Diploma of Telecommunication Engineering

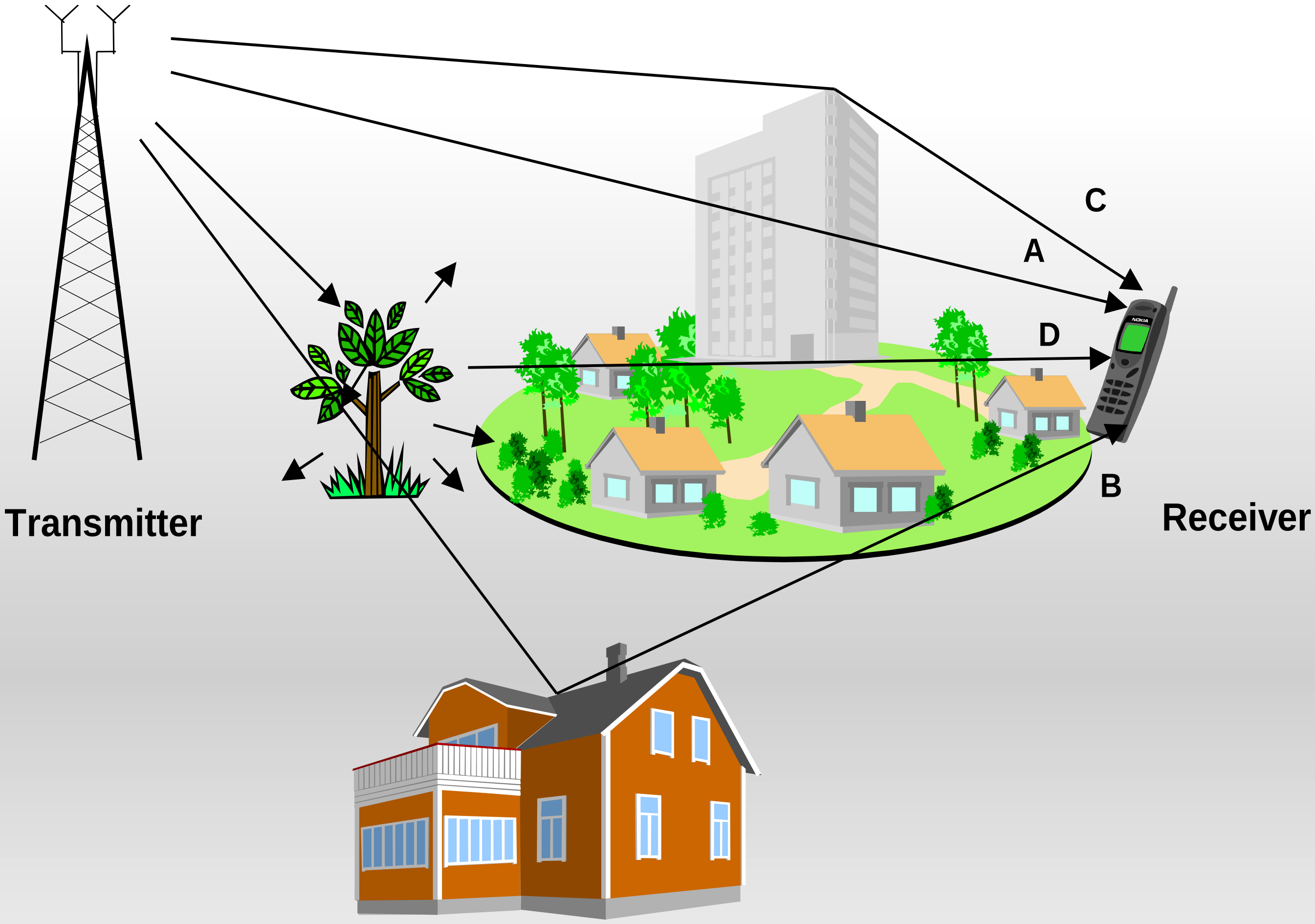
Telkom University

KOMUNIKASI NIRKABEL BROADBAND

Orthogonal Frequency Division Multiplexing (OFDM)

By : Dwi Andi Nurmantris

Review : Fading



Review : Fading

Jenis – jenis Fading

Kondisi yang ditinjau dalam analisis

Tidak Ada Pergerakan Tranceiver

- ❑ Dianalisa menggunakan DELAY SPREAD MODEL → Parameter TIME DISPERSION

Ada Pergerakan Tranceiver

- ❑ Dianalisa menggunakan TIME VARYING MODEL / DOPPLER SPREAD MODEL→ Parameter FREQUENCY DISPERSION

Berdasarkan atas multipath **Time Delay Spread**	**FLAT FADING** • BW sinyal < BW koheren • Delay spread < periode simbol	Akibat sinyal datang dengan delay yang berbeda-beda
	FREQUENCY SELECTIVE FADING • BW sinyal > BW koheren • Delay spread > periode simbol	
Berdasarkan atas **Doppler Spread**	**FAST FADING** • Doppler spread >> • Coherence time < periode simbol • Variasi kanal **lebih cepat** dari variasi sinyal baseband	akibat pergerakan
	SLOW FADING • Doppler spread << • Coherence time > periode simbol • Variasi kanal **lebih lambat** dari variasi sinyal baseband	

Review : Fading

Parameter Fading

	Time Dispersion	Frequency Dispersion
Time Domzain Parameter	❑ Mean Excess Delay ❑ RMS Delay Spread ❑ Maksimum Excess Delay	❑ Coherence Time
Frequency Domain parameter	❑ BW Coherence	❑ Doppler Spread

Review : Fading

Parameter Fading

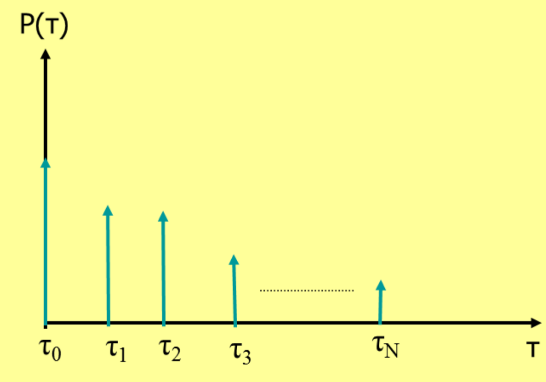
Mean Excess Delay

$$\bar{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)}$$

RMS Delay Spread

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$

$$\overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$



Power Delay Profile

Maximum Excess Delay (XdB) or Excess Delay Spread (XdB):

Time delay during which multi-path energy falls to X dB below the maximum (Note that the strongest component does not necessarily arrive at τ_0)

COHERENCE BANDWIDTH

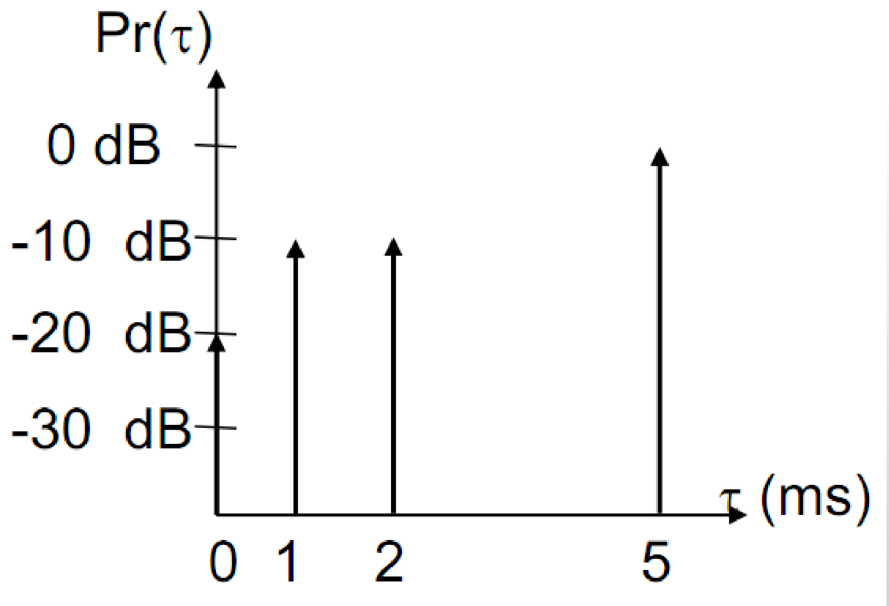
A statistical measure of the range of frequencies over which the channel is can be considered to be **"flat"** (i.e., a channel which passes all spectral components with approximately equal gain and linear phase)

$$B_C = \frac{1}{5\sigma_\tau}$$

Review : Fading

Contoh

Hitunglah mean excess delay, rms delay spread, dari suatu kanal multipath yang profile multipath-nya diberikan pada gambar disamping. Berikan analisa apakah kanal multipath tersebut termasuk Frequency selective fading ataukah flat fading jika bandwith komunikasi sebesar 30 Khz dan 200 Khz?



Review : Fading

Jawab

Mean excess delay,

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)}$$

$$\bar{\tau} = \frac{(1)(5)+(0.1)(1)+(0.1)(2)+(0.01)(0)}{(0.01+0.1+0.1+1)} = 4.38\ \mu s$$

Momen kedua delay profile,

$$\overline{\tau^2} = \frac{(1)(5)^2+(0.1)(1)^2+(0.1)(2)^2+(0.01)(0)^2}{(0.01+0.1+0.1+1)} = 21.07\ \mu s^2$$

RMS delay spread,

$$\sigma_\tau = \sqrt{21.07-(4.38)^2} = 1.37\ \mu s$$

Coherence bandwidth,

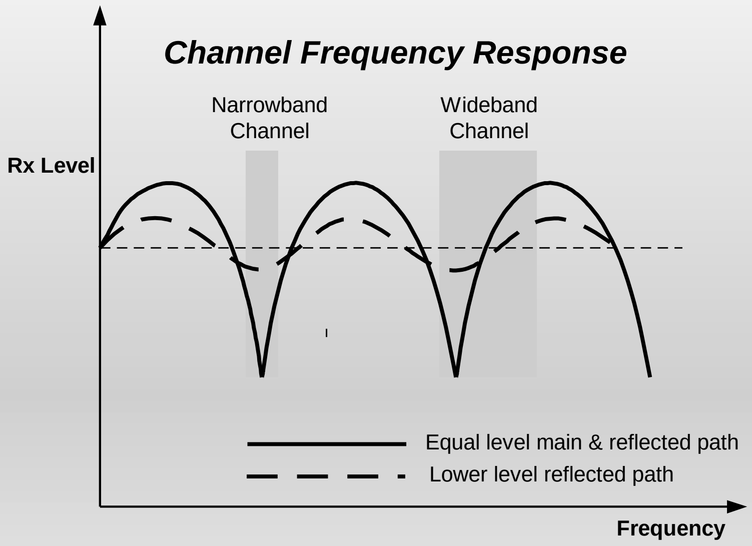
$$B_C \approx \frac{1}{5\sigma_\tau} = 146\ \text{kHz}$$

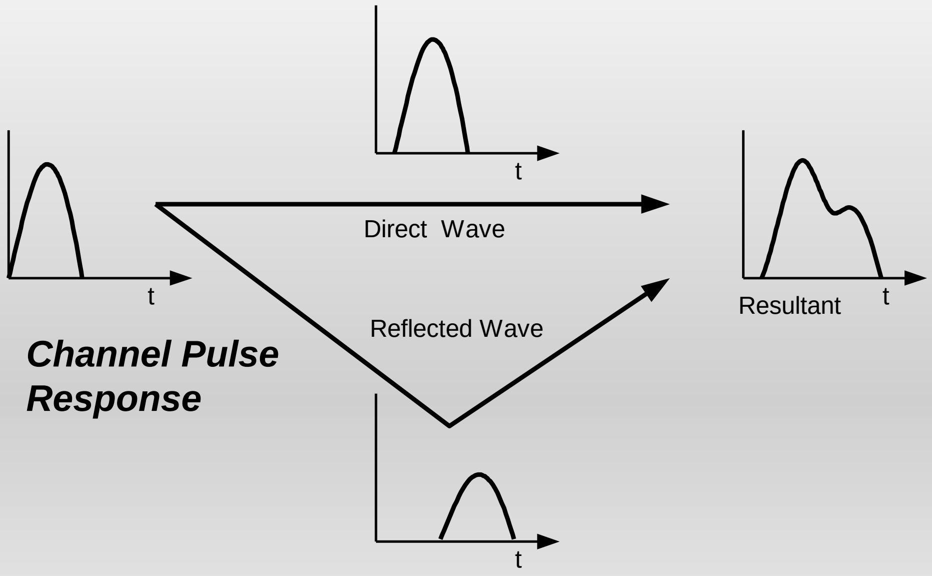
Jadi,

- Untuk BW informasi = 30 kHz , BW informasi< BW koheren sehingga merupakan **Flat Fading**
- Untuk BW informasi= 200 kHz , Bw informasi >BW koheren sehingga masuk kategori **Frequency Selective Fading**

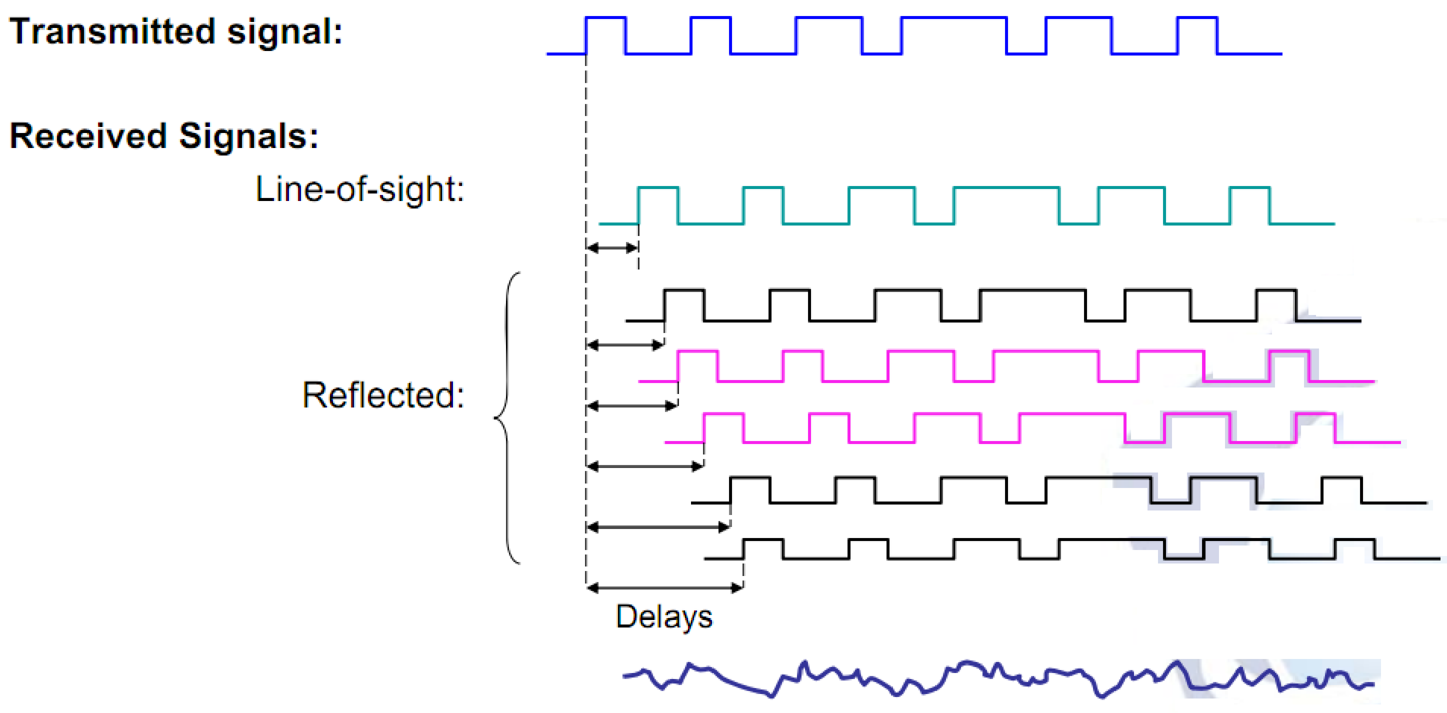
Fading Effect

Sinyal multipath juga akan menyebabkan **distorsi** sinyal / cacat sinyal.Problem ini secara khusus berkaitan dengan bandwidth sinyal yangdigunakan dalam komunikasi mobile





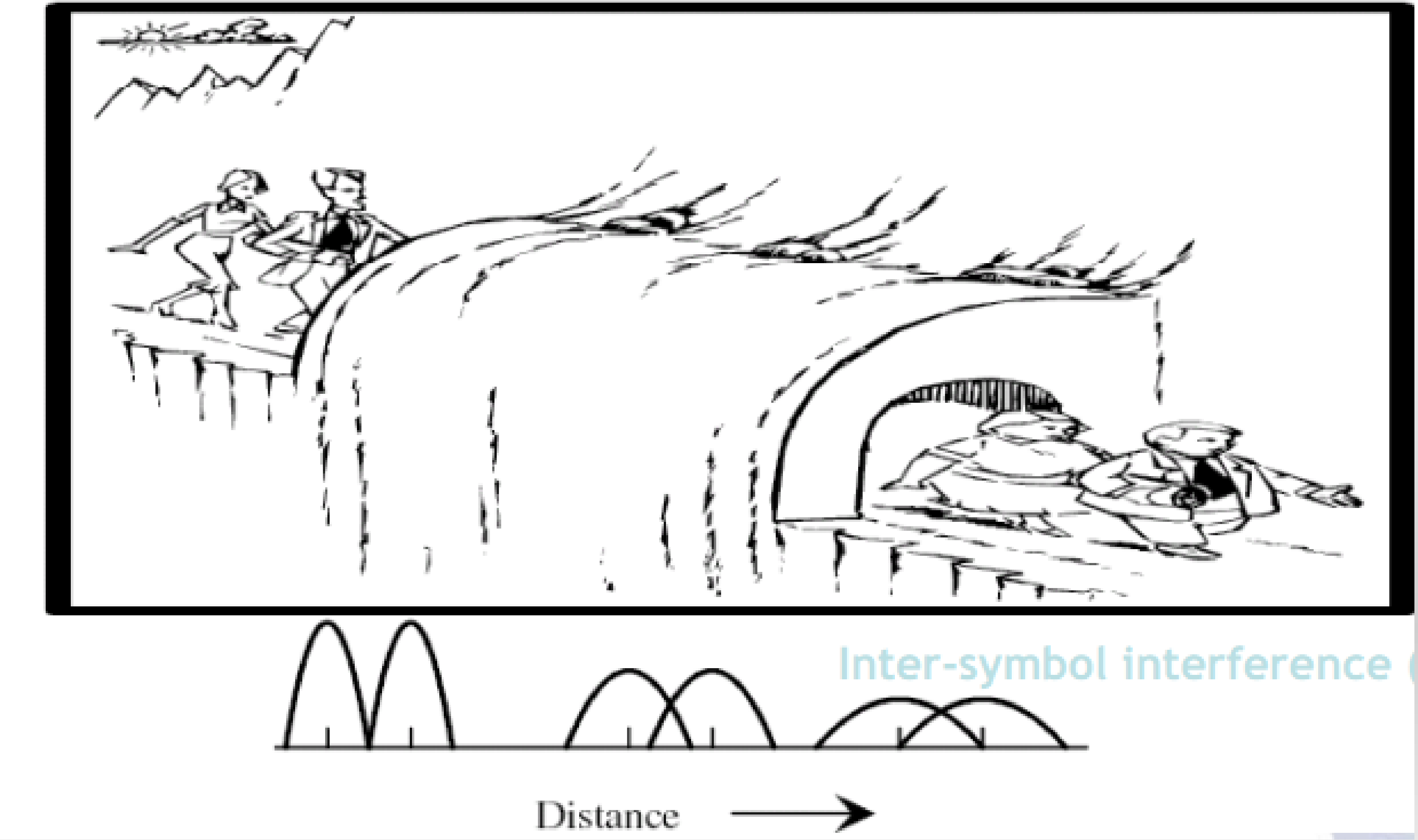
Fading Effect



The symbols add up on the channel

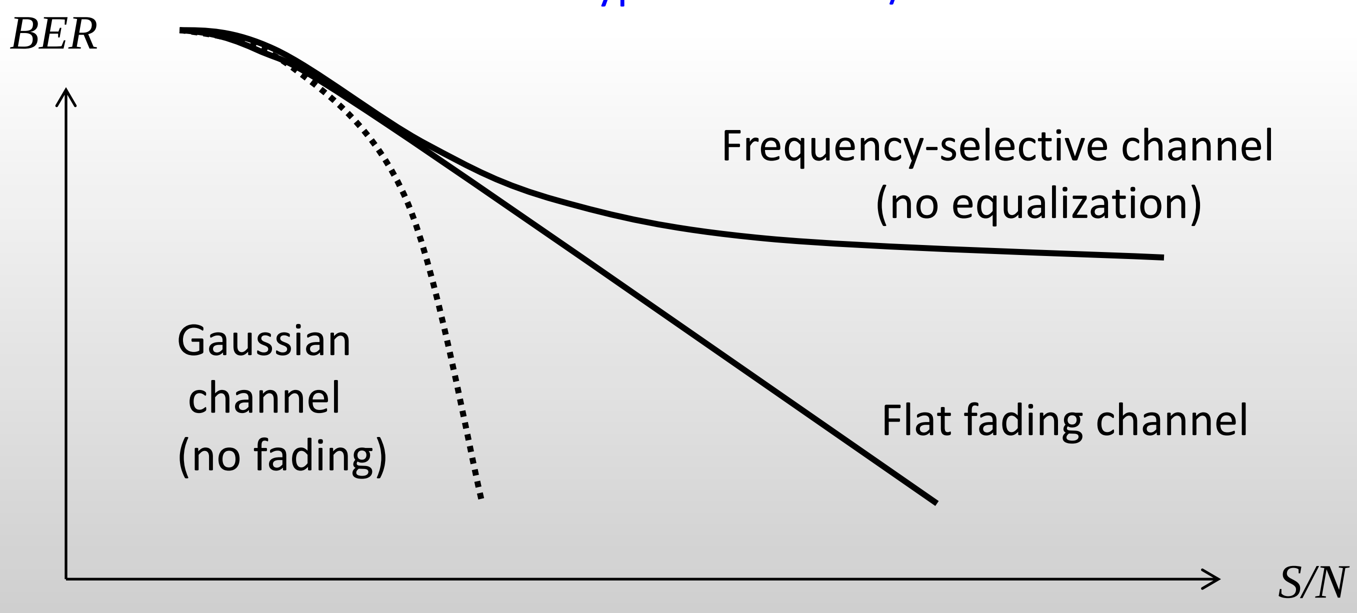
→ **Distortion → Intersymbol Interference**

Fading Effect



Fading Effect

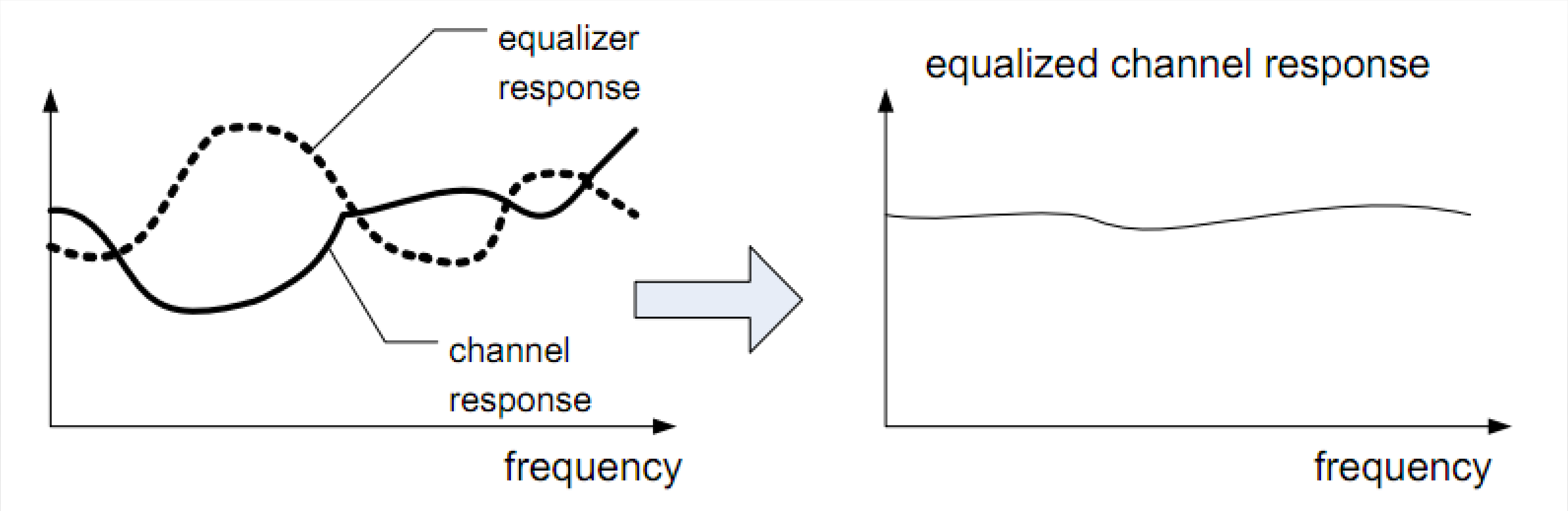
Typical BER vs. S/N curves



Distortion → Intersymbol Interference → Error

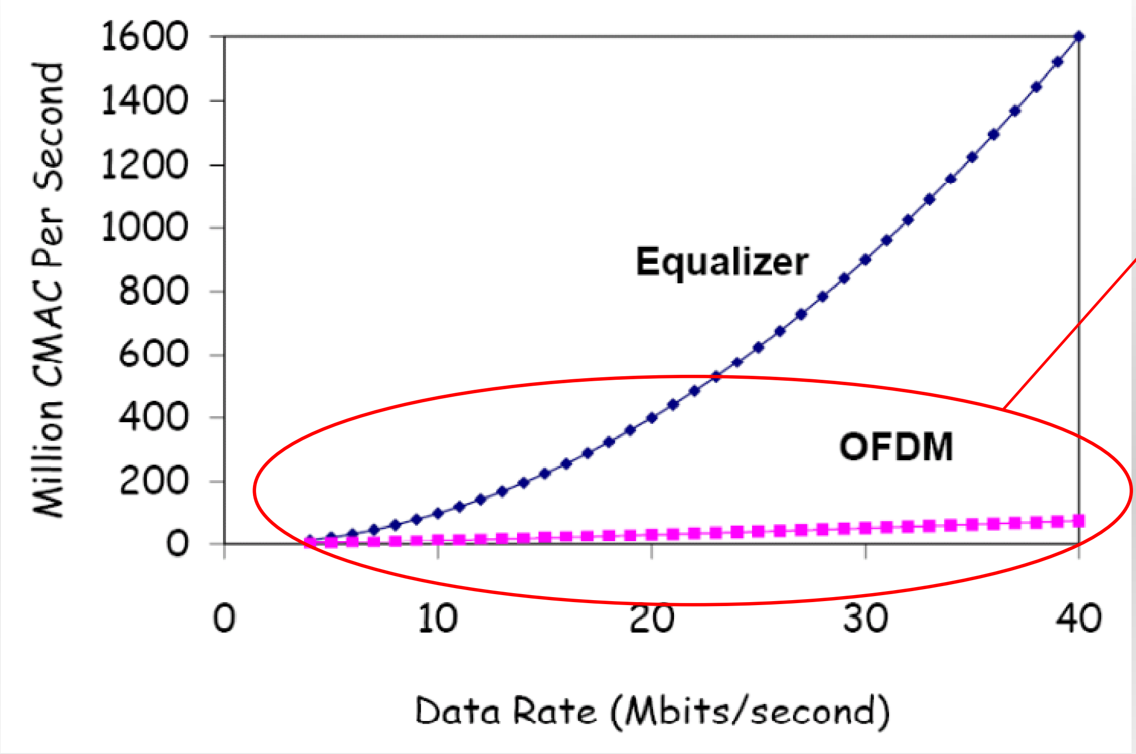
ISI COMBAT

We can improve the ISI Effect by including an additional filtering stage at the receiver. This is known as an ***equalisation* filter / Equalizer**



ISI COMBAT

We can improve the ISI Effect by including an additional filtering stage at the receiver. This is known as an ***equalisation* filter / Equalizer** → ***But Has high Complexity in High datarate***



Potential Solution on Fading and ISI Problem → **Multicarrier Base**

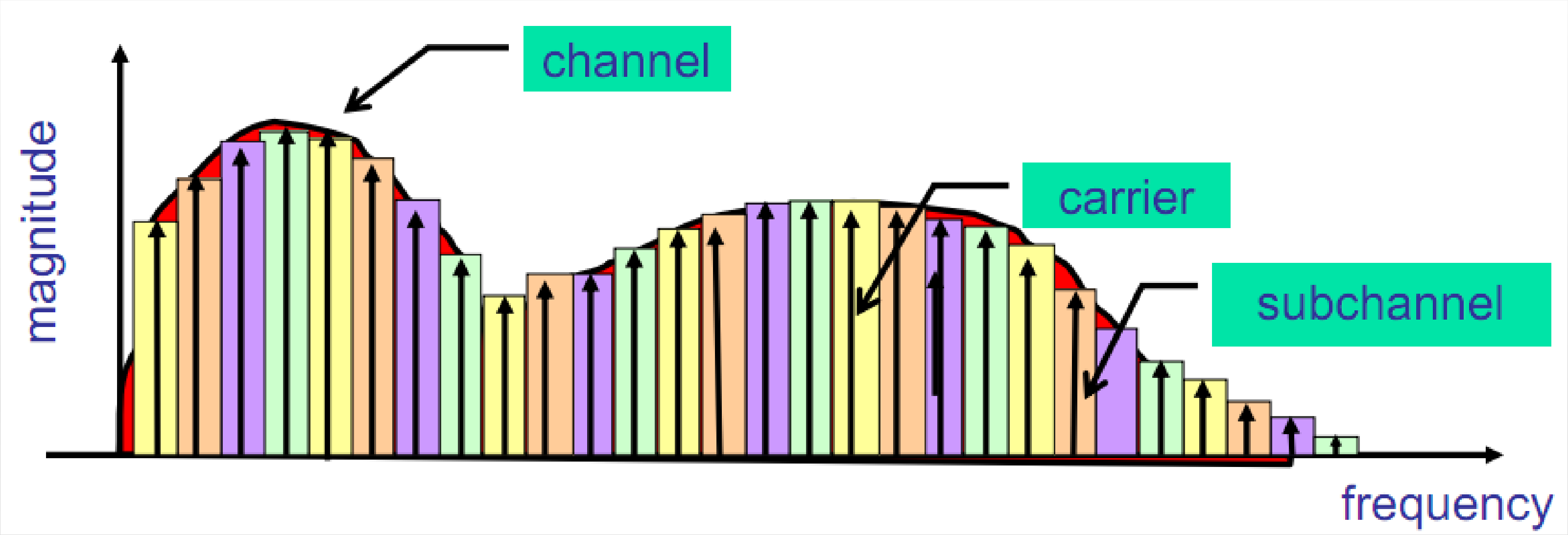
CMAC : complex multiply and accumulate

ISI COMBAT

Multicarrier

Multicarrier is an alternative to equalization.

