EC 551
Telecommunication System Engineering

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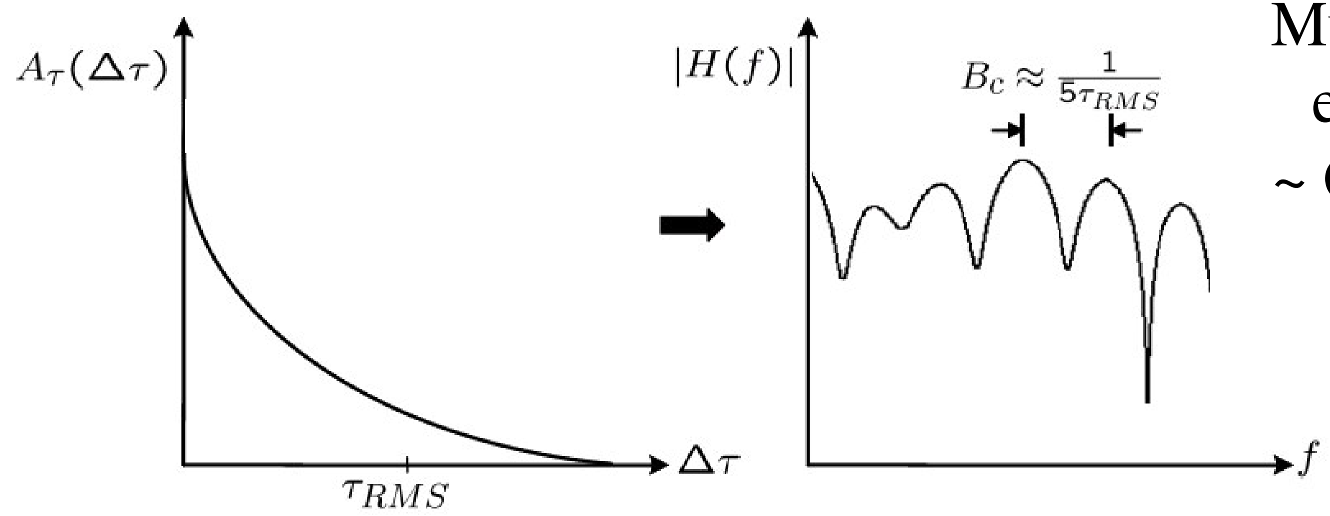
Syllabus

- Tentatively

Week 1	Overview
Week 2	**Wireless Channel characteristics**
Week 3	**OFDM and modulation techniques**
Week 4	Coding techniques in wireless systems
Week 5	WiMax Physical Layer
Week 6	WiMax MAC Layer
Week 7	WLAN Physical Layer
Week 8	WLAN MAC Layer
Week 9	Cellular Communication Concept
Week 10	FDMA, TDMA, CDMA and Duplexing
Week 11	GSM System
Week 12	GPRS System
Week 13	UMTS
Week 14	IP networks
Week 15	VOIP

<u>Multipath</u>: Time-Dispersion => Frequency Selectivity

- The impulse response of the channel is correlated in the time-domain (sum of "echoes")
  - Manifests as a power-delay profile.
- Equivalent to "selectivity" or "deep fades" in the frequency domain
- **<u>Delay spread</u>:** τ ~ *50ns (indoor) – 1µs (outdoor/cellular).*
- **<u>Coherence Bandwidth</u>**: Bc = *500kHz (outdoor/cellular) – 20MHz (indoor)*
- <u>Implications</u>: High data rate: symbol smears onto the adjacent ones (ISI).



Multipath effects ~ O(1µs)

the shape of the multipath intensity profile $A_\tau(\Delta\tau)$ determines the correlation pattern of the channel frequency response (bottom)

<u>Doppler</u>: Dispersion (Frequency) => Time-Selectivity

- The doppler power spectrum shows dispersion/flatness ~ doppler spread (100-200 Hz for vehicular speeds)
  - Equivalent to "selectivity" or "deep fades" in the time domain correlation envelope.
  - Each envelope point in time-domain is drawn from Rayleigh distribution. But because of Doppler, it is not IID, but correlated for a time period ~ Tc (correlation time).
- **<u>Doppler Spread</u>:** Ds ~ 100 Hz (vehicular speeds @ 1GHz)
- **<u>Coherence Time</u>**: Tc = 2.5-5ms.
- Implications: A deep fade on a tone can persist for 2.5-5 ms! Closed-loop estimation is valid only for 2.5-5 ms.

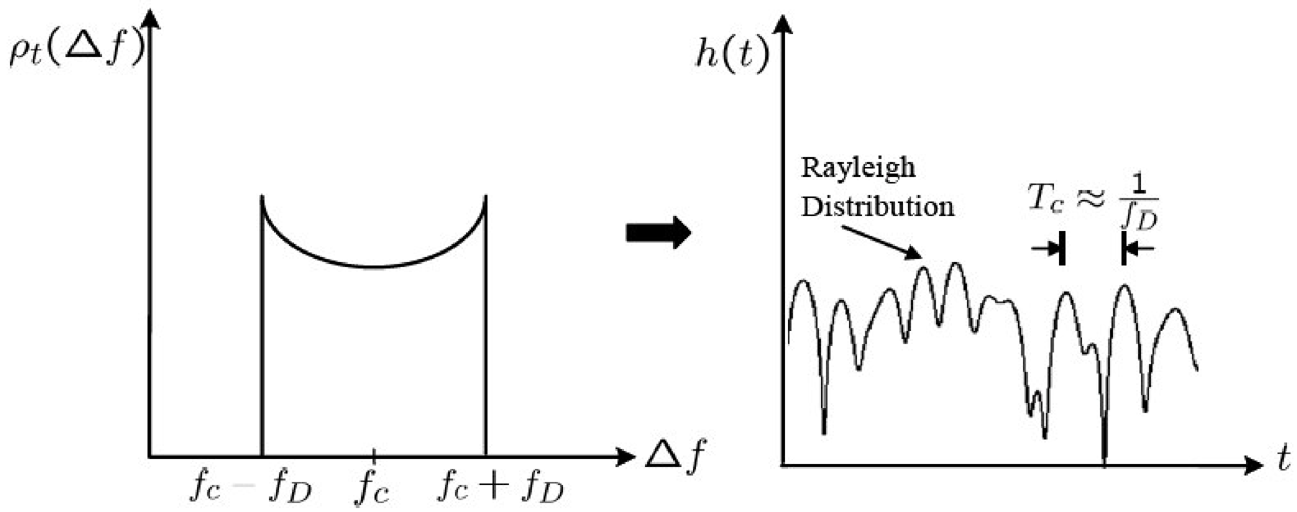


Figure 3.18: The shape of the Doppler power spectrum $\rho_t(\Delta f)$ determines the correlation envelope of the channel in time (top).

