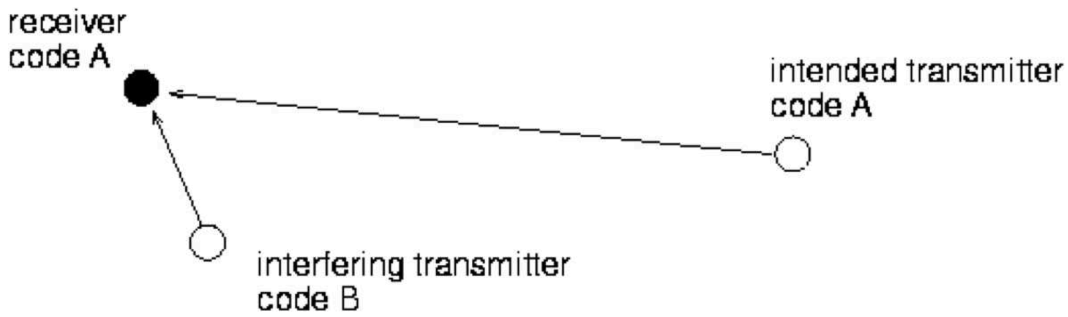


DSSS Cons

- Critical Power Control
  - **Near Far Problem**
- Coverage depends on user activity
  - **Cell Breathing**

Near-Far Problem

- The CDMA near far problem arises because some handsets will be close to the base station, whereas others will be much further away.
- For the receiver (Base Station) to be able to decode all the signals in the channel, **they should ideally all be at the same signal strength** - giving the CDMA near far problem.
  - Interference is reduced by LPF but, if it is much more high than signal, after LPF the signal to interference ratio is however low
- The schemes used to overcome the CDMA near far problem utilize fast and accurate power control systems (open loop, closed loop).
  - Reduce power tx of close handsets and increase power of far handsets so as received power are the nearly the same

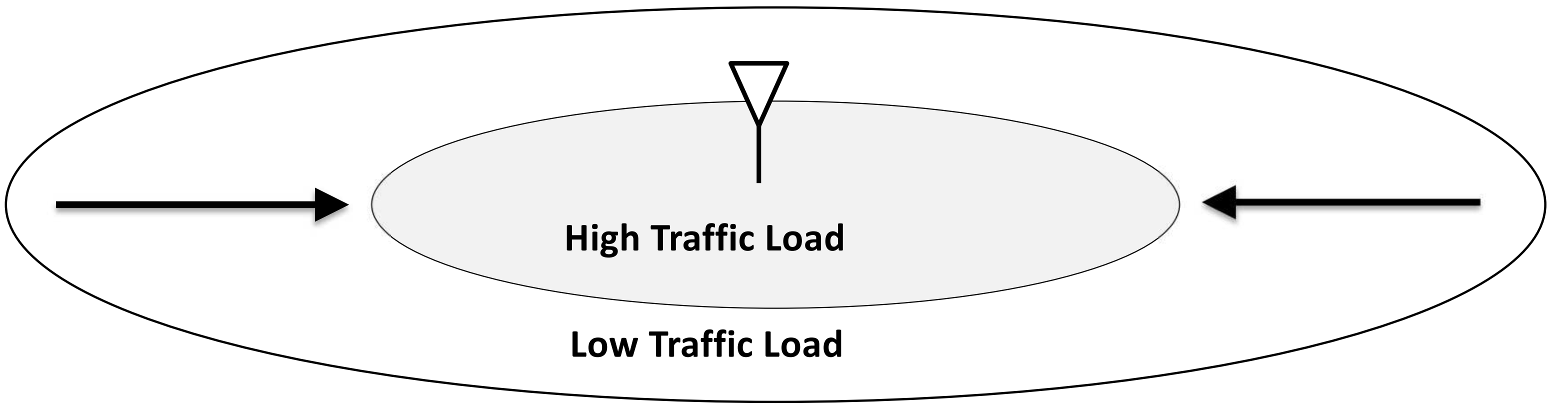


Cell Breathing

- In a CDMA system without perfect orthogonally the traffic of other users appears as a noise to the receiver.
  - This is the case of UMTS uplink, in which users are separated by scrambling codes
- Such an additional noise has a dimensioning impact that can be accounted as an increases of the minimum signal power to be received, with respect to the case of absence of interference (only thermal noise)
- Such an additional interference/noise depends on the traffic load of the cell
- The more the load, the higher the interference the higher the necessary Rx signal power to reach the desired value of Eb/N0, the shorter the cell radius

Cell Breathing

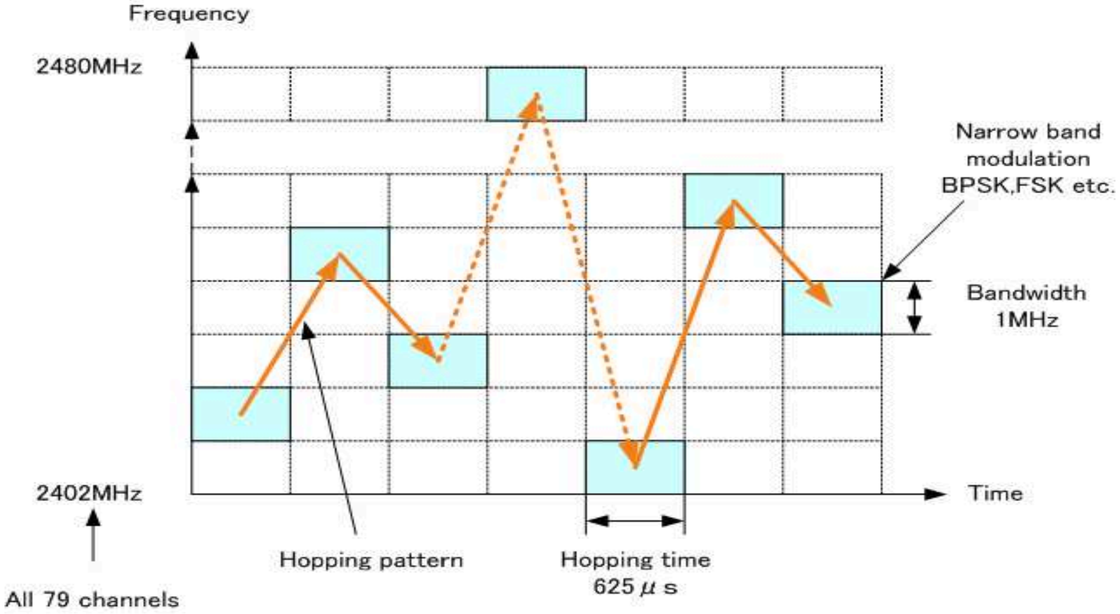
- Cell shrinks increasing the load, and some users at the edge can be even dropped out
- Difficult to dimension, unless considering the worst case



FREQUENCY HOPPING SPREAD SPECTRUM

Frequency Hopping Spread Spectrum

- Frequency hopping (FH) is the periodic changing of the frequency or the frequency set associated with transmission.
- The bandwidth of a frequency channel is enough to support user symbol rate, without hopping.
- The bandwidth of the frequency band over which the hopping occurs is much greater than the channel bandwidth
    - spreading



OFMA

(AN INTRODUCTION TO LTE: LTE, LTE-ADVANCED, SAE, VOLTE AND 4G MOBILE COMMUNICATIONS, SECOND EDITION.)

OFDMA

- Techniques to share spectrum among multiple users (Multiple access)
- Wideband systems
- Used in 4G (LTE) and 5G
- Used both to mux channels and also as line coding to improve spectral efficiency and resistance to fading
  - E.g. in 802.11g, ADSL, etc.