IDEA → Divides signal bandwidth to create flat-fading subchannels.



ISI COMBAT

Multicarrier

Berdasarkan atas multipath **Time Delay Spread**	**FLAT FADING** • BW sinyal < BW koheren • Delay spread < periode simbol
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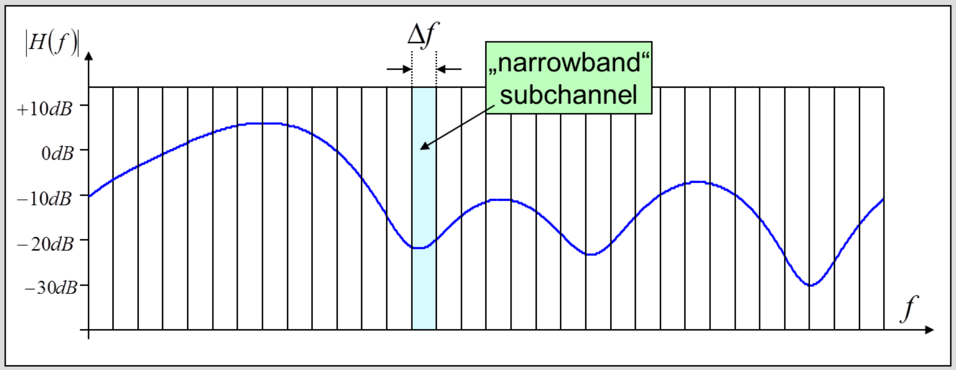
Since we avoid ISI if <u>Periode Symbol > Delay Spread</u>, just send a large number of narrowband carriers

Example: Splitting of a broadband channel into N=32 subchannels



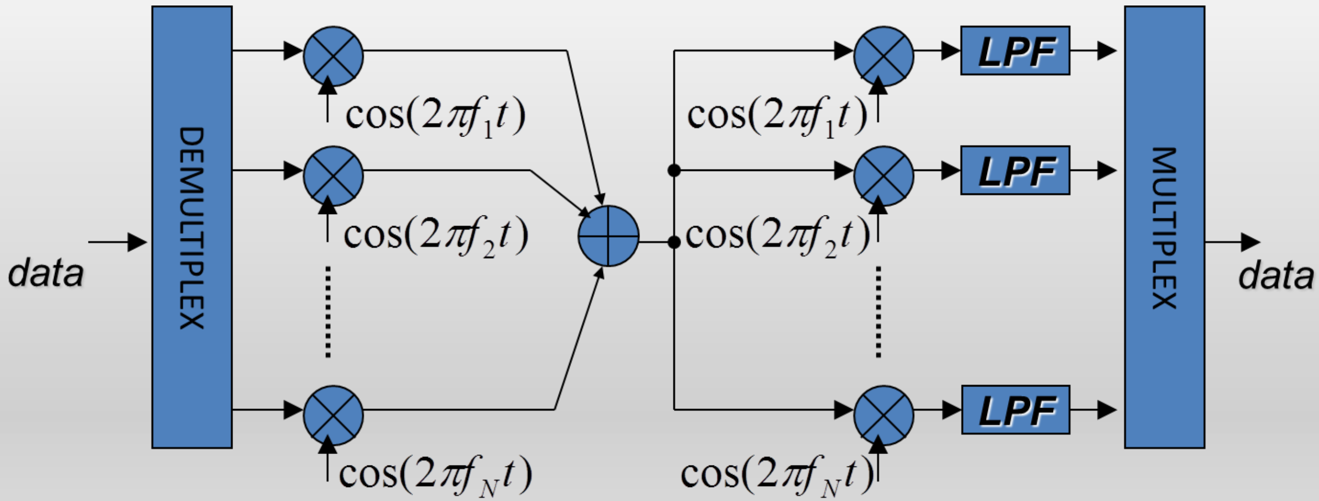
A Common Rule of Thumb:

$T_S > 10\sigma_t$ ➔ Flat fading

ISI COMBAT

Multicarrier

- Use multiple channel (carrier frequency) for one data transmission



Substream modulated onto separate carriers :

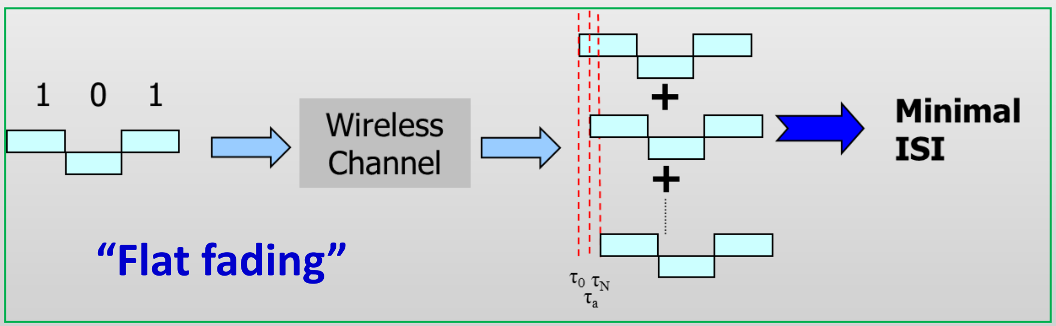
- Substream bandwidth is B/N for B total bandwidth bandwidth
- B/N<Bc implies flat fading on each subcarrier (no ISI)

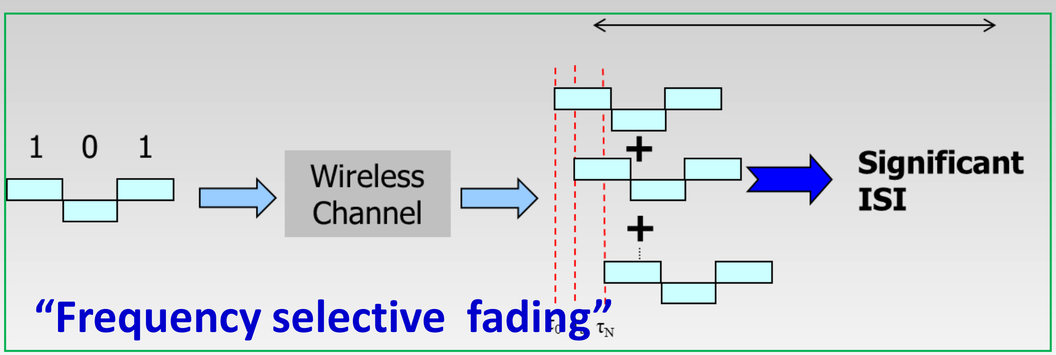
ISI COMBAT

Multicarrier

Multicarrier: interesting interpretation in both time and frequency domain

In the time domain





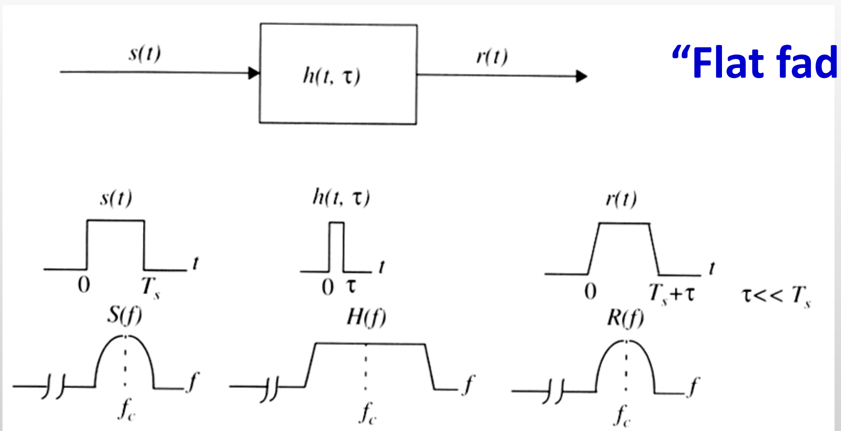
the symbol duration on each subcarrier has to be increased to assured that the symbol duration exceeds the channel delay spread for ISI free Communication

ISI COMBAT

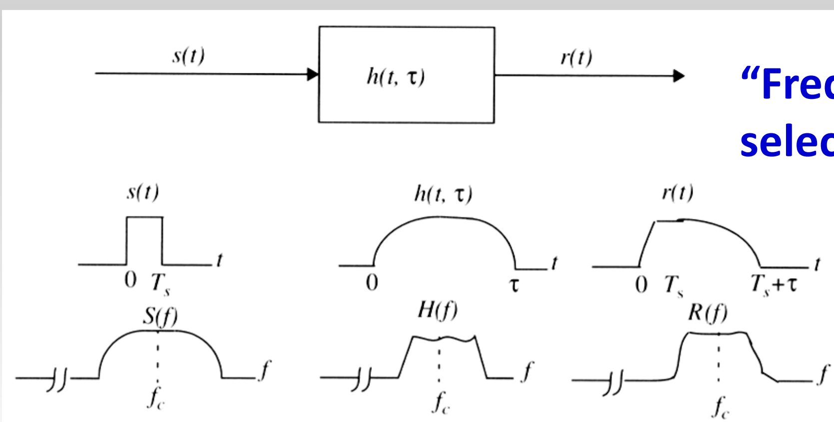
Multicarrier

Multicarrier: interesting interpretation in both <u>time and frequency domain</u>

<u>In the Frequency domain</u>

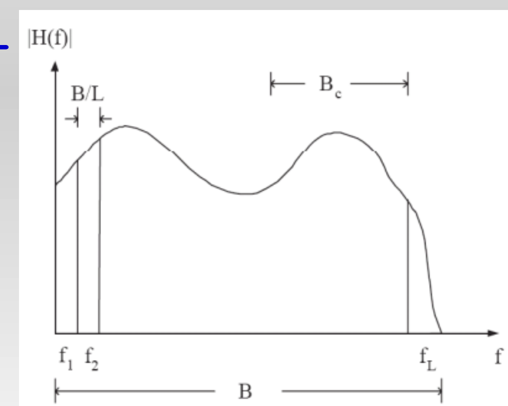


"Flat fading"



"Frequency selective fading"

The Total bandwidth B must be devided into L sub-carriers have bandwidth B/L << Bandwidth Coherence To assures "flat fading"



ISI COMBAT

Contoh

Suatu kanal Komunikasi Wireless memiliki karakteristik fading → Delay Spread (σ_τ)sebesar 1 μs. Diasumsikan untuk menghindari ISI maka durasi simbol Ts > = 10 σ_τ

Tentukan :

a. Bandwidth komunikasi maksimum yang diperbolehkan ?
b. Jika multicarrier digunakan, dan kita akan menggunakan bandwidth total sebesar 5 Mhz berapa jumlah subcarrier yang digunakan?

Solusi

a. Jika asumsi kita menggunakan Ts = 10 σ_τ untuk menghindari ISI → maka maksimum bandwidth komunikasi yang bisa digunakan adalah 1/Ts = $^{1}/_{10\ \sigma_\tau}$ = $^{0.1}/_{\sigma_\tau}$= 100 Khz
b. Jika multicarrier digunakan, dengan bandwidth total 5 Mhz dan bandwidth subcarrier sebesar 100 Khz, maka jumlah subcarrier yang digunakan minimal sebanyak $^{5Mhz}/_{100Khz} = 50\ subcarrier$

WHAT IS OFDM

- OFDM
  =Orthogonal Frequency Division Multiplexing

- Many orthogonal sub-carriers are multiplexed in one symbol
  - What is the orthogonal?
  - How multiplexed?

WHAT IS OFDM

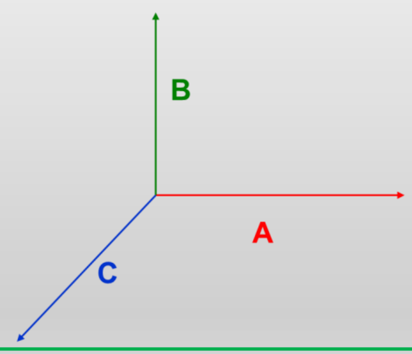
Orthogonality of subcarriers

orthogonal have meaning :

- The signals /Subcarriers are in that form so that they do not interfere with each other
- crosstalk between the signals/subcarriers is eliminated
- the signals/Subcarriers are still received without adjacent carrier interference

Vector space

- Pada vector space, orthogonal berarti saling tegak lurus
- **A**, **B** and **C** vectors in space are orthogonal to each other



Real Function space

- Real Function space, orthogonal berarti memenuhi :

$$\int_{kT}^{(k+1)T} s_1(t)s_2(t)dt = 0$$

$$S_1(t) = A\sin(2\pi f_1 t)$$

$$S_2(t) = B\sin(2\pi f_2 t)$$

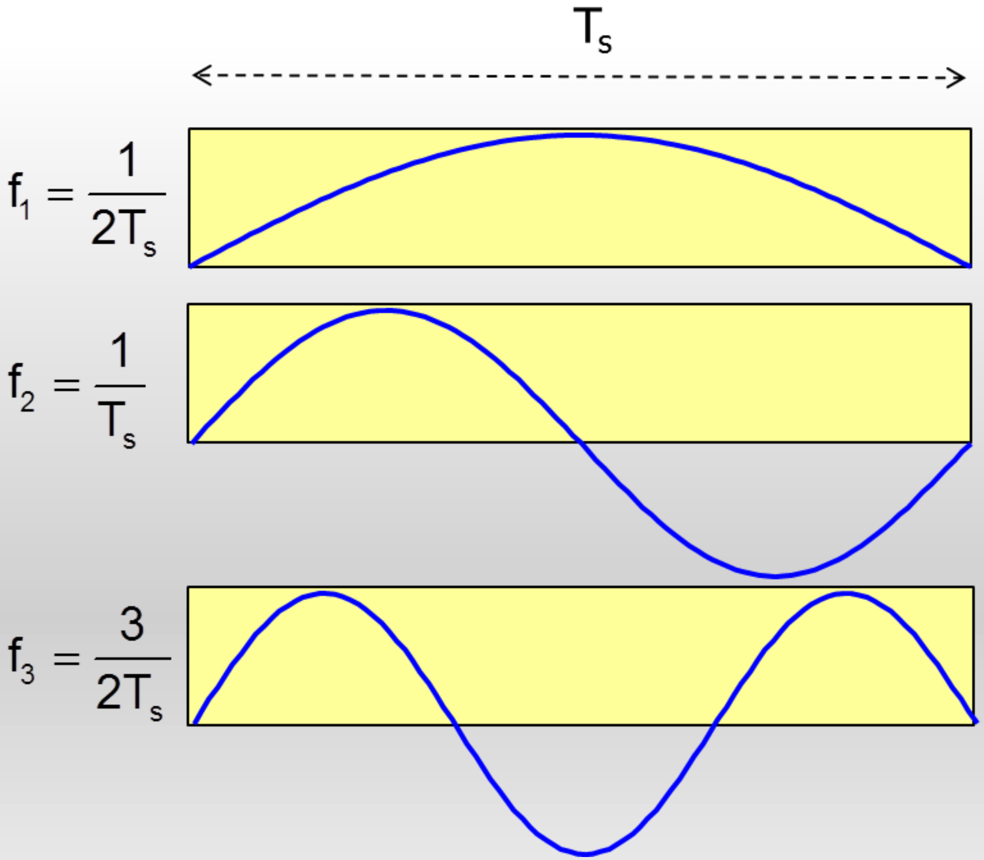
$$\int_0^T S_1(t)S_2(t)dt = 0$$

WHAT IS OFDM

Orthogonality of subcarriers

The sinusoid signals with frequencies f_1, f_2, f_3 are all **mutually orthogonal** over the symbol period T_s

$$S_1(t) = Sin(2\pi f_1 t)$$
$$S_2(t) = Sin(2\pi f_2 t)$$
$$S_3(t) = Sin(2\pi f_3 t)$$



WHAT IS OFDM

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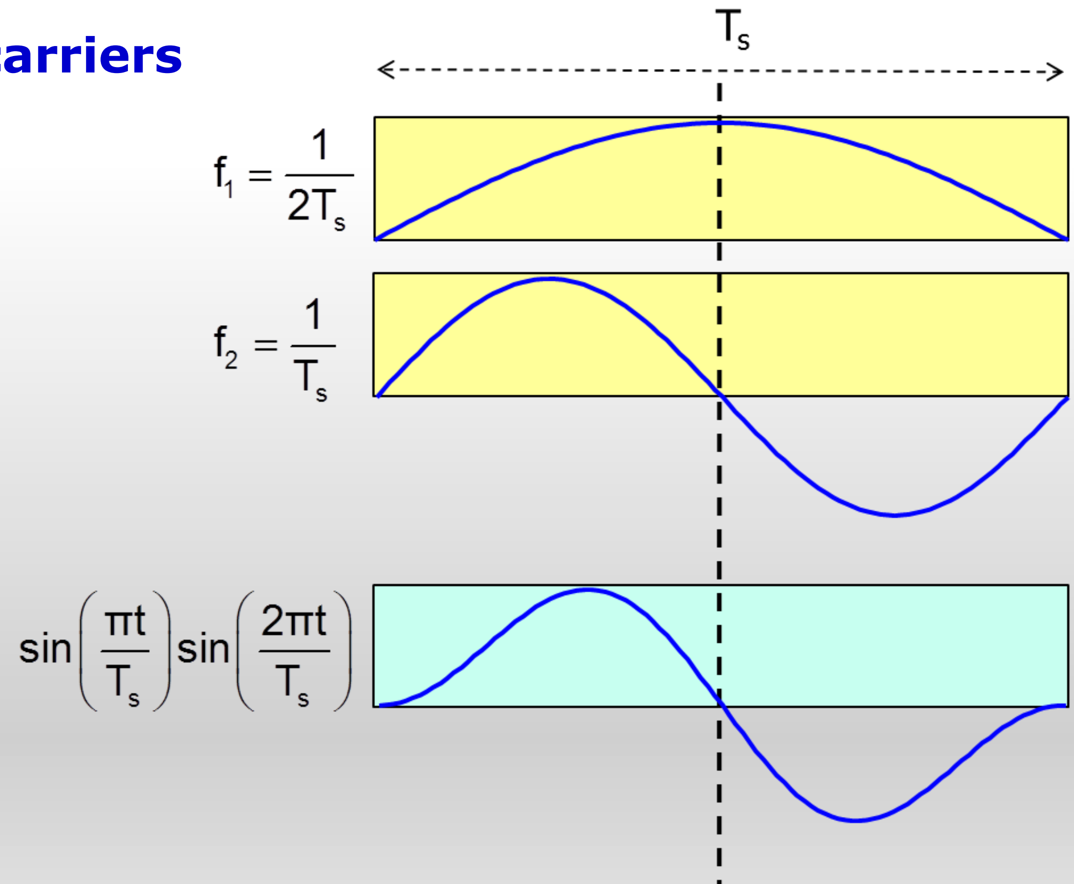

$$\int_0^{T_s} \sin\left(\frac{\pi t}{T_s}\right)\sin\left(\frac{2\pi t}{T_s}\right)dt = \int_0^{T_s} \cos\left(\frac{\pi t}{T_s}\right)dt - \int_0^{T_s} \cos\left(\frac{3\pi t}{T_s}\right)dt$$

$$\int_0^{T_s} \sin\left(\frac{\pi t}{T_s}\right)\sin\left(\frac{2\pi t}{T_s}\right)dt = \left[\frac{\sin(\pi t/T_s)}{(\pi t/T_s)} - \frac{\sin(3\pi t/T_s)}{(3\pi t/T_s)}\right]_0^{T_s} = 0$$

WHAT IS OFDM

Orthogonality of subcarriers

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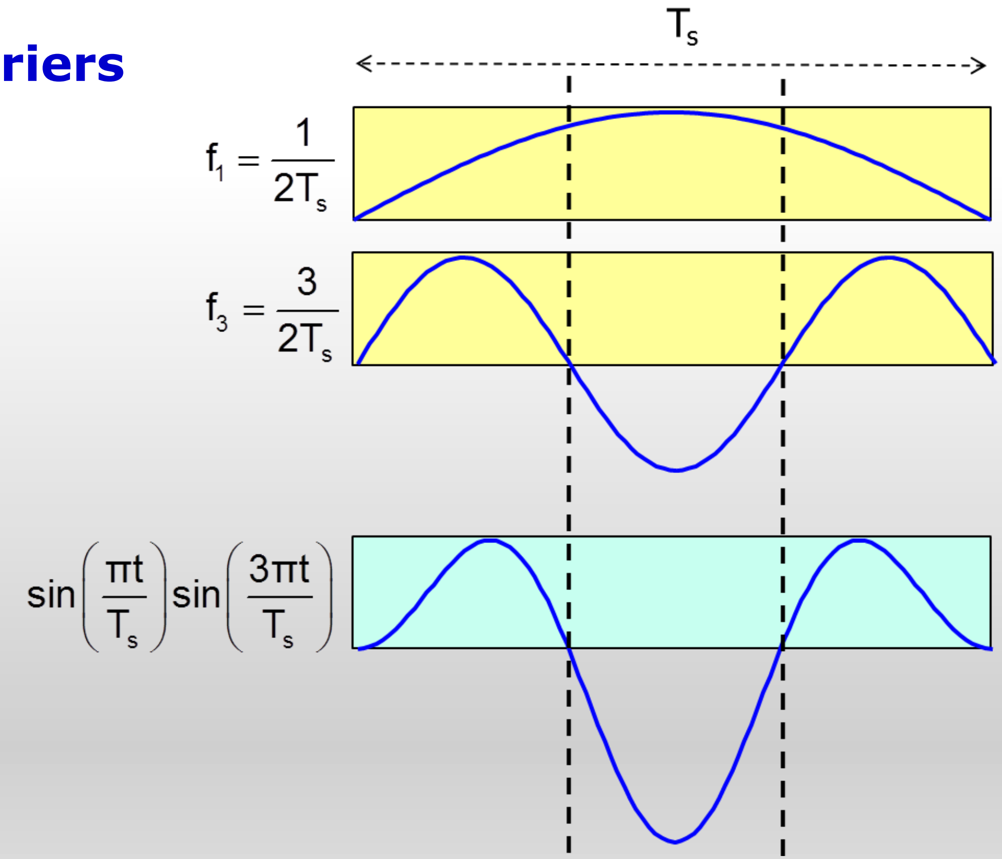

$$\int_0^{T_s} \sin\left(\frac{\pi t}{T_s}\right)\sin\left(\frac{3\pi t}{T_s}\right)dt = \int_0^{T_s} \cos\left(\frac{2\pi t}{T_s}\right)dt - \int_0^{T_s} \cos\left(\frac{4\pi t}{T_s}\right)dt$$

$$\int_0^{T_s} \sin\left(\frac{\pi t}{T_s}\right)\sin\left(\frac{3\pi t}{T_s}\right)dt = \left[\frac{\sin(2\pi t/T_s)}{(2\pi t/T_s)} - \frac{\sin(4\pi t/T_s)}{(4\pi t/T_s)}\right]_0^{T_s} = 0$$

WHAT IS OFDM

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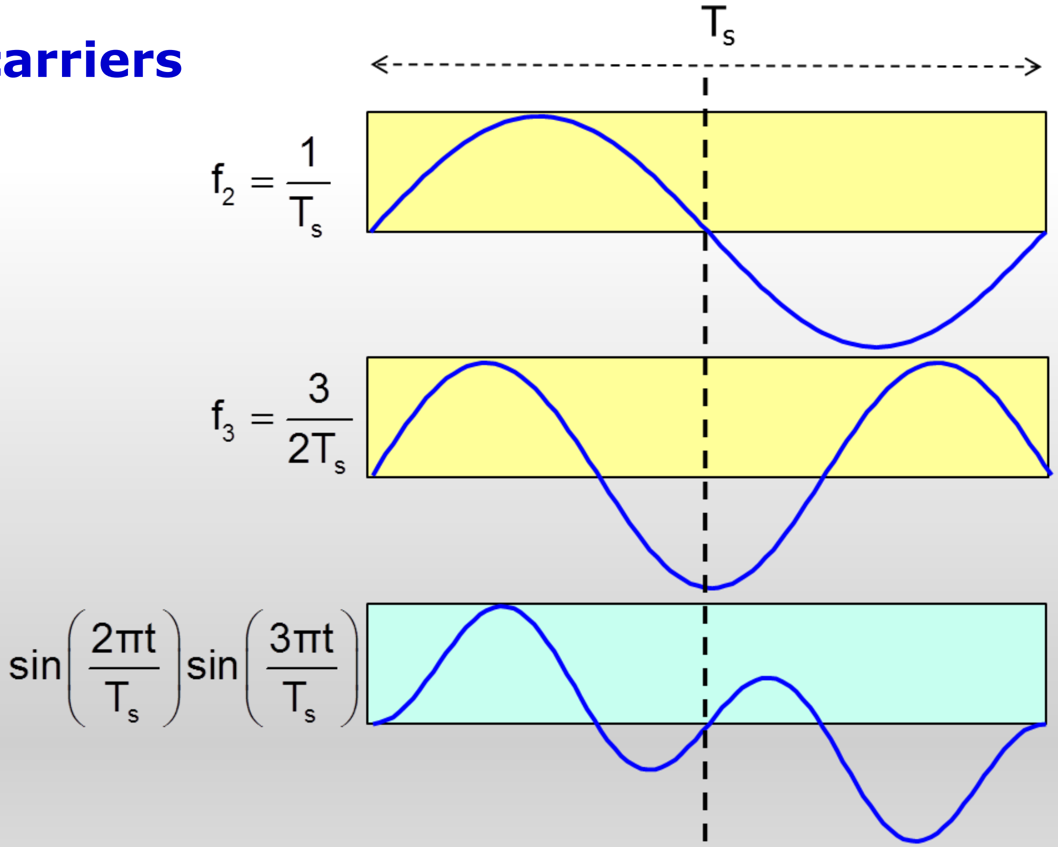