Fading Summary: Time-Varying Channel Impulse Response

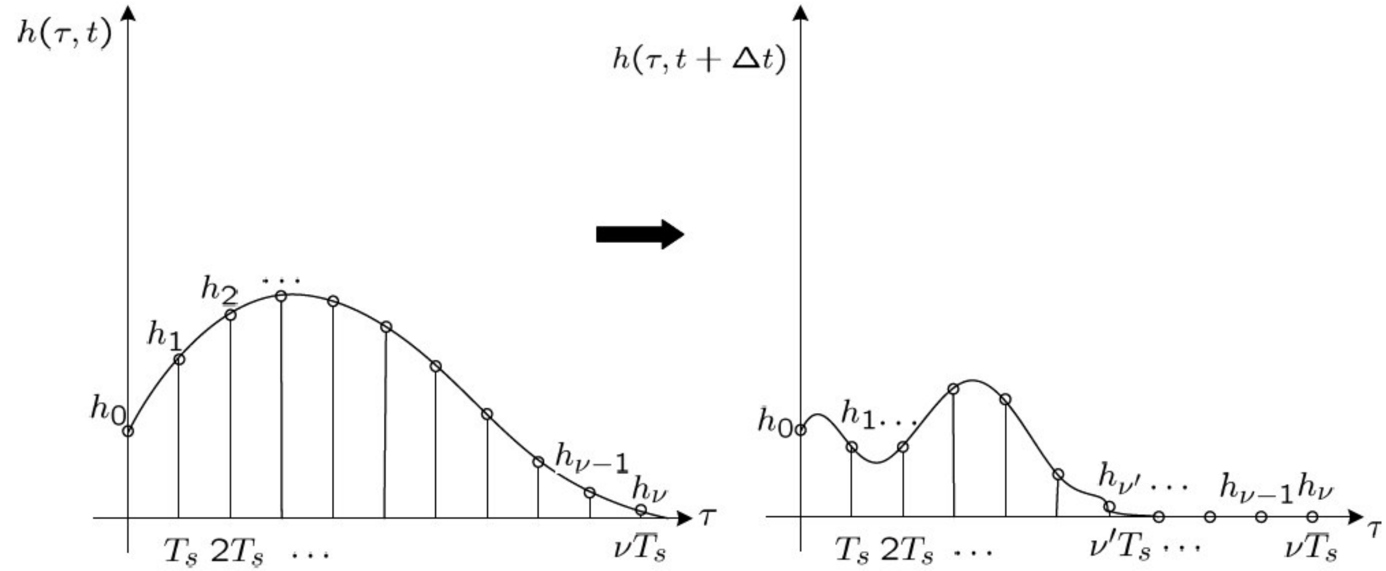


Figure 3.12: The delay τ corresponds to how *long* the channel impulse response lasts. The channel is time varying, so the channel impulse response is also a function of time, i.e. $h(\tau,t)$, and can be quite different at time $t+\Delta t$ than it was at time t.

- **#1:** At each tap, channel gain |h| is a Rayleigh distributed *r.v.*. The random *process* is not IID.
- **#2:** Response spreads out in the time-domain (τ), leading to inter-symbol interference and deep fades in the frequency domain: "***frequency-selectivity***" caused by multi-path fading
- **#3:** Response completely vanish (deep fade) for certain values of t: "***Time-selectivity***" caused by doppler effects (frequency-domain dispersion/spreading)

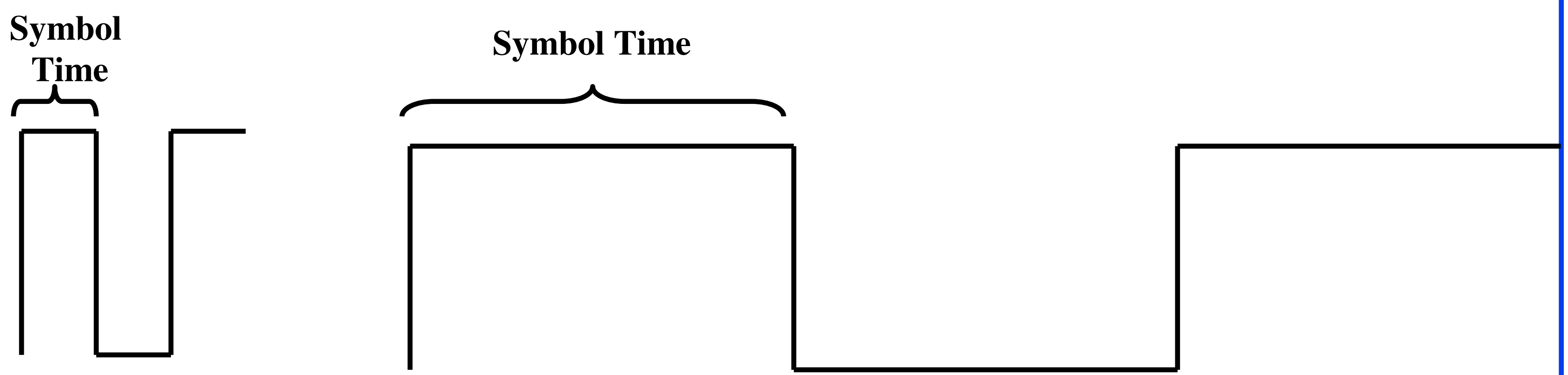
Fading: Jargon

- **<u>Flat fading</u>**: no multipath ISI effects.
  - Eg: narrowband, indoors
- **<u>Frequency-selective fading:</u>** multipath ISI effects.
  - Eg: broadband, outdoor.

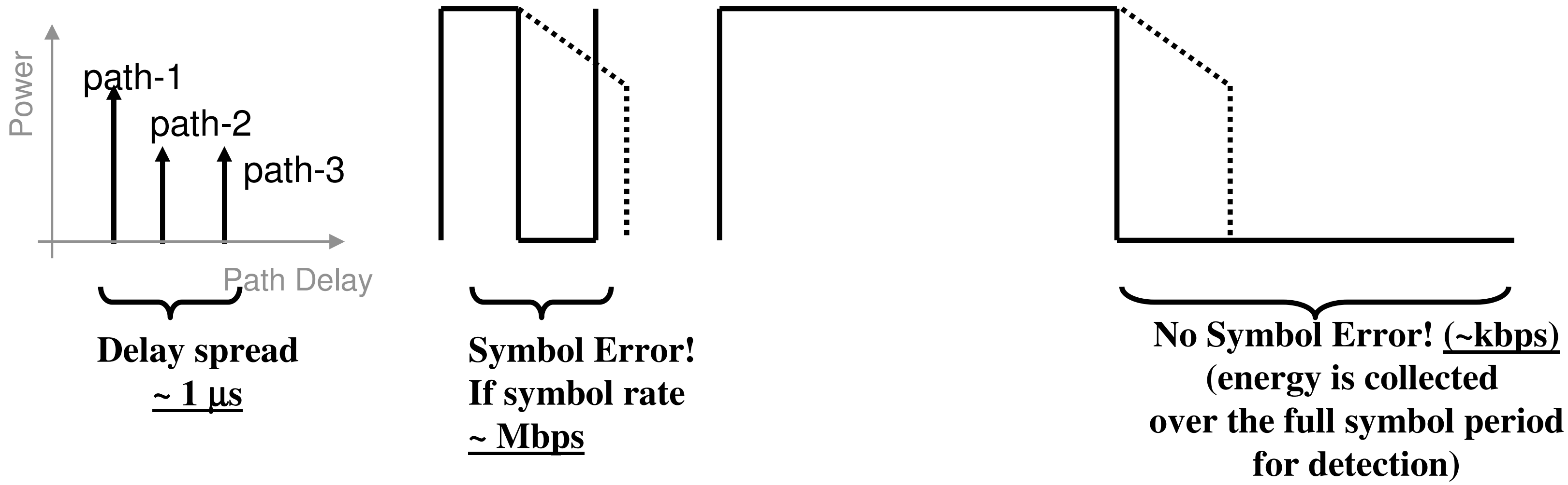
- **<u>Slow fading:</u>** no doppler effects.
  - Eg: indoor Wifi home networking
- **<u>Fast Fading:</u>** doppler effects, time-selective channel
  - Eg: cellular, vehicular

- Broadband cellular + vehicular => Fast + frequency-selective

Power Delay Profile => Inter-Symbol interference



- Higher bandwidth => higher symbol rate, and smaller time per-symbol
- Lower symbol rate, more time, energy per-symbol
- If the delay spread is longer than the symbol-duration, symbols will "smear" onto adjacent symbols and cause symbol errors



Multipath Fading Example

Example 3.5:

Consider a wideband channel with multipath intensity profile

$$A_c(\tau) = \begin{cases} e^{-\tau/.00001} & 0 \le \tau \le 20 \ \mu\text{sec.} \\ 0 & \text{else} \end{cases} .$$

Find the mean and rms delay spreads of the channel and find the maximum symbol rate such that a linearly-modulated signal transmitted through this channel does not experience ISI.