Sub-carriers

- An OFDM transmitter takes a block of symbols from the outgoing information stream and transmits each symbol on a different radio frequency that is known as a **sub-carrier**.
- More symbols at a time, more sub-carriers to be used at a time
- A symbol value is mapped on the (I,Q) power levels of a given sub-carrier
- The bandwidth of each individual sub-carrier is small, so it can only support a low symbol rate. Collectively, however, the sub-carriers make possible to achieve high symbol rate
- Parallel transmissions over multiple sub-carrier

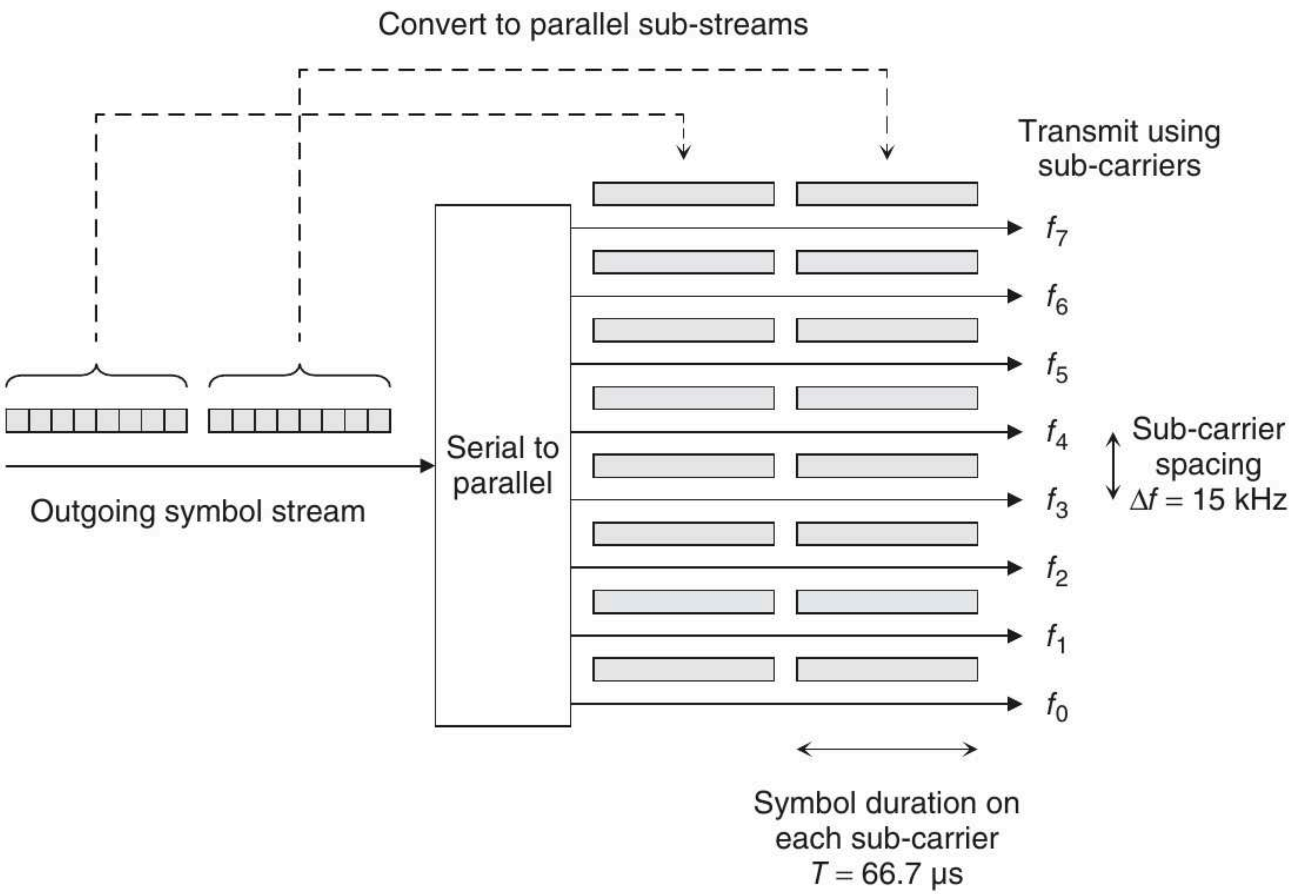
Sub-carriers and Symbol Transmission:

In OFDM, a block of symbols from the outgoing data stream is transmitted simultaneously using multiple sub-carriers.
Each symbol is transmitted on a different radio frequency, known as a sub-carrier. These sub-carriers are orthogonal to each other, meaning they do not interfere with one another.
Symbol Mapping:

The value of each symbol is mapped onto the power levels of the In-phase (I) and Quadrature (Q) components of a given sub-carrier.
By adjusting the amplitude and phase of the I and Q components, the symbol value is transmitted over the sub-carrier.
Bandwidth and Symbol Rate:

Each individual sub-carrier has a small bandwidth, which limits the symbol rate that it can support.
However, by using multiple sub-carriers in parallel, OFDM systems can achieve high symbol rates collectively.
The parallel transmission over multiple sub-carriers enables efficient utilization of the available frequency spectrum, leading to high data transmission rates.

Sub-carriers

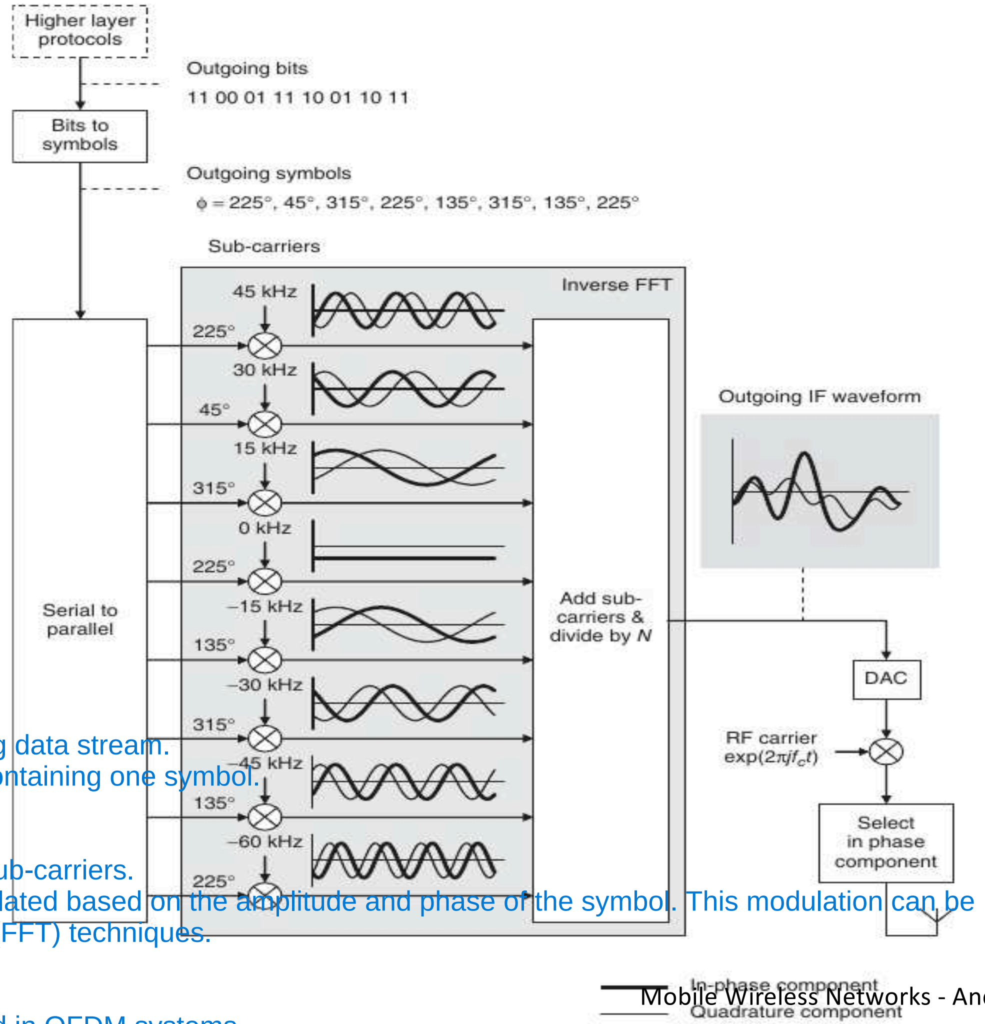


Sub-carriers

- Sub-carrier spacing Δf proportional to the symbol duration Ts, $\Delta f = 1/Ts$
- LTE
  - symbol duration 66.7 μs, sub-carrier spacing 15 kHz
  - Each base station can support up to 2048 sub-carriers
  - Each of these subcarriers can be a BPSK, QPSK, 16-QAM or 64-QAM
- 802.11g (54Mbps)
  - 52 OFDM sub-carriers,
  - Each of these subcarriers can use BPSK, QPSK, 16-QAM or 64-QAM