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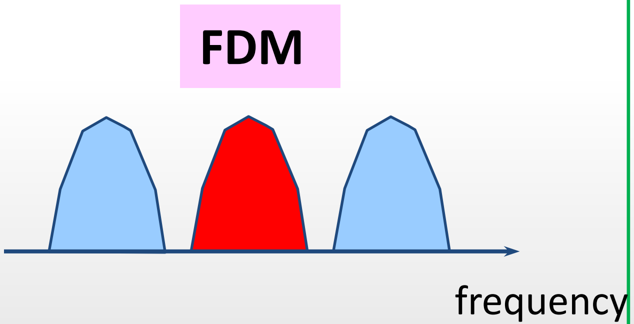
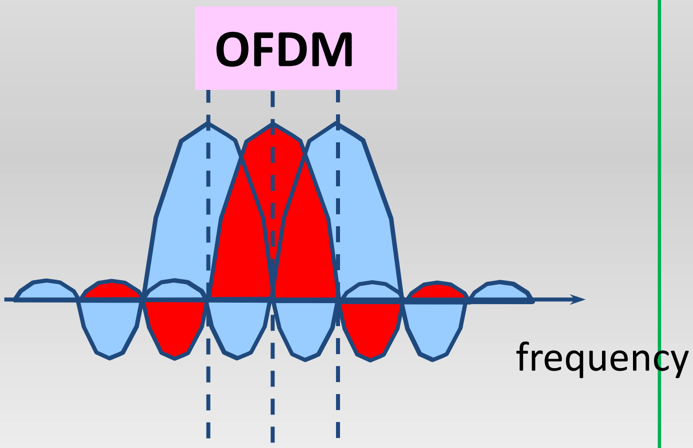
$$\int_0^{T_s} \sin\left(\frac{2\pi t}{T_s}\right)\sin\left(\frac{3\pi t}{T_s}\right)dt = \left[\frac{\sin(\pi t/T_s)}{(\pi t/T_s)} - \frac{\sin(5\pi t/T_s)}{(5\pi t/T_s)}\right]_0^{T_s} = 0$$

MULTICARRIER vs OFDM

- The technique of OFDM is based on the well-known technique of FDM
- FDM technique:
  - Different streams of information are mapped onto separate parallel frequency channels
  - Guard bands are inserted to reduce interference between adjacent channels



- OFDM technique
  - Multiple carriers carry the information stream
  - Carrier spectrum are are overlapped and orthogonal to each other
  - A guard time is added to each symbol to combat the channel delay spread

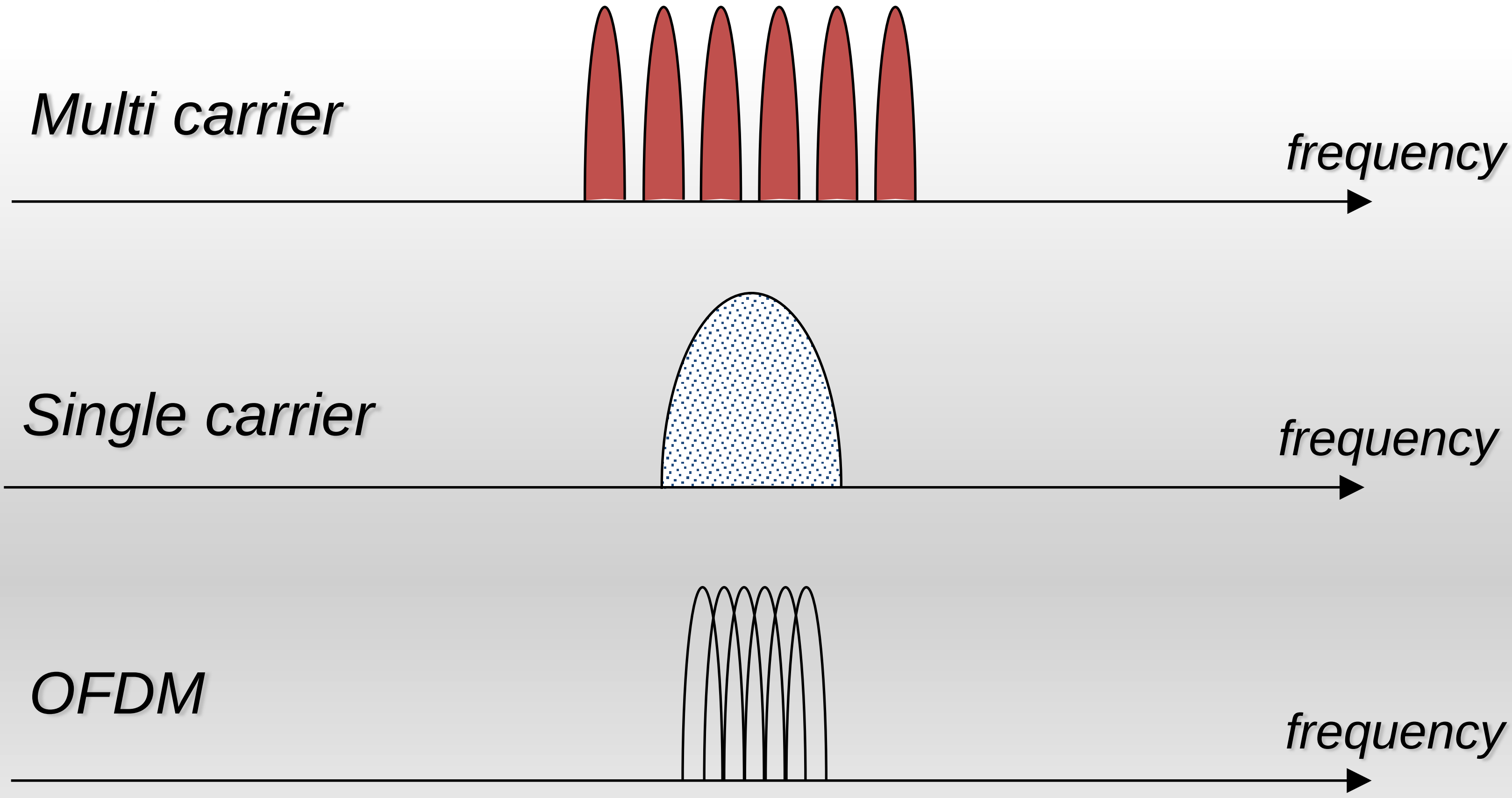


MULTICARRIER vs OFDM

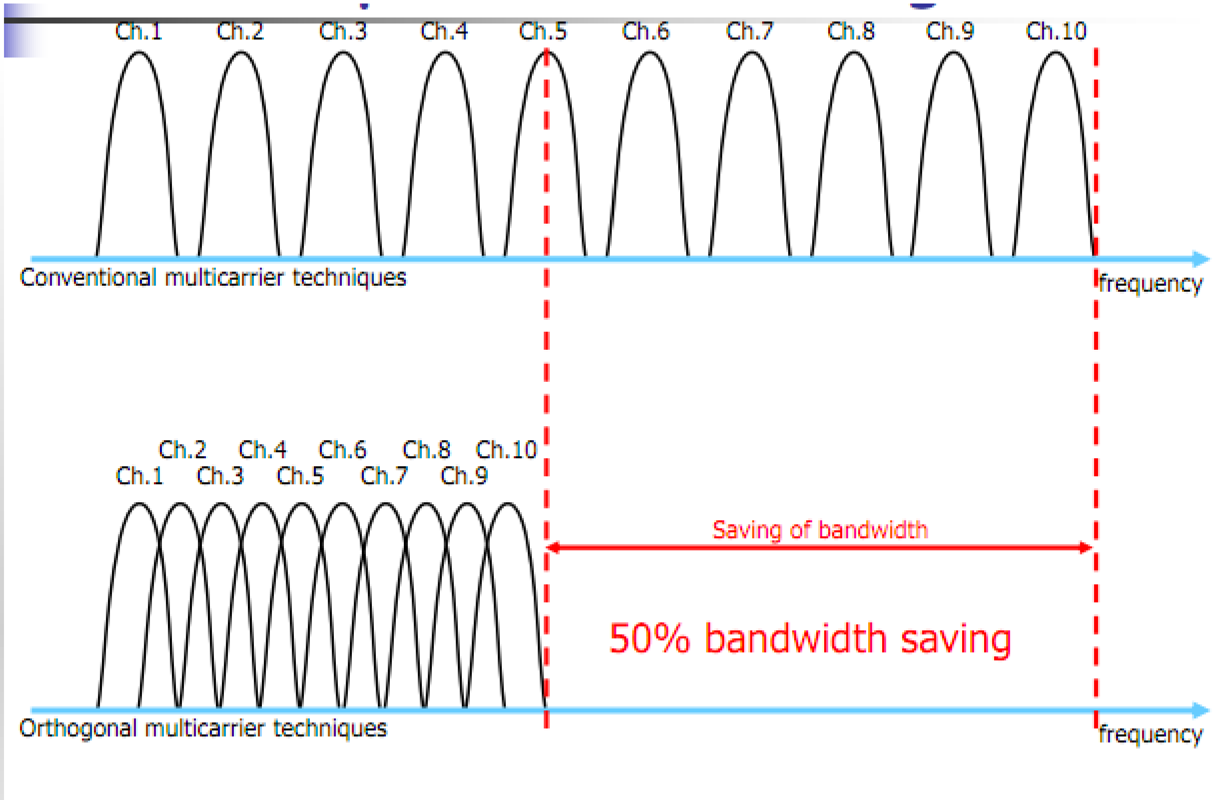
- OFDM is multi carrier modulation
- OFDM sub-carrier spectrum is overlapping
- In FDMA, band-pass filter separates each transmission
- In OFDM, each sub-carrier is separated by DFT because carriers are orthogonal
- Each sub-carrier is modulated by PSK, QAM

Thousands of PSK/QAM symbol can be simultaneously transmitted in one OFDM symbol

MULTICARRIER vs OFDM



MULTICARRIER vs OFDM



For FDM if the system bandwidth is B, number of sub-carriers is given by:

$$N_C = \frac{B}{(1+\alpha)/T_S} = \frac{BT_S}{(1+\alpha)}$$

$$0 \le \alpha \le 1 \Rightarrow \text{Rolloff Factor}$$

For ***OFDM*** if the system bandwidth is B, Number of sub-carriers is given by:

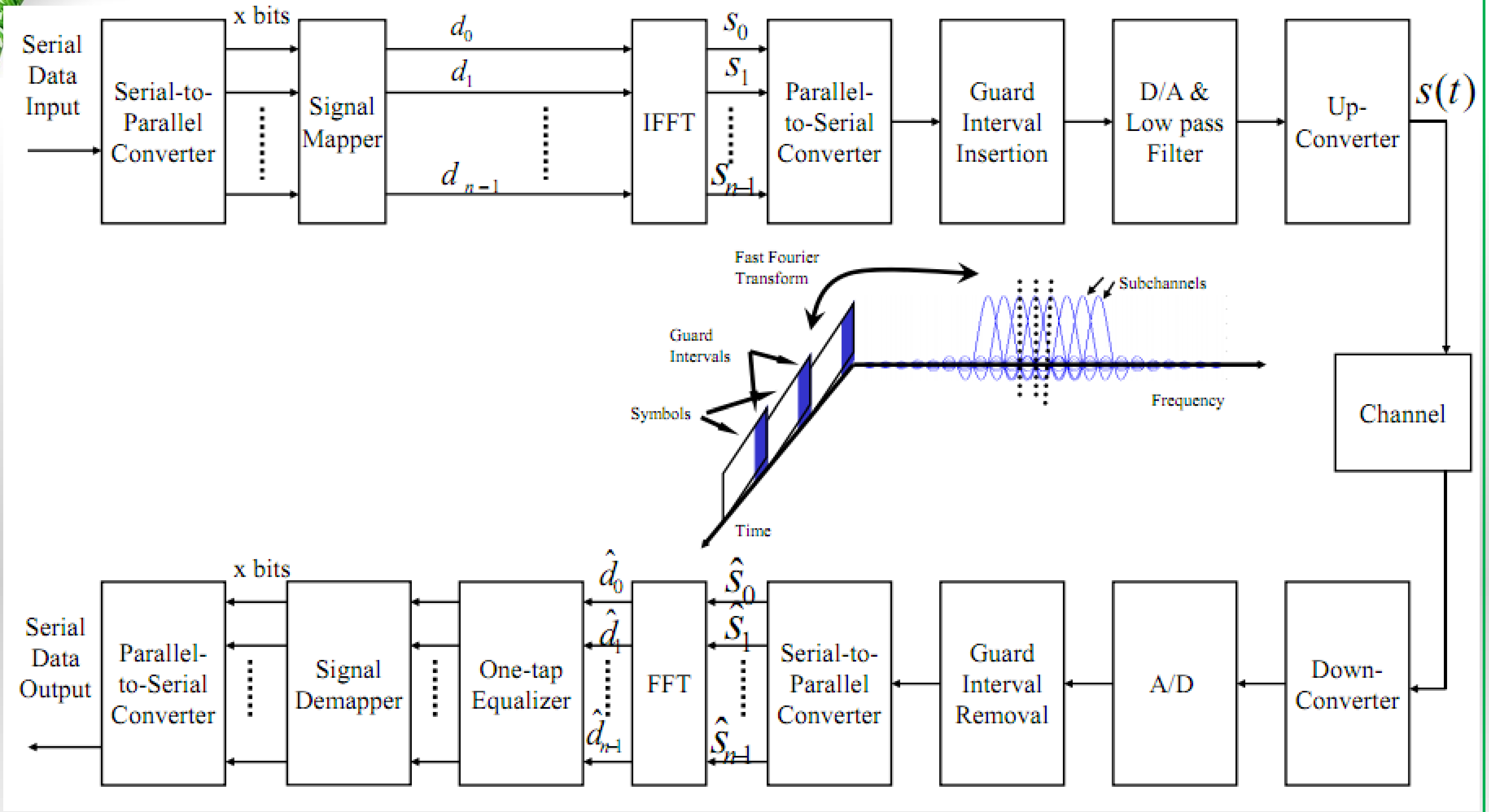
$$N_C = \frac{B}{1/2T_S} = 2BT_S$$

OFDM **has the potential to at least double the number of sub-carriers**
→ double the total transmission rate over the system bandwidth

OFDM

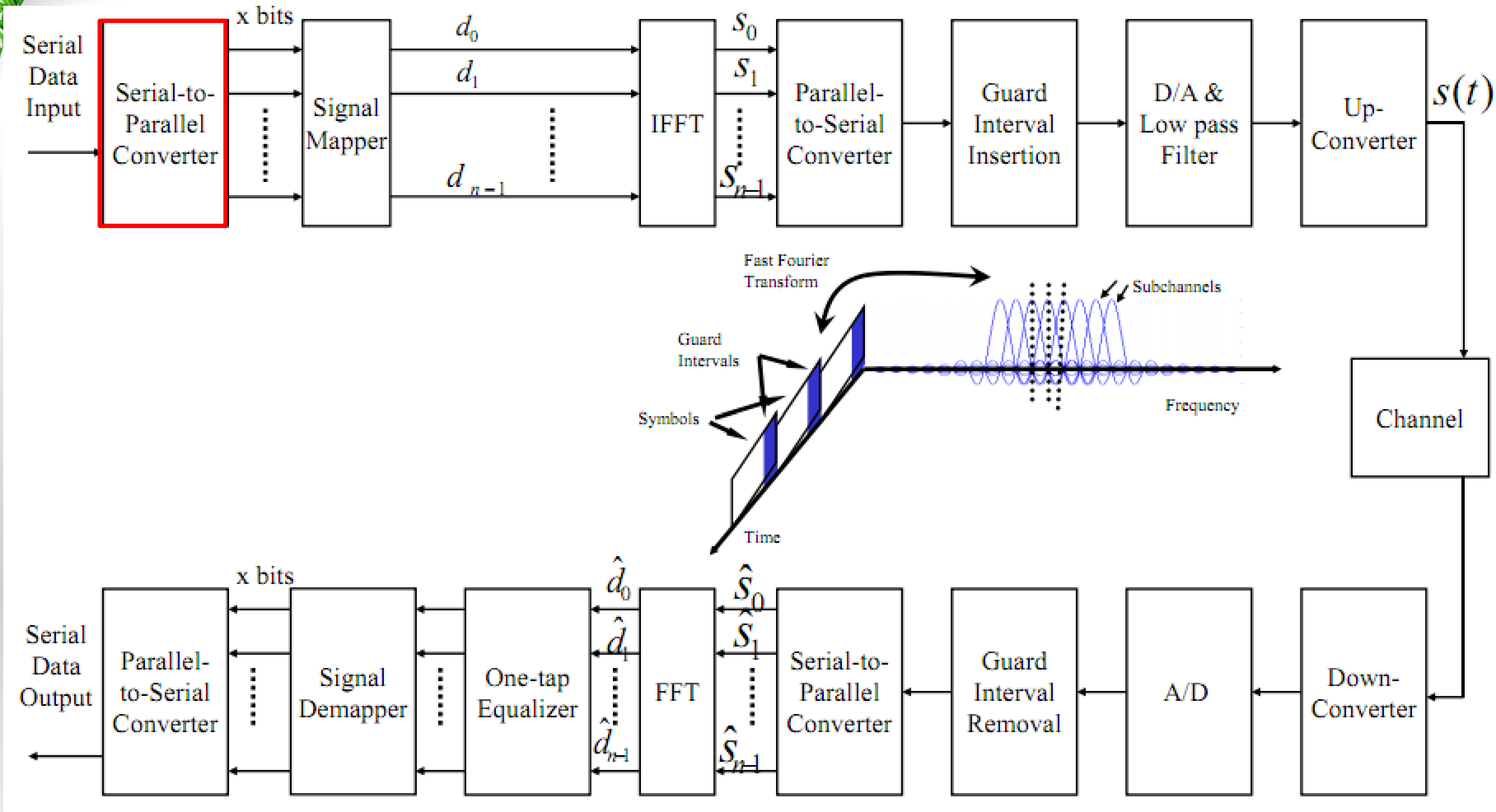
- A type of multi-carrier modulation
- Single high-rate bit stream is converted to low-rate N parallel bit stream
- Each parallel bit stream is modulated on one of N sub-carriers
- Each sub-carrier can be modulated by QFSK or QAM
- Add a guard time to each OFDM symbol to avoid inter-symbol interference of fading channel
- To achieve high bandwidth efficiency, the sub-carriers are closely spaced and overlapped
- Sub-carriers are orthogonal over the symbol time

OFDM SYSTEM



Serial Data Input
Serial-to-Parallel Converter
x bits
Signal Mapper
d_0
d_1
d_{n-1}
IFFT
s_0
s_1
s_{n-1}
Parallel-to-Serial Converter
Guard Interval Insertion
D/A & Low pass Filter
Up-Converter
$s(t)$
Channel
Fast Fourier Transform
Subchannels
Guard Intervals
Symbols
Frequency
Time
Serial Data Output
Parallel-to-Serial Converter
x bits
Signal Demapper
One-tap Equalizer
$\hat{d}_0$
$\hat{d}_1$
$\hat{d}_{n-1}$
FFT
$\hat{s}_0$
$\hat{s}_1$
$\hat{s}_{n-1}$
Serial-to-Parallel Converter
Guard Interval Removal
A/D
Down-Converter

OFDM SYSTEM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$s(t)$
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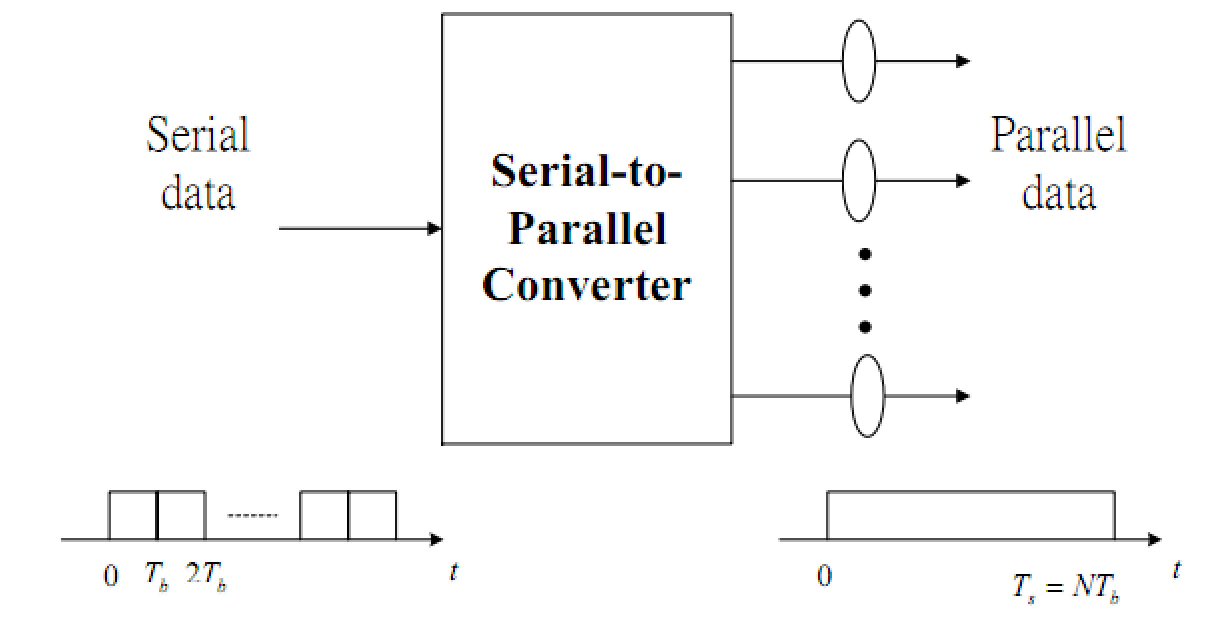
Subchannels
Guard Intervals
Symbols
Frequency
Time
Channel
x bits
$\hat{d}_0$
$\hat{d}_1$
$\hat{d}_{n-1}$
$\hat{s}_0$
$\hat{s}_1$
$\hat{s}_{n-1}$
Serial Data Output
Parallel-to-Serial Converter
Signal Demapper
One-tap Equalizer
FFT
Serial-to-Parallel Converter
Guard Interval Removal
A/D
Down-Converter

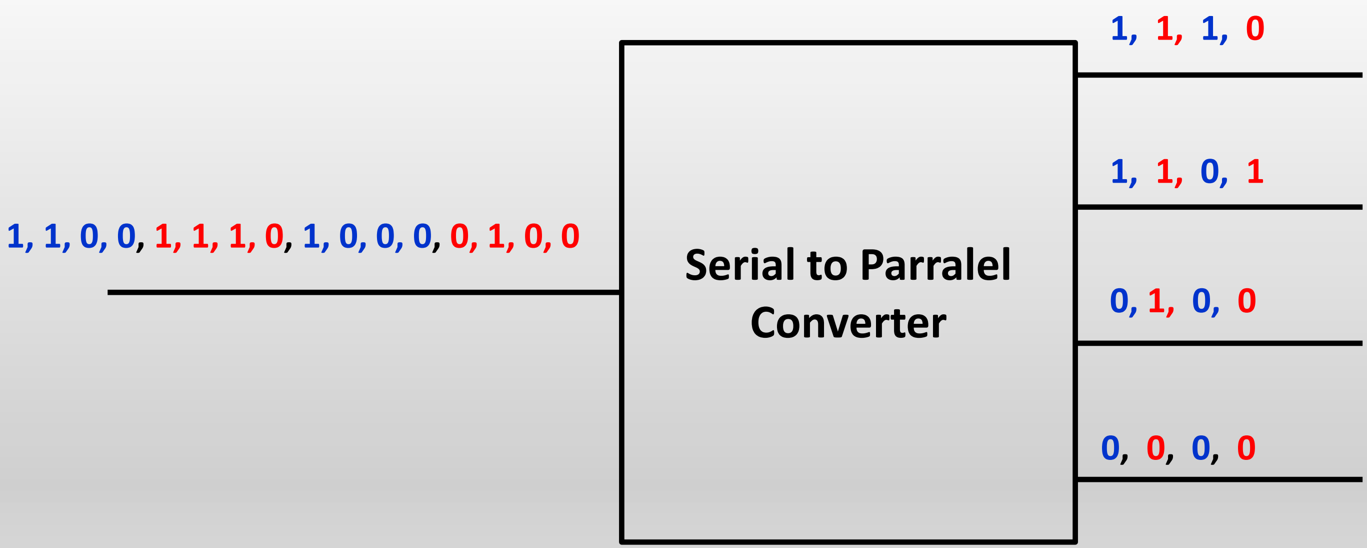
OFDM SYSTEM



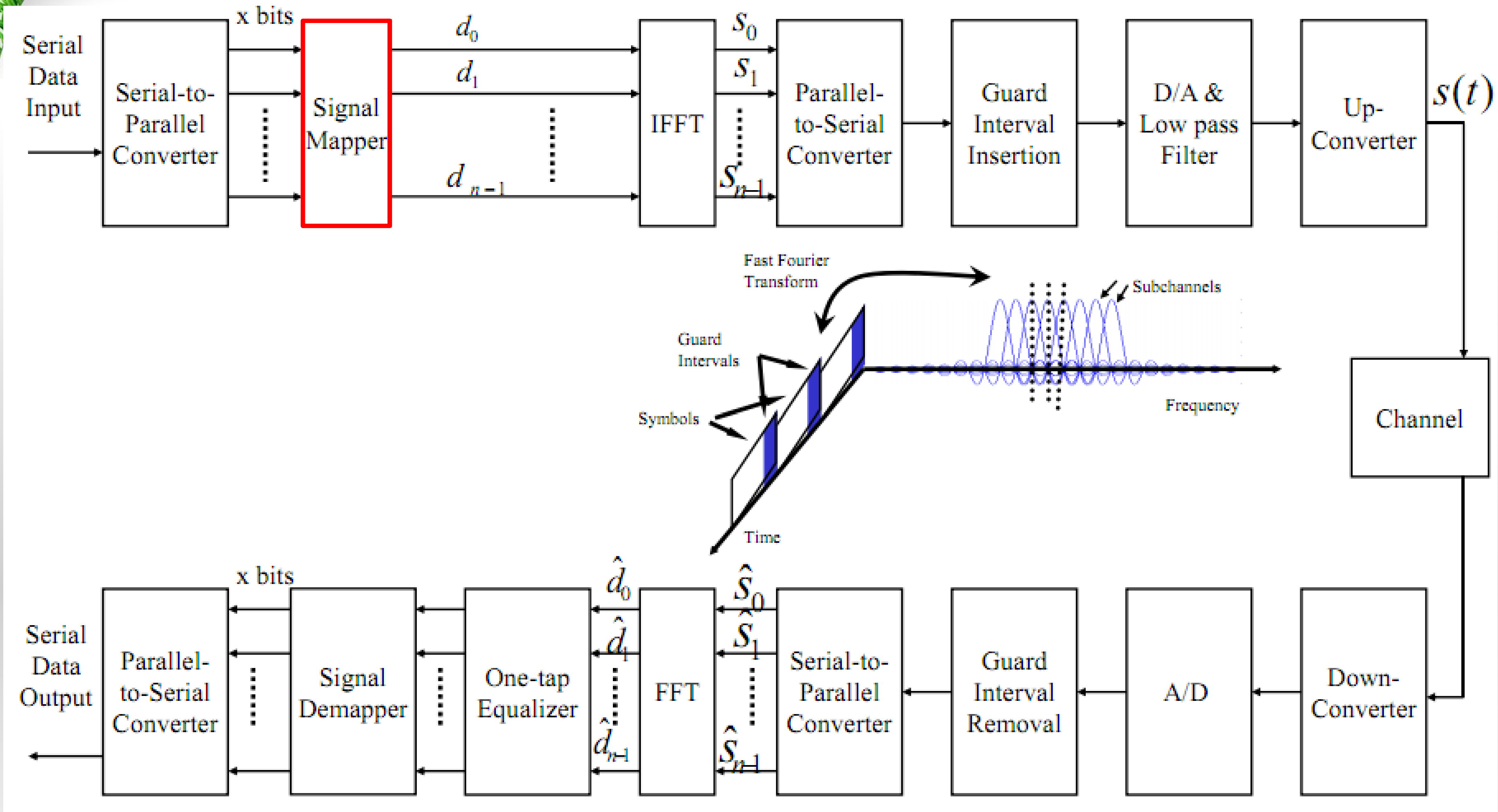
In a conventional serial data system, the symbols are transmitted sequentially, with the frequency spectrum of each data symbol allowed to occupy the entire available bandwidth.

