EC744 Wireless Communications
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OFDM

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Motivation

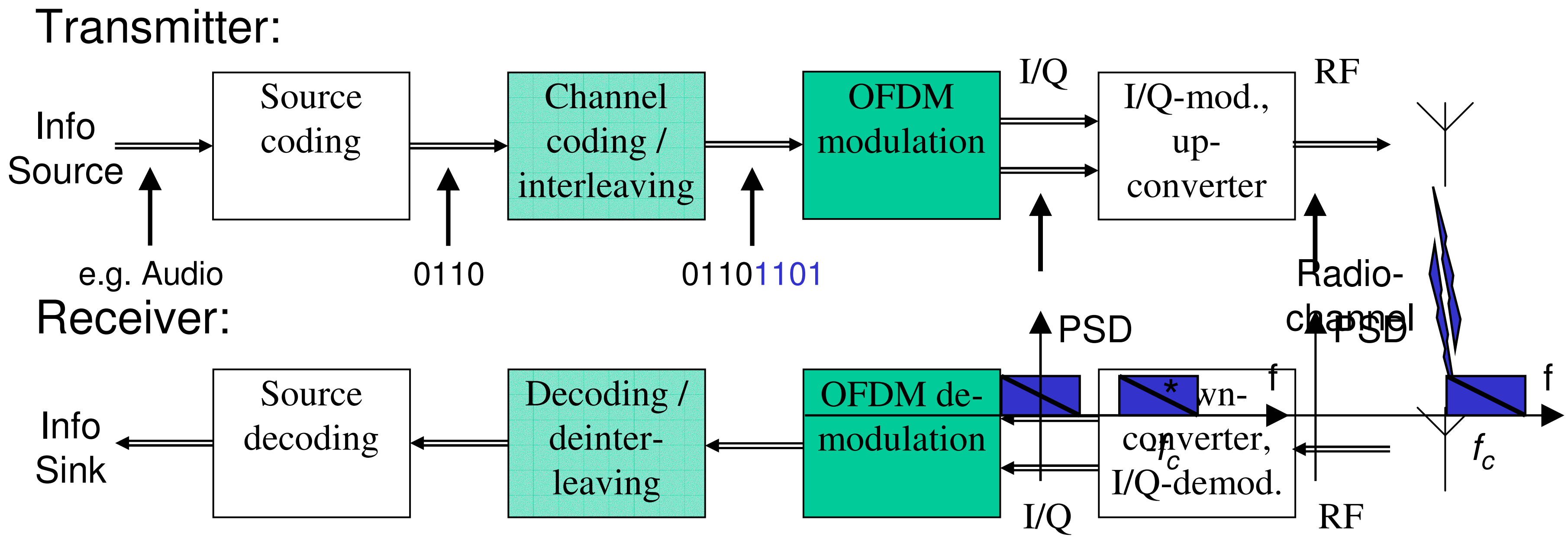
- High bit-rate wireless applications in a multipath radio environment.

- OFDM can enable such applications without a high complexity receiver.

- OFDM is part of WLAN, DVB, and BWA standards and is a strong candidate for some of the 4G wireless technologies.

What is OFDM?

- Modulation technique
  - Requires channel coding
  - Solves multipath problems

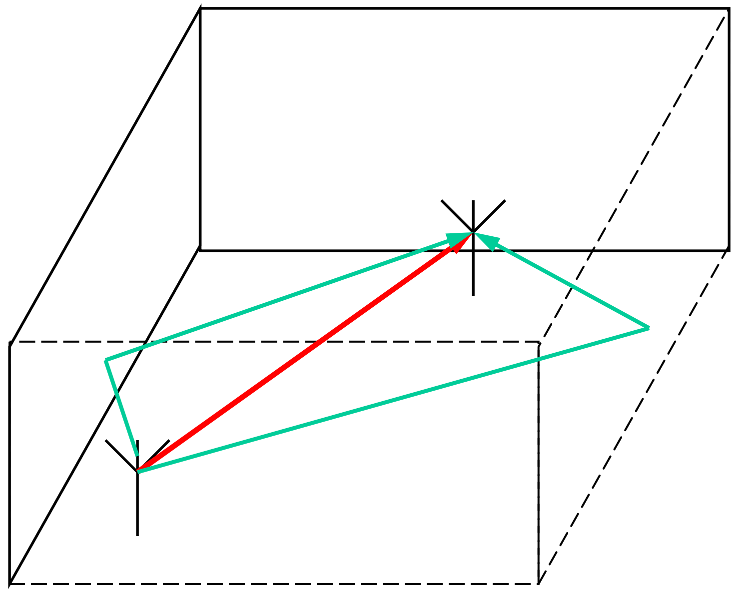


Multipath Transmission

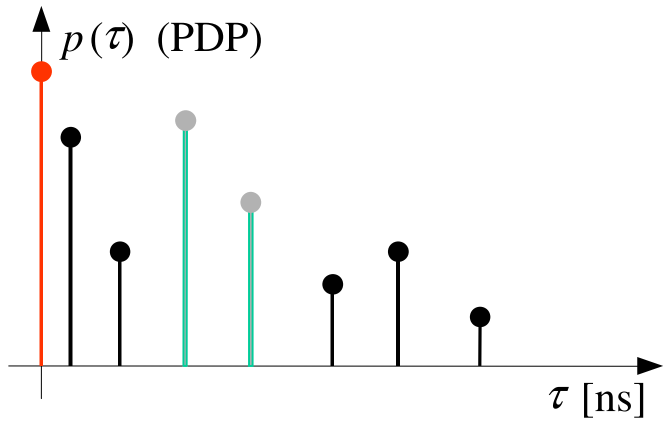
- Fading due to constructive and destructive addition of multipath signals.
- Channel delay spread can cause ISI.
- Flat fading occurs when the symbol period is large compared to the delay spread.
- Frequency selective fading and ISI go together.

Multipath Propagation

- Reflections from walls, etc.



- Time dispersive channel
  – Impulse response:



- Problem with high rate data transmission:
  – inter-symbol-interference

Delay Spread

- Power delay profile conveys the multipath delay spread effects of the channel.

- RMS delay spread quantifies the severity of the ISI phenomenon.

- The ratio of RMS delay spread to the data symbol period determines the severity of the ISI.

Inter-Symbol-Interference

Transmitted signal:

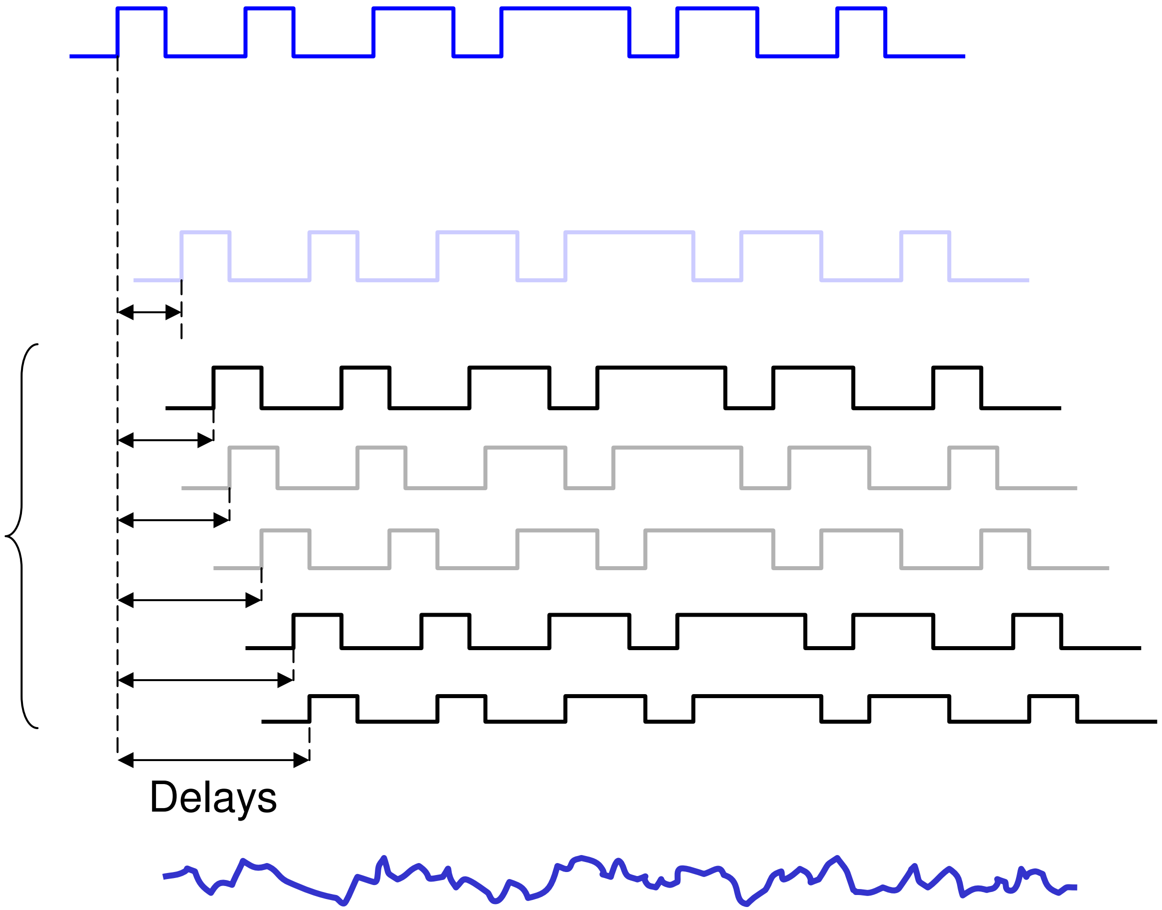
Received Signals:

Line-of-sight:

Reflected:

The **symbols add up** on the channel

→ **Distortion!**



Multipath Radio Channel

Concept of parallel transmission (1)

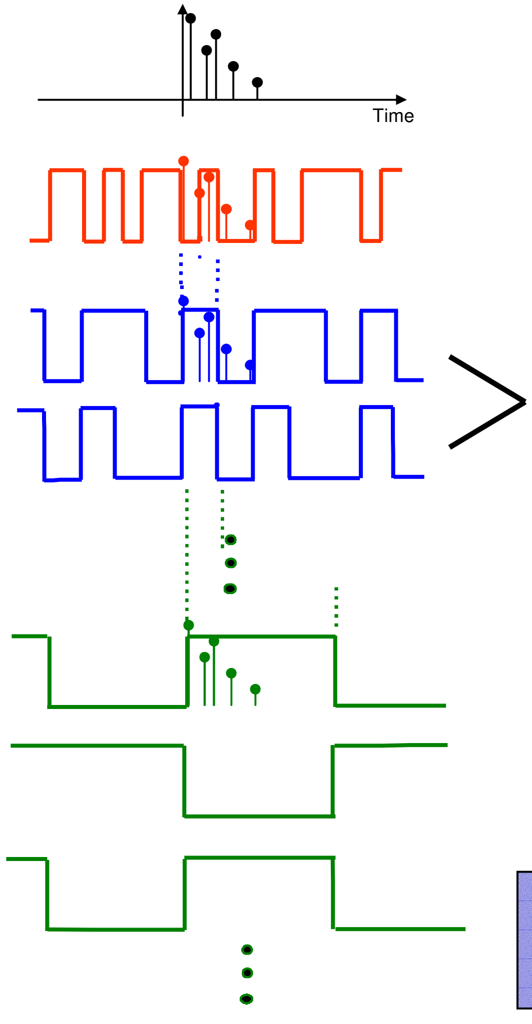
Channel impulse response

1 Channel (serial)

2 Channels

8 Channels

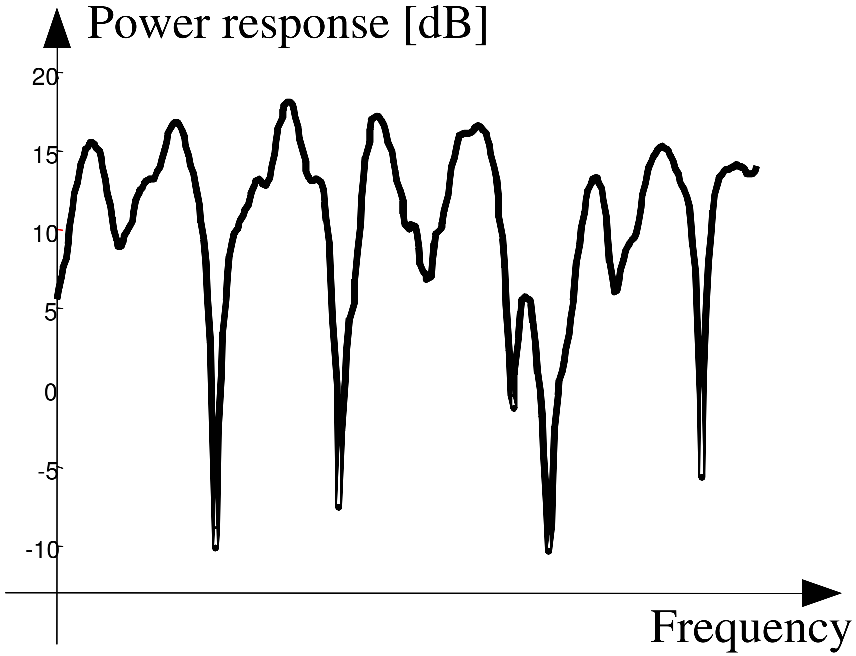
⋮



Channels are transmitted at different frequencies (sub-carriers)

In practice: **50 … 8000** Channels (sub-carriers)

The Frequency-Selective Radio Channel



- Interference of reflected (and LOS) radio waves
  - Frequency-dependent fading

Concept of parallel transmission (2)

Channel impulse response

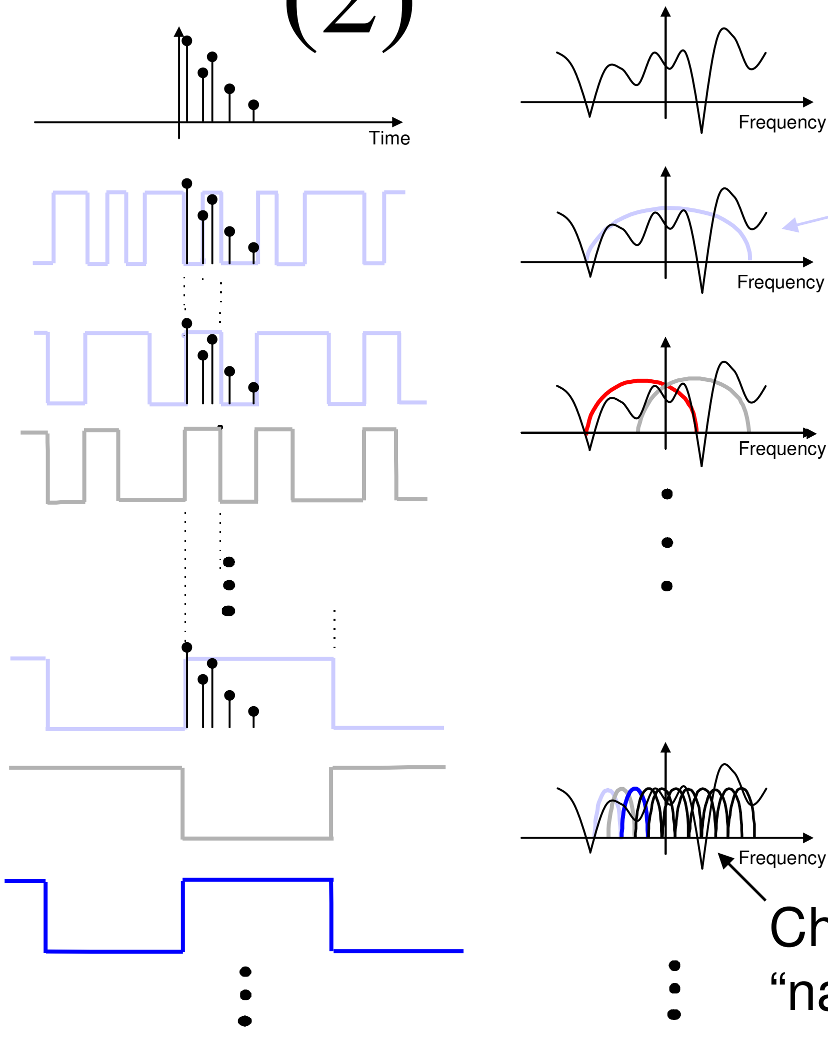
Channel transfer function

1 Channel (serial)

Signal is "broadband"