The Transmitter

- The serial-to-parallel converter then takes a block of N complex symbols, eight in this example, and directs them onto N parallel sub-streams
- Each symbol of a sub-stream modulate the I,Q amplitudes of a sub-carrier
- Extremely simple digital modulation using Inverse DFT (or inverse FFT)



Serial-to-Parallel Conversion:

The serial-to-parallel converter takes a block of N complex symbols from the outgoing data stream.
These symbols are then divided into N parallel sub-streams, with each sub-stream containing one symbol.
Modulation onto Sub-Carriers:

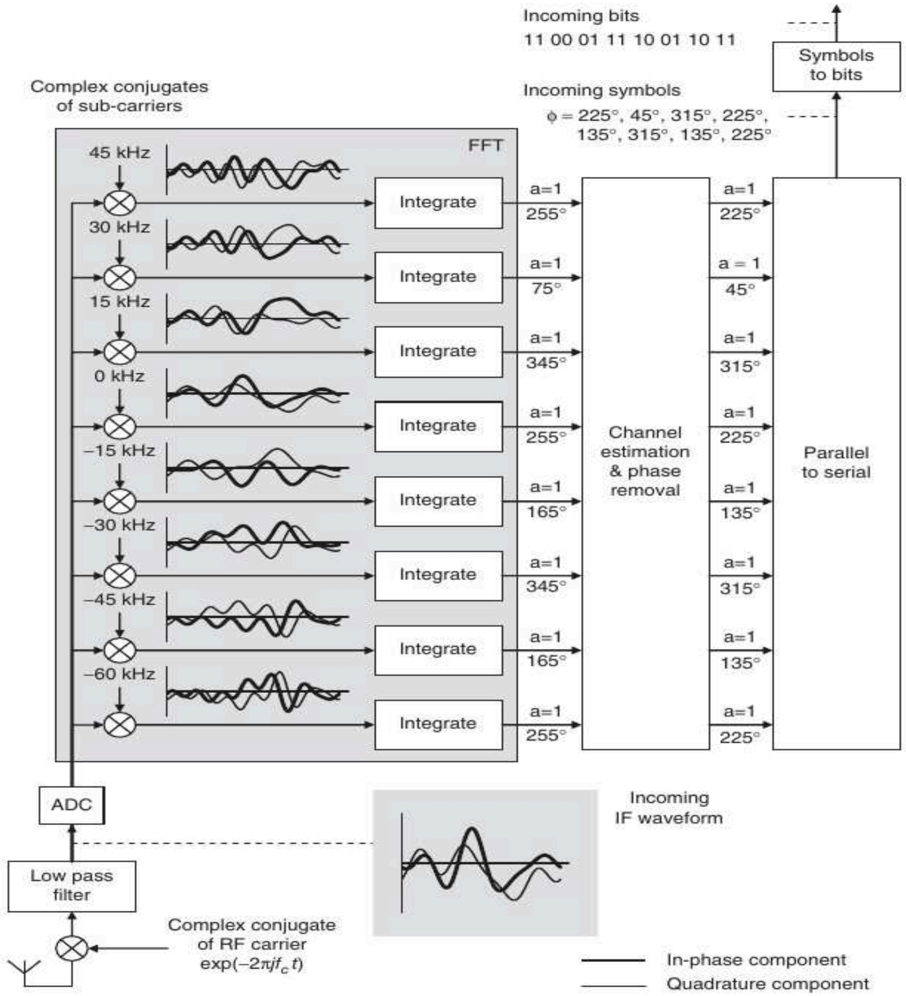
Each symbol from the sub-stream is used to modulate the amplitudes of one of the sub-carriers.
Typically, the In-phase (I) and Quadrature (Q) components of a sub-carrier are modulated based on the amplitude and phase of the symbol. This modulation can be achieved using inverse Discrete Fourier Transform (DFT) or Fast Fourier Transform (FFT) techniques.
Inverse DFT/FFT Modulation:

Inverse DFT or FFT modulation is a straightforward digital modulation technique used in OFDM systems.
It involves applying the inverse DFT or FFT operation to the symbol values to generate the time-domain OFDM signal.
The resulting time-domain signal represents the modulation of the sub-carriers with the symbol values.
OFDM Signal Generation:

After modulation onto the sub-carriers, the parallel sub-streams are combined to form the complete OFDM signal.

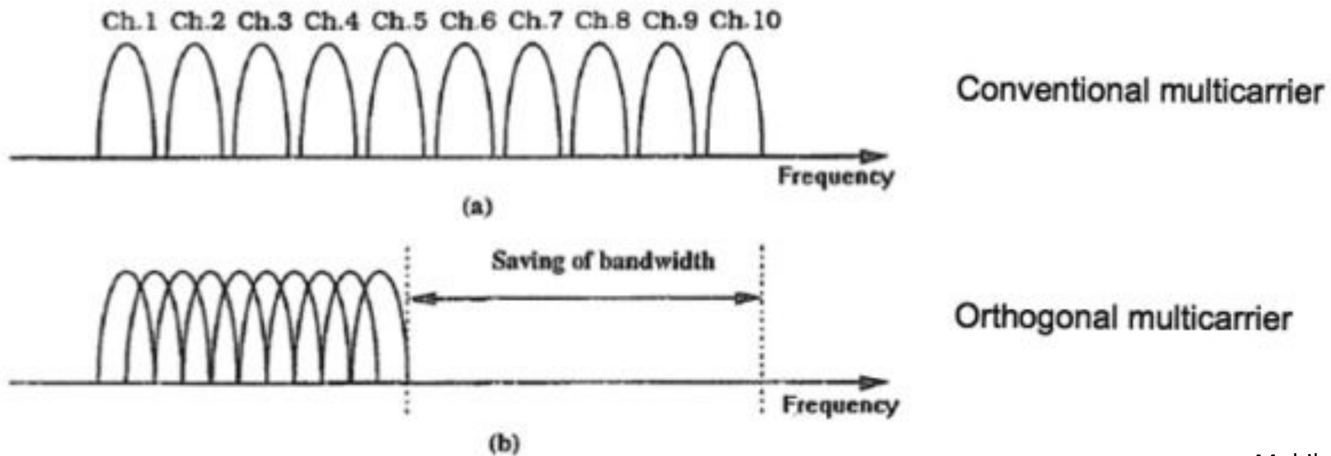
The Receiver

- DFT/FFT of the incoming signals recover the complex symbols
- To cope with possible phase shift introduced by the cannel the transmitter send some reference symbols known a-priori that are used for channel equalization purposes
  - 30 degree of phase shift in figure
  - In reality phase shift depends over time and frequency, thus reference symbols are scattered across time and frequencies



Orthogonal

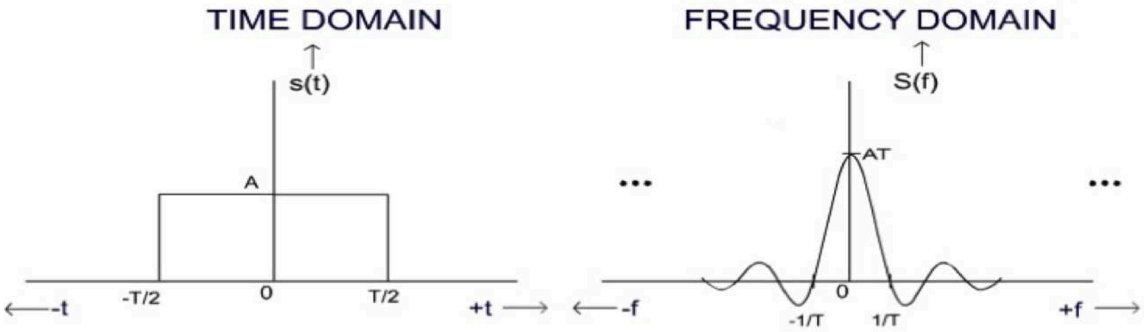
- In traditional FDMA, carriers are spaced apart with large enough guard intervals to guarantee no inter-carrier interference occurs
- OFDM divides a given channel into many narrower subcarriers. The spacing is such that the subcarriers are orthogonal, so they won't interfere with one another despite the lack of guard bands between them. This comes about by having the subcarrier spacing equal to the reciprocal of symbol time.