The spectrum of an individual data element normally occupies only a small part of available bandwidth.

OFDM SYSTEM


1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0, 0, 1, 0, 0
Serial to Parralel Converter
1, 1, 1, 0
1, 1, 0, 1
0, 1, 0, 0
0, 0, 0, 0

OFDM SYSTEM


Serial Data Input
Serial-to-Parallel Converter
x bits
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d_0
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Symbols
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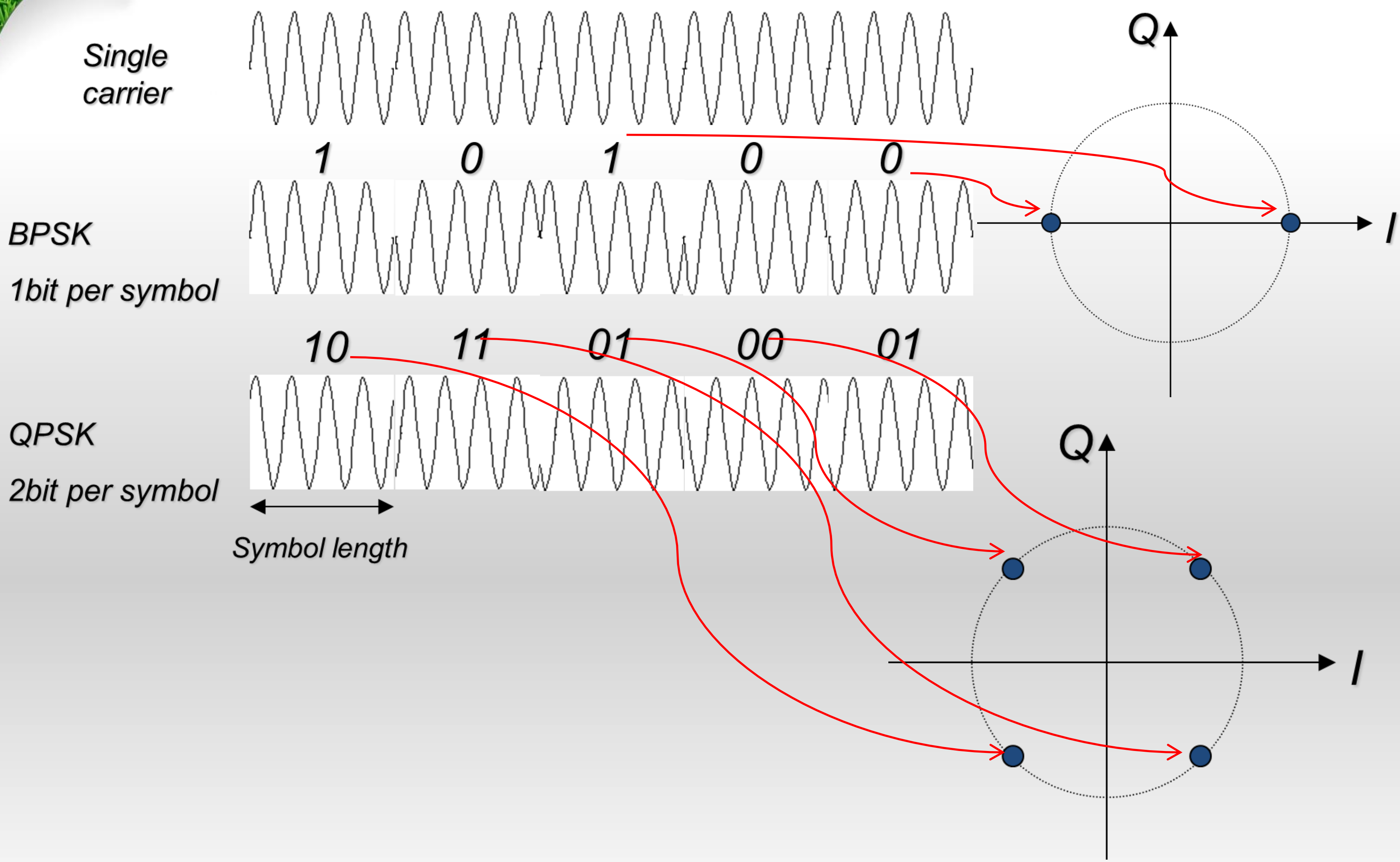
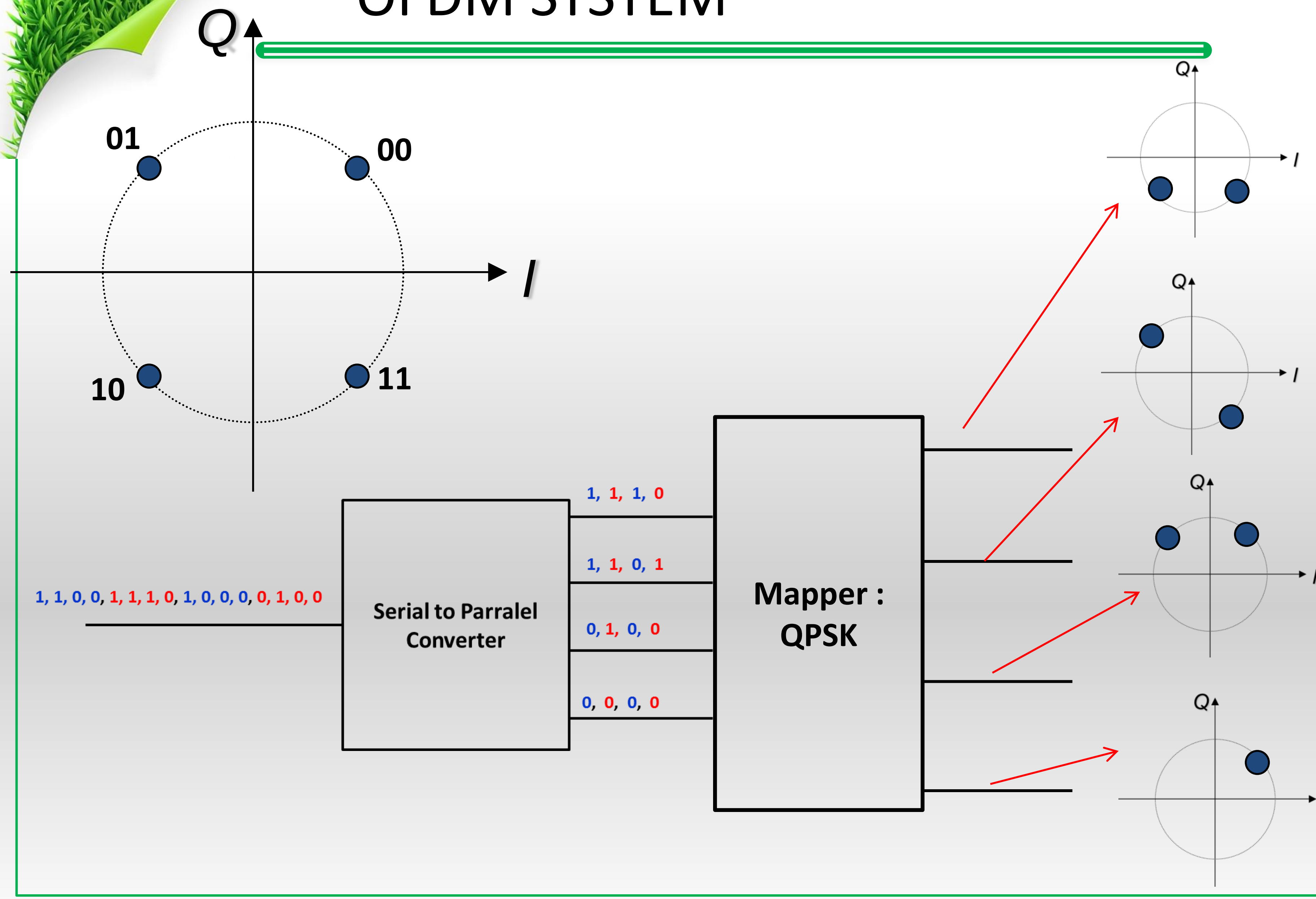
Time
Serial Data Output
Parallel-to-Serial Converter
x bits
Signal Demapper
One-tap Equalizer
$\hat{d}_0$
$\hat{d}_1$
$\hat{d}_{n-1}$
FFT
$\hat{S}_0$
$\hat{S}_1$
$\hat{S}_{n-1}$
Serial-to-Parallel Converter
Guard Interval Removal
A/D
Down-Converter

OFDM SYSTEM

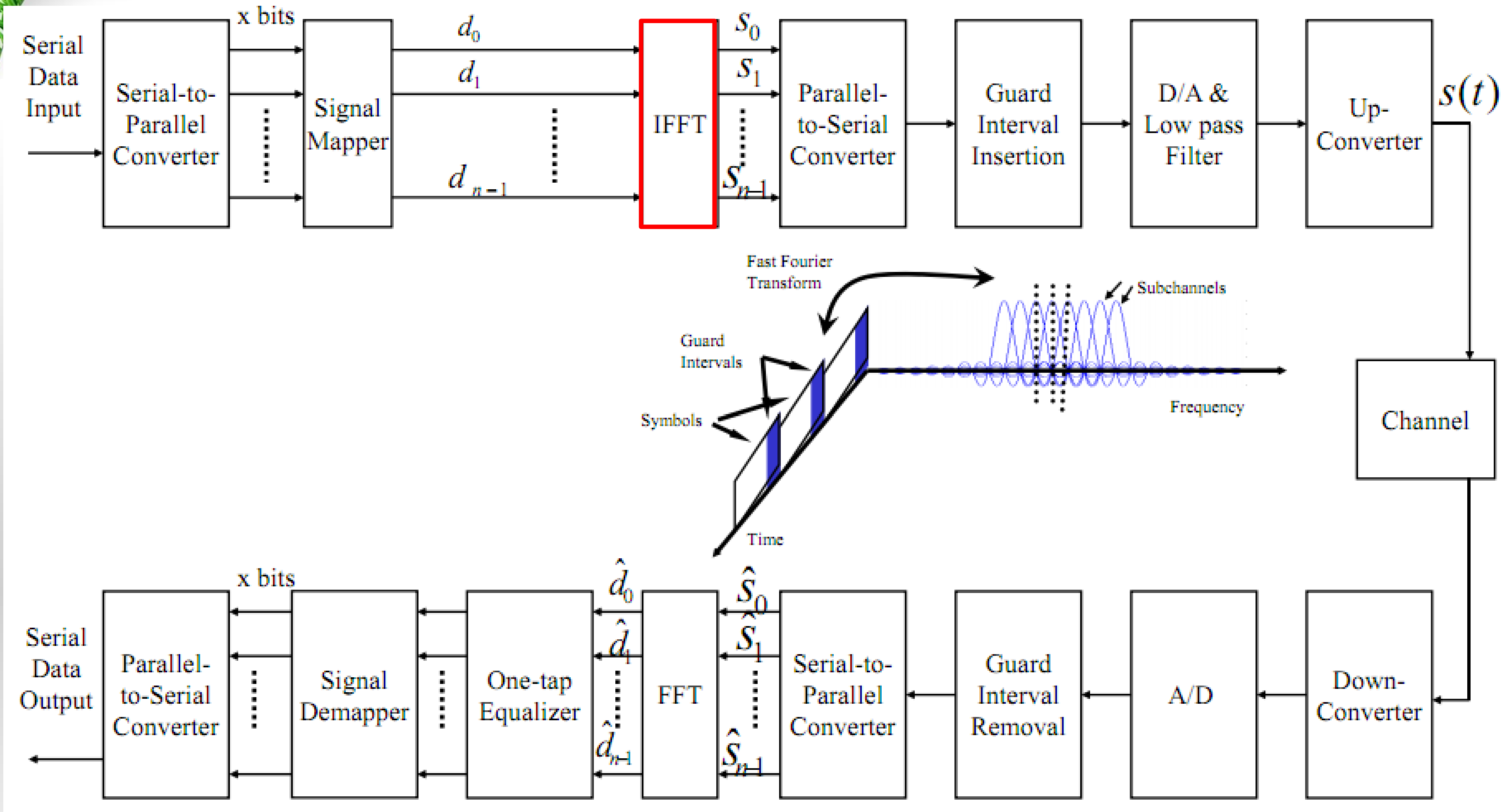


Single carrier
1 0 1 0 0
BPSK
1bit per symbol
10 11 01 00 01
QPSK
2bit per symbol
Symbol length
Q
I
Q
I

OFDM SYSTEM


Q
I
01
00
10
11
1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0, 0, 1, 0, 0
Serial to Parralel Converter
1, 1, 1, 0
1, 1, 0, 1
0, 1, 0, 0
0, 0, 0, 0
Mapper : QPSK

OFDM SYSTEM



Serial Data Input
Serial-to-Parallel Converter
x bits
Signal Mapper
d_0
d_1
d_{n-1}
IFFT
s_0
s_1
s_{n-1}
Parallel-to-Serial Converter
Guard Interval Insertion
D/A & Low pass Filter
Up-Converter
$s(t)$
Fast Fourier Transform
Subchannels
Guard Intervals
Symbols
Frequency
Time
Channel
Serial Data Output
Parallel-to-Serial Converter
x bits
Signal Demapper
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$\hat{d}_0$
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FFT
$\hat{s}_0$
$\hat{s}_1$
$\hat{s}_{n-1}$
Serial-to-Parallel Converter
Guard Interval Removal
A/D
Down-Converter

OFDM SYSTEM

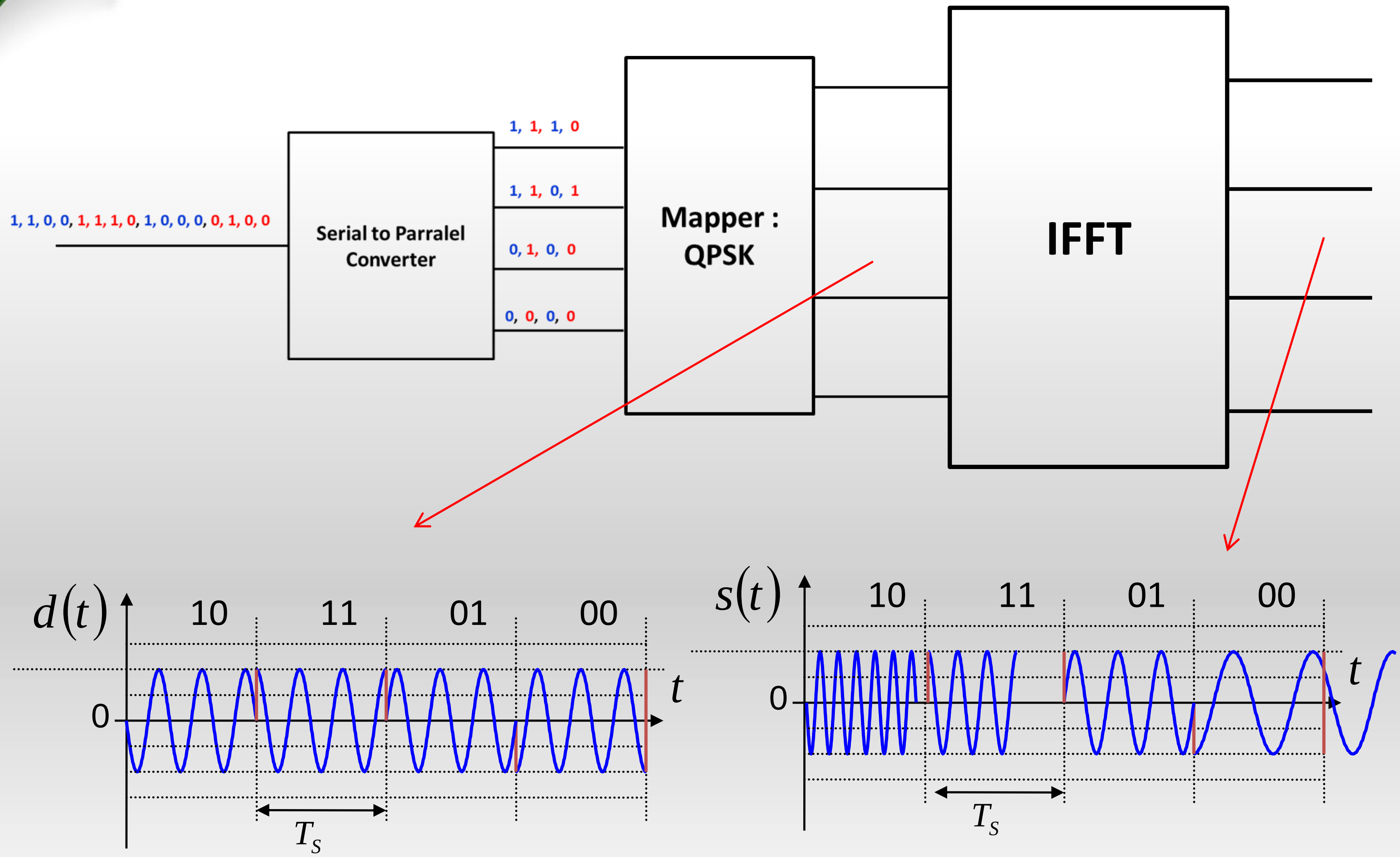
- Inverse DFT and DFT are critical in the implementation of an OFDM system.

$$IDFT \ x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j\frac{2\pi}{N}kn}$$

$$DFT \ X[k] = \sum_{n=0}^{N-1} x[n]e^{-j\frac{2\pi}{N}kn}$$

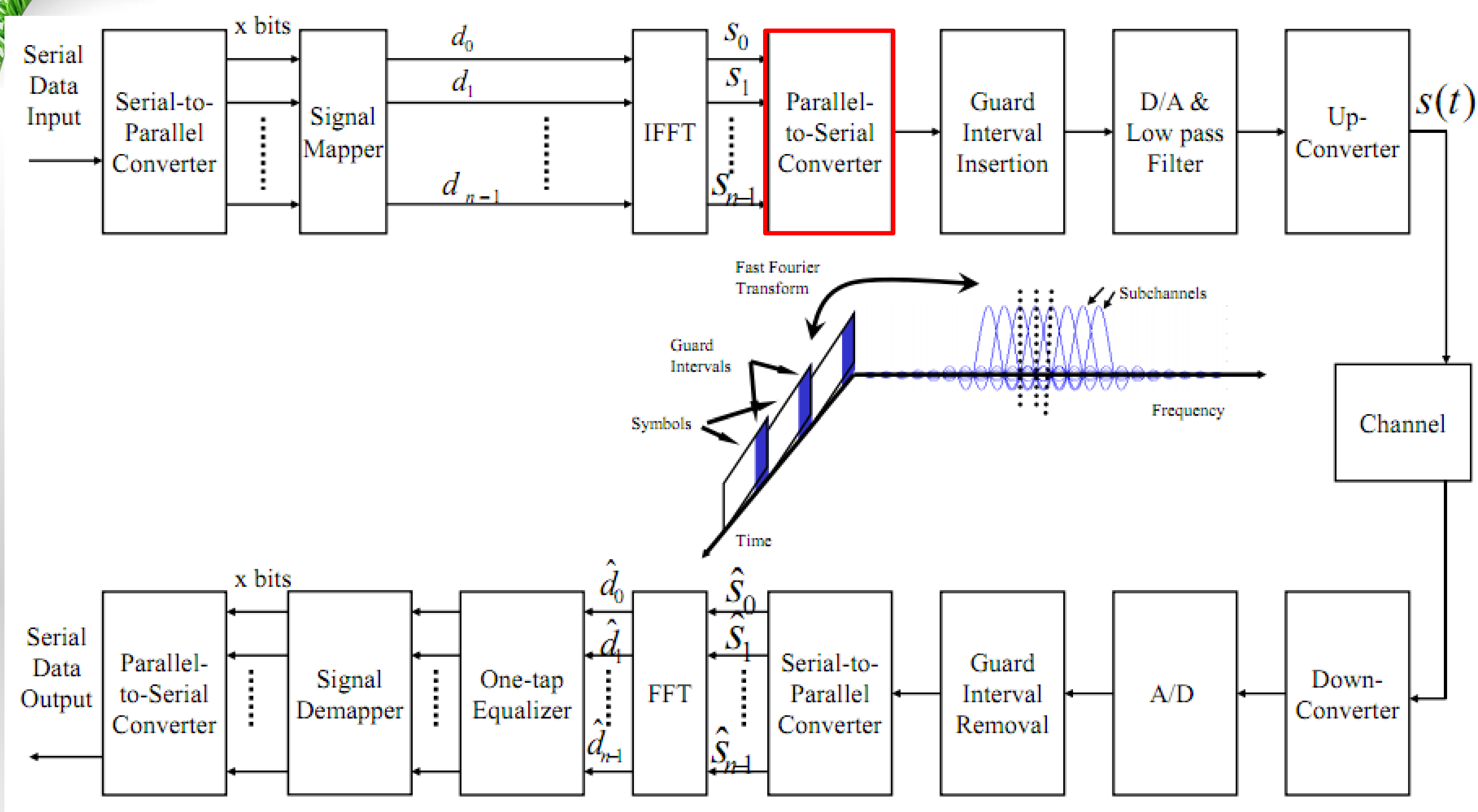
- IDFT and DFT was implemented using **IFFT and FFT algorithms**

OFDM SYSTEM



1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0, 0, 1, 0, 0
Serial to Parralel Converter
1, 1, 1, 0
1, 1, 0, 1
0, 1, 0, 0
0, 0, 0, 0
Mapper : QPSK
IFFT
d(t)
10
11
01
00
0
t
T_S
s(t)
10
11
01
00
0
t
T_S

OFDM SYSTEM


Serial Data Input
Serial-to-Parallel Converter
x bits
Signal Mapper
d_0
d_1
d_{n-1}
IFFT
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S_{n-1}
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$\hat{S}_{n-1}$
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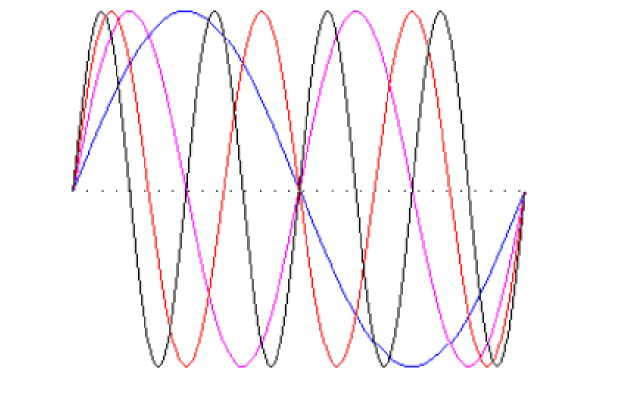
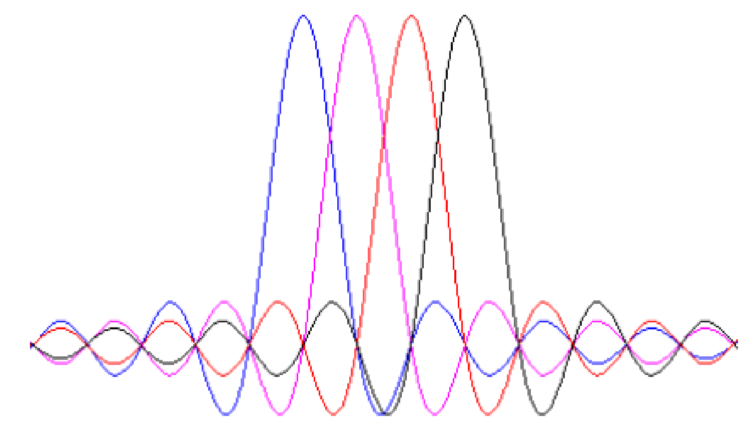
OFDM SYSTEM