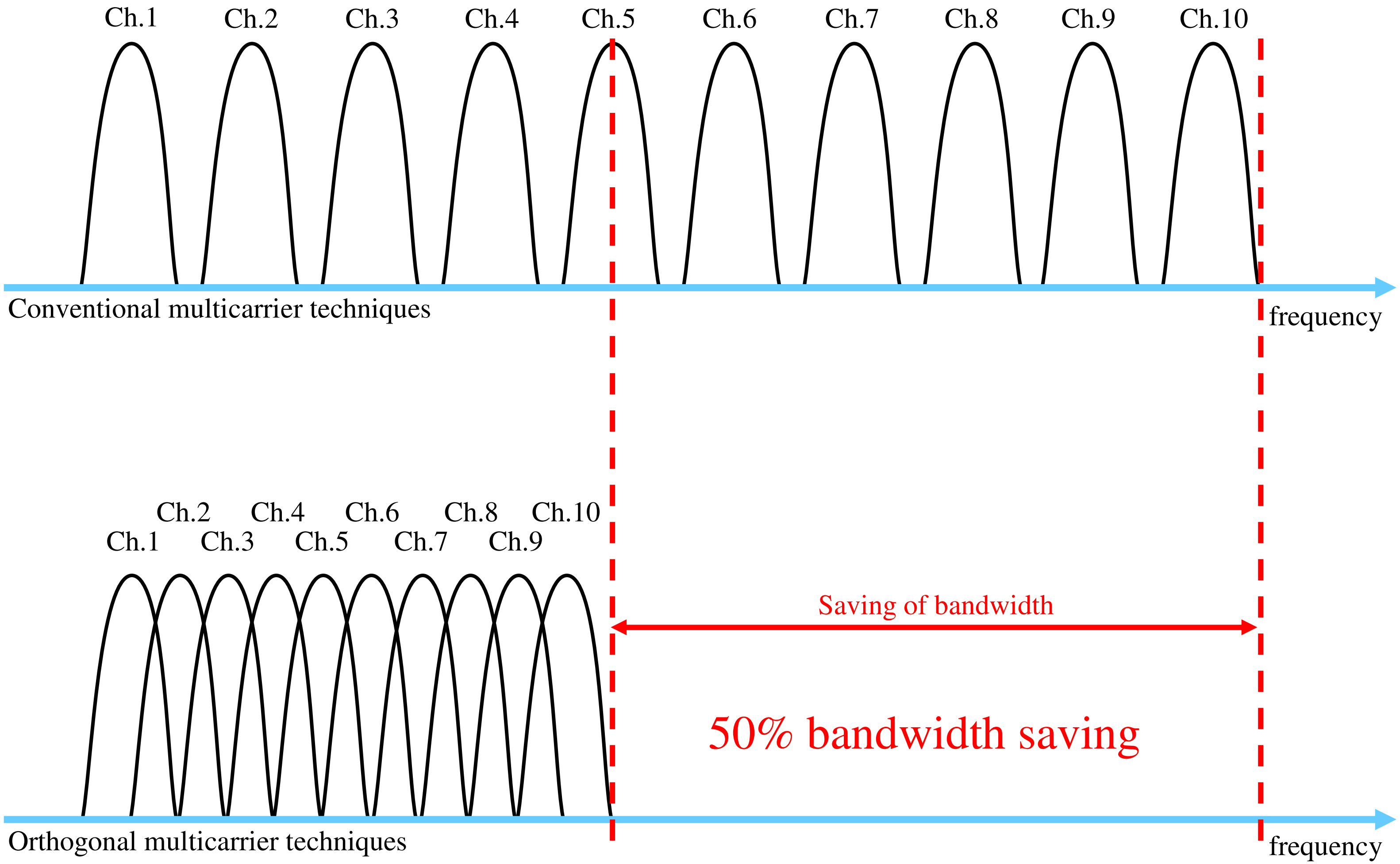
2 Channels

8 Channels



Channels are "narrowband"

Concept of an OFDM signal



A Solution for ISI channels

- Conversion of a high-data rate stream into several low-rate streams.

- Parallel streams are modulated onto orthogonal carriers.

- Data symbols modulated on these carriers can be recovered without mutual interference.

- Overlap of the modulated carriers in the frequency domain - different from FDM.

OFDM

- OFDM is a multicarrier block transmission system.
- Block of ‘N’ symbols are grouped and sent parallely.
- No interference among the data symbols
  sent in a block.

OFDM Mathematics

$$s(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi f_k t} \qquad t \equiv [\,0, T_{os}]$$

Orthogonality Condition

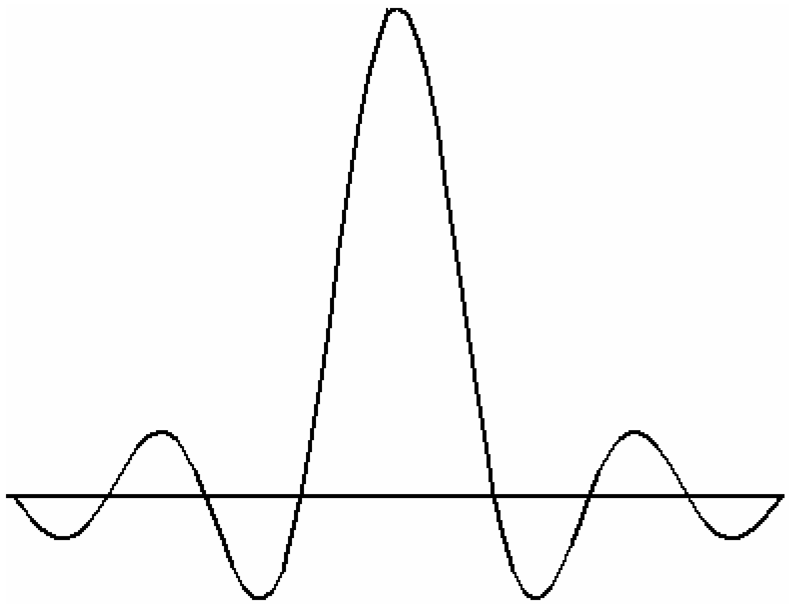
$$\int_0^{T_{os}} g_1(t).g_2^*(t)\,dt = 0$$