Solution: The average delay spread is

$$\mu_{T_m} = \frac{\int_0^\infty \tau A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau},$$

$$\mu_{T_m} = \frac{\int_0^{20*10^{-6}} \tau e^{-\tau/.00001} d\tau}{\int_0^{20*10^{-6}} e^{-\tau/.00001} d\tau} = 6.87 \ \mu\text{sec.}$$

The rms delay spread is

$$\sigma_{T_m} = \sqrt{\frac{\int_0^\infty (\tau - \mu_{T_m})^2 A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau}}.$$

$$\sigma_{T_m} = \sqrt{\frac{\int_0^{20*10^{-6}} (\tau - \mu_{T_m})^2 e^{-\tau} d\tau}{\int_0^{20*10^{-6}} e^{-\tau} d\tau}} = 5.25 \ \mu\text{sec.}$$

We see in this example that the mean delay spread is roughly equal to its rms value. To avoid ISI we require linear modulation to have a symbol period T_s that is large relative to σ_{T_m}. Taking this to mean that $T_s > 10\sigma_{T_m}$ yields a symbol period of $T_s = 52.5\,\mu$sec or a symbol rate of $R_s = 1/T_s = 19.04$ Kilosymbols per second. This is a highly constrained symbol rate for many wireless systems. Specifically, for binary modulations where the symbol rate equals the data rate (bits per second, or bps), high-quality voice requires on the order of 32 Kbps and high-speed data requires on the order of 10-100 Mbps.

Key Wireless Channel Parameters

Table 3.1: Key wireless channel parameters

Symbol	Parameter
α	path loss exponent
σ_s	Log normal shadowing standard deviation
f_D	Doppler spread (maximum Doppler frequency), $f_D = \frac{v f_c}{c}$
T_c	Channel coherence time, $T_c \approx f_D^{-1}$
$\tau_{\max}$	Channel delay spread (maximum)
τ_{RMS}	Channel delay spread (RMS)
B_c	Channel coherence bandwidth, $B_c \approx \tau^{-1}$
~~θ_{RMS}~~	~~Angular spread (RMS)~~

Fading: Design Impacts (Eg: Wimax)

Table 3.3: Summary of Broadband Fading Parameters, with Rules of Thumb

Quantity	If "Large"?	If "Small"?	WiMAX Design Impact
Delay Spread, τ	If $\tau \gg T$, then frequency selective	If $\tau \ll T$, then frequency flat	The larger the delay spread relative to the symbol time, the more severe the ISI.
Coherence Bandwidth, B_c	If $\frac{1}{B_c} \ll T$, then frequency flat	If $\frac{1}{B_c} \gg T$, then frequency selective	Provides a guideline to subcarrier width $B_{sc} \approx B_c/10$, and hence number of subcarriers needed in OFDM: $L \geq 10B/B_c$.
Doppler spread, $f_D = \frac{f_c v}{c}$	If $f_c v \gg c$, then fast fading	If $f_c v \leq c$, then slow fading	As f_D/B_{sc} becomes nonnegligible, subcarrier orthogonality is compromised
Coherence Time, T_c	If $T_c \gg T$, then slow fading	If $T_c \leq T$, then fast fading	T_c small necessitates frequent channel estimation and limits the OFDM symbol duration, but provides greater time diversity.

Orthogonal Frequency Division Multiplexing

Motivation

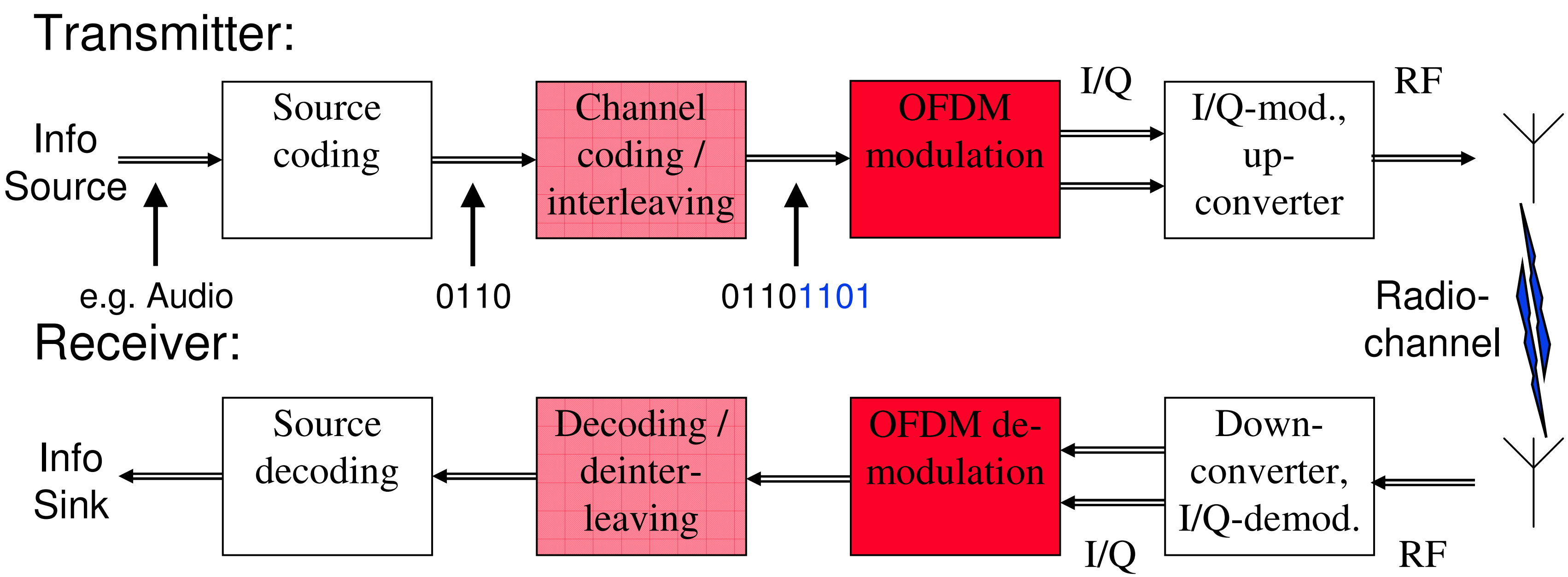
- High bit-rate wireless applications in a multipath radio environment.

- 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.

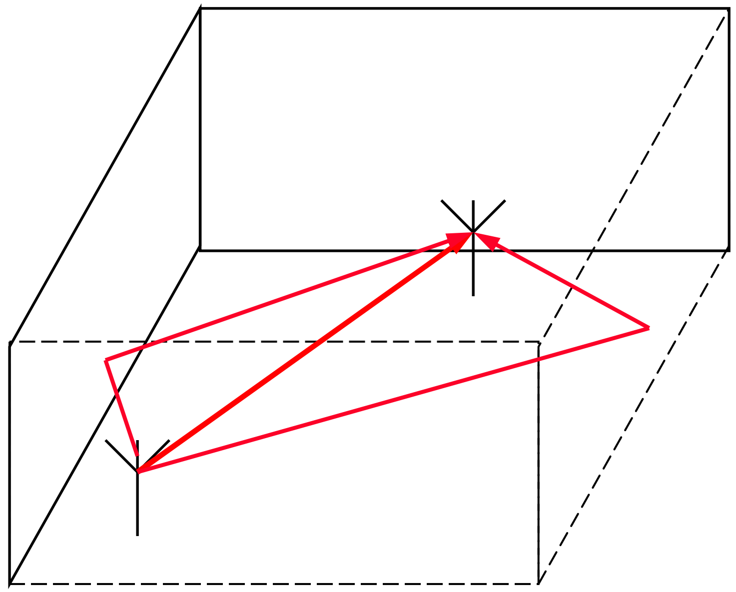
What is OFDM?

- Modulation technique
  - Requires channel coding
  - Solves multipath problems

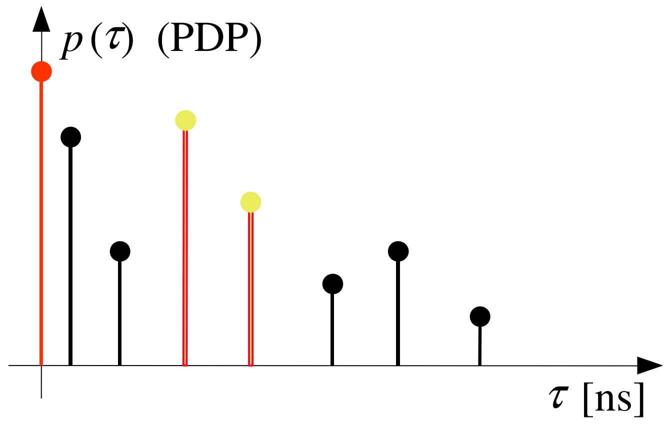


Multipath Propagation

- Reflections from walls, etc.