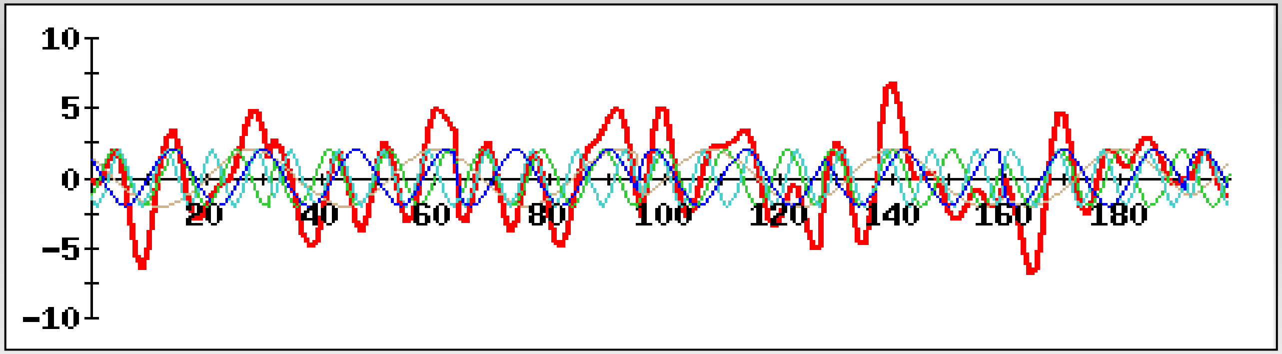
Time domain OFDM Signal



Example of four subcarriers within one OFDM symbol

Frequency domain OFDM Signal

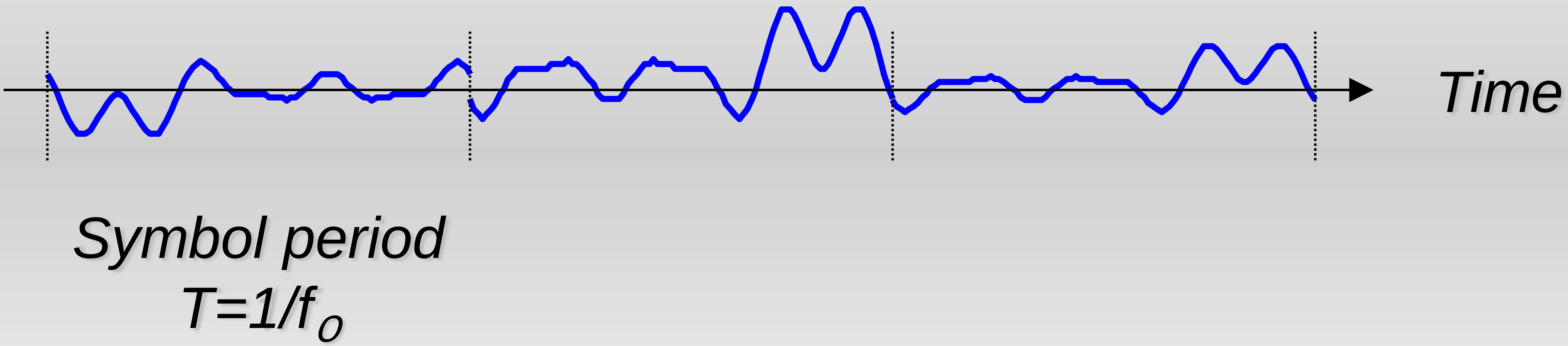




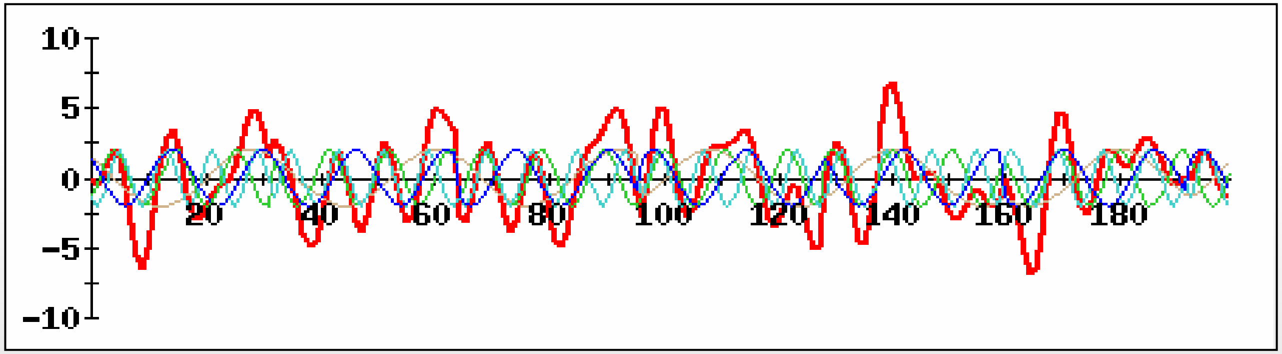
OFDM SYSTEM

Time domain OFDM Signal

- Each symbol carries information
- Each symbol wave is sum of many sinusoidal
- Each sinusoidal wave can be PSK, QAM modulated



OFDM SYSTEM- PAPR



- Dynamic range at output of IFFT is much larger than at input (The large amplitude variation)
- Large Amplitude variation causes **Peak to average power ratio (PAPR)**

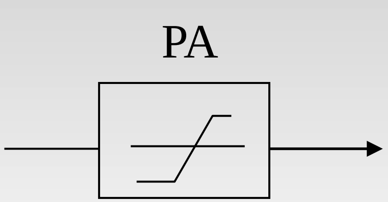
$$PAPR = \frac{|x(t)|^2}{P_{avg}}$$

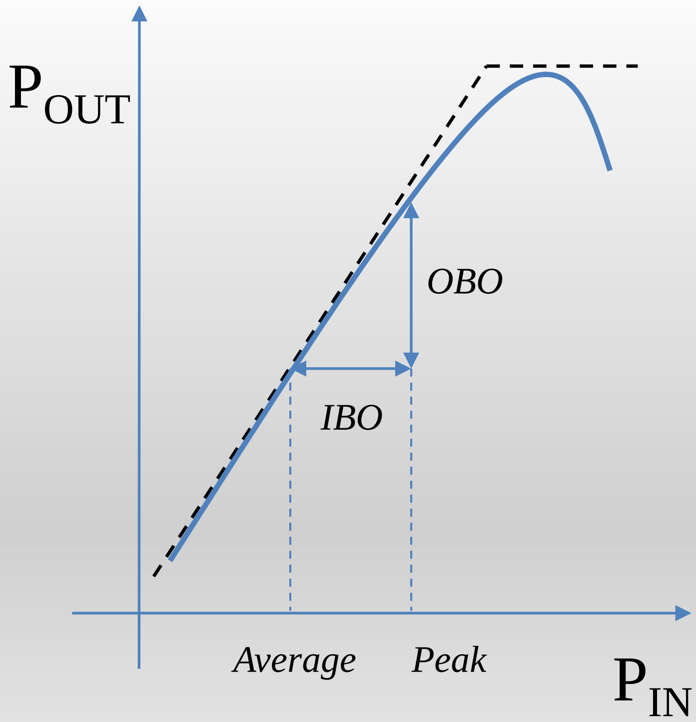
- The large amplitude variation increases in-band noise and increases the BER when the signal has to go through **amplifier nonlinearities.**

OFDM SYSTEM- PAPR

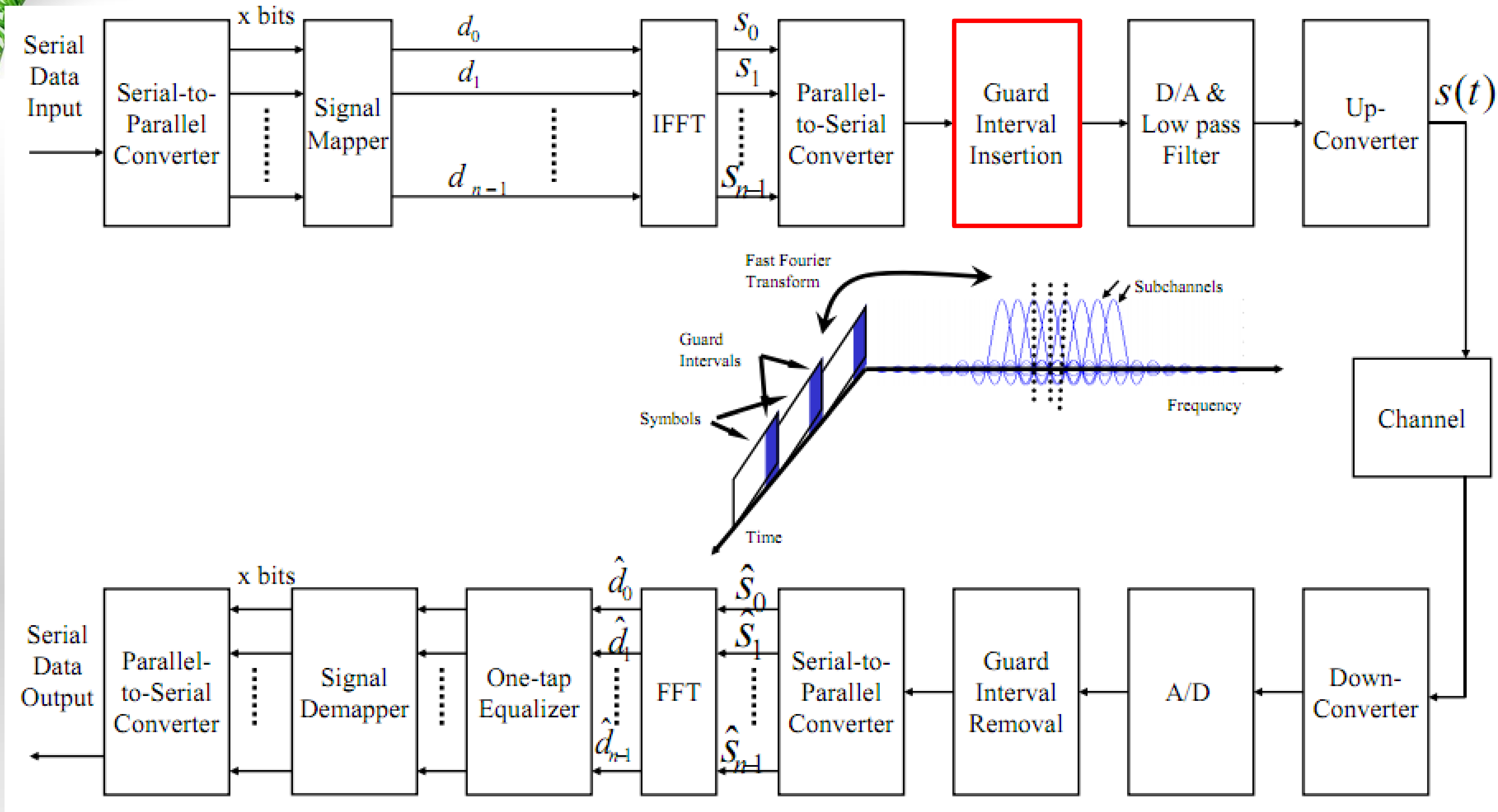
PAPR Problem

- High efficiency power amplifiers are desirable
  - For the handset, long battery life
  - For the base station, reduced operating costs
- A large PAPR is negative for the power amplifier efficiency
- Non-linearity results in inter-modulation
  - Degrades BER performance
  - Out-of-band radiation





OFDM SYSTEM



Serial Data Input
Serial-to-Parallel Converter
x bits
Signal Mapper
d_0
d_1
d_{n-1}
IFFT
s_0
s_1
s_{n-1}
Parallel-to-Serial Converter
Guard Interval Insertion
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OFDM SYSTEM

Two different sources of interference can be identified in the OFDM system.

1. **Intersymbol interference (ISI)** is defined as the crosstalk between signals within the same sub-channel of consecutive FFT frames, which are separated in time by the signaling interval T.

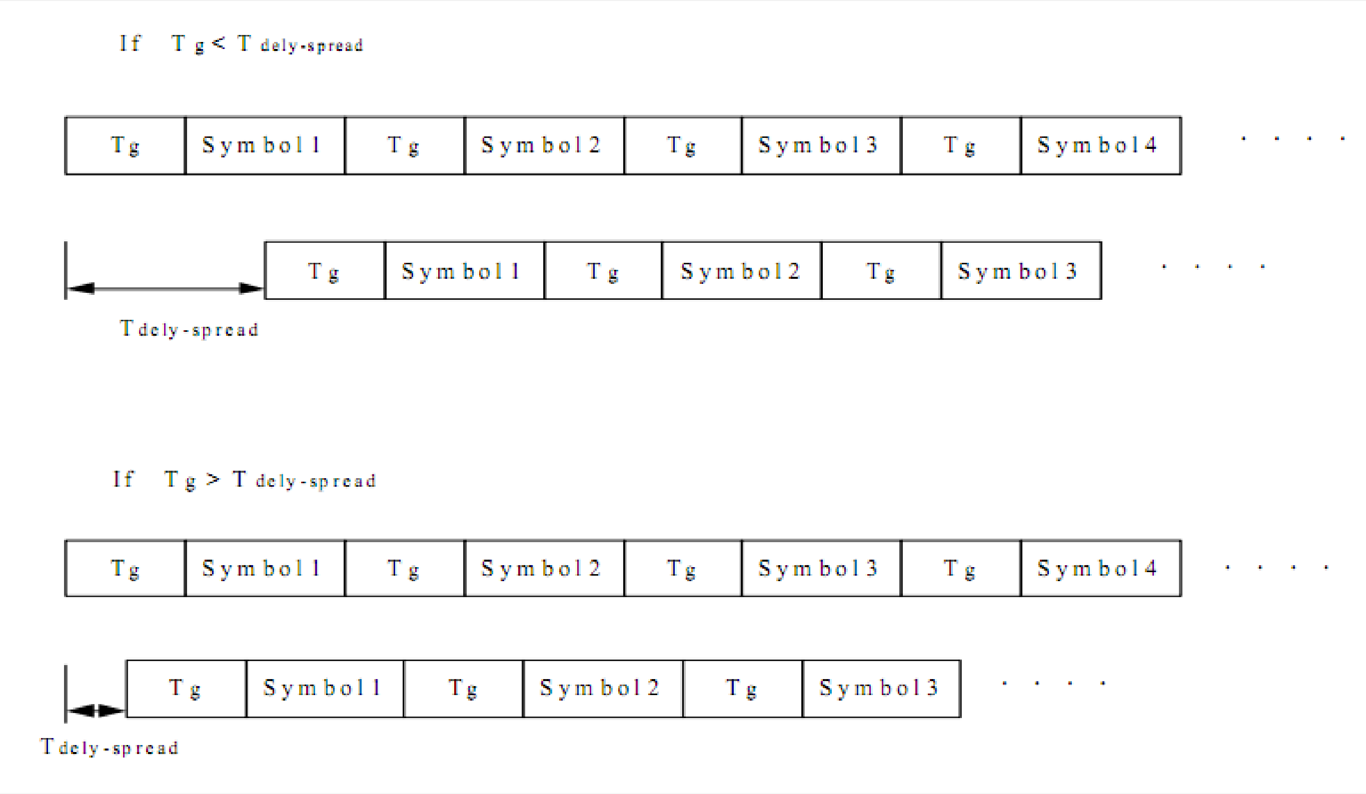
    ⟶ Eliminate using **GUARD INTERVAL TIME** (consist of no signals)

2. **Inter carrier interference (ICI)** is the crosstalk between adjacent subchannels or frequency bands of the same FFT frame.

    ⟶ Eliminate using **CYCLIC PREFIC**

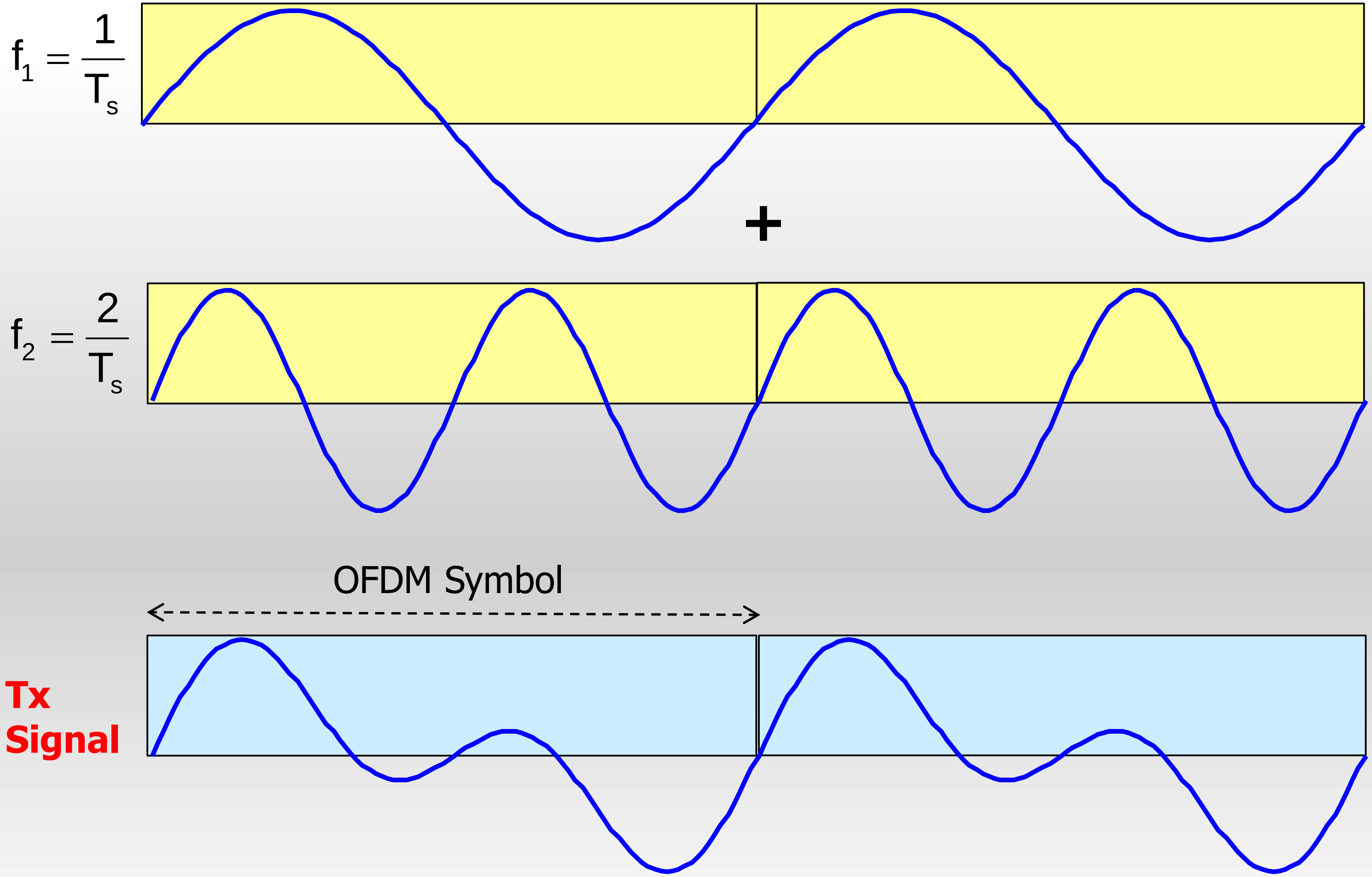
OFDM SYSTEM

- For the purpose to eliminate the effect of ISI, the guard interval could consist of no signals at all need to be added
- Guard interval is used must Tg > T delay Spread



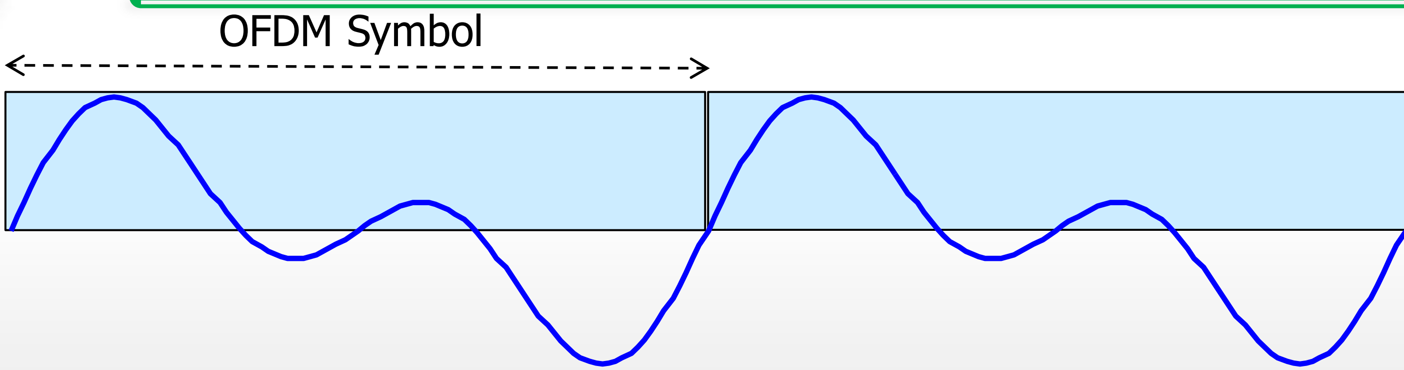
OFDM SYSTEM

Assume ***OFDM*** over two subcarriers: $f_1=1/T_s$, $f_2=2/T_s$

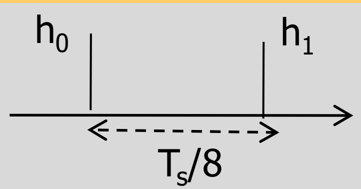


OFDM SYSTEM

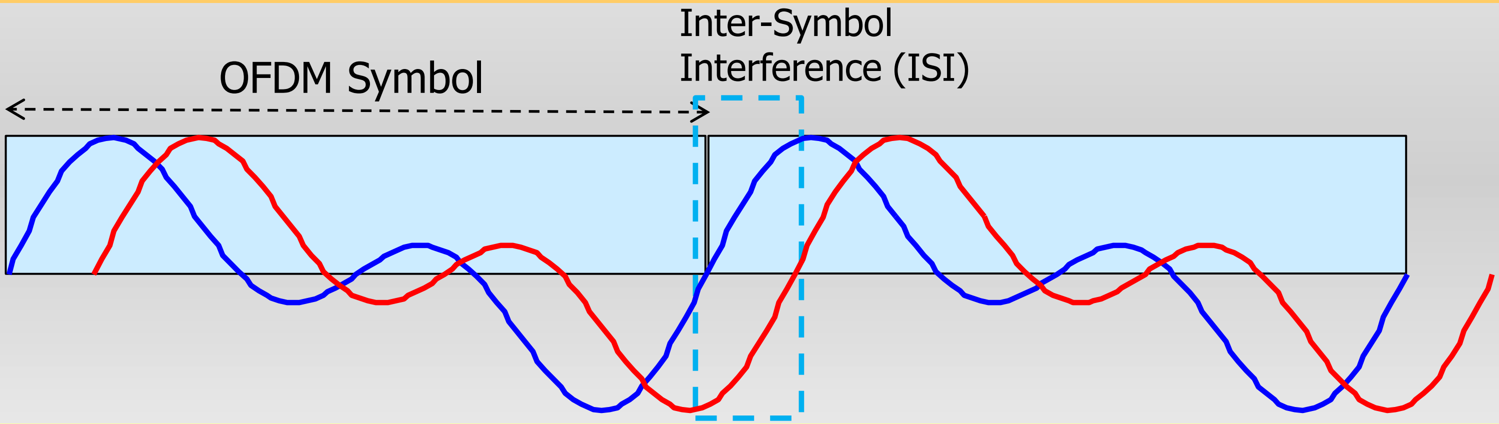
Tx Signal



Suppose multi-path channel with delay $T_s/8$

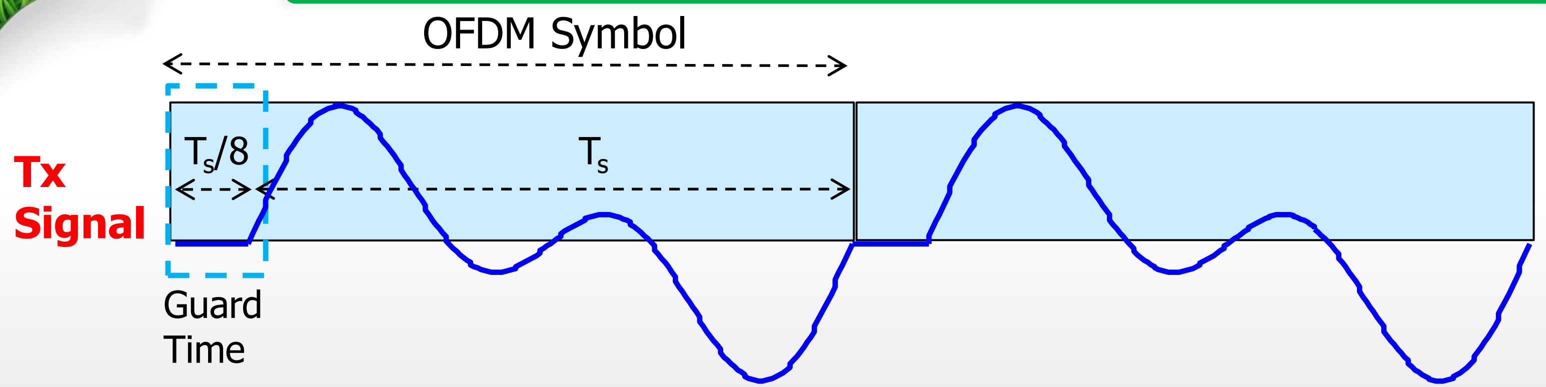


Rx Signal



Inter-symbol interference (ISI) occurs when one OFDM symbol affects the next one due to the multi-path channel

OFDM SYSTEM



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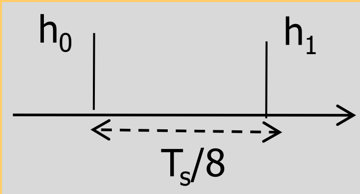
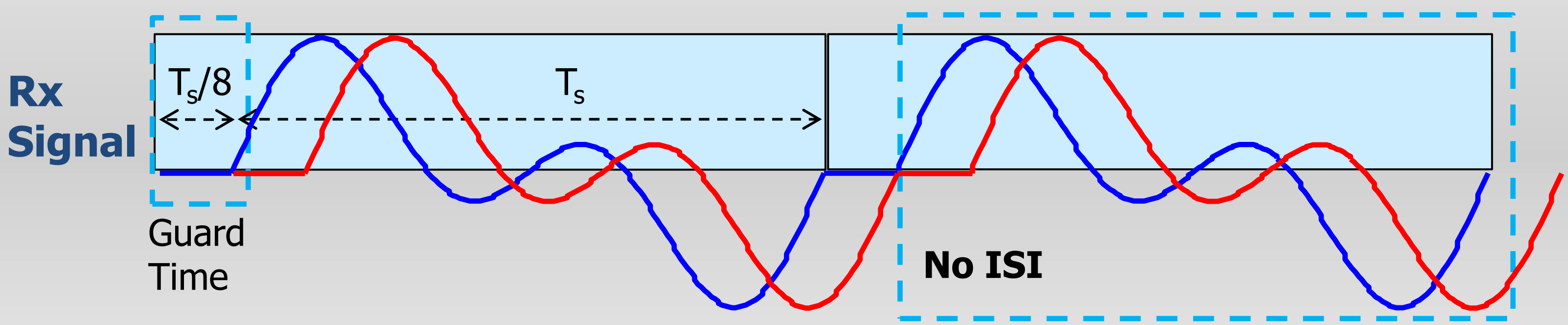
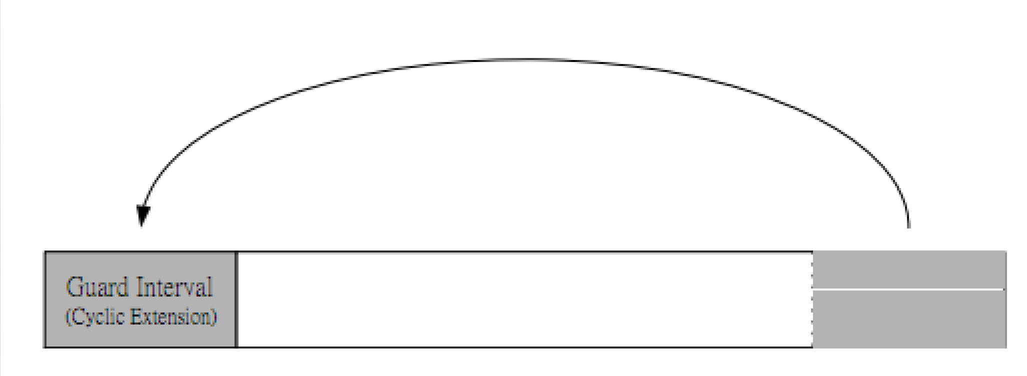




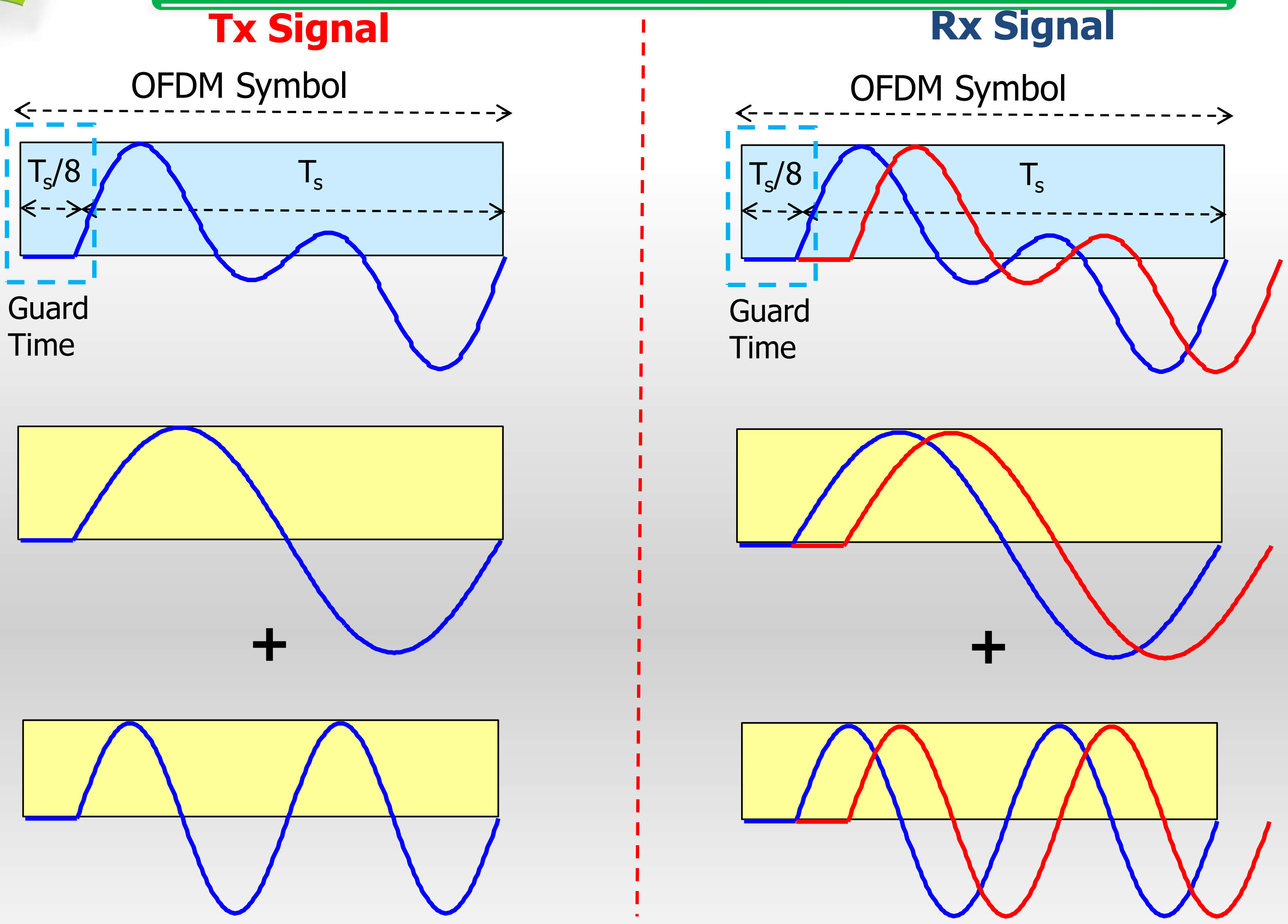
- Guard Time eliminates ISI between neighboring OFDM symbols
- However each OFDM symbol suffers from ***inter-carrier interference (ICI)***
- Guard time corresponds to a reduction of bit rate

OFDM SYSTEM

- To eliminate ICI, the OFDM symbol is **cyclically** extended in the guard interval.
- This ensures that delayed replicas of the OFDM symbol always have an integer number of cycles within the FFT interval, as long as the delay is smaller than the guard interval.