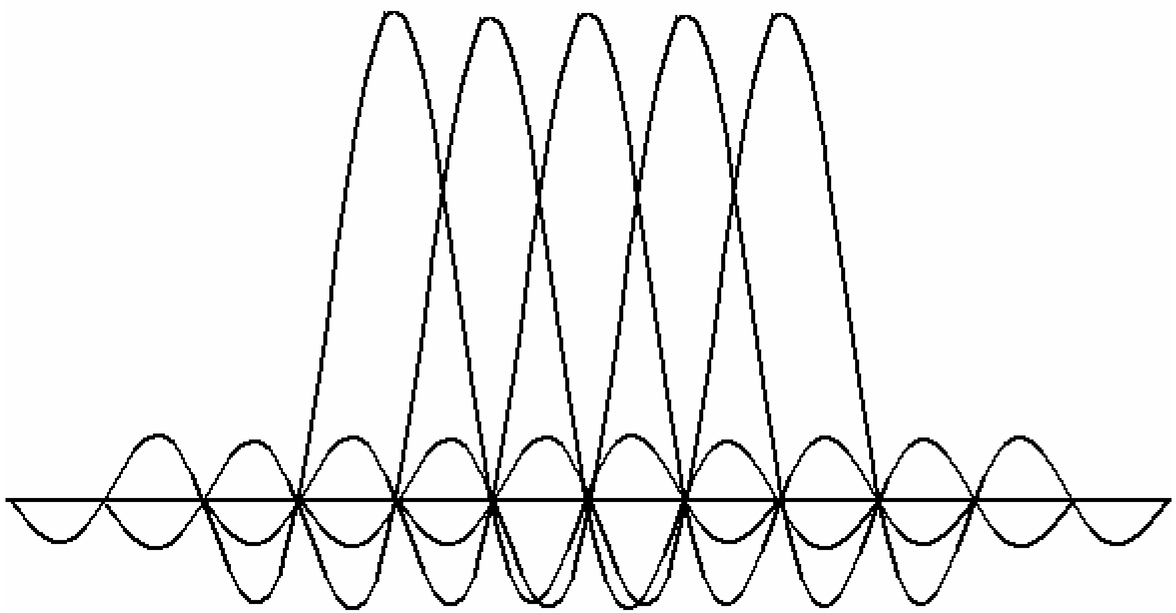
In our case

$$\int_0^{T_{os}} e^{j2\pi f_p t}.e^{-j2\pi f_q t}\,dt = 0$$

For $p \neq q$ Where $f_k = k/T_{os}$

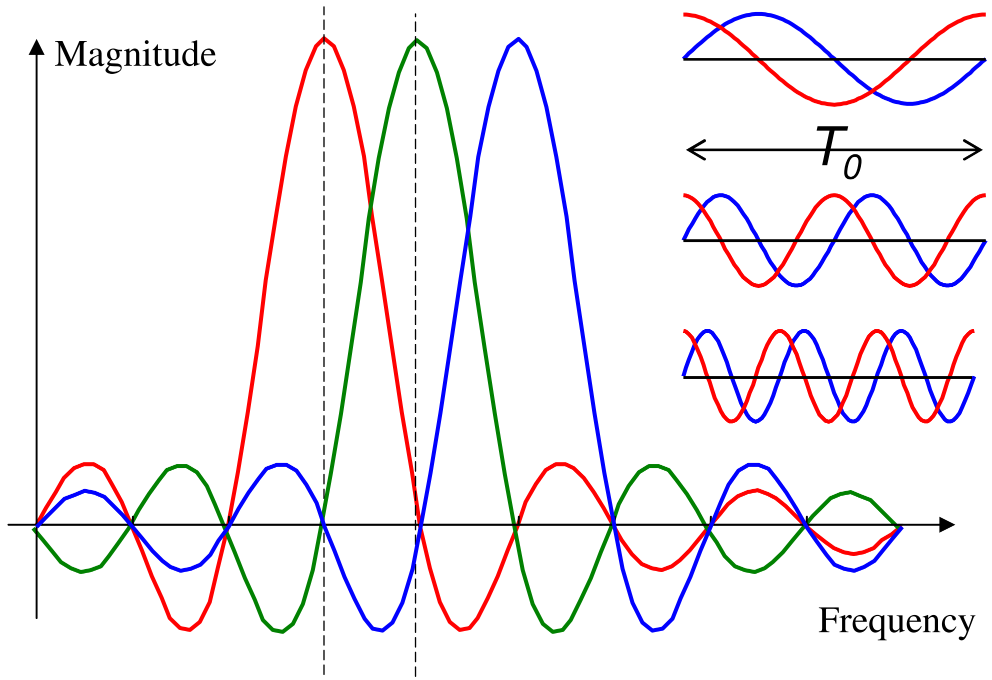
Transmitted Spectrum





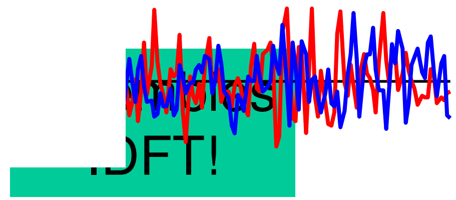
Spectrum of the modulated data symbols

- Rectangular Window of duration T_0
- Has a sinc-spectrum with zeros at $1/T_0$
- Other carriers are put in these zeros
- → sub-carriers are orthogonal



N sub-carriers:

$$s_{BB,k}(t) = w(t-kT)\sum_{i=0}^{N-1} x_{i,k}\, e^{j2\pi i\Delta f\,(t-kT)}$$



OFDM terminology

- Orthogonal carriers referred to as subcarriers $\{f_i, i=0,....N-1\}$.
- OFDM symbol period $\{T_{os}=N \times T_s\}$.
- Subcarrier spacing $\Delta f = 1/T_{os}$.

OFDM and FFT

- Samples of the multicarrier signal can be obtained using the IFFT of the data symbols - a key issue.

- FFT can be used at the receiver to obtain the data symbols.

- No need for ‘N’ oscillators,filters etc.

- Popularity of OFDM is due to the use of IFFT/FFT which have efficient implementations.

OFDM Signal

$$s(t) = \sum_{n=-\infty}^{\infty} \left(\sum_{k=0}^{N-1} X_{n,k}\, g_k (t - nT_{os}) \right)$$

$$g_k(t) = \begin{cases} e^{j2\pi f_k t} & t \equiv [0, T_{os}] \\ 0 & \text{Otherwise} \end{cases}$$

$$f_k = \frac{k}{T_{os}}$$

K=0,..........N-1

By sampling the low pass equivalent signal at a rate N times higher than the OFDM symbol rate $1/T_{os}$, OFDM frame can be expressed as:

$$F_n(m) = \sum_{k=0}^{N-1} X_{n,k}\, g_k(t - nT_{os}) \Big|_{t=(n+\frac{m}{N})T_{os}} \qquad m = 0....N\text{-}1$$

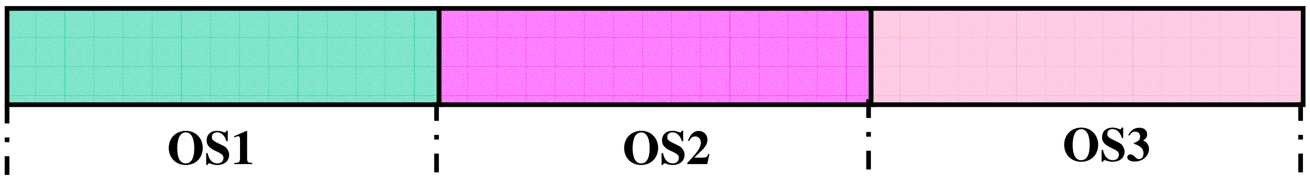
$$F_n(m) = \left(\sum_{k=0}^{N-1} X_{n,k}\, e^{j2\pi k \frac{m}{N}} \right) = N.IDFT\left\{ X_{n,k} \right\}$$

Interpretation of IFFT&FFT

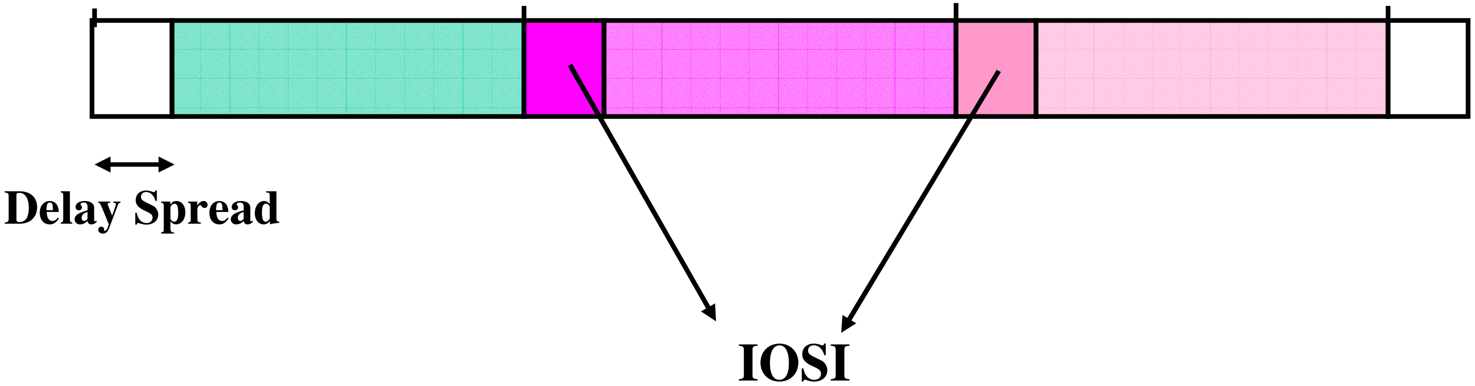
- IFFT at the transmitter & FFT at the receiver
- Data symbols modulate the spectrum and the time domain symbols are obtained using the IFFT.
- Time domain symbols are then sent on the channel.
- FFT at the receiver to obtain the data.

Interference between OFDM Symbols

- Transmitted Signal



- Due to delay spread ISI occurs



- Solution could be guard interval between OFDM symbols

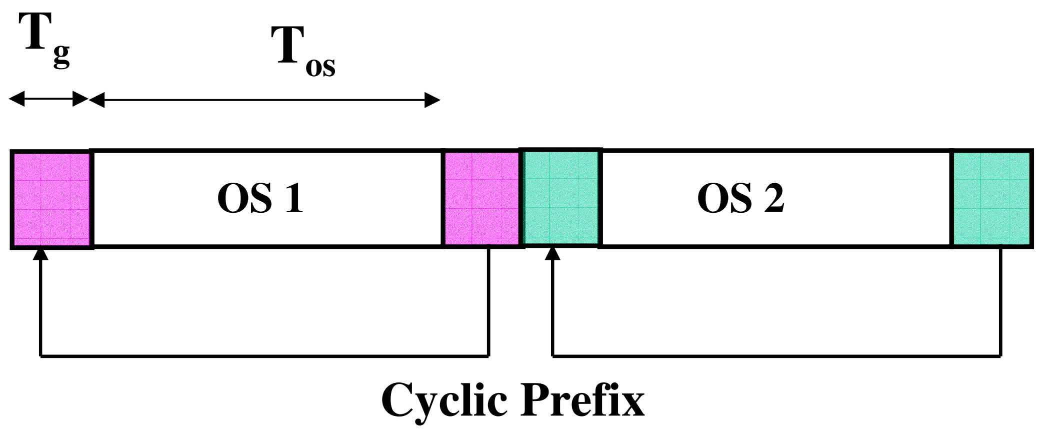
Cyclic Prefix

- Zeros used in the guard time can alleviate interference between OFDM symbols (IOSI problem).
- Orthogonality of carriers is lost when multipath channels are involved.
- Cyclic prefix can restore the orthogonality.