- Time dispersive channel
  - Impulse response:



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

Inter-Symbol-Interference

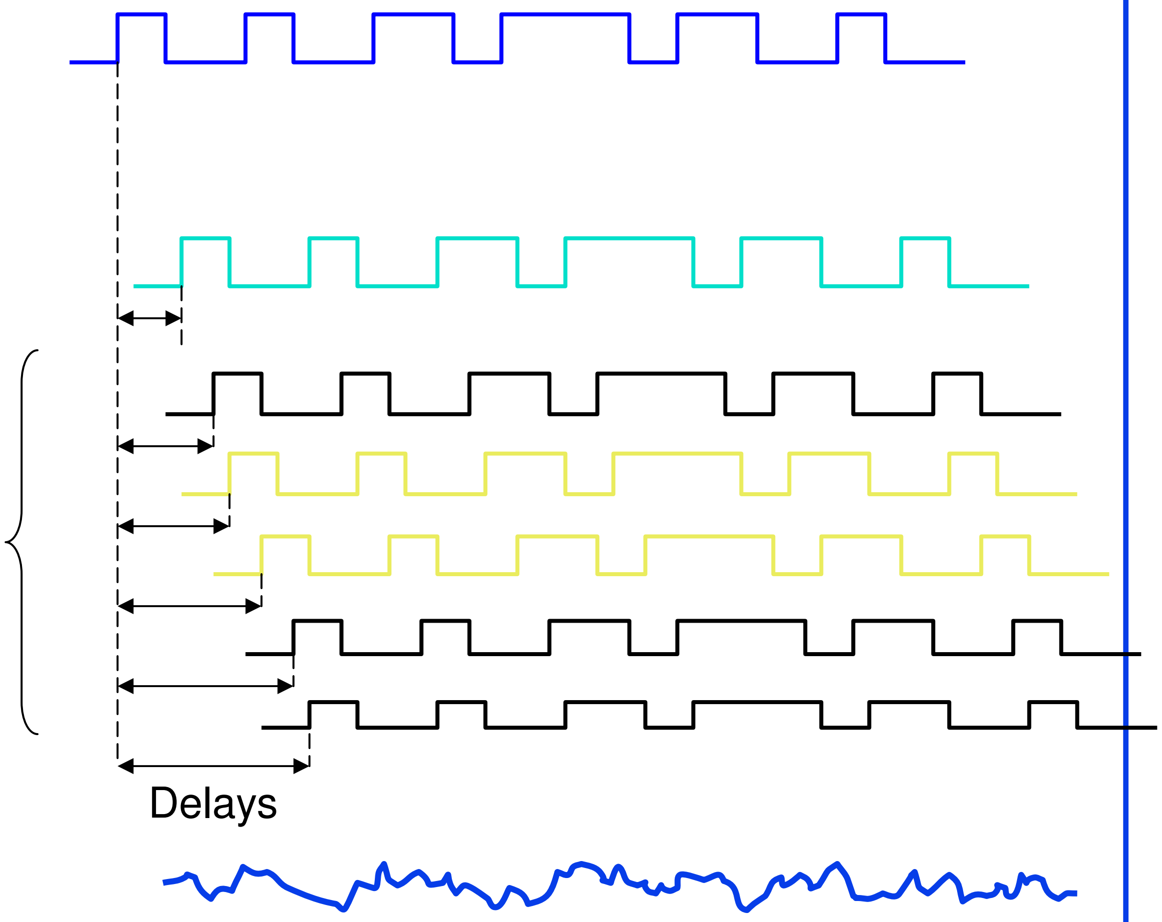
Transmitted signal:

Received Signals:

Line-of-sight:

Reflected:

The **symbols add up** on the channel



→ **Distortion!**

Concept of parallel transmission (1)