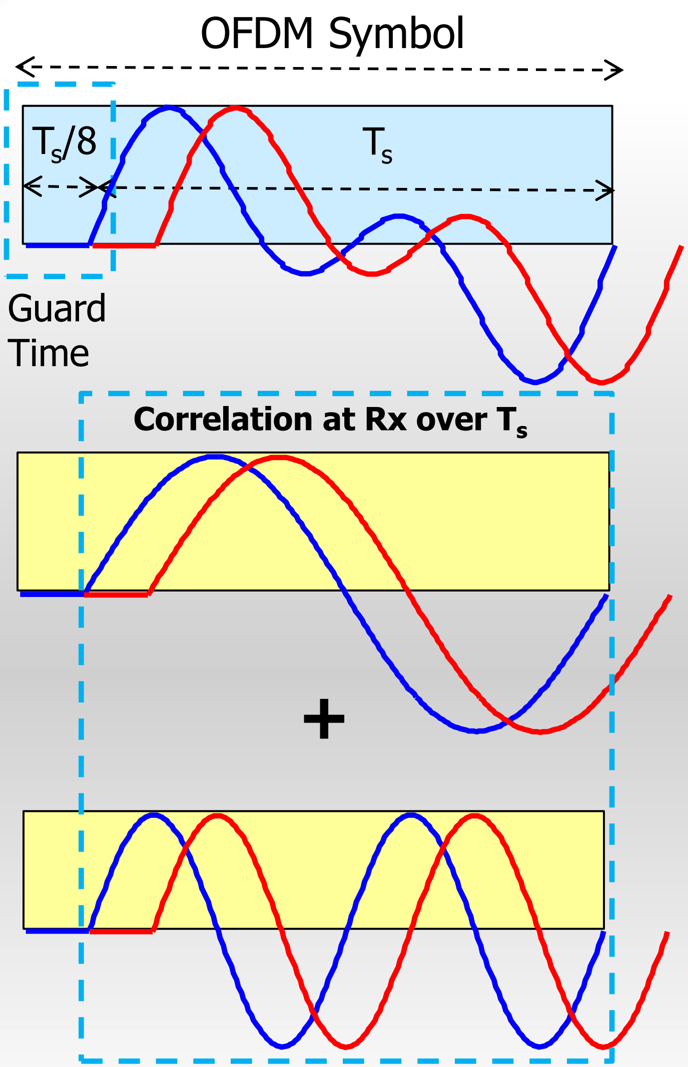


OFDM SYSTEM

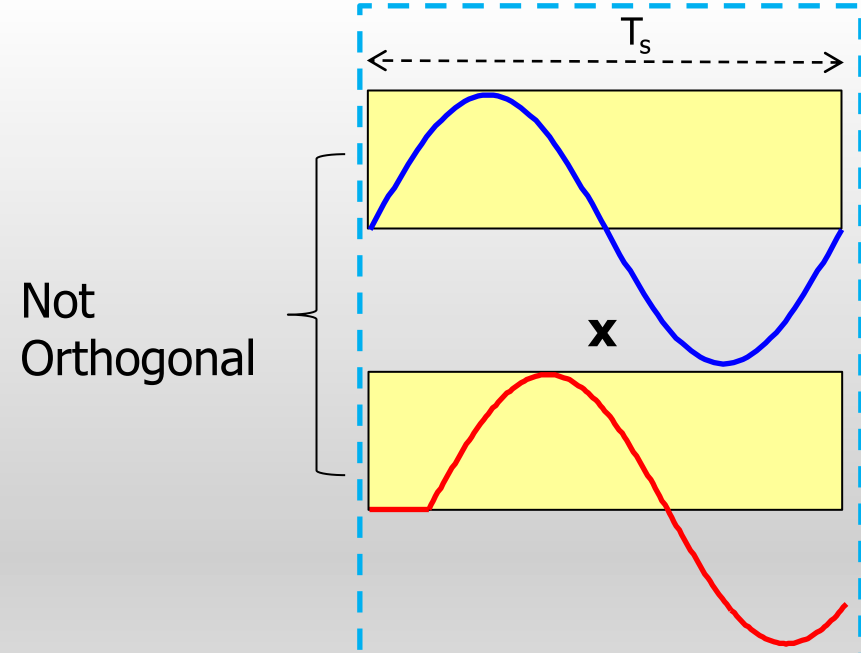

Tx Signal
Rx Signal
OFDM Symbol
$T_s/8$
T_s
Guard Time
OFDM Symbol
$T_s/8$
T_s
Guard Time
+
+

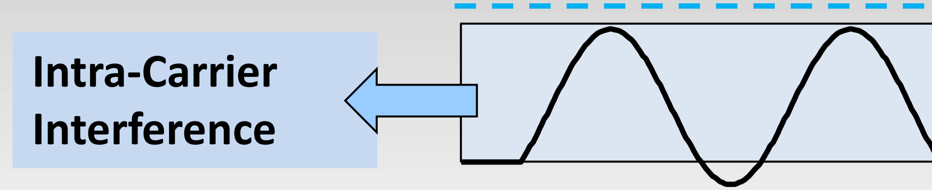
OFDM SYSTEM

Rx Signal

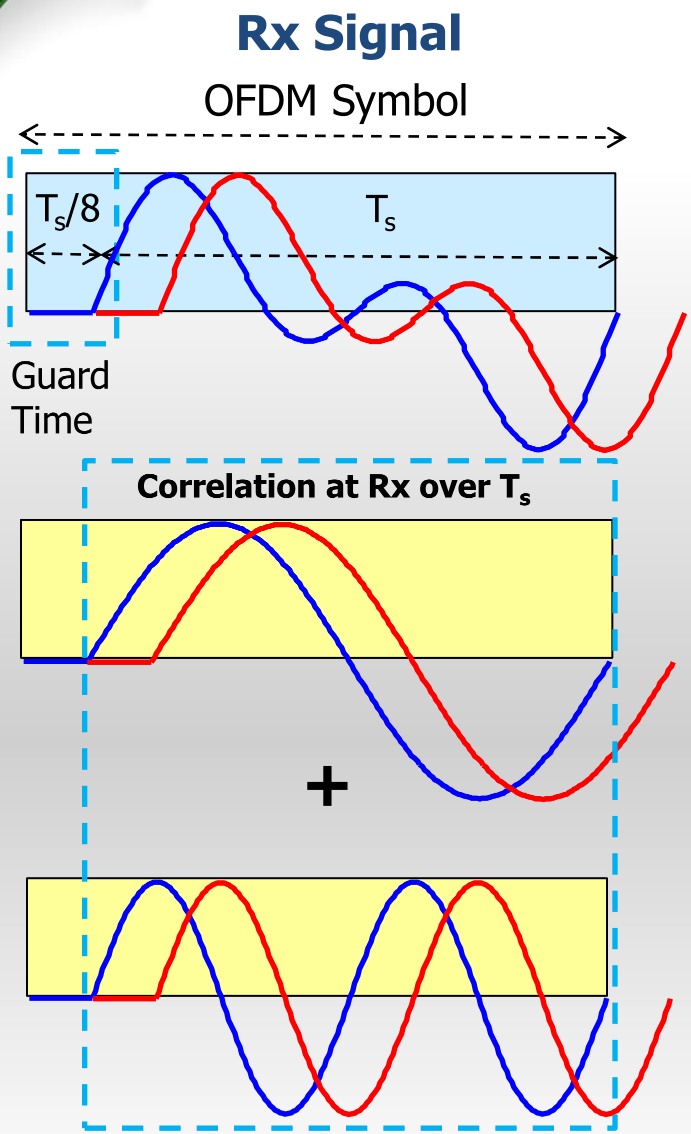


Consider the receiver for $f_1=1/T_s$ that correlates over T_s with $\sin(2\pi t/T_s)$





OFDM SYSTEM



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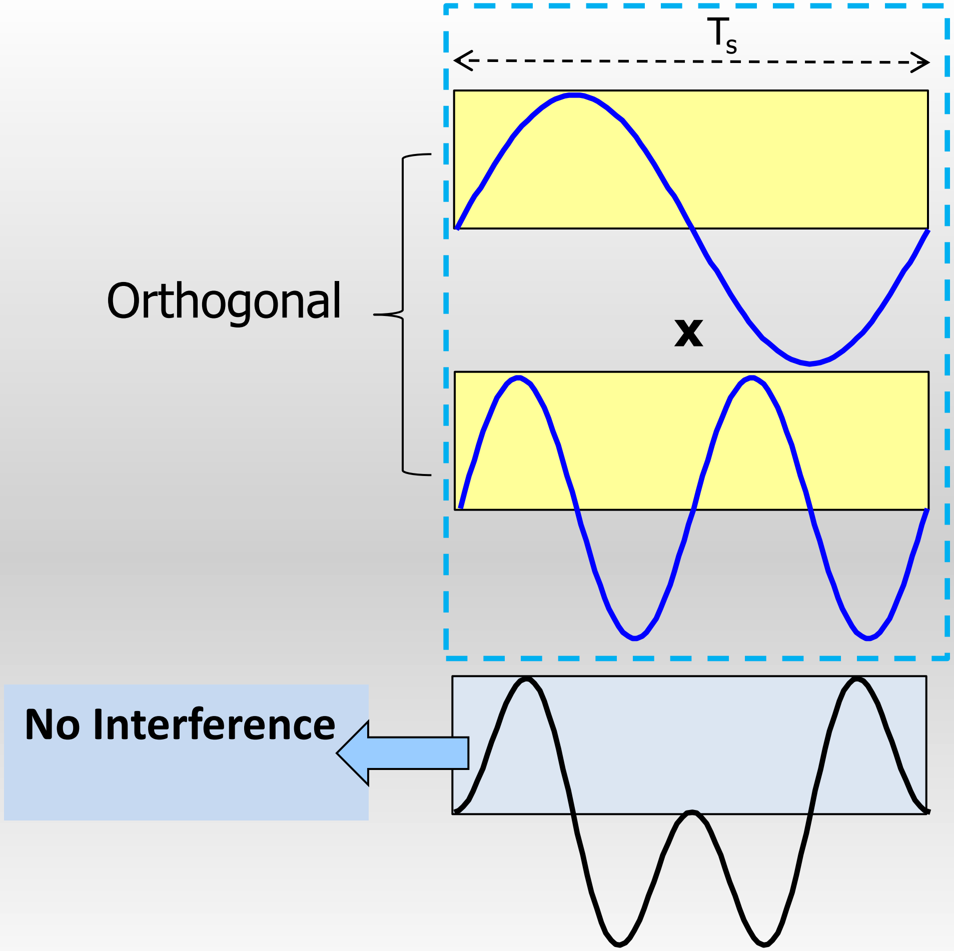
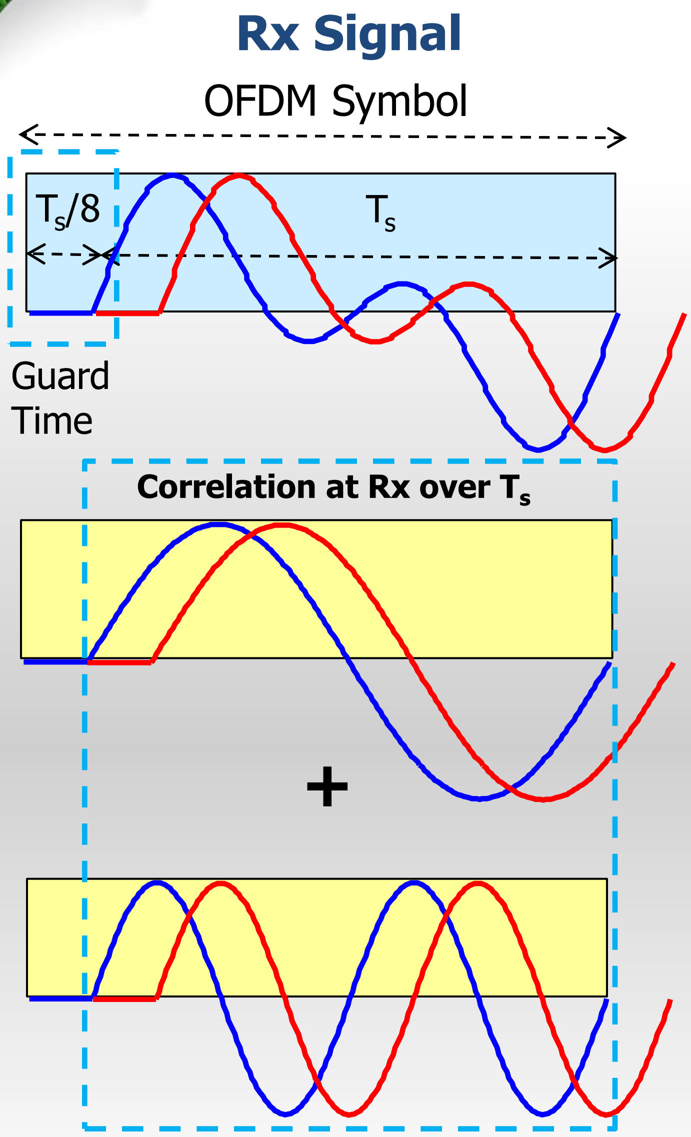


OFDM SYSTEM



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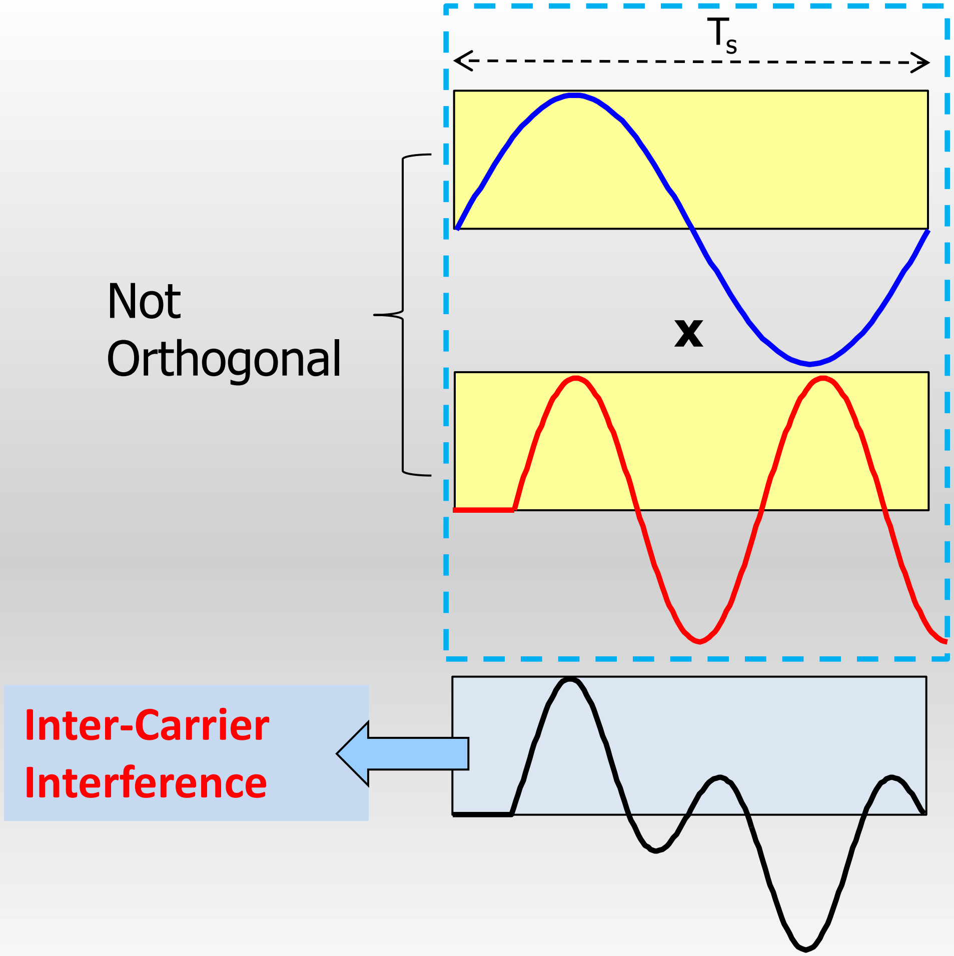
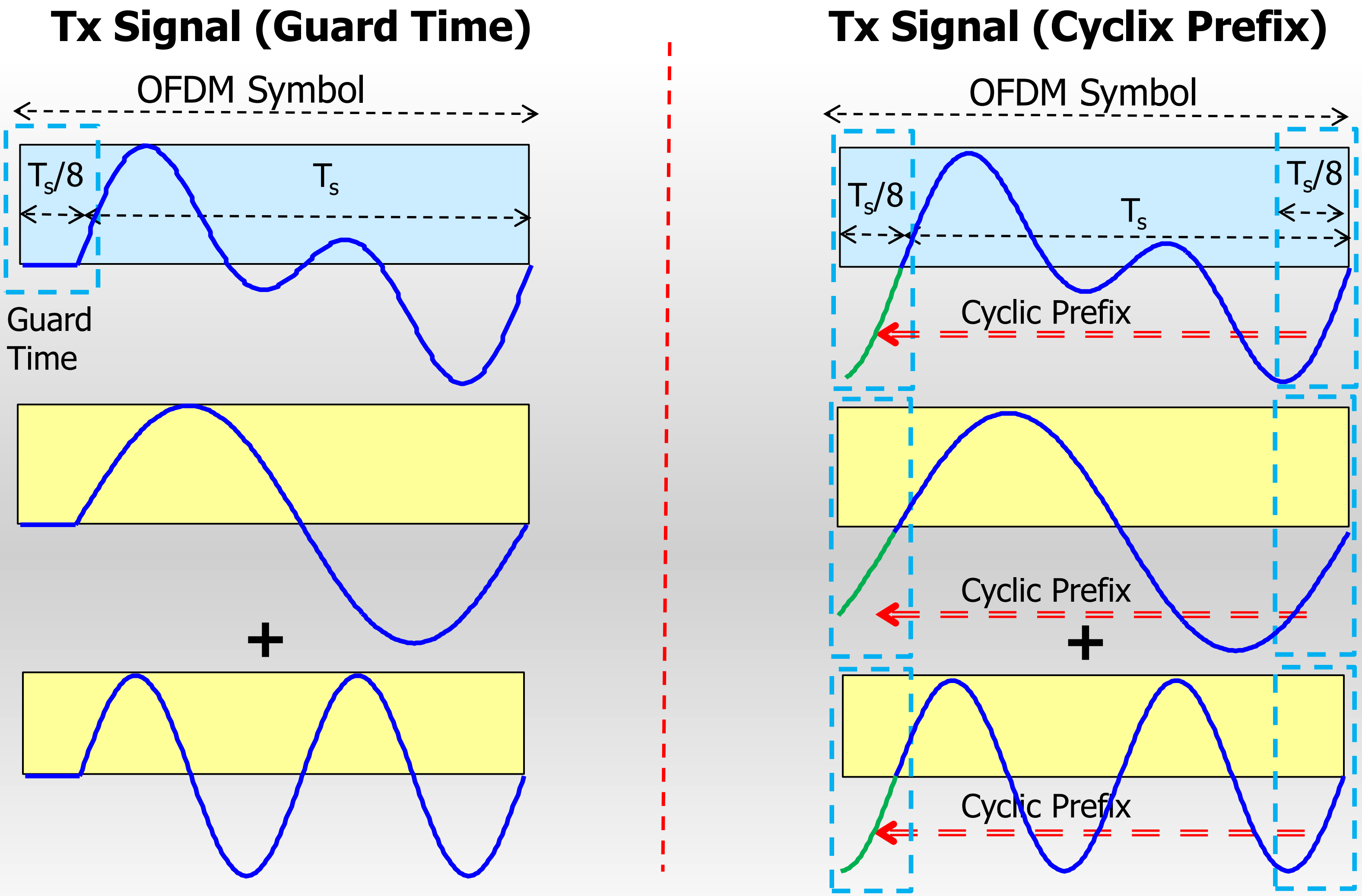


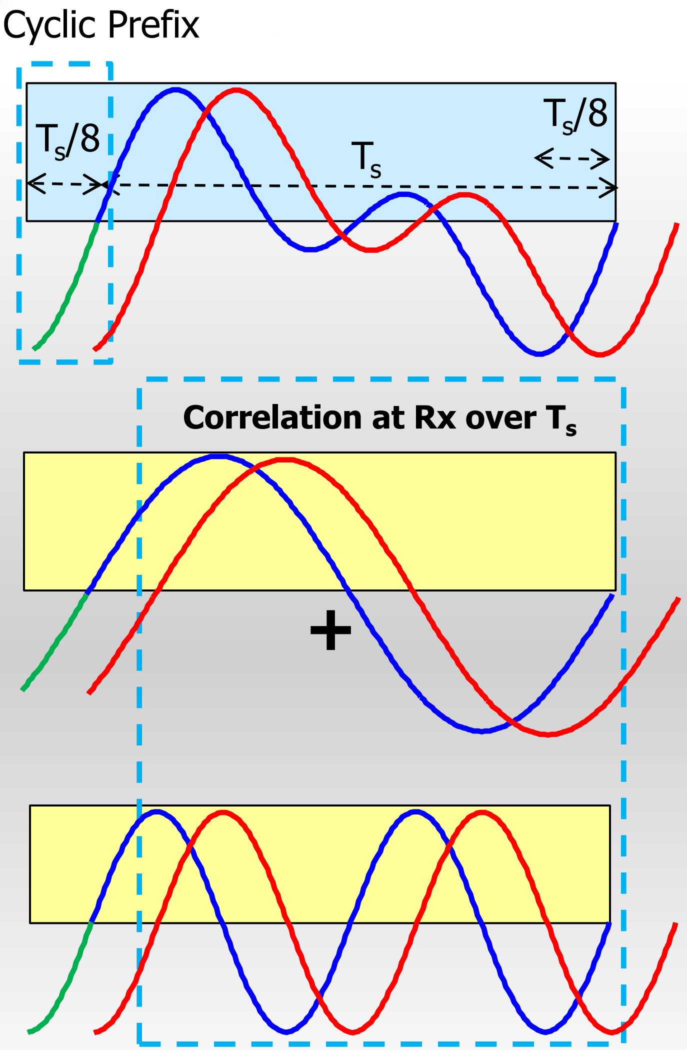
OFDM SYSTEM

The cyclic prefix is used to eliminate ***Inter-carrier interference***

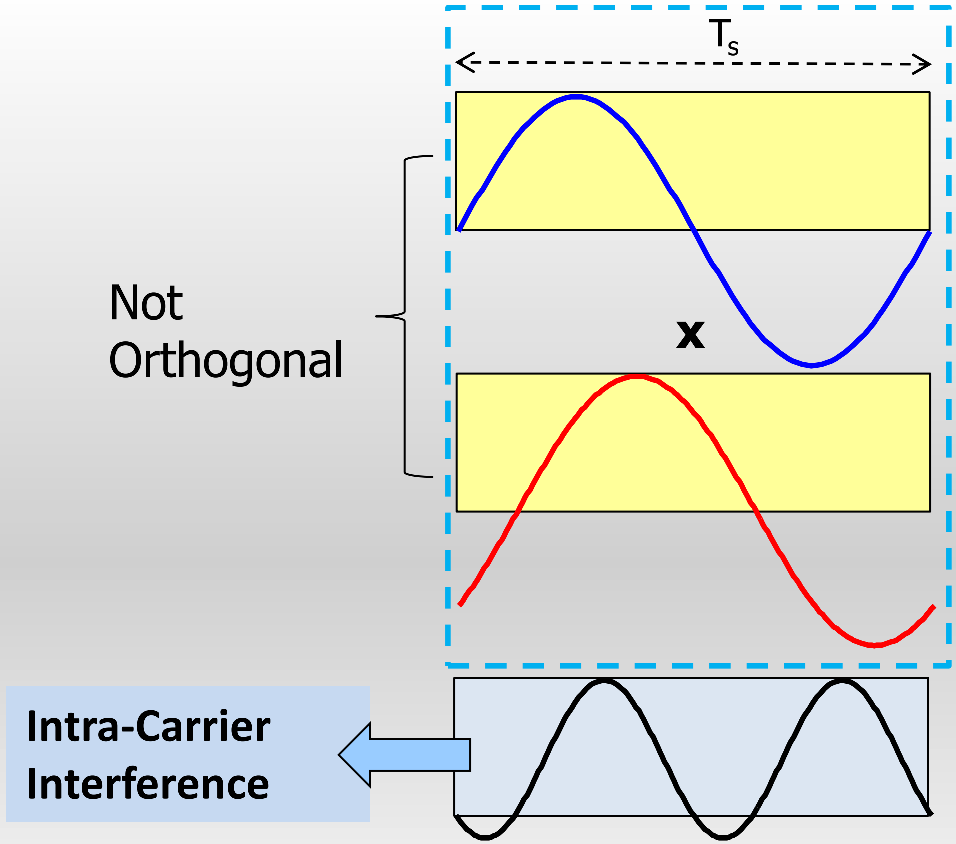


OFDM SYSTEM

Rx Signal (Cyclix Prefix)