Cyclic Prefix

- Convert a linear convolution channel into a circular convolution channel.
- This restores the orthogonality at the receiver.
- Energy is wasted in the cyclic prefix samples.

Cyclic Prefix Illustration



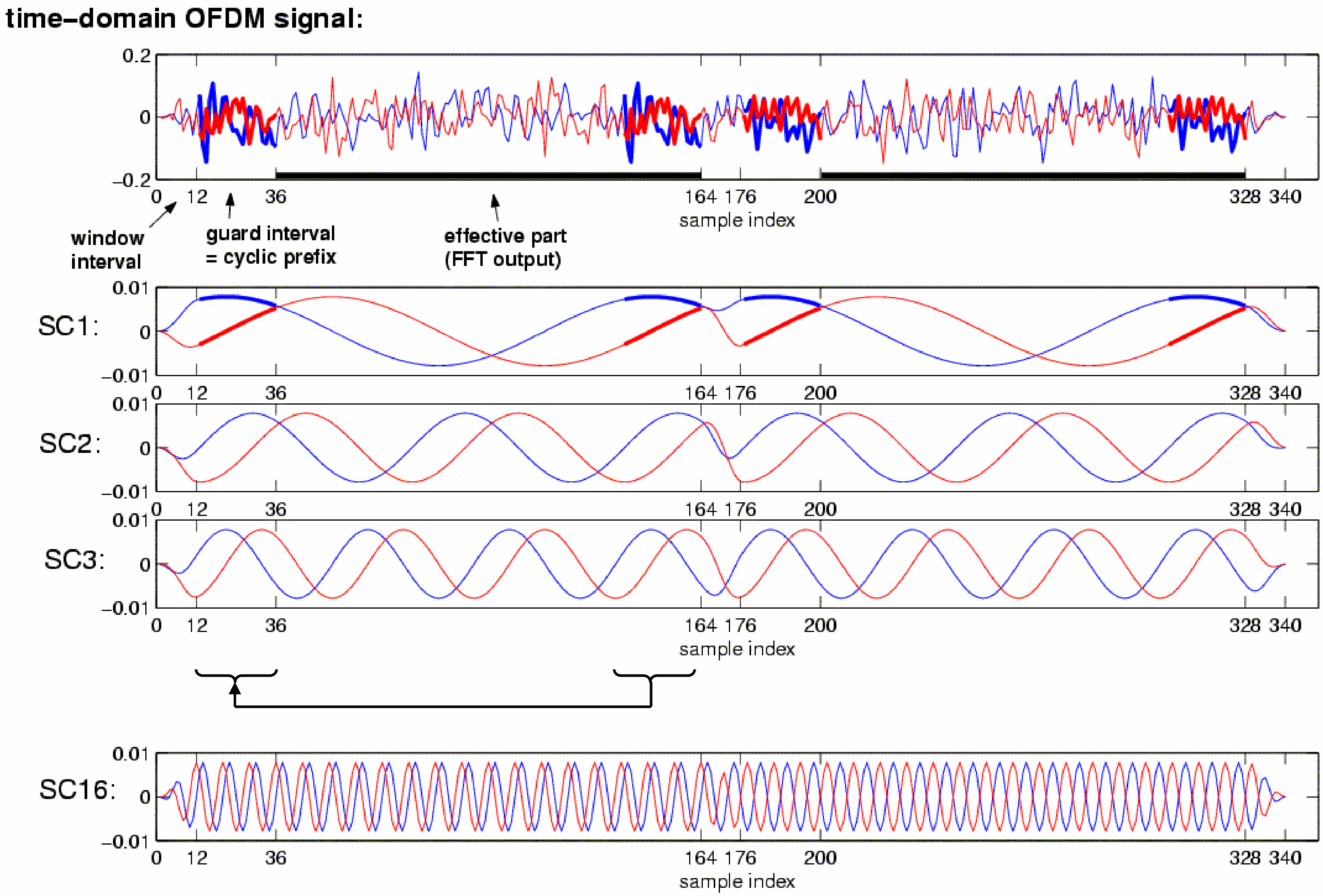
OS1,OS2 - OFDM Symbols

T_g - Guard Time Interval

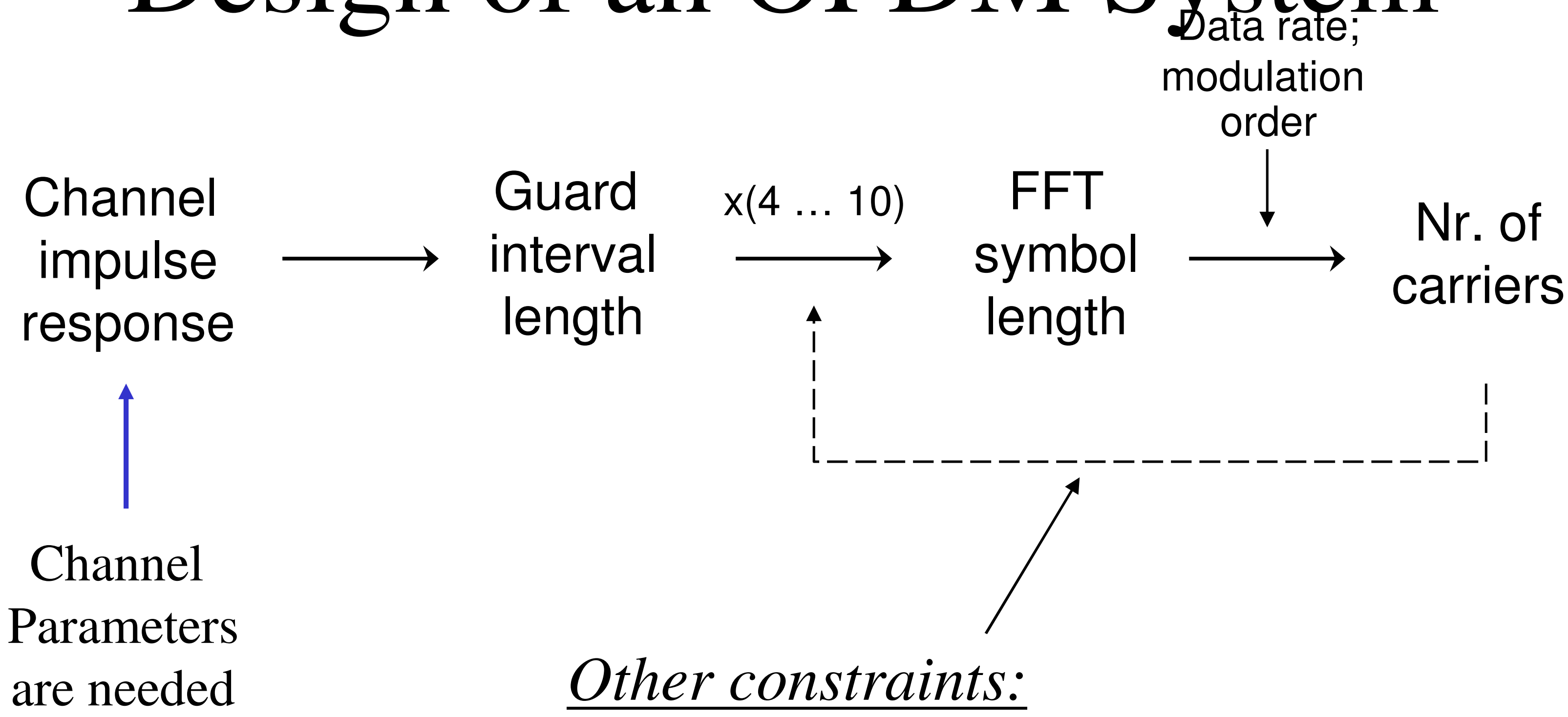
T_s - Data Symbol Period

T_{os} - OFDM Symbol Period - $N * T_s$

Guard interval (2) - Cyclic extension



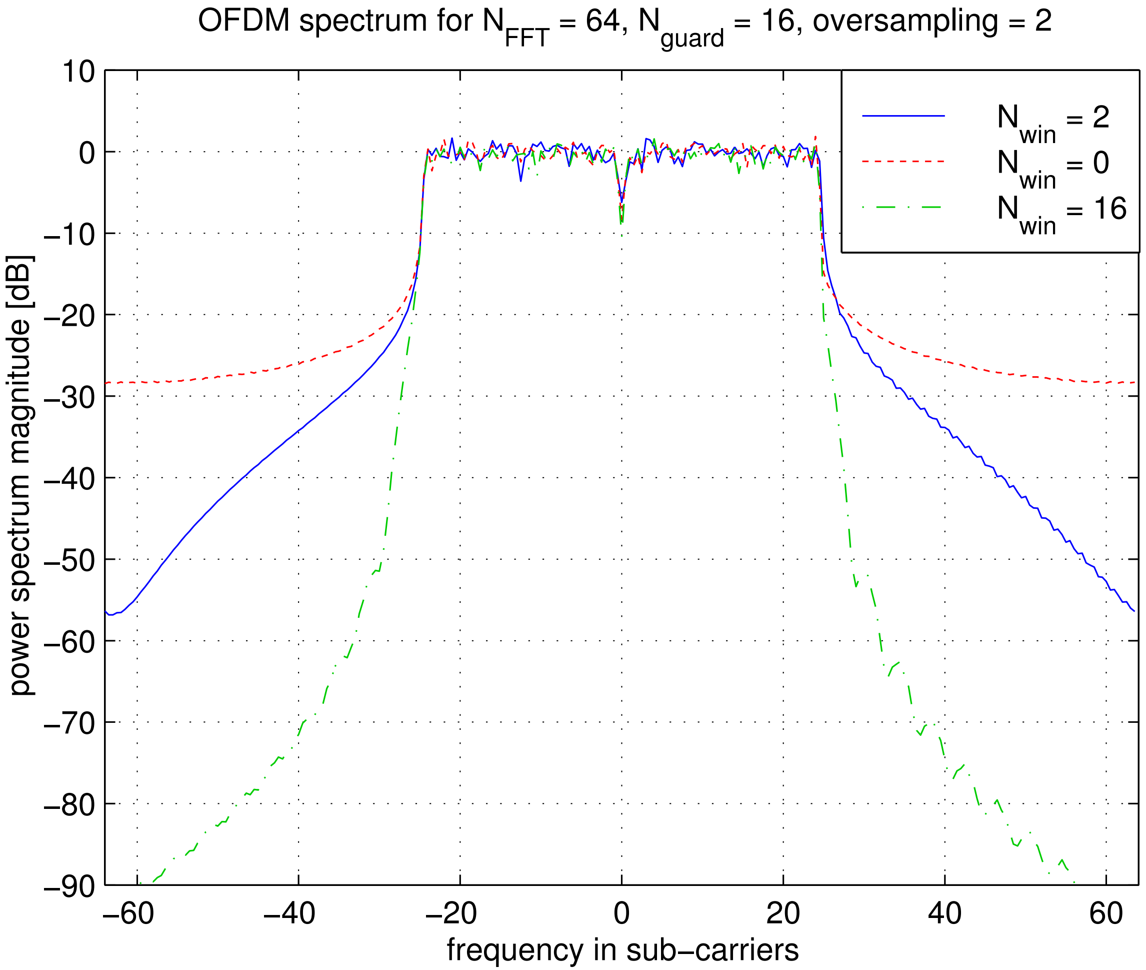
Design of an OFDM System



<u>Other constraints:</u>

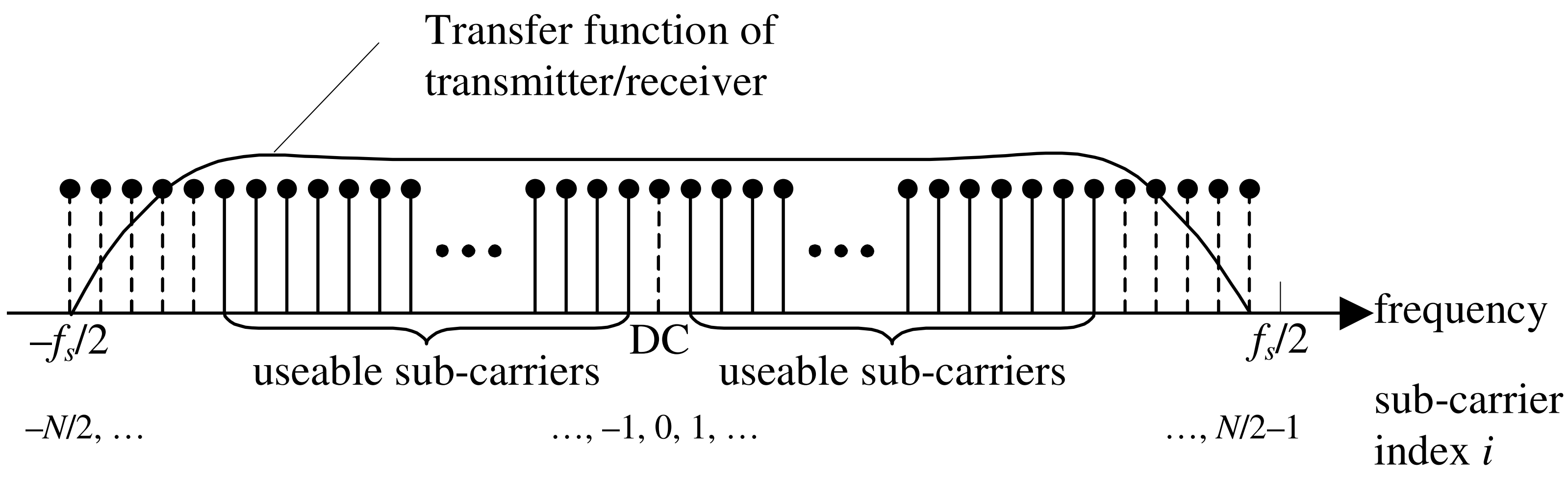
- Nr. of carriers should match FFT size and data packet length
- considering coding and modulation schemes