Orthogonal

- Symbol duration = Ts
- During symbol transmission the amplitude and phase are constants, i.e. symbol signal is a Rect of size Ts which multiplies a couple (I,Q) of sinusoids with a given amplitude and phase
- In frequency domain this is a Sinc function, centered in a the sub-carried frequency f_i, with zeros in $f_i + k/Ts$ (k=-n,…-1,1,…n)

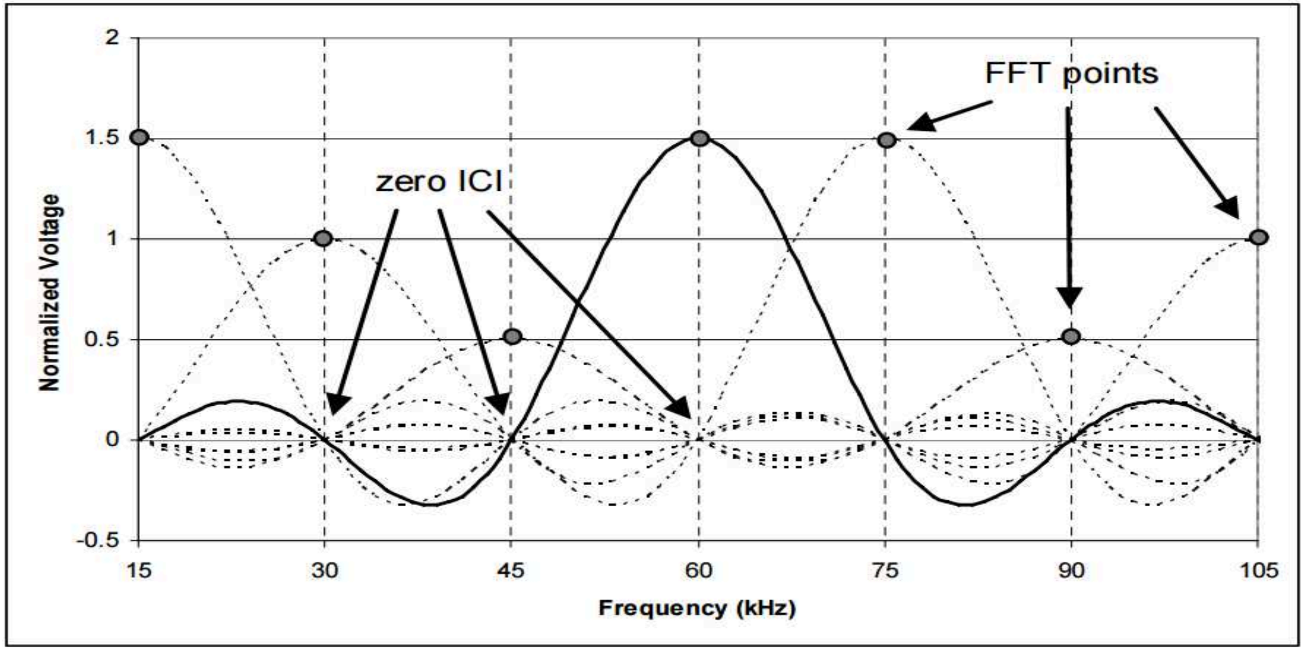
T=Ts
rect-sync
Time frequency relation



$$s(t) = \begin{cases} A & |t| < T/2 \\ A/2 & |t| = T/2 \\ 0 & |t| > T/2 \end{cases} \quad \longleftrightarrow \quad S(f) = AT\frac{\sin(\pi Tf)}{\pi Tf}$$

Orthogonal

- Spacing sub-carriers of 1/Ts implies orthogonality (zero inter-symbol-interference) in the DFT sampling points, i.e. sub-carrier frequencies whose values represent symbols



Fast Fourier Transform

- Discrete Fourier Transform (DFT) can be implemented extremely quickly with Fast Fourier Transform (FFT)
- There is one important restriction: for the FFT to work efficiently, the number of data points in each calculation should be either an exact power of two
- We typically handle this restriction by rounding the number of data points in the FFT up to the next highest power of two.
- In LTE, for example, we typically transmit on 1200 sub-carriers by means of FFTs that contain 2048 data points, with the unused data points set to zero.

Efficient Implementation of DFT:

DFT is a mathematical operation used to transform a discrete signal from the time domain to the frequency domain.
FFT is an algorithm that greatly speeds up the computation of the DFT for certain input sizes, typically those that are powers of two.
Power-of-Two Restriction:

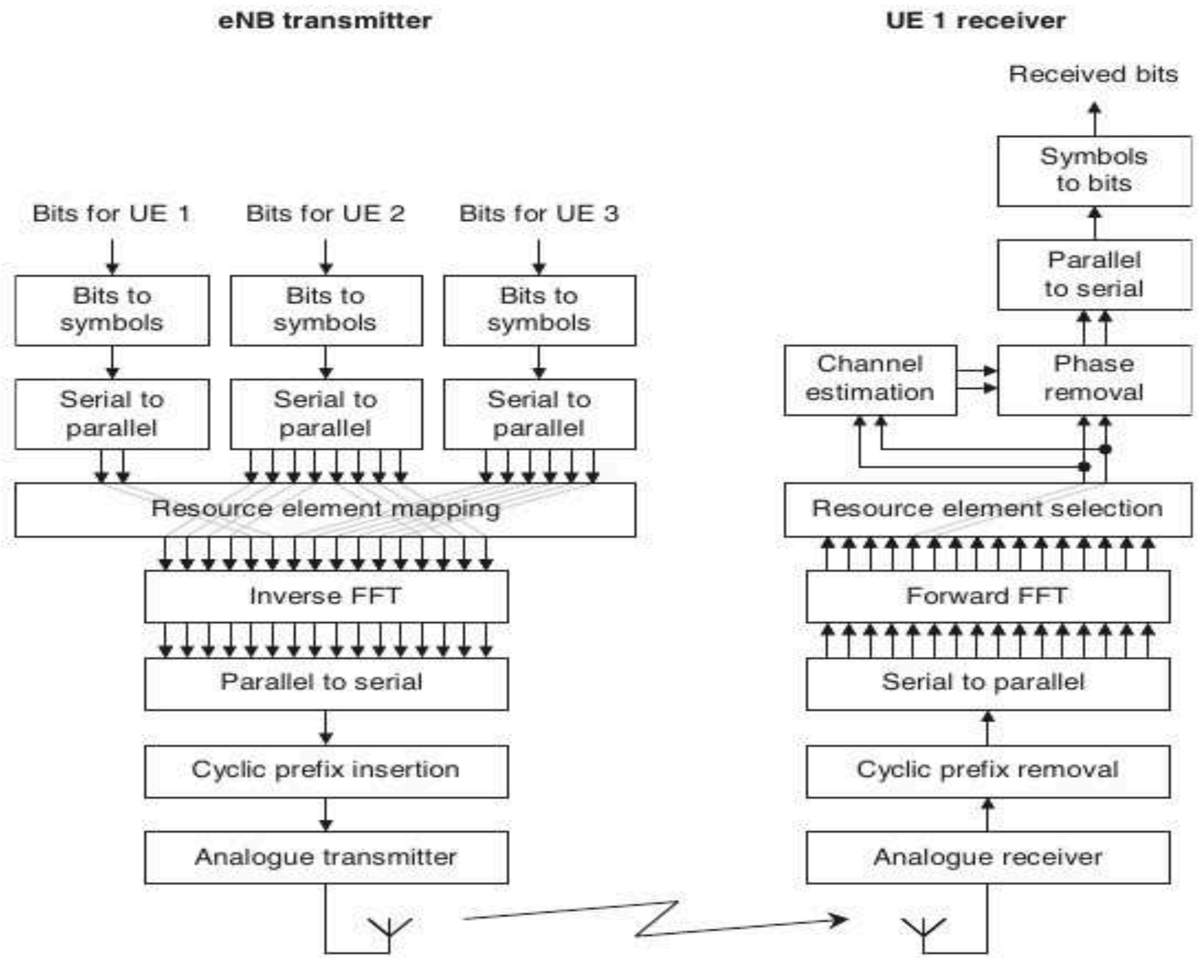
FFT algorithms are most efficient when the number of data points in the input signal is a power of two.
This means that for optimal performance, the number of samples in the input signal should be 2^N, where N is an integer.
Handling Non-Power-of-Two Inputs:

In practice, if the number of data points in the signal is not a power of two, the input size is often rounded up to the nearest power of two before applying the FFT algorithm.
Unused data points may be padded with zeros to reach the required input size.
Application in LTE:

In Long-Term Evolution (LTE) cellular networks, FFT is used for the modulation and demodulation of OFDM signals.
LTE typically uses OFDM with a certain number of sub-carriers. For example, in LTE, there are 1200 sub-carriers.
To efficiently process these sub-carriers using FFT, the FFT size is often chosen to be larger than the number of sub-carriers, rounded up to the nearest power of two.
For instance, LTE may use an FFT size of 2048, with the extra data points padded with zeros.