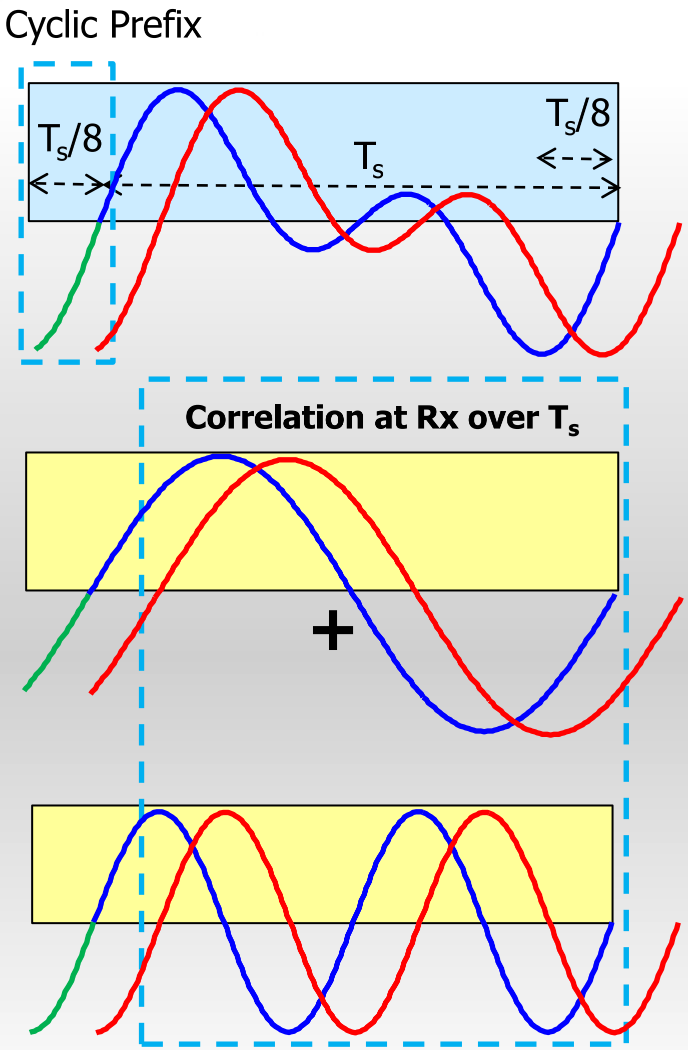


Consider the receiver for $f_1=1/T_s$ that correlates over T_s with $\sin(2\pi t/T_s)$



OFDM SYSTEM

Rx Signal (Cyclix Prefix)



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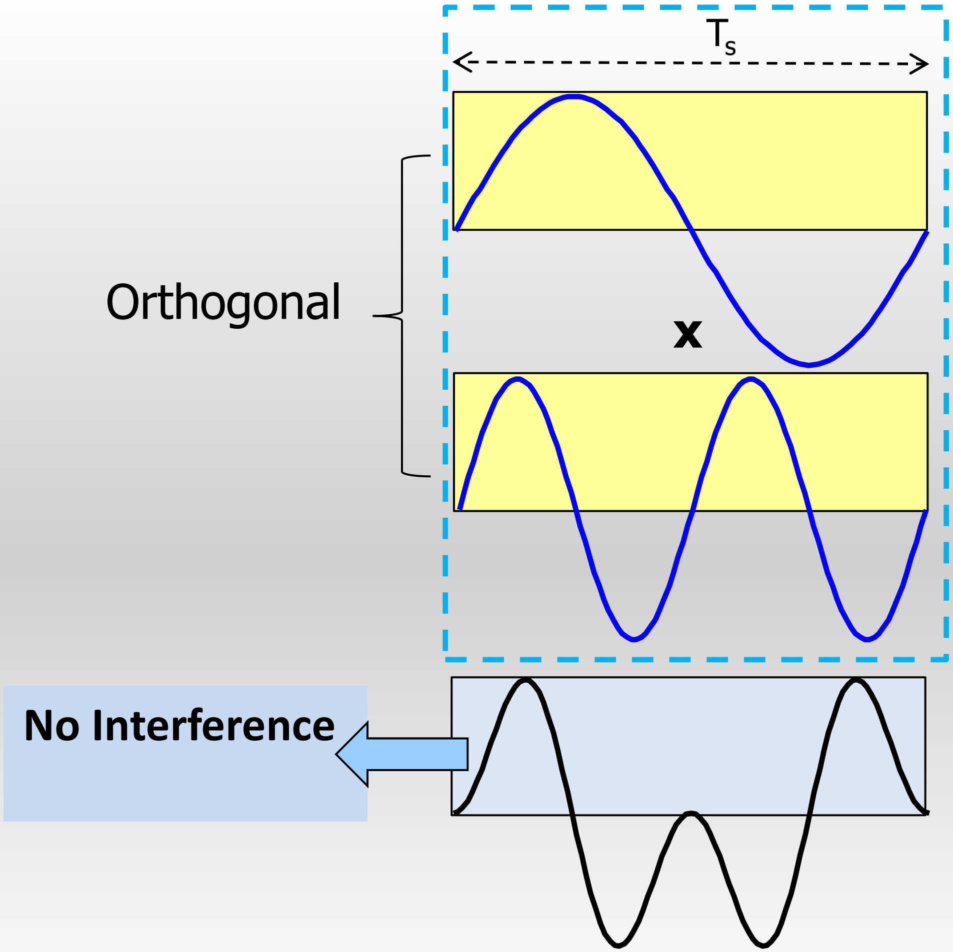
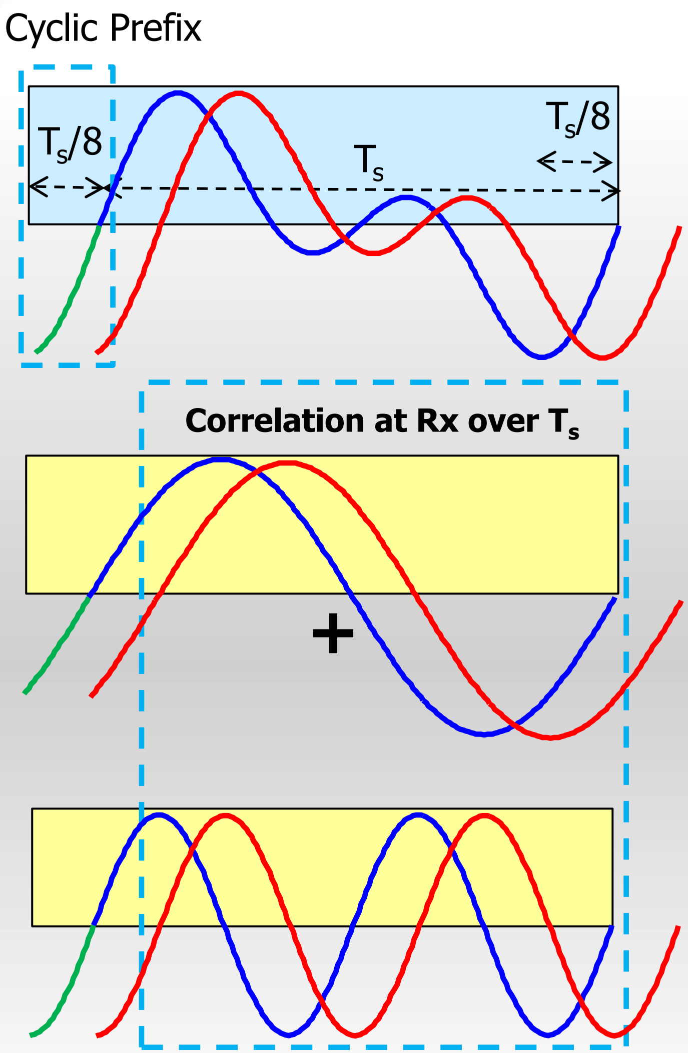
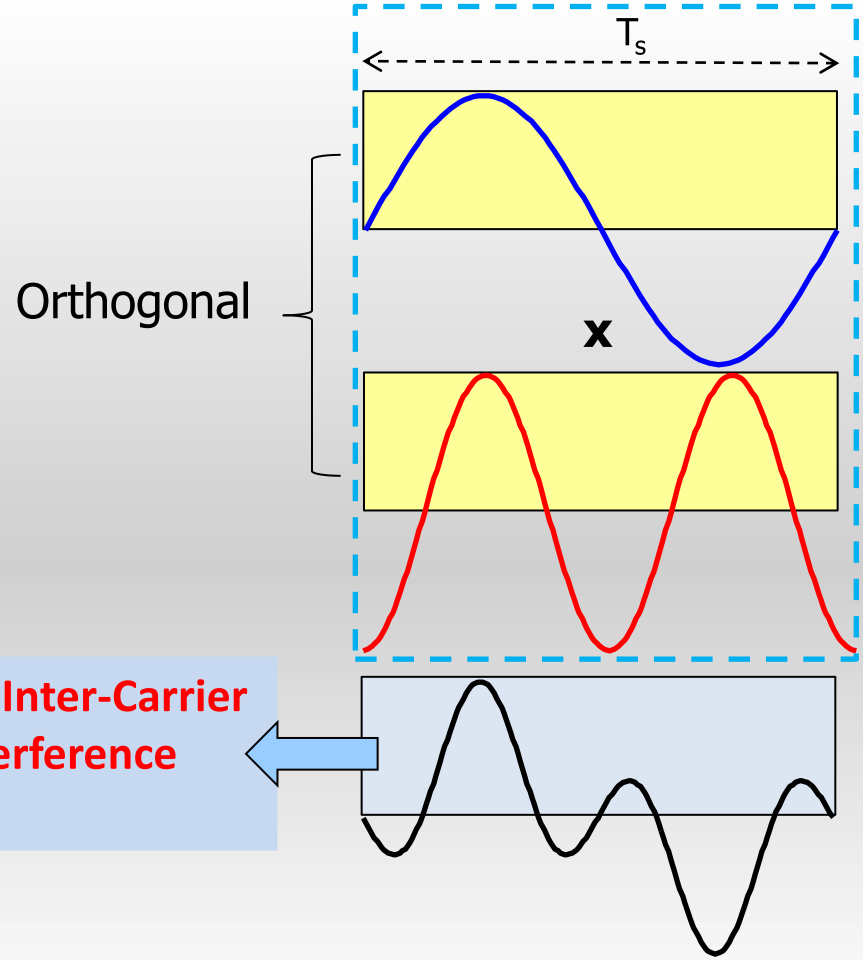


OFDM SYSTEM

Rx Signal (Cyclix Prefix)



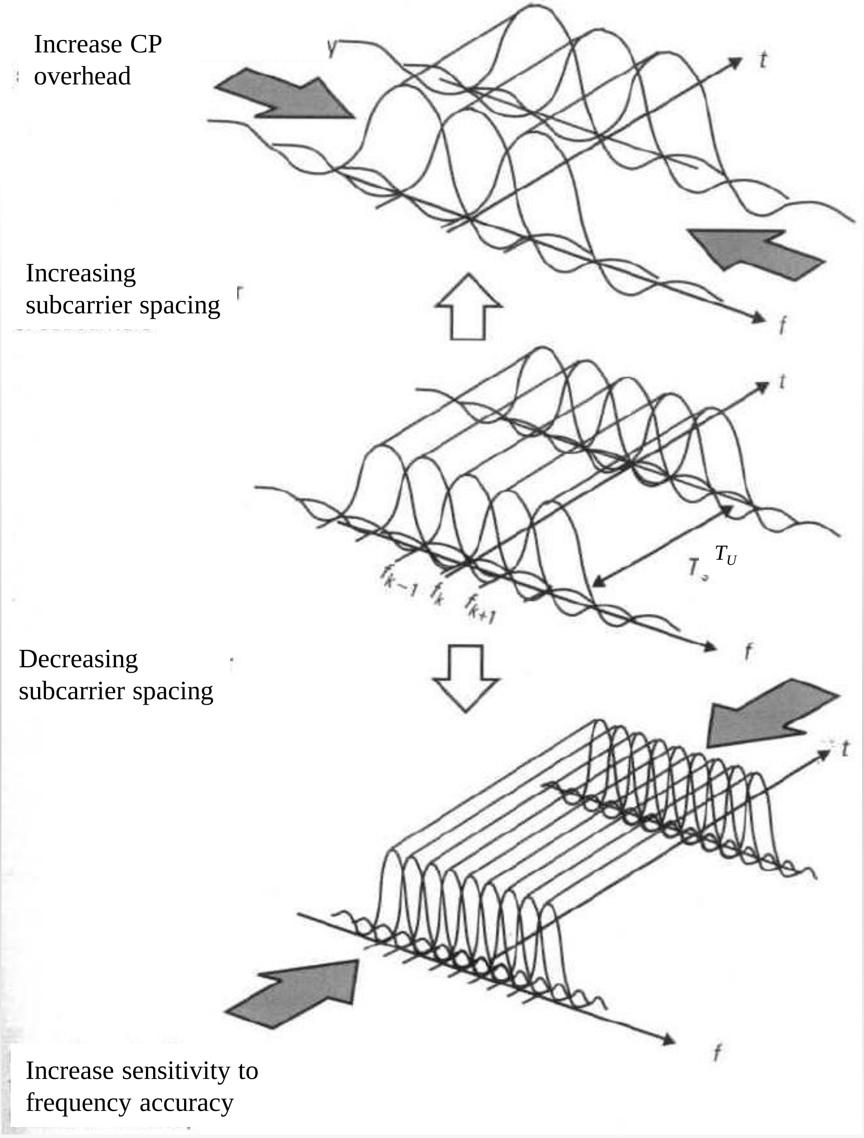
Consider the receiver for $f_1=1/T_s$ that correlates over T_s with $\sin(2\pi t/T_s)$



No Inter-Carrier Interference

OFDM PARAMETER

- Symbol time (T_U) and subcarrier spacing (Δf) are inverse
  - $T_U = 1/\Delta f$
- Consequences of increasing the subcarrier spacing
  - Increase cyclic prefix overhead
- Consequences of decreasing the subcarrier spacing
  - Increase sensitivity to frequency inaccuracy
  - Increasing number of subcarriers increases Tx and Rx complexity



OFDM modulation and datarate

Modulation with Sub Channels	Data Rate Per Subchannel (Kbps)	Total Data Rate (Mbps)
BPSK	125	6
BPSK	187.5	9
QBPSK	250	12
QBPSK	375	18
16QAM	500	24
16QAM	750	36
64QAM	1000	48
64QAM	1125	54

OFDM Varians

- Coded OFDM (COFDM)
- Orthogonal Frequency-Division Multiple Access (OFDMA)
- Flash OFDM (F-OFDM)
- Vector OFDM (VOFDM)
- Wideband OFDM (WOFDM)

OFDM Varians

- Coded OFDM (COFDM)
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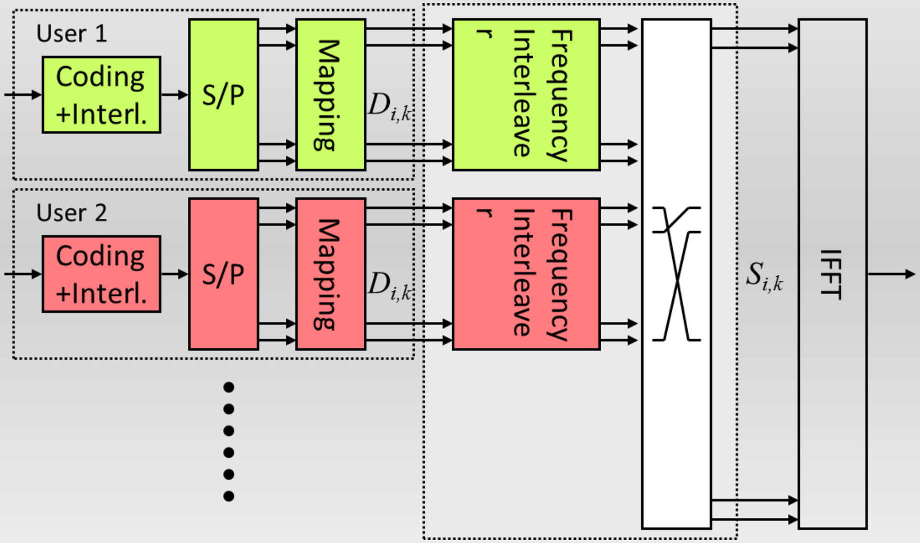


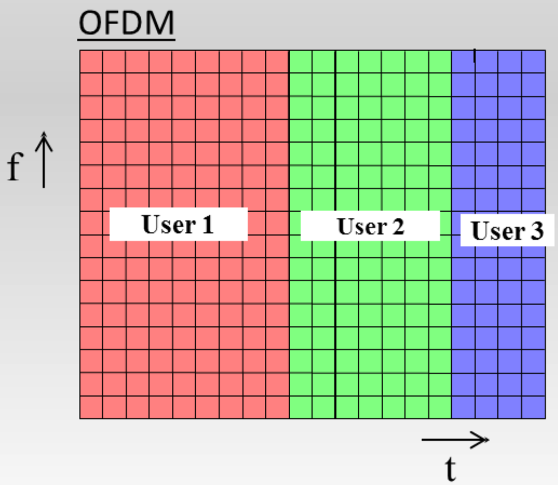
- ❑ Coded OFDM, or COFDM, is a term used for a system in which the error control coding and OFDM modulationprocesses work closely together.
- ❑ It is a form of OFDM where error correction coding is incorporated into the signal.
- ❑ An important step in a COFDM system is to interleave and code the bits prior to the IFFT. This step serves the purpose of taking adjacent bits in the source data and spreading them out across multiple subcarriers.

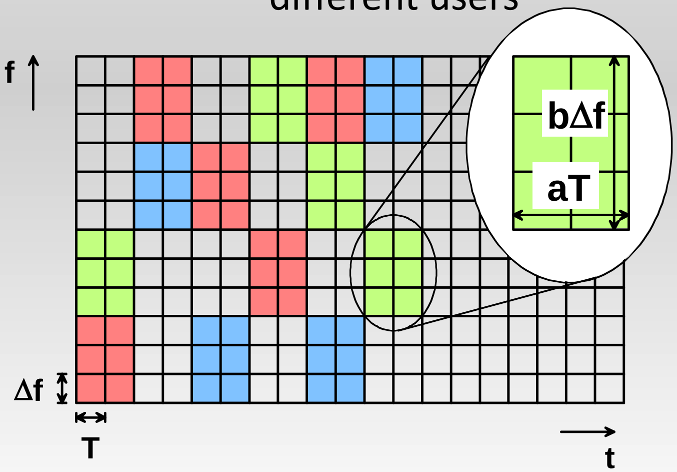
Adopted for → HDSL, ADSL, VHDSL , digital audiobroadcasting (DAB), digital television and HDTV terrestrial broadcasting.

OFDM Varians

- Coded OFDM (COFDM)
- Orthogonal Frequency-Division Multiple Access (OFDMA)
- Flash OFDM (F-OFDM)
- Vector OFDM (VOFDM)
- Wideband OFDM (WOFDM)

- It is a multi-user version of the OFDM digital modulation scheme.
- Multiple access is achieved in OFDMA by assigning <u>subsets of subcarriers</u> to individual users.
- In OFDMA the subcarrier of the symbol may be devided between multiple users thus enabling better use of radio resources
- This allows simultaneous low data rate transmission from several users.
- OFDMA supports differentiated quality of service by assigning different number of sub-carriers to different users





Adopted for →
Wi-Fi,
WiMAX, 3GPP
UMTS & 3GPP@
LTE

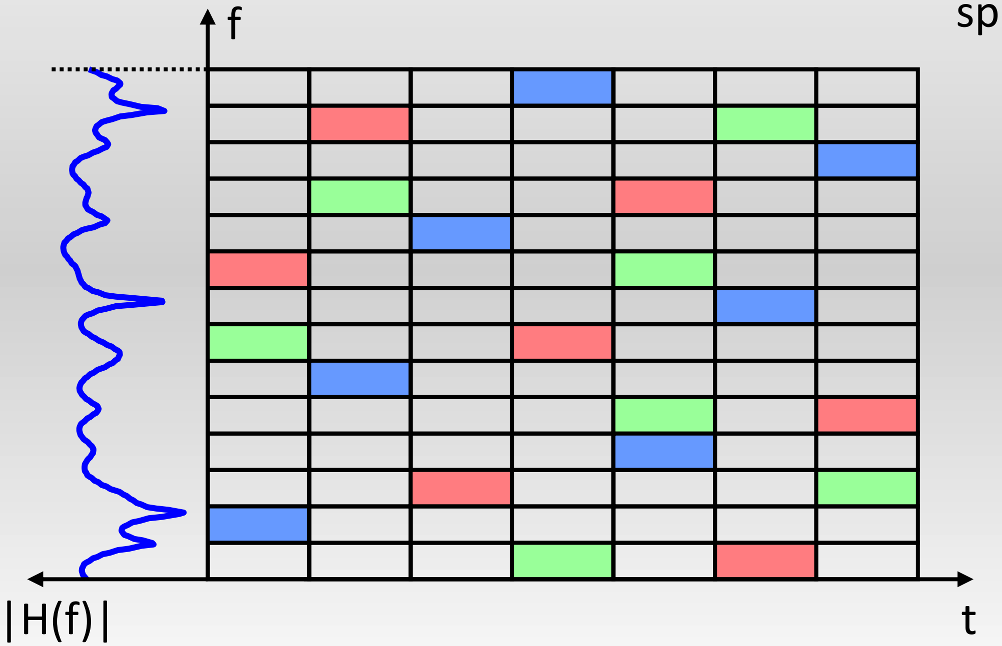
OFDM Varians

- Coded OFDM (COFDM)
- Orthogonal Frequency-Division Multiple Access (OFDMA)
- Flash OFDM (F-OFDM)
- Vector OFDM (VOFDM)
- Wideband OFDM (WOFDM)

❑ Flash-OFDM, also referred to as F-OFDM, was based on OFDM and also specified higher protocol layers.

❑ F-OFDMt is a fast hopped form of OFDM.

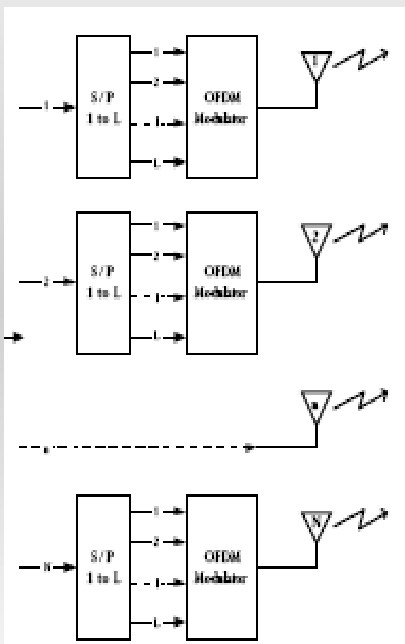
❑ It uses multiple tones and fast hopping to spread signals over a given spectrum band.

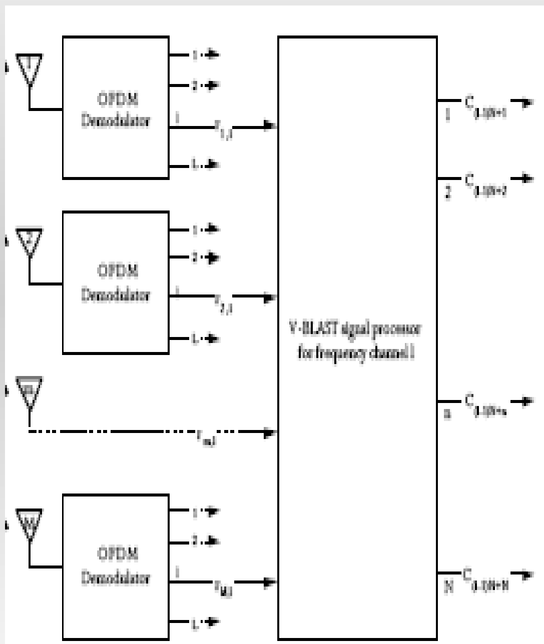


Adopted for → IEEE 802.20 or Mobile Broadband Wireless Access

OFDM Varians

- Coded OFDM (COFDM)
- Orthogonal Frequency-Division Multiple Access (OFDMA)
- Flash OFDM (F-OFDM)
- Vector OFDM (VOFDM)
- Wideband OFDM (WOFDM)





- VOFDM uses the concept of MIMO (Multiple inputmultiple output) technology.
- By using spatial diversity, a wireless system's tolerance to noise, interference, and multipath can be greatly increased.
- Vector OFDM can deliver multiple signals on a single antenna or receive them on multiple antennas. This increases the likelihood of a good signal being received.
- By placing two or more antennas in a wireless system with each having a different set of multipath signals,

OFDM Varians

- Coded OFDM (COFDM)
- Orthogonal Frequency-Division Multiple Access (OFDMA)
- Flash OFDM (F-OFDM)
- Vector OFDM (VOFDM)
- Wideband OFDM (WOFDM)

- ❑ In Wideband OFDM, the spacing between the channels is large enough so that any frequency errors between the transmitter and receiver have no effect on the performance of the system.
- ❑ It is particularly applicable to Wi-Fi systems. WOFDM allows several independent channels to operate within the same band.