Spectral Shaping by Windowing



OFDM Symbol Configuration (2)

- Not all FFT-points can be used for data carriers
  - Lowpass filters for AD- and DA-conversion
    - oversampling required
  - DC offsets; carrier feedtrough; etc.

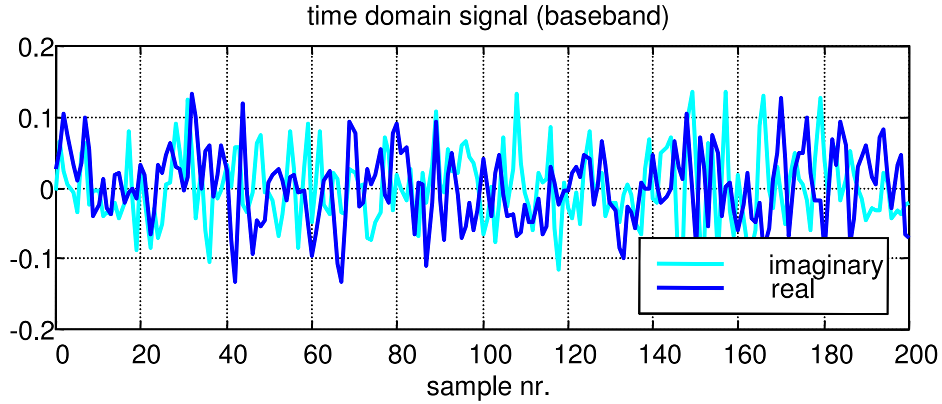


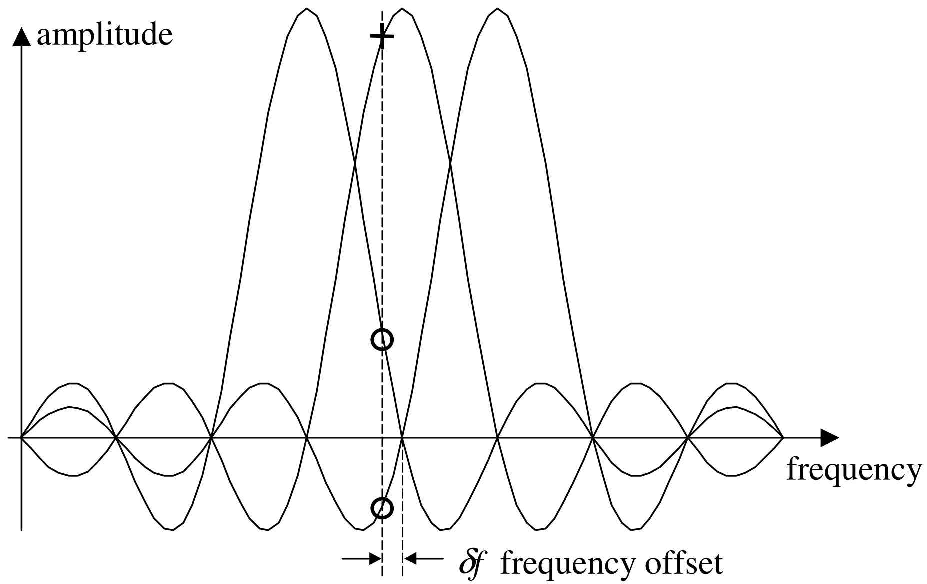
Advantages of OFDM

- Solves the multipath-propagation problem
  - Simple equalization at receiver
- Computationally efficient
  - For broadband systems more efficient than SC
- Supports several multiple access schemes
  - TDMA, FDMA, MC-CDMA, etc.
- Supports various modulation schemes
  - Adaptability to SNR of sub-carriers is possible
- Elegant framework for MIMO-systems
  - All interference among symbols is removed