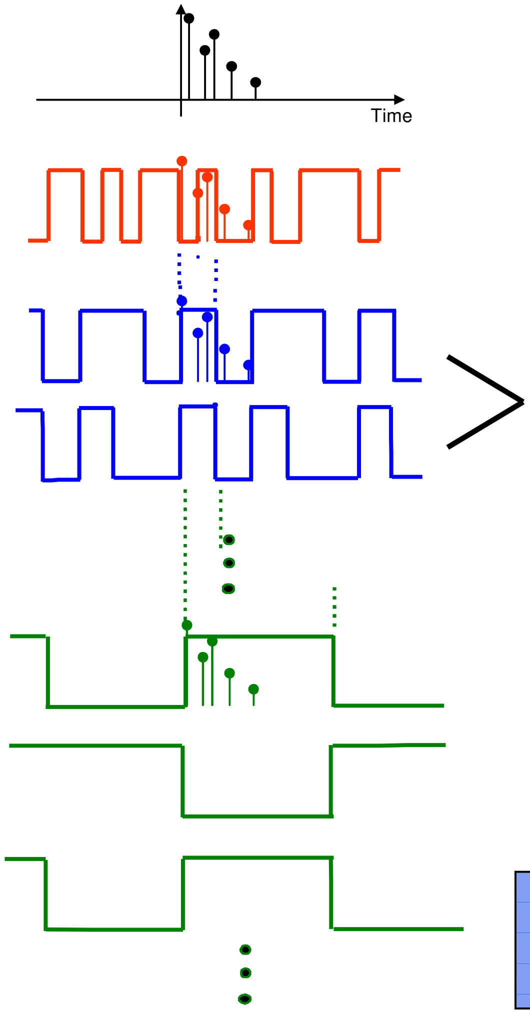
Channel impulse response

1 Channel (serial)

2 Channels

8 Channels

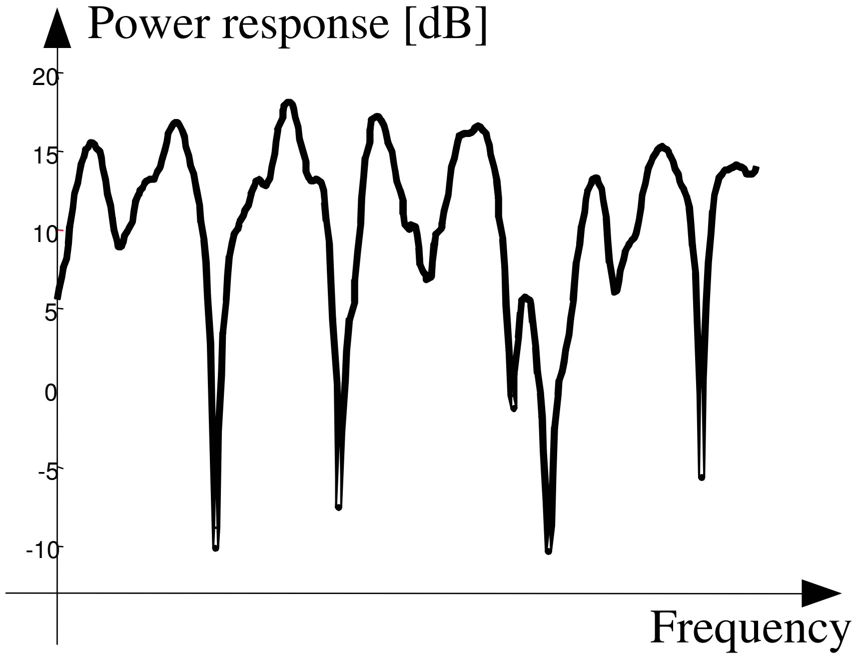
⋮



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

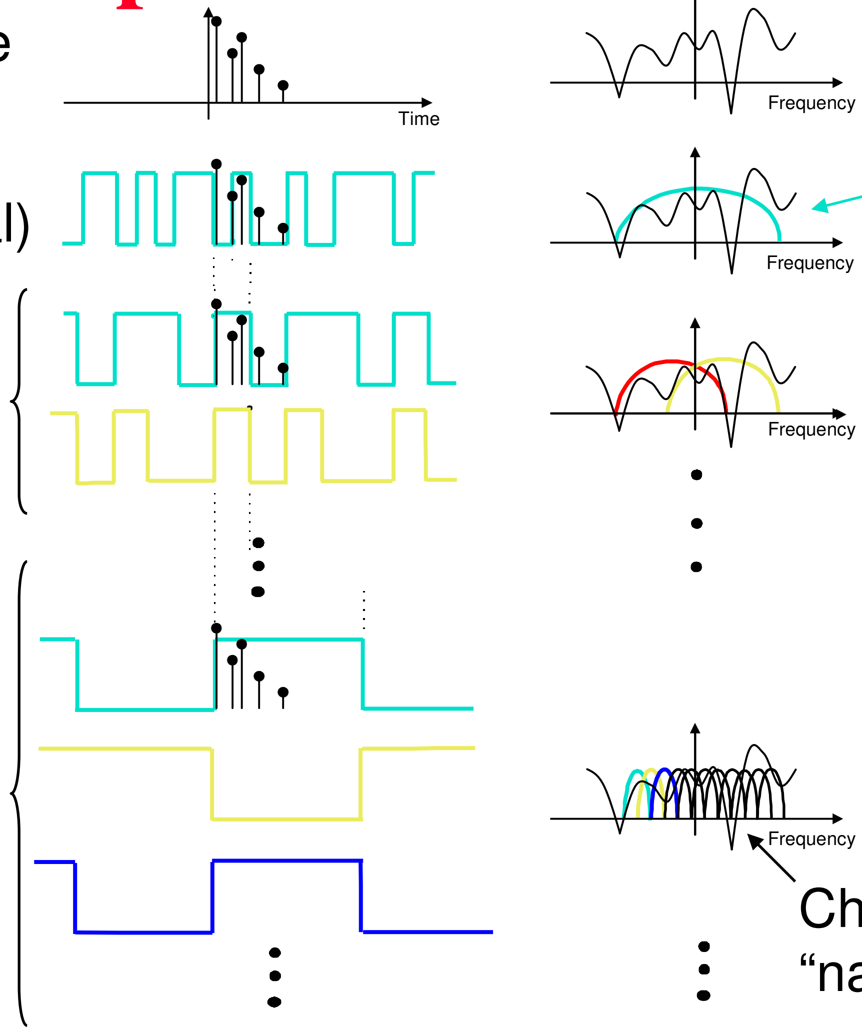
Concept of parallel transmission (2)

Channel impulse response

1 Channel (serial)

2 Channels

8 Channels

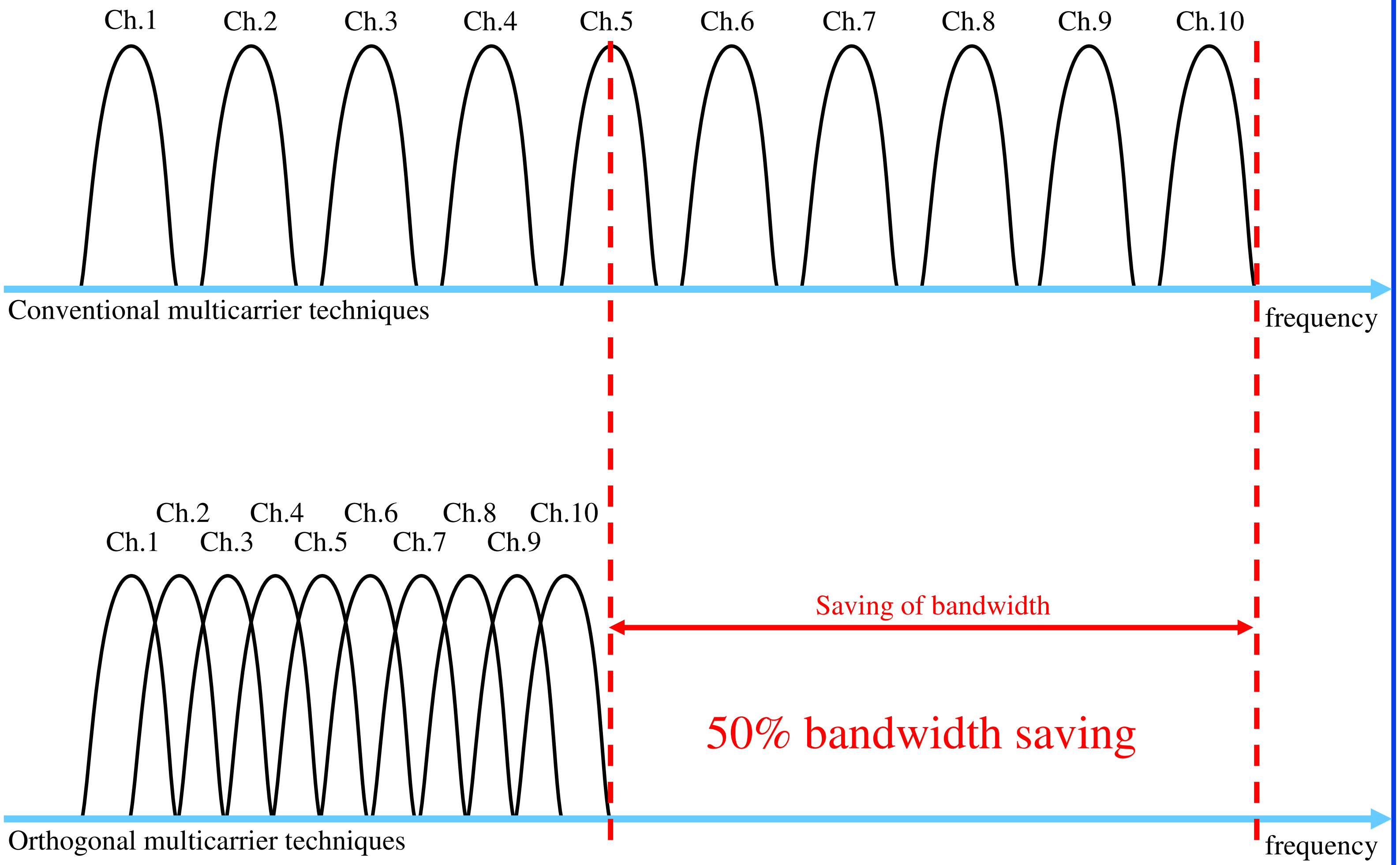


Channel transfer function

Signal is "broadband"