Adopted for →
EEE 802.11a/g/n

ADVANTAGES OF OFDM

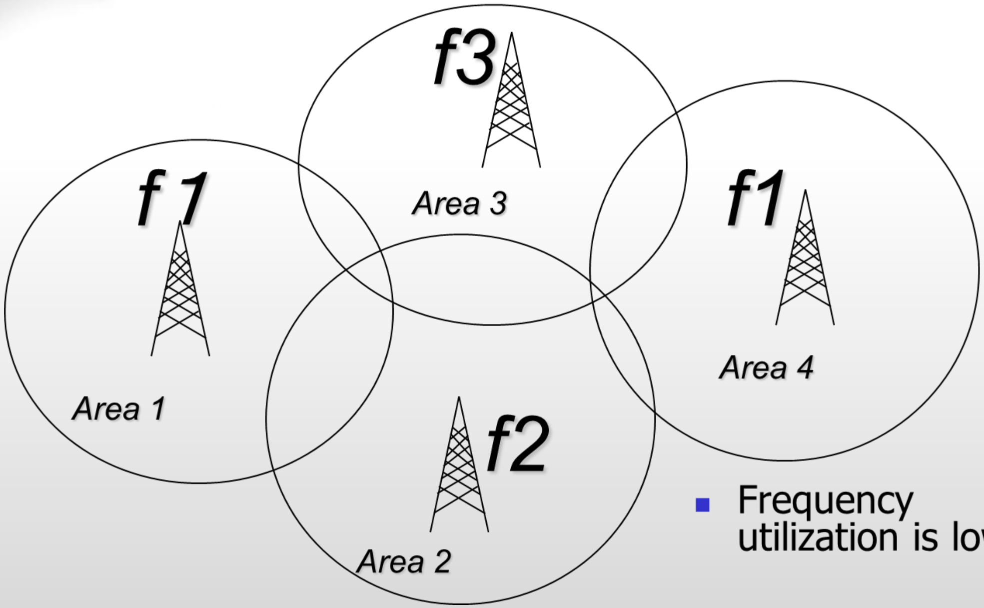
- Robust in multi-path propagation environment
- More tolerant of delay spread
  - Due to the use of many sub-carriers, the symbol duration is increased, relative to delay spread
  - Inter-symbol interference is avoided through the use of guard interval
  - Simplified or eliminate equalization needs, as compared to single carrier modulation
- More resistant to fading
  - Low symbol rate per carrier provides the robustness against frequency selective fading or narrowband interference
  - FEC is used to correct for sub-carriers that suffer from deep fade
- Multi-carrier with single frequency network (SFN)

ADVANTAGES OF OFDM

OFDM Good for Broadband Systems

- Most broadband systems are subjects to multipath transmission
- Conventional solution to multipath is an equalizer in the receiver
  - Equalizers are too complicated at high data rates
- With OFDM there is a simple way of dealing with multipath
  - Relatively simple DSP algorithms

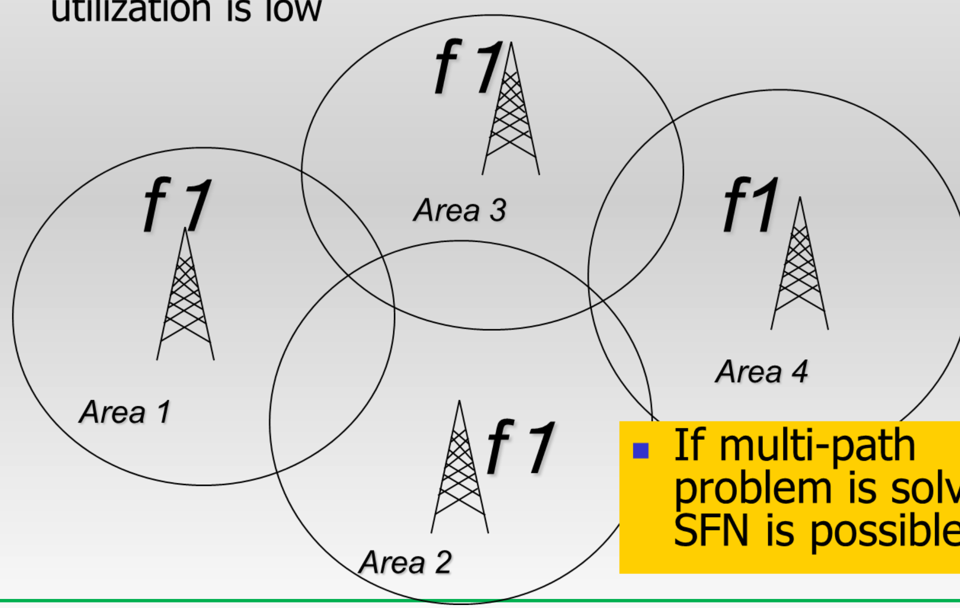
ADVANTAGES OF OFDM



- Frequency utilization is low

Multiple Frequency Network

Single Frequency Network



- If multi-path problem is solved, SFN is possible

ADVANTAGES OF OFDM

- Feature of OFDM
  1. High Frequency utilization by the square spectrum shape
  2. Multi-path problem is solved by GI
  3. Multiple services in one OFDM by sharing sub-carriers (3 services in ISDB-T)
  4. SFN
  5. Implementation was complicated but NOW possible because of LSI technology progress

CHALLENGES FOR OFDM

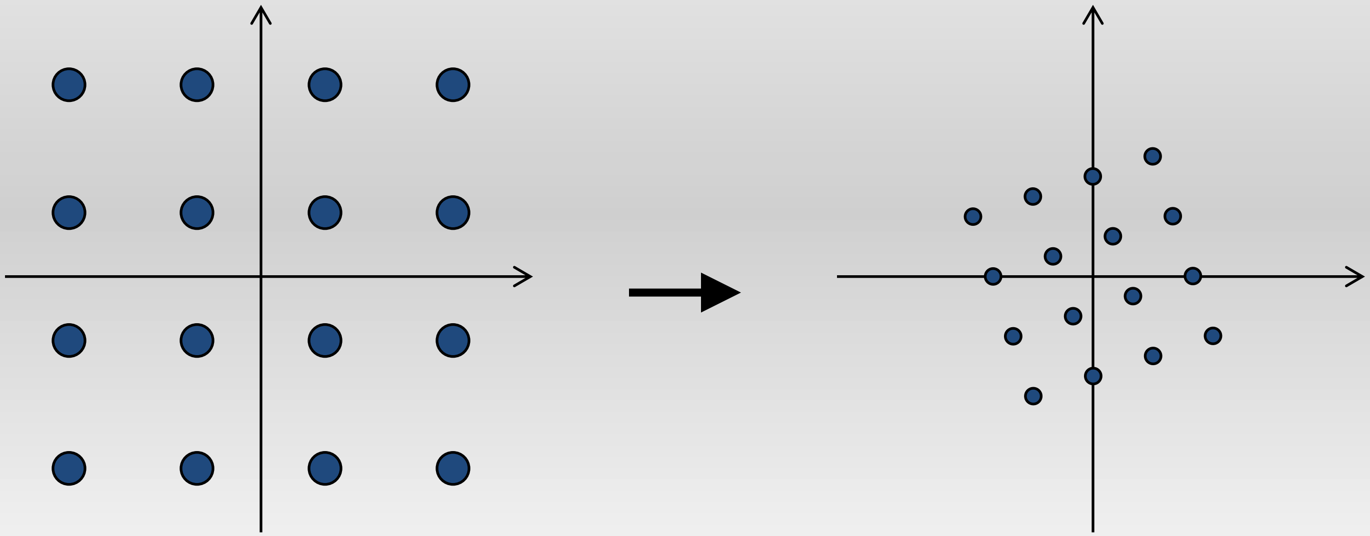
- Synchronization challenges
  - Transmitter frequency ≠ Receiver frequency
    - Mesochronous: same frequency, different phase
    - Pleisochrnous: slightly different frequencies
    - Asynchronous: totally different frequencies
  - Transmitter sampling time ≠ Receiver sampling time
  - Symbol timing is unknown to receiver
- Peak-to Average Power Ratio (PAPR)
  - Dynamic range at output of IFFT is much larger than at input
  - it is about 2 dB higher than that of the ATSC 8-VSB system. A larger Tx (more dynamic range) might be required or using pre-distortion and better filtering to reduce the first adjacent channel interference
- Channel estimation for time varying environment

MATERI

- WHY OFDM?
- WHAT IS OFDM?
- OFDM SIGNAL GENERATION
- OFDM SPECTRUM
- OFDM VARIANT
- ADVANTAGES OF OFDM
- CHALLENGES OF OFDM

GUARD TIME INTERVAL Tg

- By adding GI, orthogonality can be maintained
- However, multi-path causes Amplitude and Phase distortion for each sub-carrier
- The distortion has to be compensated by Equalizer



OFDM SIGNAL GENERATION

$$s(t) = \sum_{n=0}^{N-1} \left[a_n \cos\left\{ 2\pi(f_c + nf_0)t \right\} - b_n \sin\left\{ 2\pi(f_c + nf_0)t \right\} \right]$$

- Direct method needs

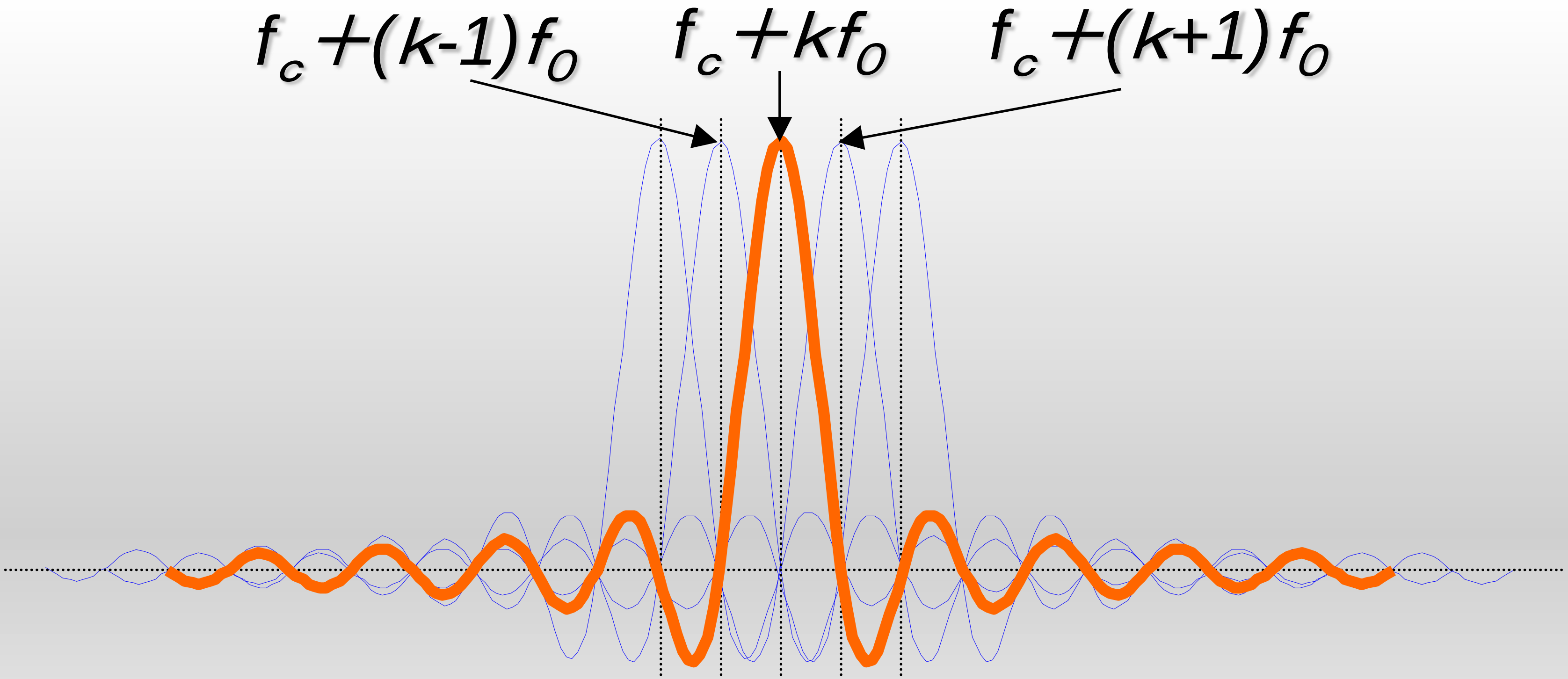
  N digital modulators

  N carrier frequency generator

  ➔ Not practical

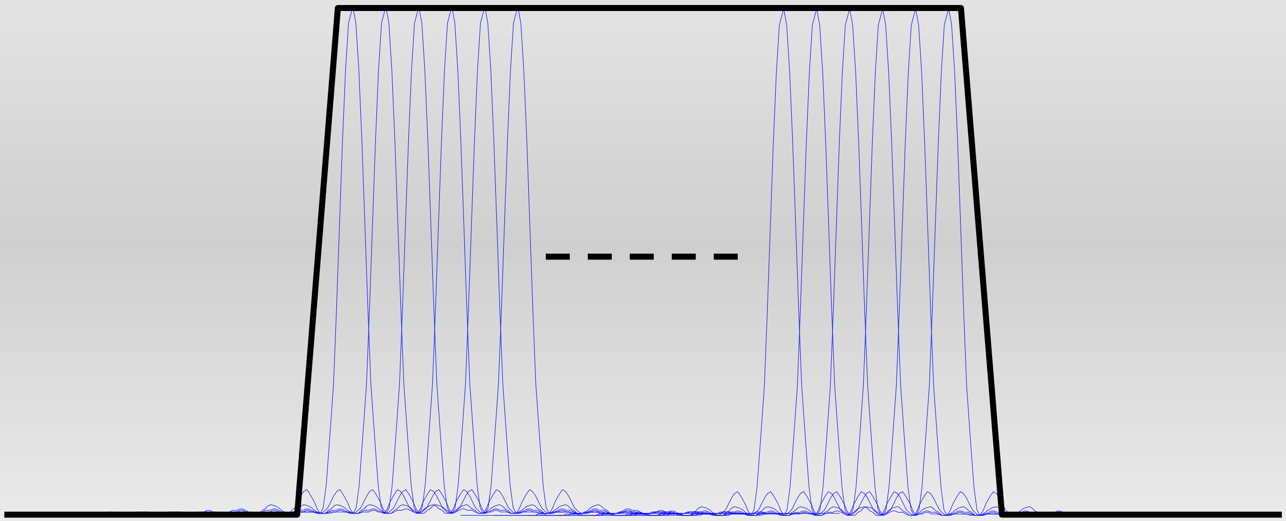
- In 1971, method using DFT is proposed to OFDM siganal generation

OFDM SPECTRUM

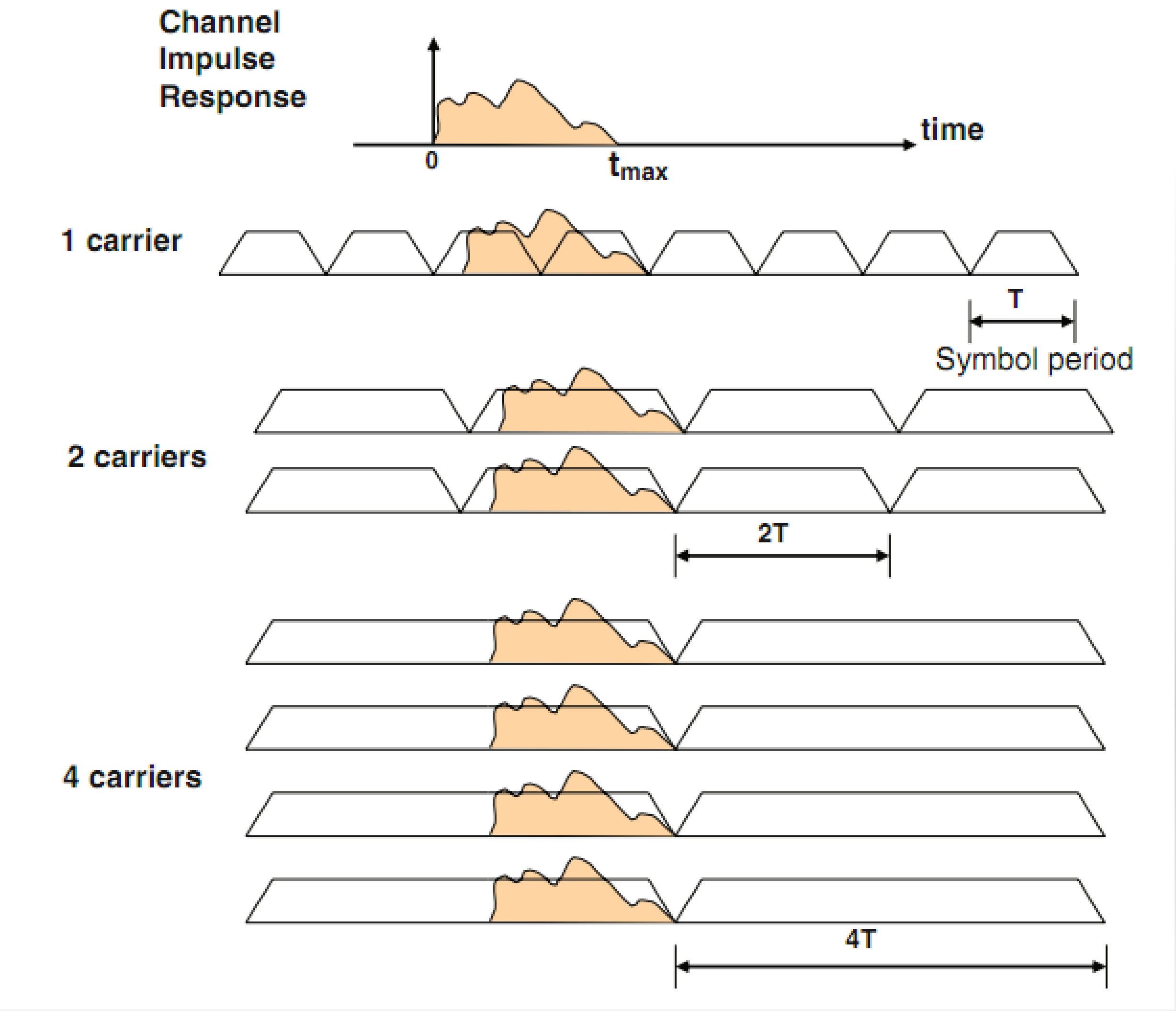


OFDM SPECTRUM

- Total Power spectrum is almost square shape



OFDM



Channel
Impulse
Response
time
0
tmax
1 carrier
T
Symbol period
2 carriers
2T
4 carriers
4T

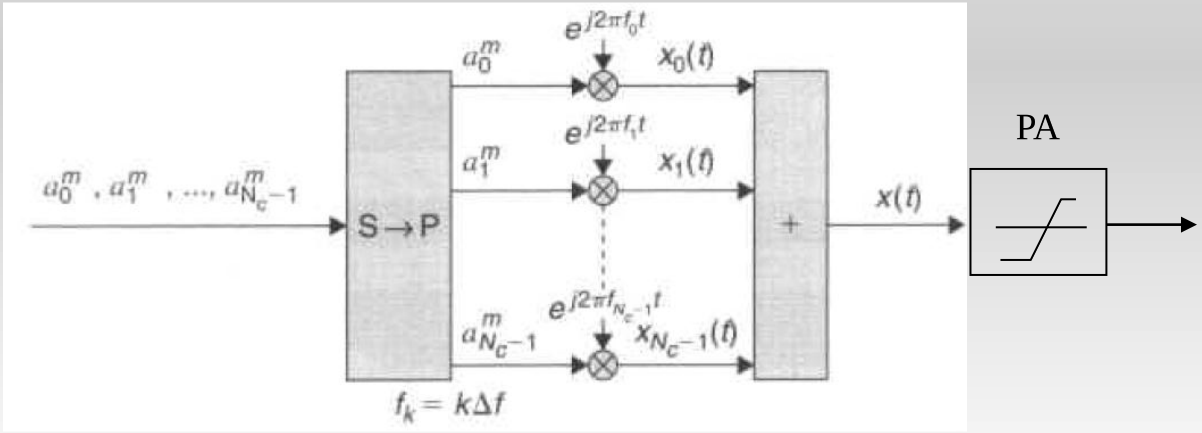
CHALLENGES FOR OFDM

PAPR Problem

- A OFDM signal consists of a number of independently modulated symbols
- The sum of independently modulated subcarriers can have large amplitude variations

$$x(t) = \sum_{k=0}^{N_c - 1} a_k \cdot e^{j2\pi k \Delta f\, t}$$

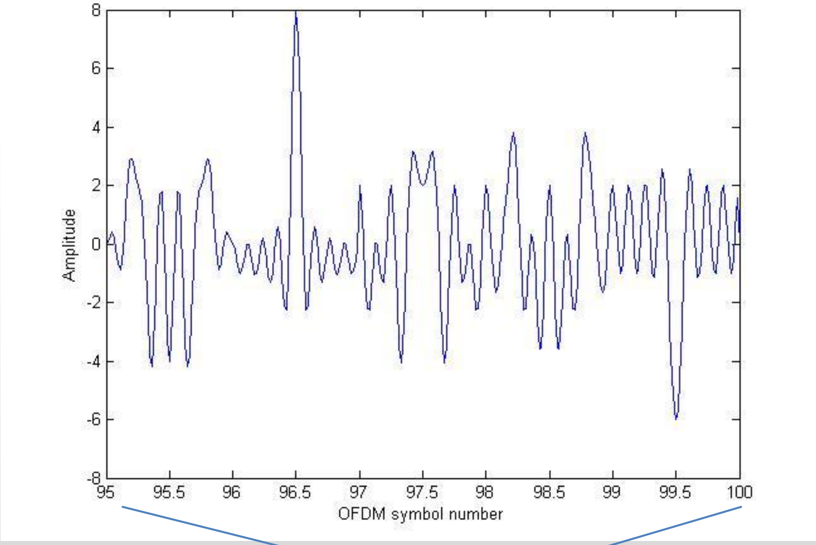
- Results in a large *peak-to-average-power ratio* (PAPR)

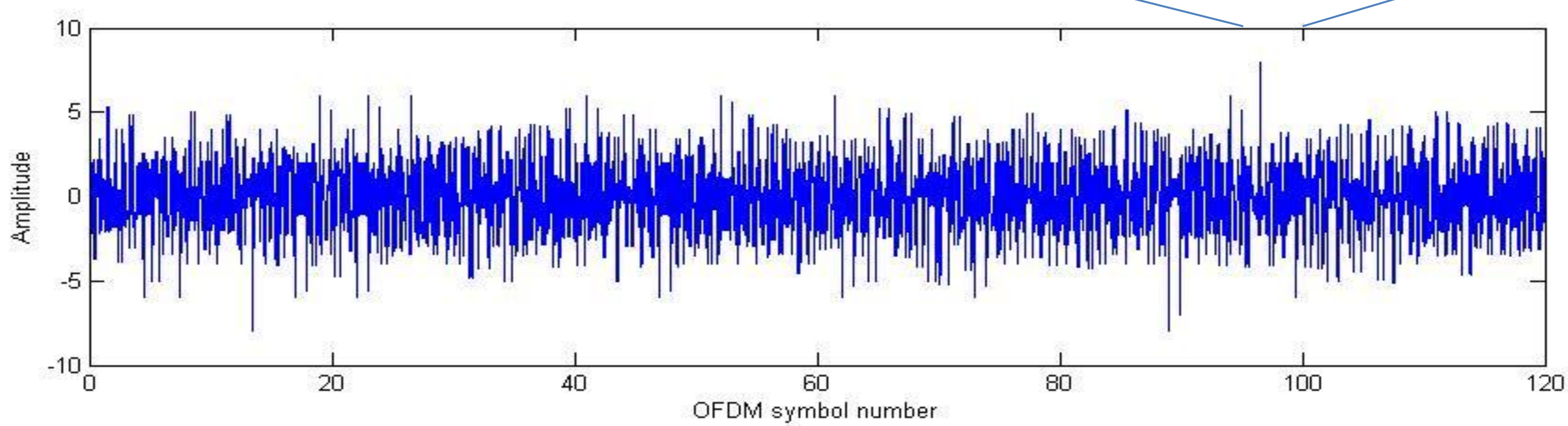


CHALLENGES FOR OFDM

PAPR Problem

- Example with 8 carriers and BPSK modulation
  - x(t) plotted
- It can be shown that the PAPR becomes equal to N_c



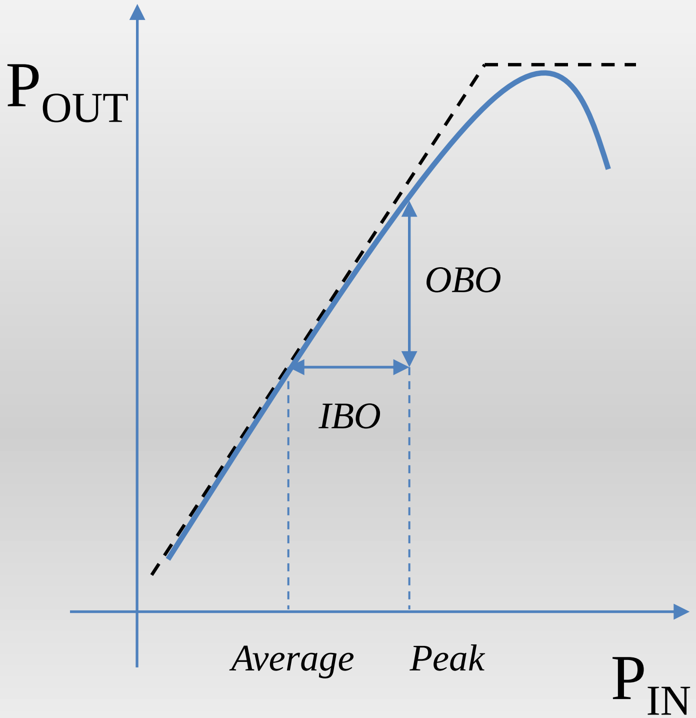


CHALLENGES FOR OFDM

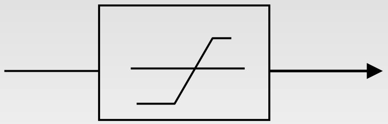
PAPR Problem

- High efficiency power amplifiers are desirable
  - For the handset, long battery life
  - For the base station, reduced operating costs
- A large PAPR is negative for the power amplifier efficiency
- Non-linearity results in inter-modulation
  - Degrades BER performance
  - Out-of-band radiation

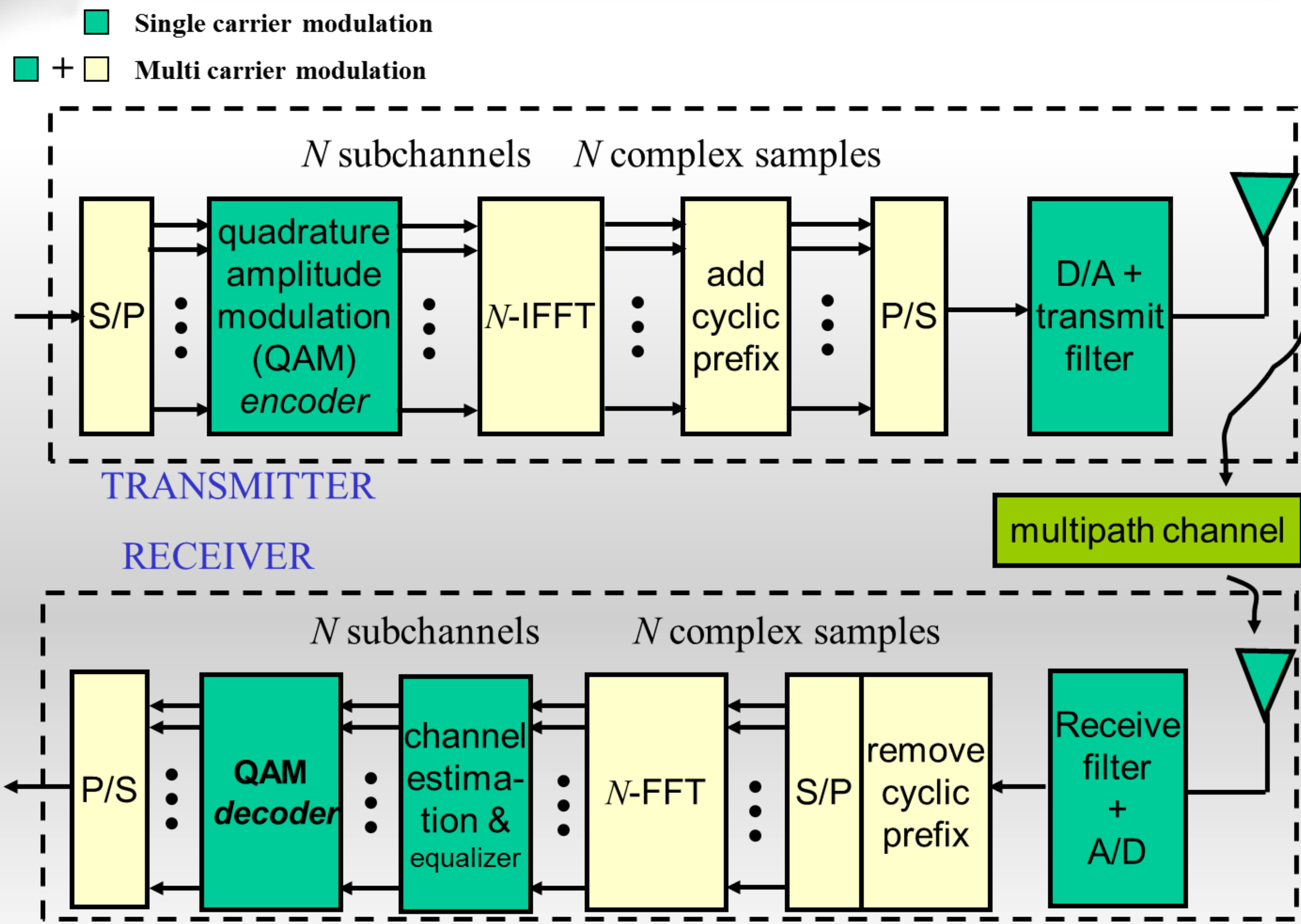
AM/AM characteristic



PA



OFDM SYSTEM


Single carrier modulation
+ Multi carrier modulation
N subchannels
N complex samples
S/P
quadrature amplitude modulation (QAM) encoder
N-IFFT
add cyclic prefix
P/S
D/A + transmit filter
TRANSMITTER
multipath channel
RECEIVER
N subchannels
N complex samples
P/S
QAM decoder
channel estima-tion & equalizer
N-FFT
S/P
remove cyclic prefix
Receive filter + A/D