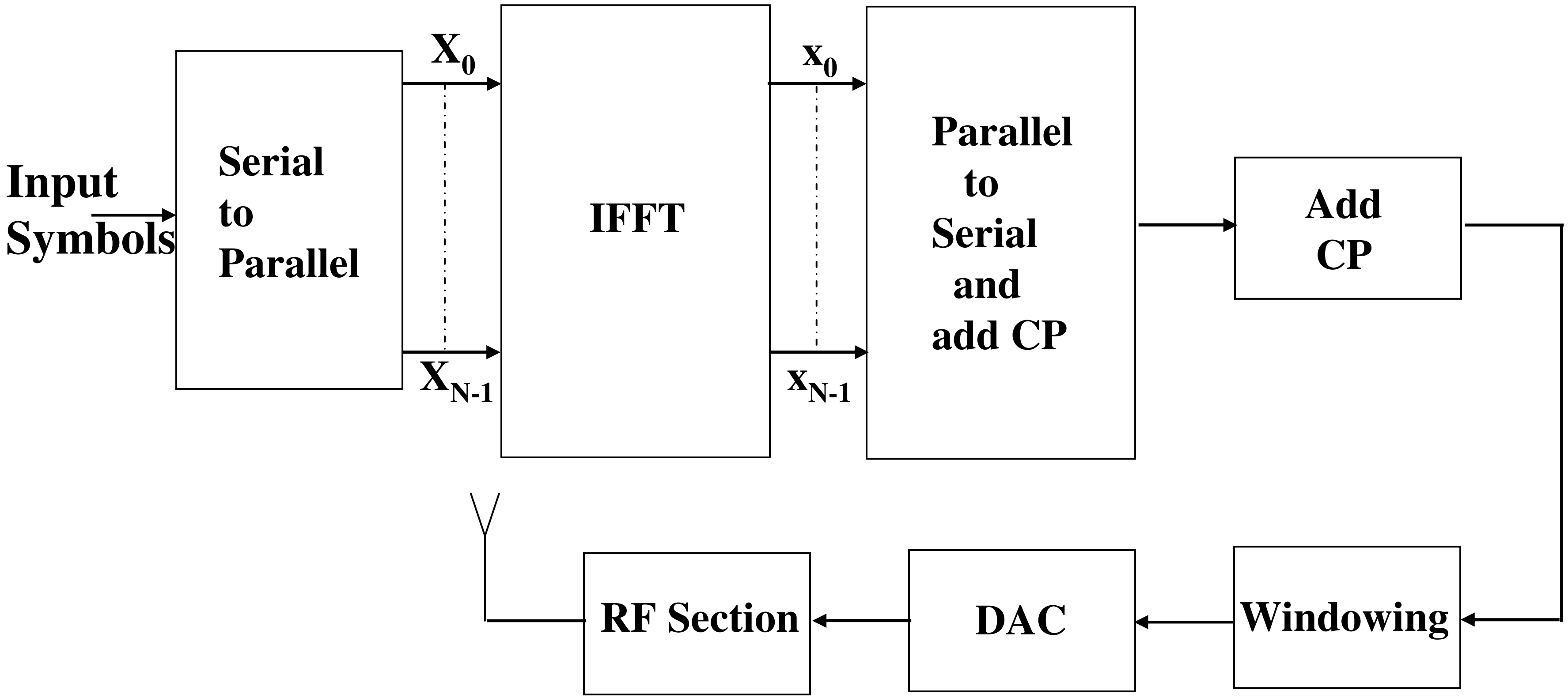
Problems of OFDM (Research Topics)

- Synchronization issues:
  - **Time synchronization**
    - Find start of symbols
  - **Frequency synchr.**
    - Find sub-carrier positions
- Non-constant power envelope
  - Linear amplifiers needed
- Channel estimation:
  - To retrieve data
  - **Channel** is **time-variant**