Multiplexing

- A central controller assign sub-carriers to different users for a given amount of time (OFDMA/TDMA)
- Users or base station (eNB) maps on these sub-carriers their uplink/downlink symbols



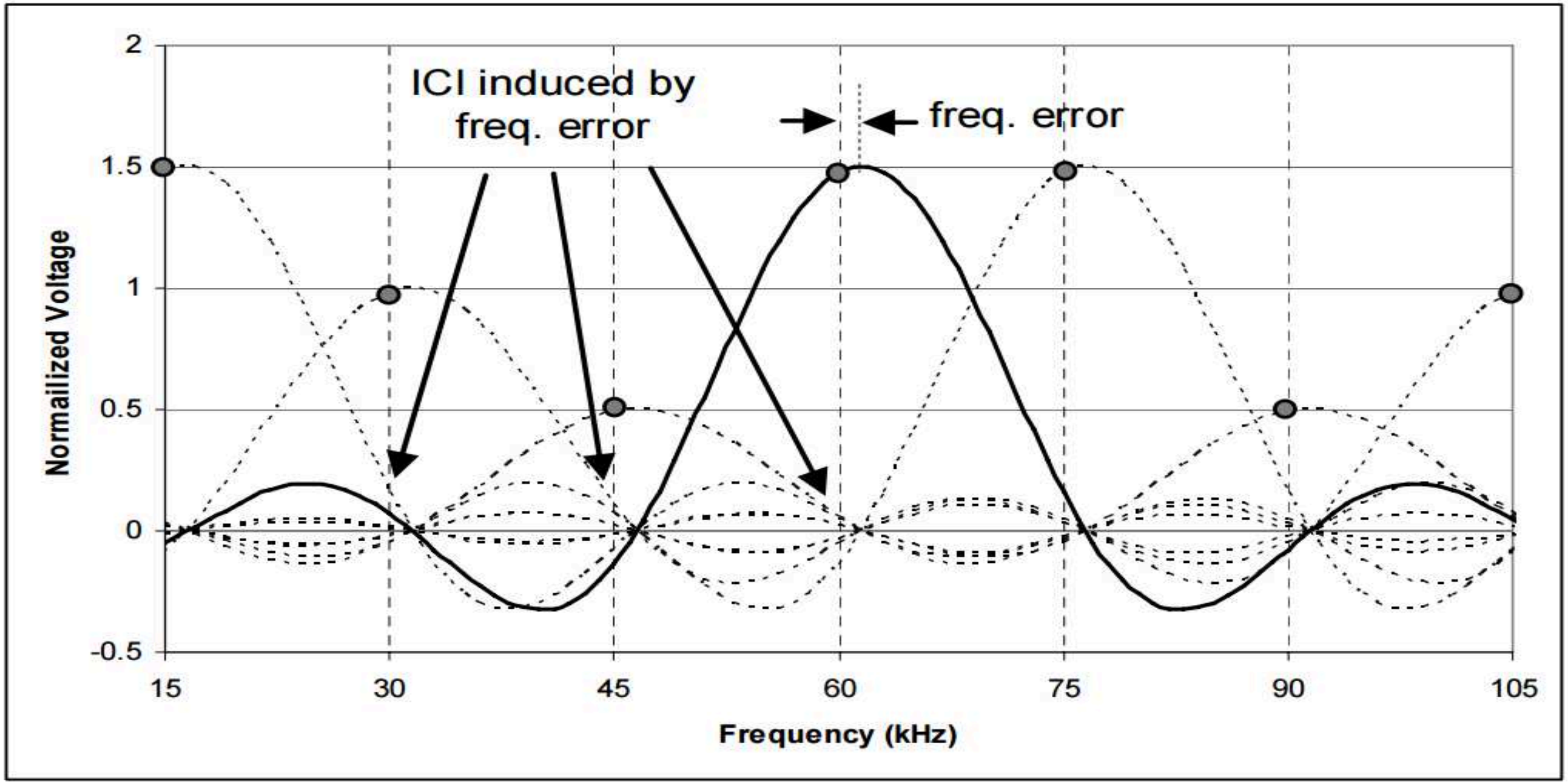
ICI and Doppler shift

- Due to mobile movements sub-carriers may be affected by a Doppler shift.
- Different path may have a different Doppler shift
- Energy of a sub-carrier is spread around the sub-carrier frequency
- Such a frequency error leads to lost of perfect orthogonally and inter-carrier-interference
- Interference is however limited if the OFDMA channel spacing is much more greater than the maximum doppler shift f_D

$$\Delta f >> f_D$$

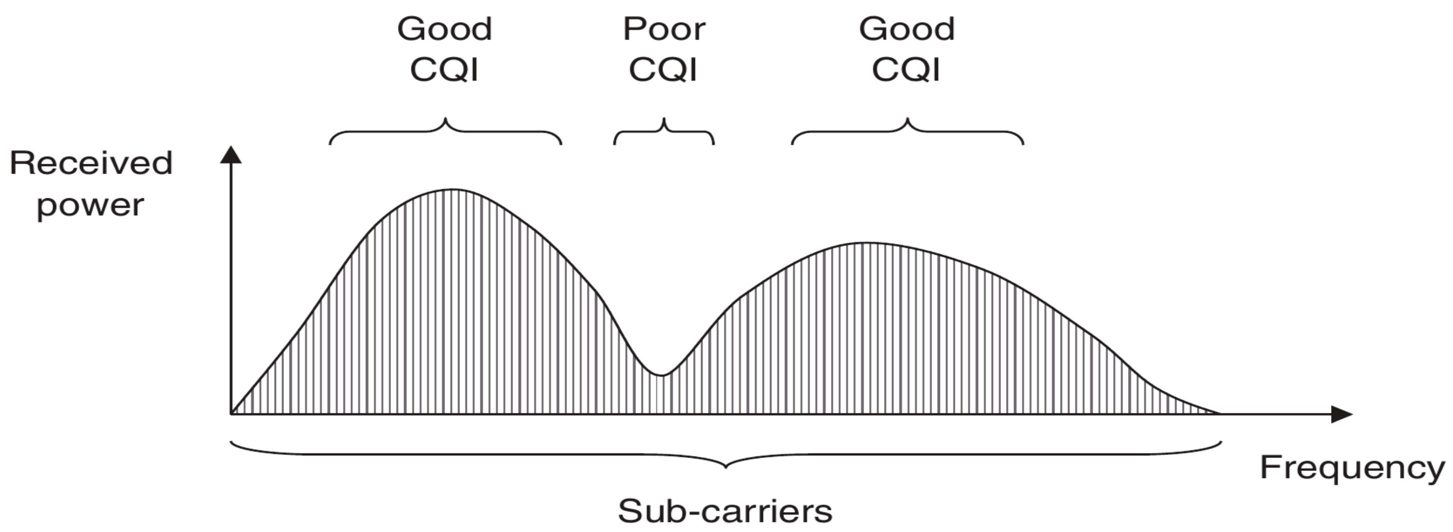
- E.g. LTE is designed to operate with a maximum mobile speed of 350 km/h which gives a maximum Doppler shift at 3.5Ghz of about 1.1 kHz. This is 7% of the sub-carrier spacing, so it satisfies the constraint above.