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

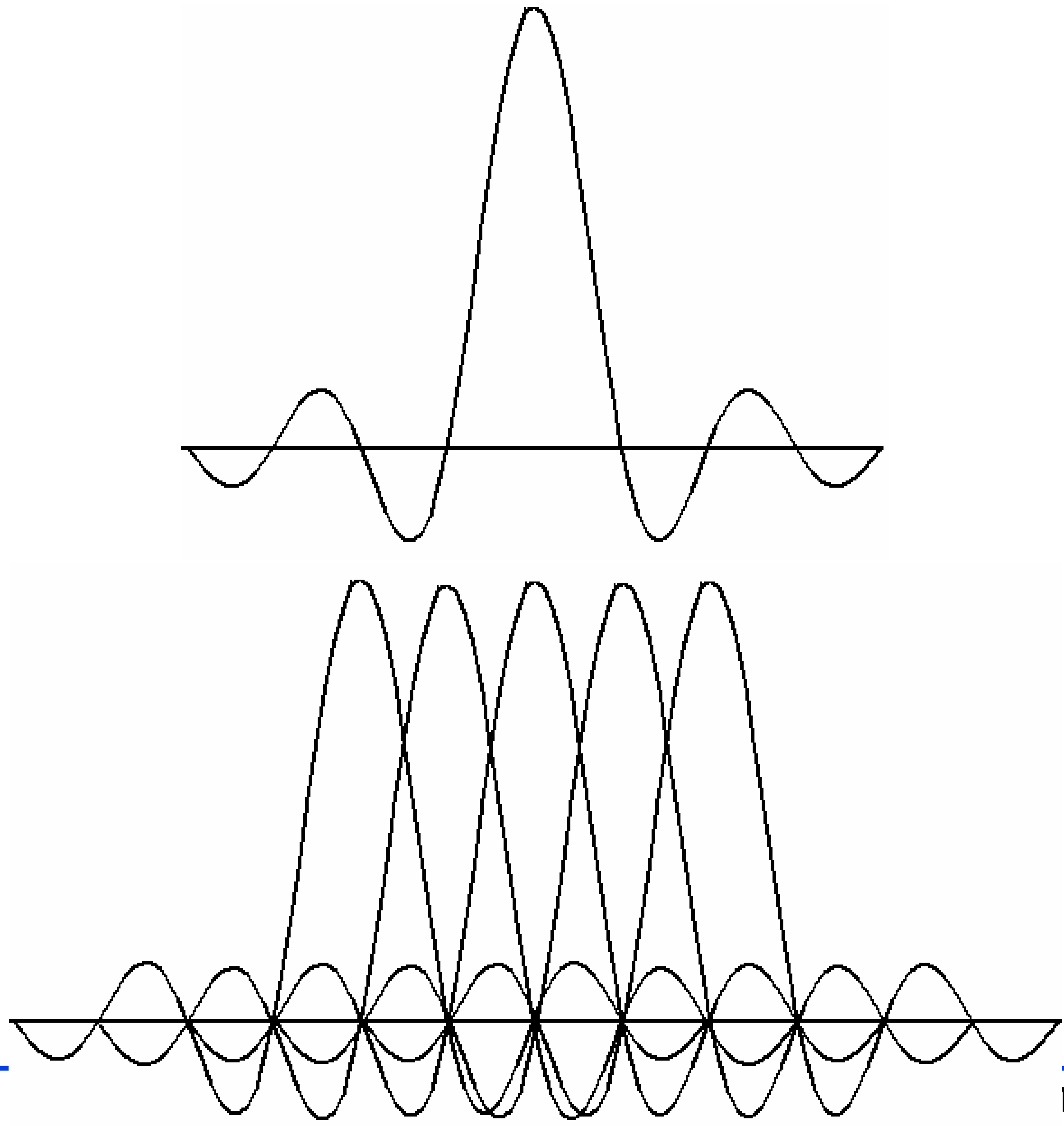
$$\int_0^{T_{os}} g_1(t).g_2^*(t)dt = 0$$

In our case

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

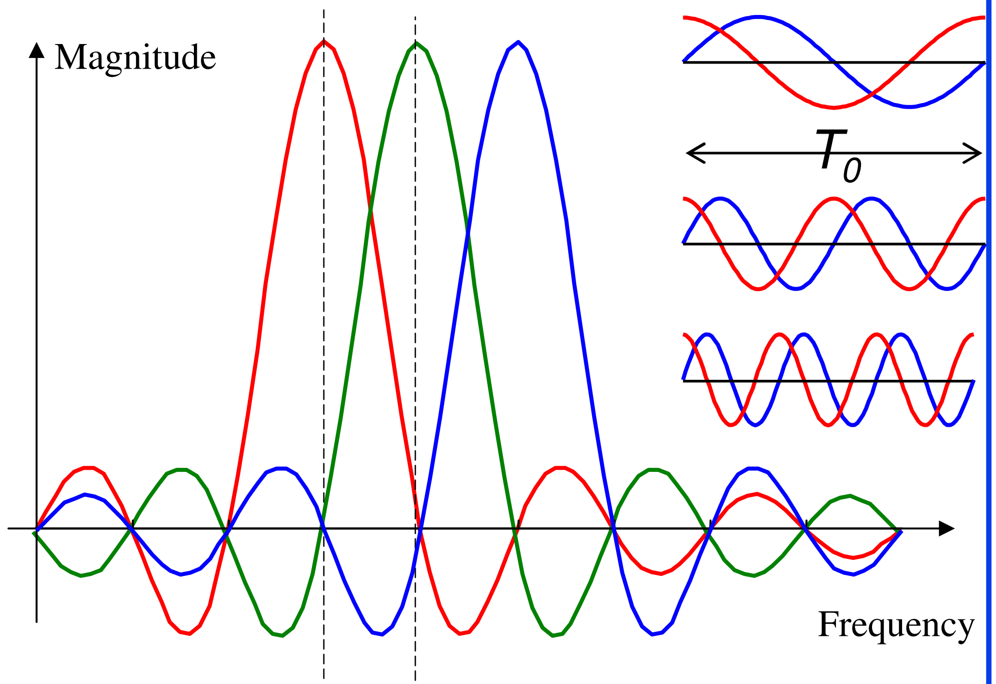
For $p \neq q$ Where $f_k = k/T_{os}$

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.

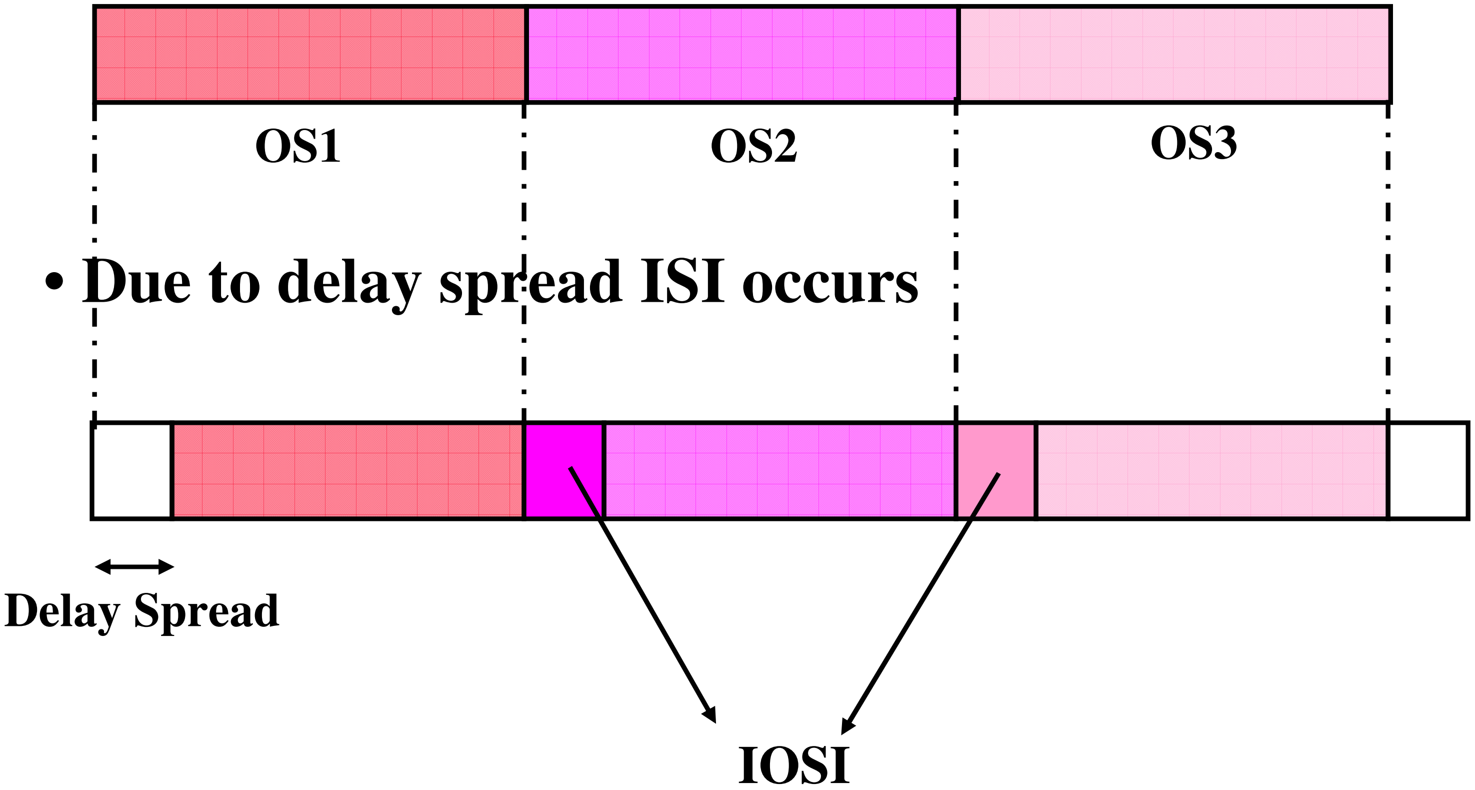
- Popularity of OFDM is due to the use of IFFT/FFT which have efficient implementations.