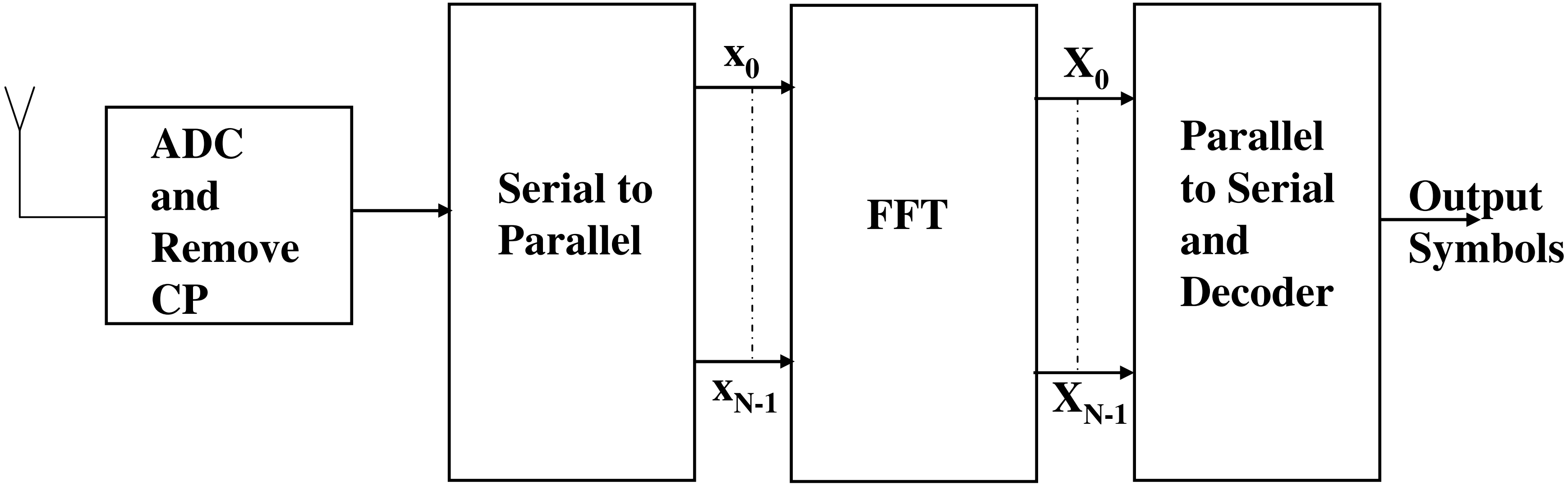




OFDM Transmitter



OFDM Receiver



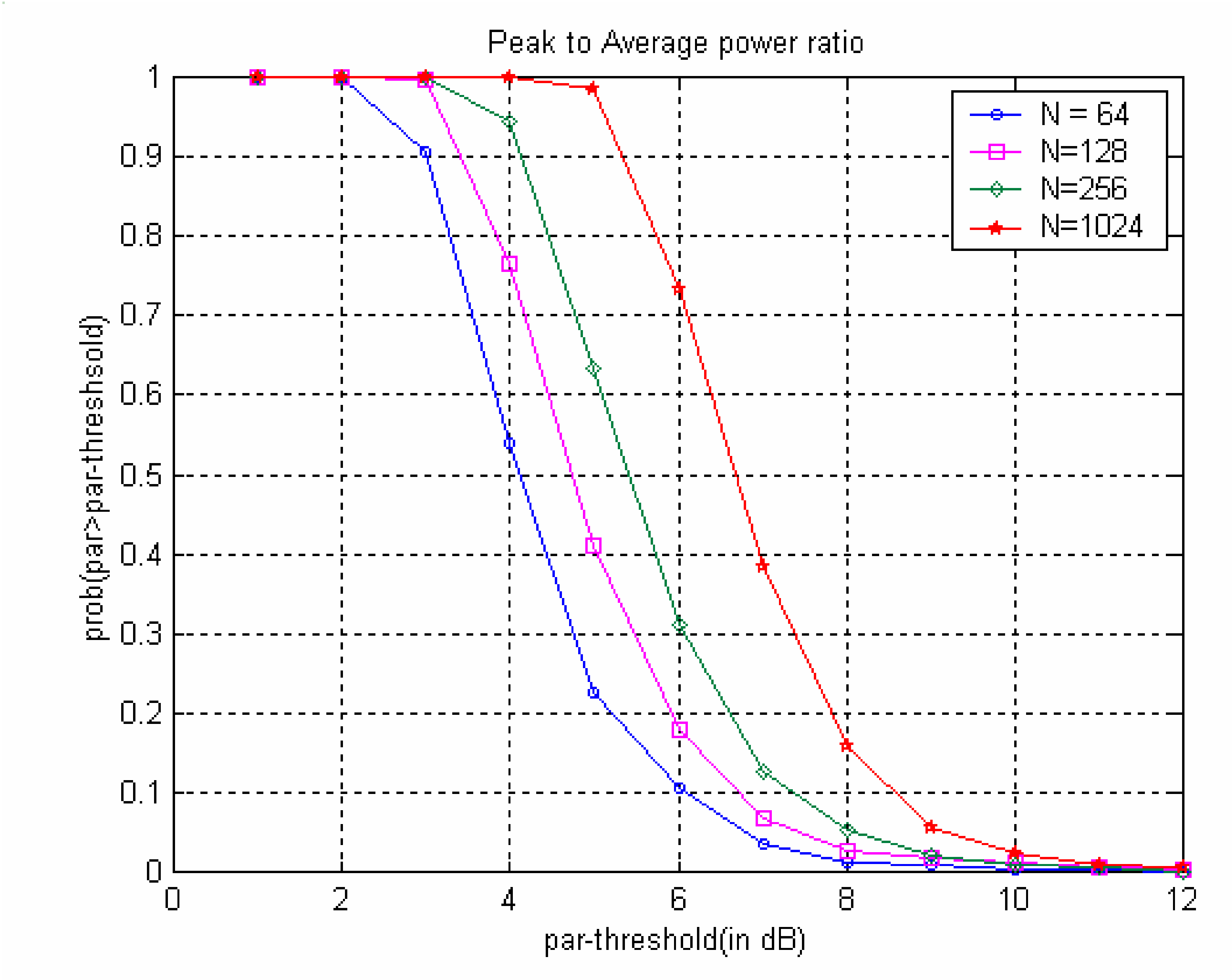
Synchronization

- Timing and frequency offset can influence performance.
- Frequency offset can influence orthogonality of subcarriers.
- Loss of orthogonality leads to Inter Carrier Interference.

Peak to Average Ratio

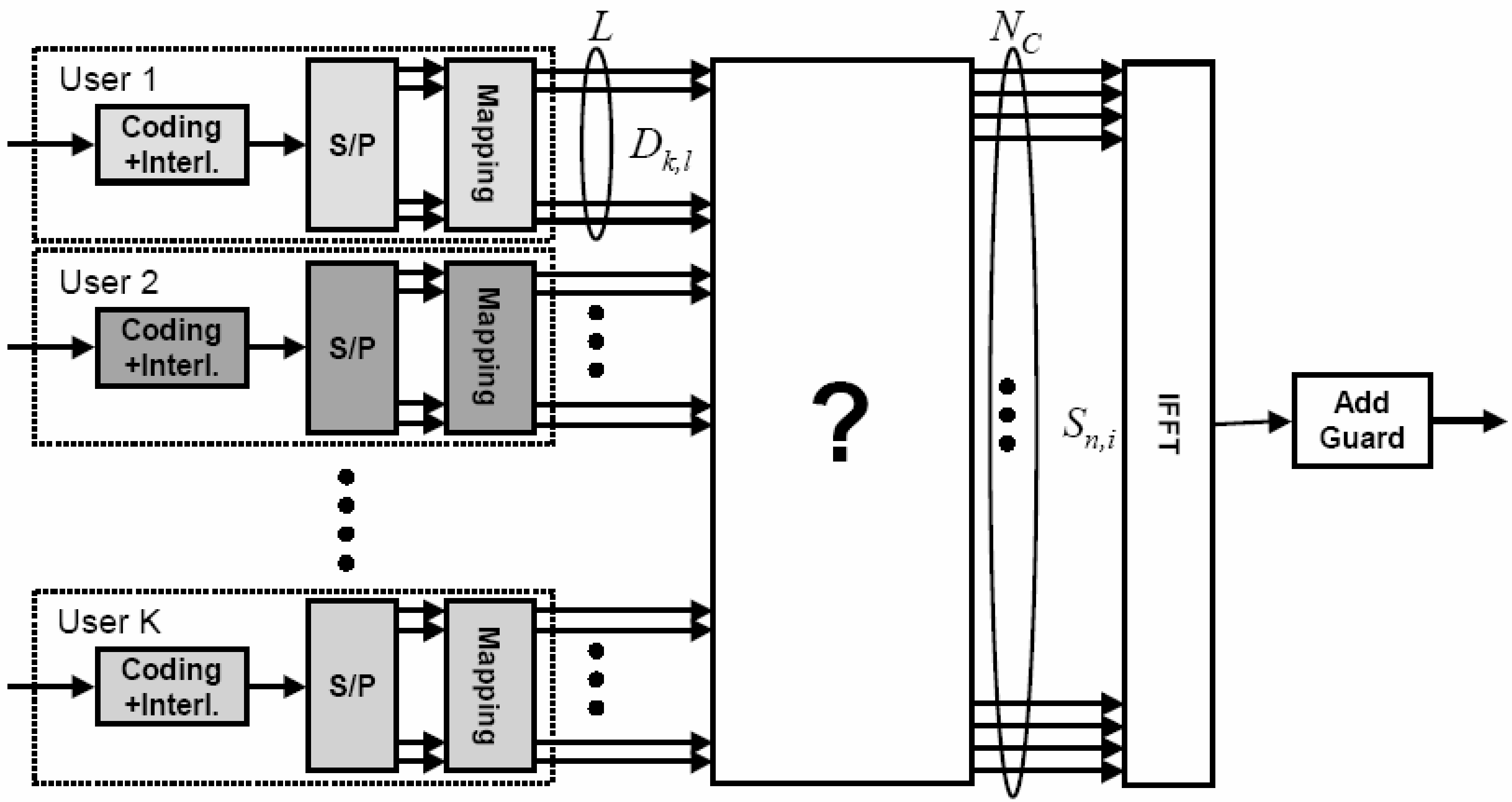
- Multicarrier signals have high PAR as compared to single carrier systems.
- PAR increases with the number of subcarriers.
- Affects power amplifier design and usage.

Peak to Average Power Ratio



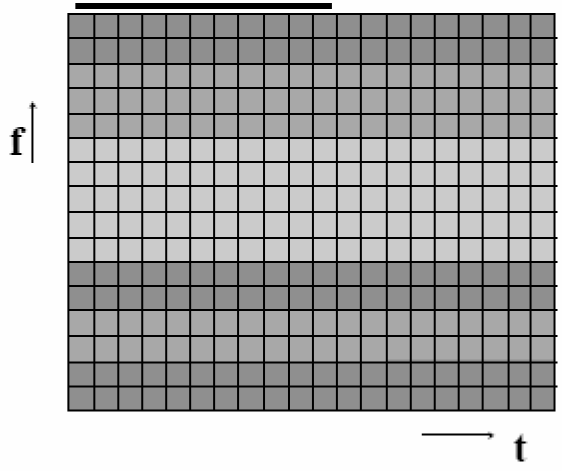
OFDM for Communication Systems

For a given OFDM system find a suitable multiple access scheme that maps the user data to a modulation block !

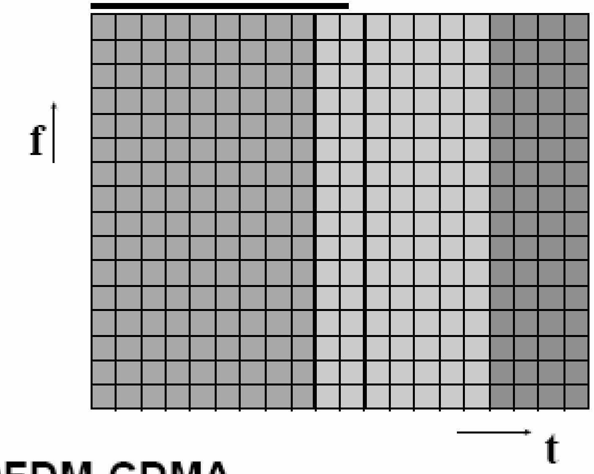


OFDM Multiple Access Schemes

OFDM-FDMA



OFDM-TDMA



OFDM-CDMA