ICI and Doppler shift



Frequency-Specific Scheduling

- Dividing the frequency band in sub-carriers,
  - OFDMA can easily measure a channel quality indicator (CQI) of each sub-carriers and avoid to use sub-carriers with poor quality
  - Seeing a flat fading channel in each sub-carrier

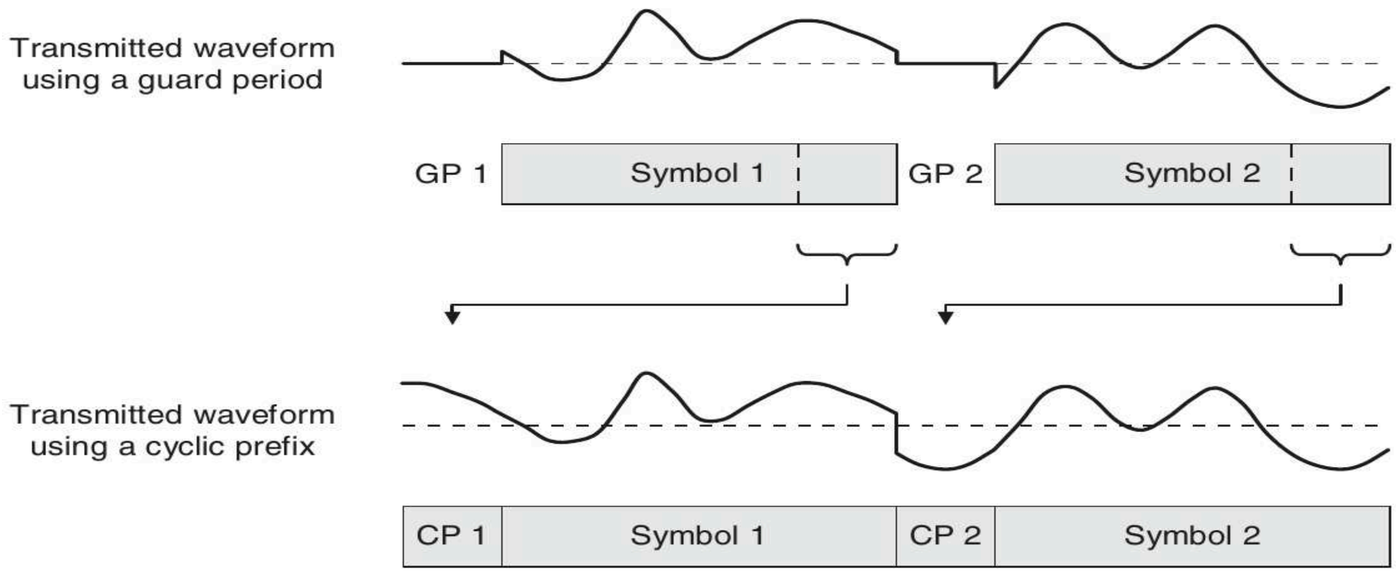


ISI and multipath

- With respect to single carrier systems OFDMA dramatically reduce inter-symbol-interference (ISI) due to multipath
- Parallel transmissions of different symbols on different sub-carriers makes possible to have high symbol rate but also a long symbol duration to cope better with channel delay spread
  - Symbol rate 120 ksps
  - Single carrier, symbol duration = 1/120e3 = 8.3 μs
  - OFDMA over 8 sub-carriers, symbol rate per carrier 15 ksps, symbol duration = 1/15e3 = 66.67 μs
- The use of a cyclic prefix makes possible to exploit multipath energies
  - Cyclic prefix for OFDMA give the benefit of a Rake receiver in case of CDMA but without any Rake....but consume overhead

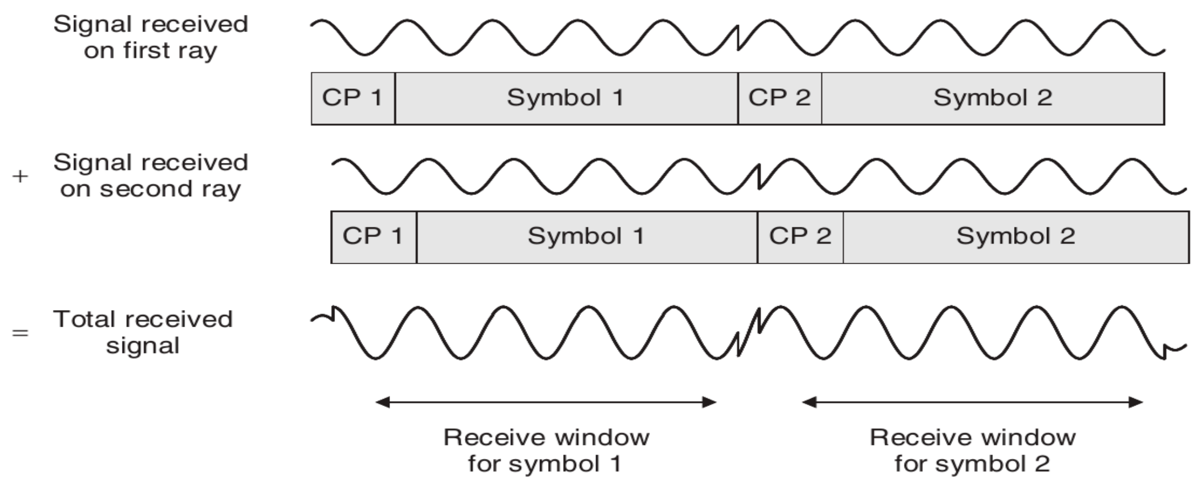
Cyclic Prefix – the intelligent receiver technique to exploit multipath

- To avoid ISI we can insert a guard time period between symbols, which is equal to the maximum expected delay
- But leaving void this guard time would not allow to exploit multi-path energies



Cyclic Prefix

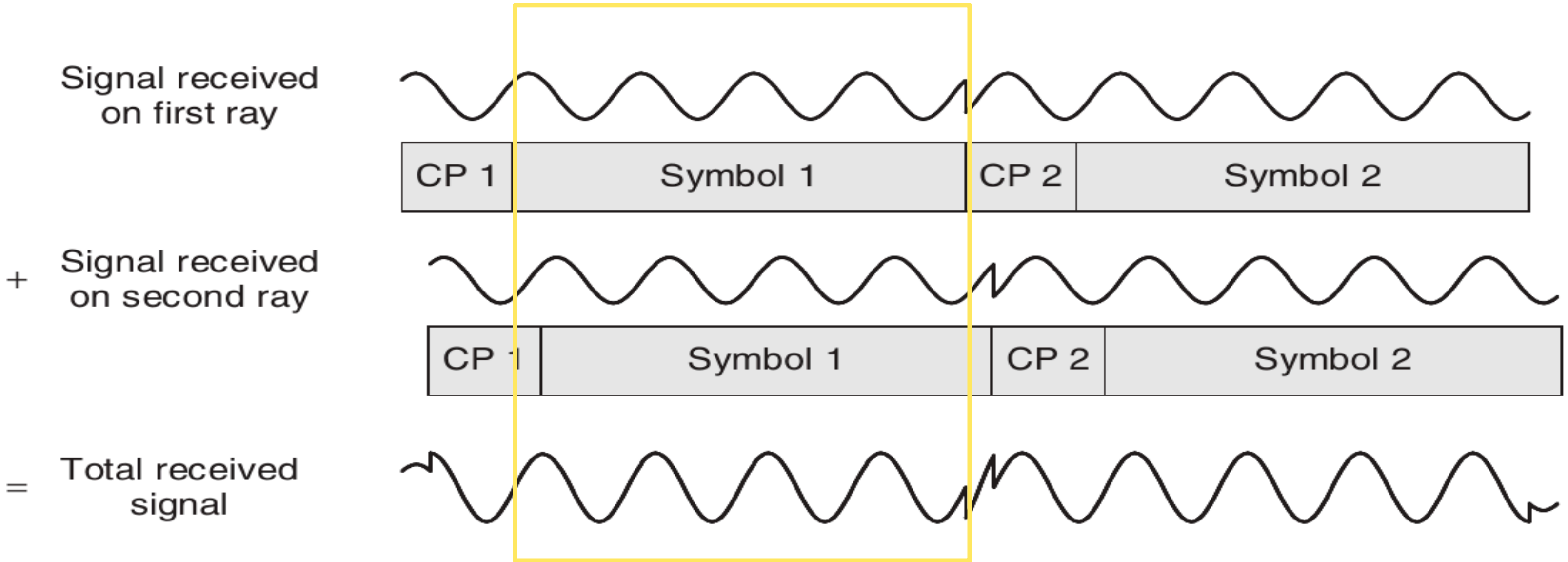
- Cyclic prefix insertion fills guard time with a copy of the data at the end of the following symbol
- In a multipath environment, the receiver picks up multiple copies of the transmitted signal with multiple arrival times.