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

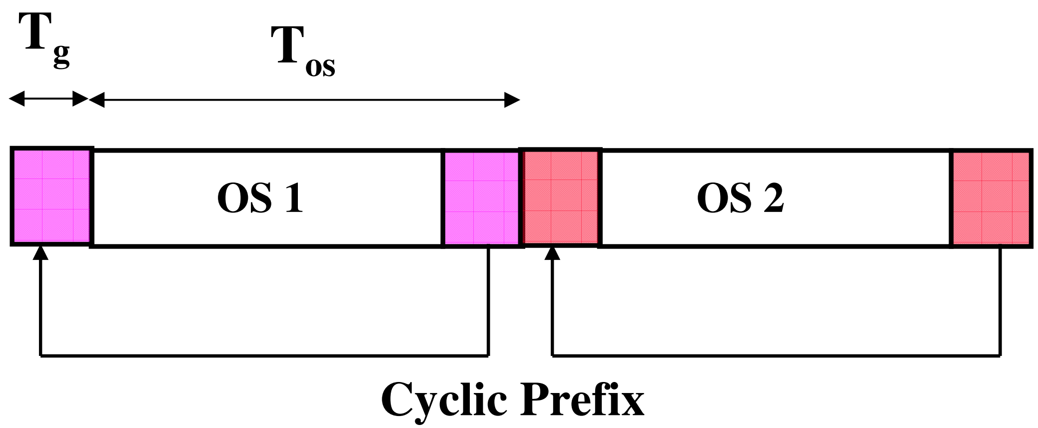
Cyclic Prefix

- 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 Illustration



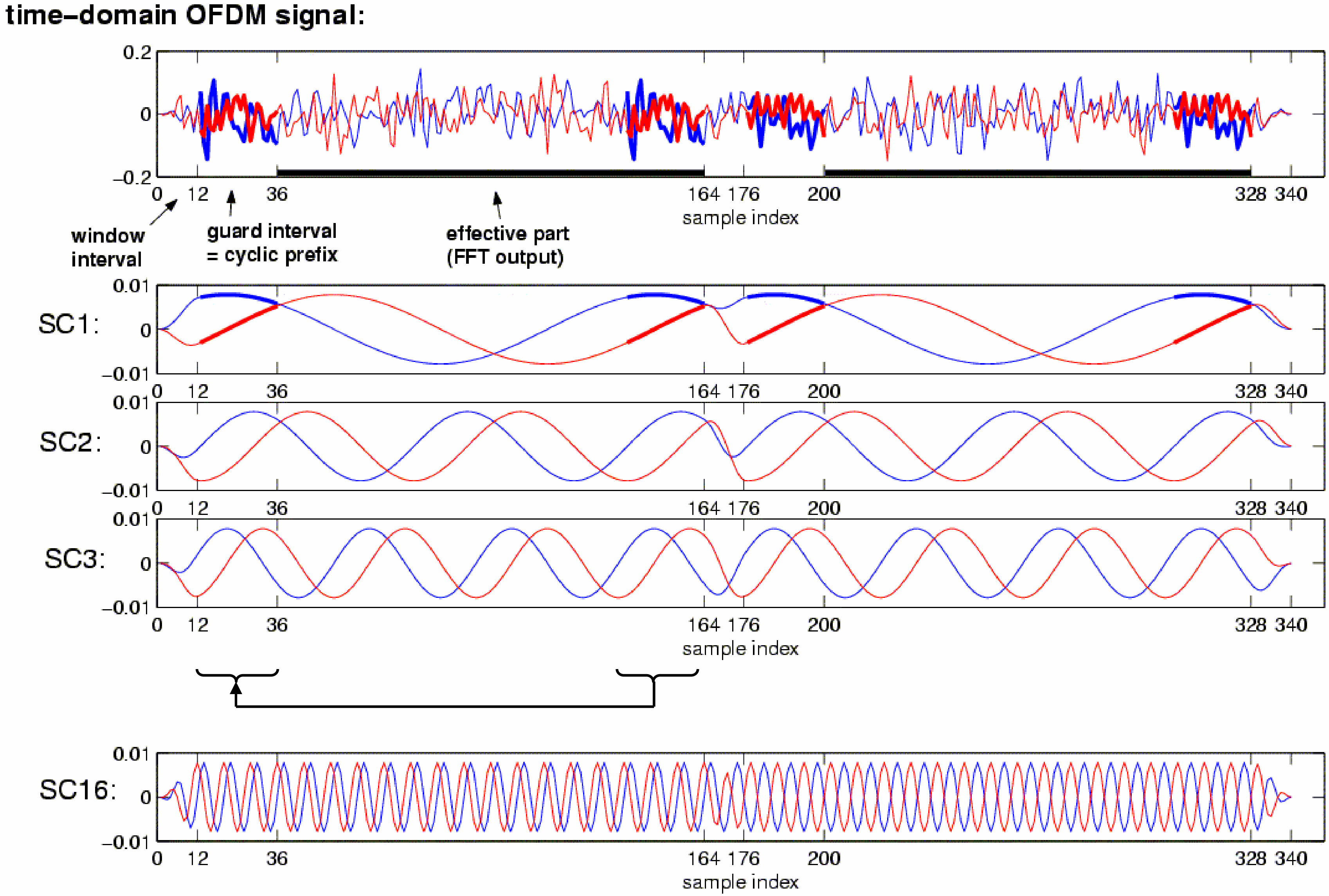
OS1,OS2 - OFDM Symbols

T_g - Guard Time Interval

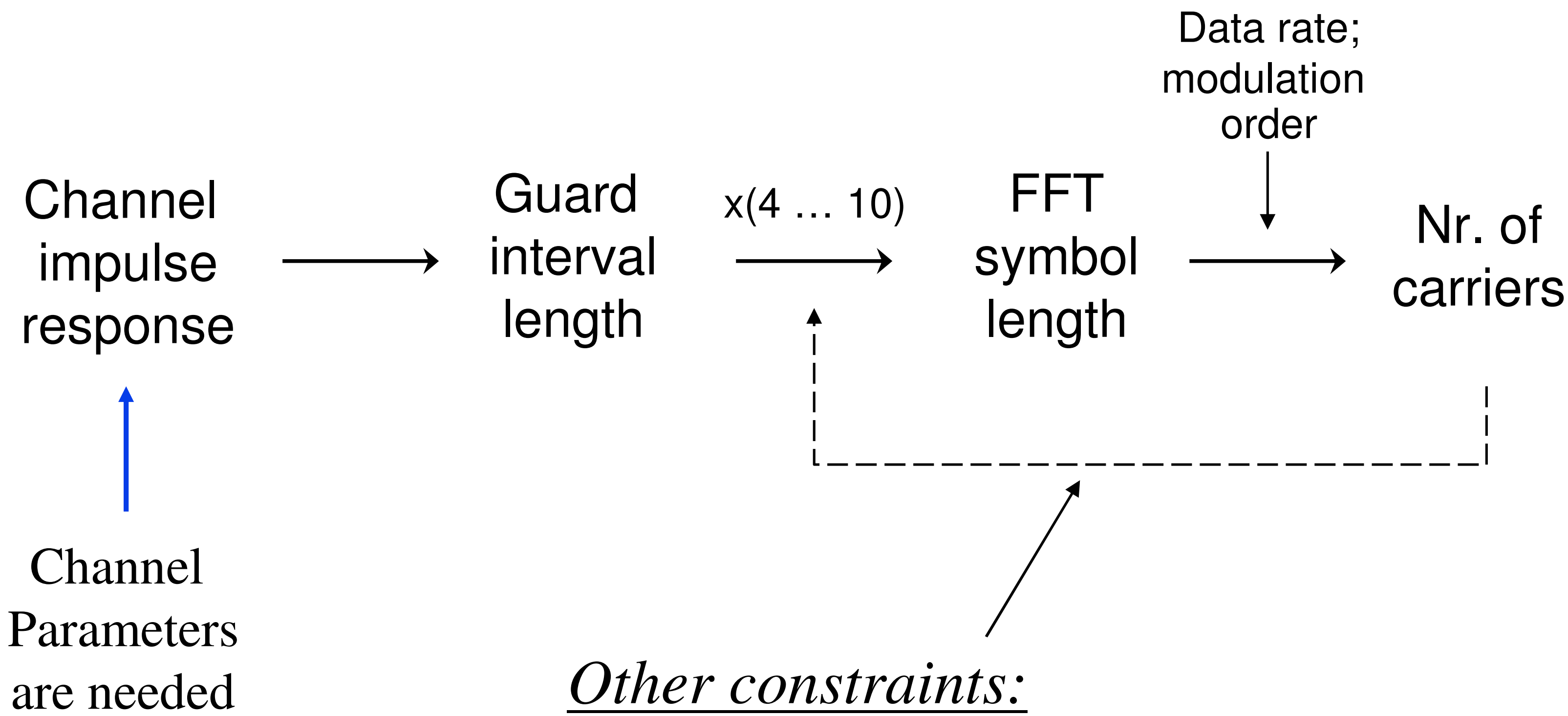
T_s - Data Symbol Period

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

Guard interval (2) - Cyclic extension