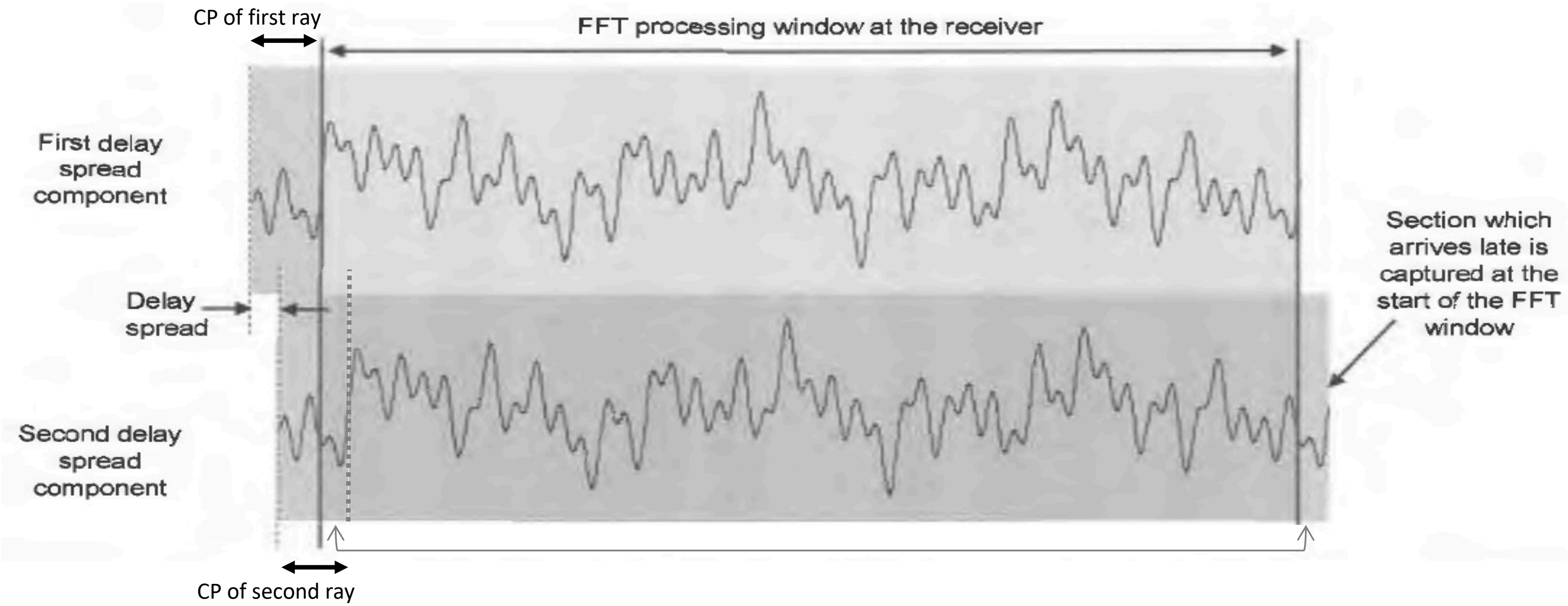
Cyclic Prefix

- The receiver window starts at the reception of the first copy and after the cyclic prefix (CP)
- In the window the receiver receives the main symbol, a first part of delayed symbols and the end part of their CP

Receive window of symbol 1



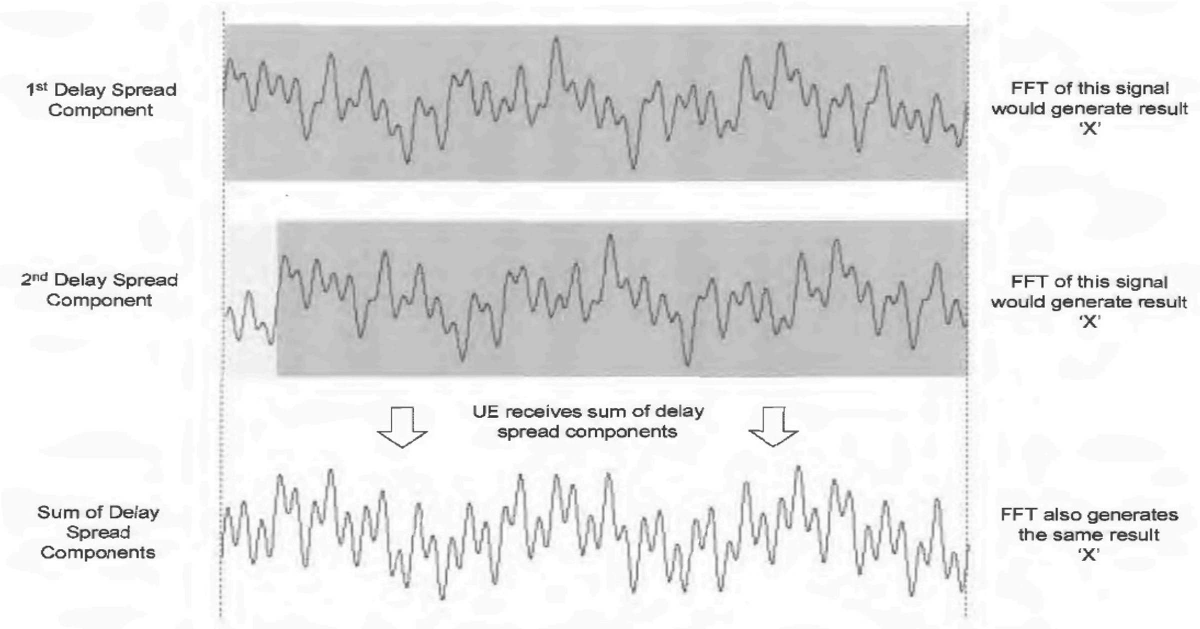
Cyclic Prefix



- Consider the two ray case. The section of the symbol of the second ray cut off by the receiver window is exactly equal to the part of the cyclic prefix captured at the start of the window
- The time domain representation of each delay spread component within the processing window is different. However, the frequency domain representation of each delay spread component within the processing window is identical

Cyclic Prefix

- Moving a section of the time domain signal from the end, and adding it to the start does not change the frequency content of the signal
- FFT generates the same amplitude and phase values, i.e. the same OFDMA symbols
- As long as the delay spread is less than the duration of the cyclic prefix, each delay spread component provides a complete representation of the signal within the FFT processing window.
- This makes possible to exploits all the energy received on different paths without the need to synchronize with individual delay spread components (e.g. Rake)



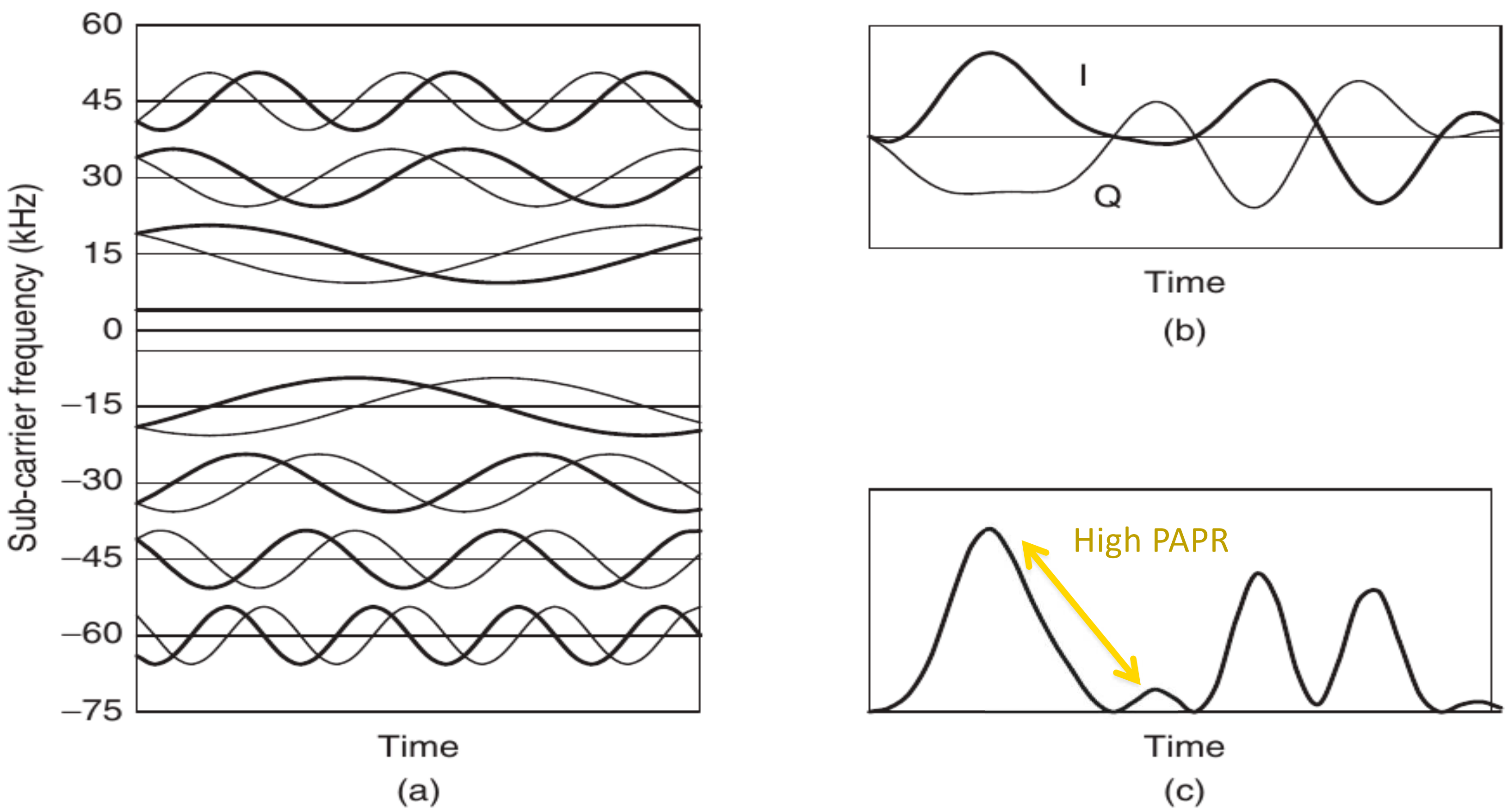
OFDMA Pros

- Resistance to multipath
- Receiver simplicity
- Multi-rate
- Frequency Diversity
  - Avoid selective fading per user
  - Different users perceive different channels qualities, a deep faded channel for one user may still be favorable to others
- Efficient use of the spectrum (orthogonally)
- No cell breathing due to intra-cell communications

OFDMA Cons

- High peak to average power ratio (PARP)
  - the power of the transmitted signal is subject to rather large variations.
  - power variations can cause problems for the transmitter’s power amplifier, which could be leaded to operate in a non –linear region with distortion
  - Any distortion of the time-domain waveform will distort the frequency-domain power spectrum as well, so the signal will leak into adjacent frequency bands and will cause interference to other receivers.
  - No problem in case of low power transmitters (e.g. WiFi), but problem arise for high power transmitters (e.g. cellular)
    - 4G,5G uses OFDM only in downlink with expensive amplifier on the base station
    - 4G,5G uses SC-FDMA / DFT-OFDMA in uplink
- Pilot signals overhead for frequency sync
- Very sensitive to phase and frequency noise, may requires guard bandwidth
- Frequency planning may be required

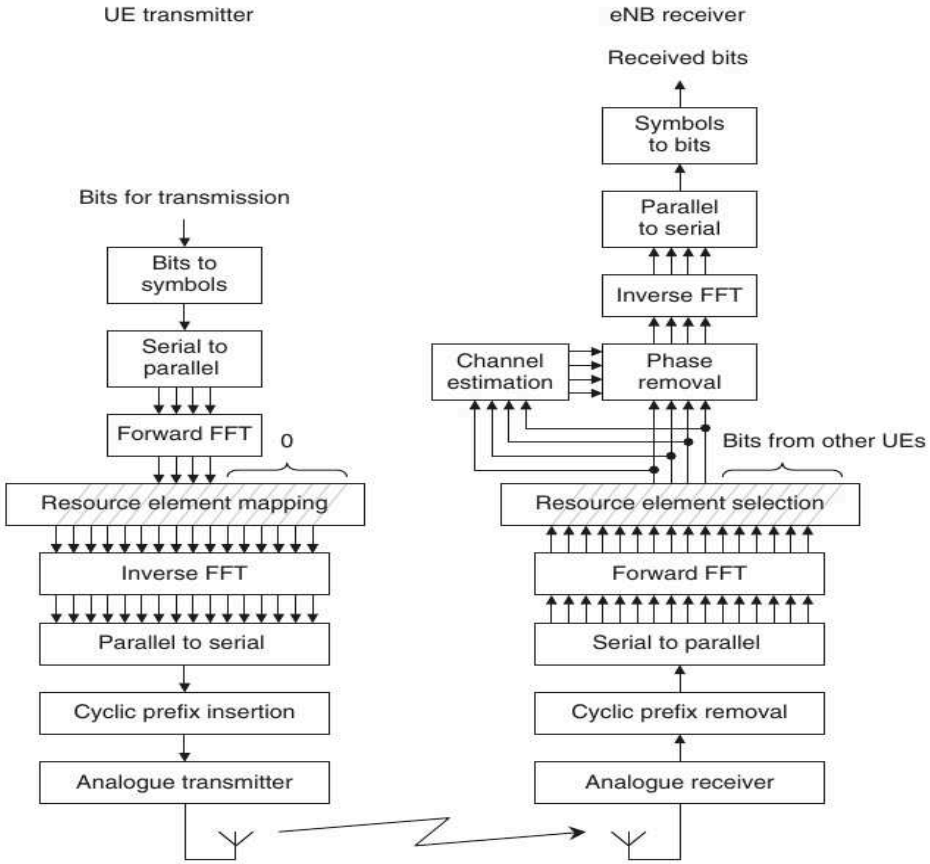
OFDMA Cons



Sub-carrier frequency (kHz)
60
45
30
15
0
–15
–30
–45
–60
–75
Time
(a)
I
Q
Time
(b)
High PAPR
Time
(c)

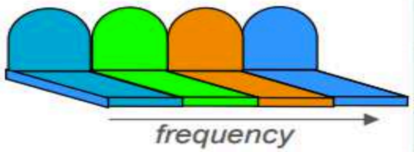
SC-FDMA (aka DFT-OFDMA)

- Single Carrier Frequency Division Multiple Access
- To reduce PARP we can mix (scrambling) all symbol values through a FFT and then go through the standard OFDM modulation
- Each device transmits using a single, contiguous block of sub-carriers, without any internal gaps, like it was a Single Carrier. This is necessary to keep the power variations to the lowest possible level.
- More limited scheduling and sub-carrier modulation flexibility wrt OFDMA
- Not usable for one to many (e.g. downlink) since would require a different FFT scrambling for each destination, thus strongly reducing the mixing benefit for the PARP reduction



FDMA, TDMA, CDMA, OFDMA

Frequency
Division
Multiple
Access



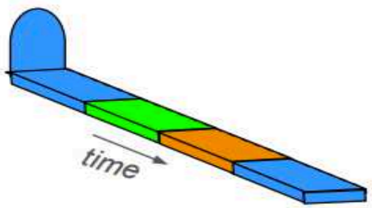
Each User has a unique
frequency

(1 voice channel per user)

All users transmit at the same time

AMPS, NMT, TACS

Time
Division
Multiple
Access



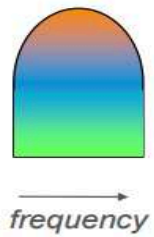
Each User has a unique
time slot

Each Data Channel has a unique
position within the time slot

Several users share the same frequency

IS-136, GSM, PDC

Spread **S**pectrum **M**ultiple **A**ccess / **C**ode **D**ivision **M**ultiple **A**ccess



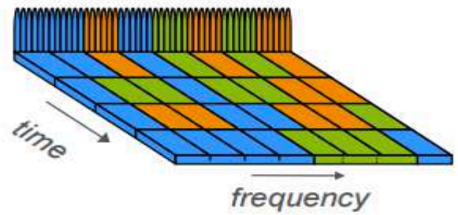
Each Transmitter has a unique
Scrambling Code

Each Data Channel has a unique **Channelization code**

Many users share the same frequency *and* time

IS-95, cdma2000, WCDMA

Orthogonal
Frequency
Division
Multiple
Access



Each User and each channel has a unique
Time and Frequency Resource

Many users are separated in frequency and/or time

LTE, Wimax (WLAN 802.11a,g)