Design of an OFDM System



Other constraints:

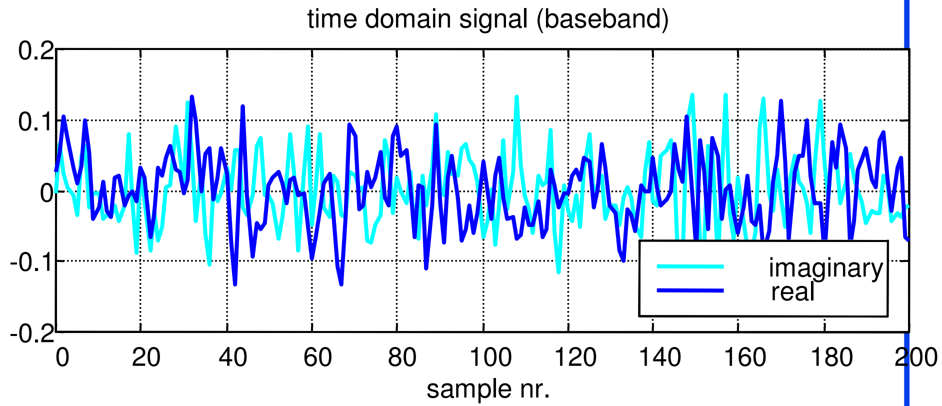
- Nr. of carriers should match FFT size and data packet length
- considering coding and modulation schemes

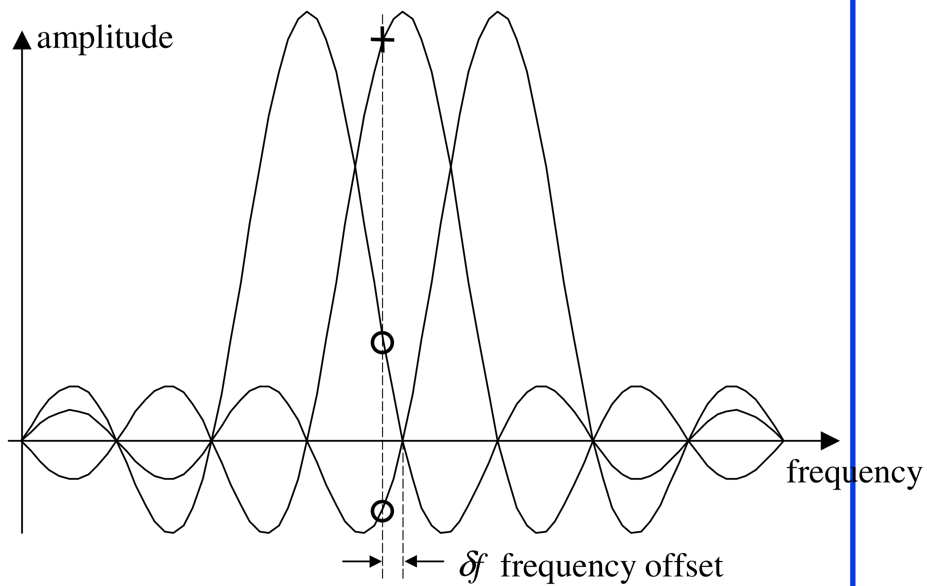
Advantages of OFDM

- 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

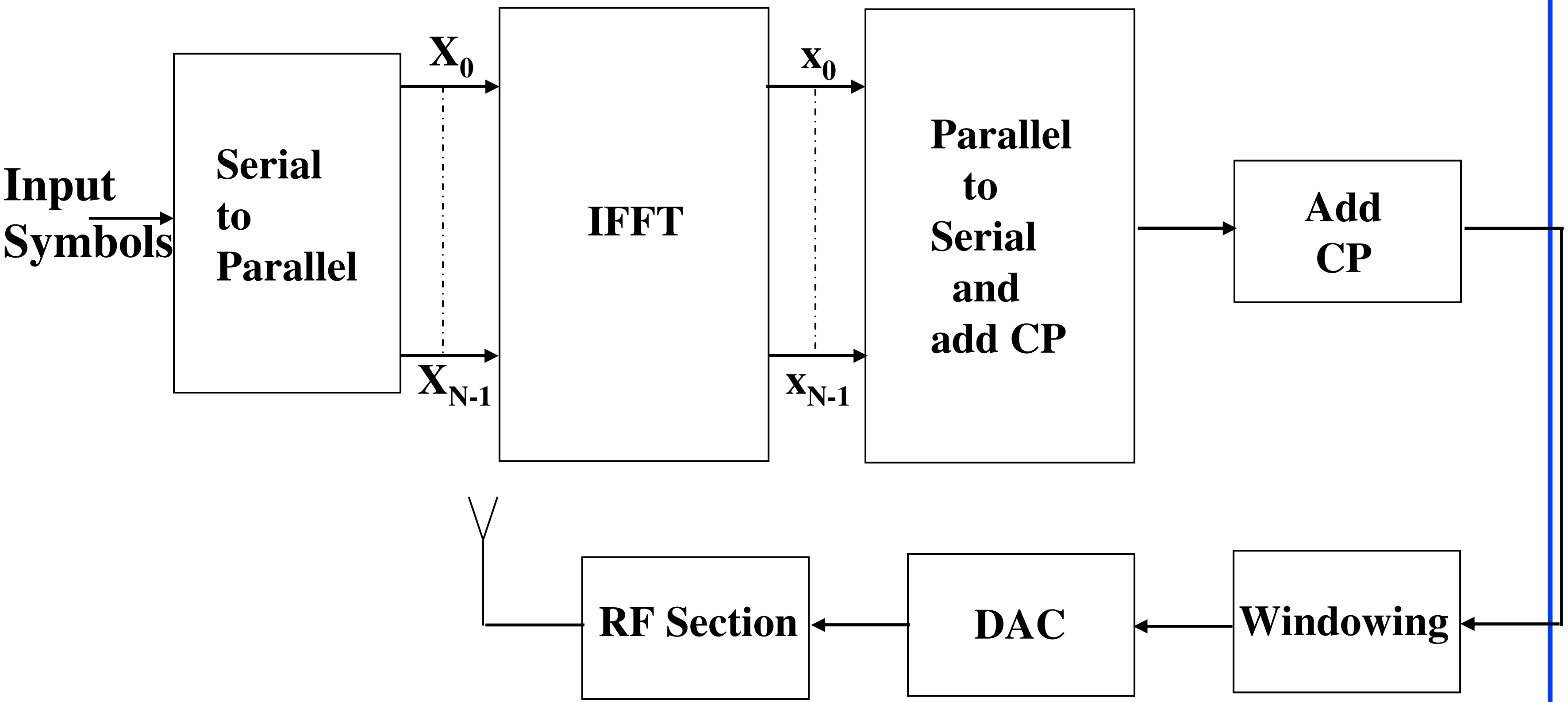
Problems of OFDM (Research Topics)

- 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**

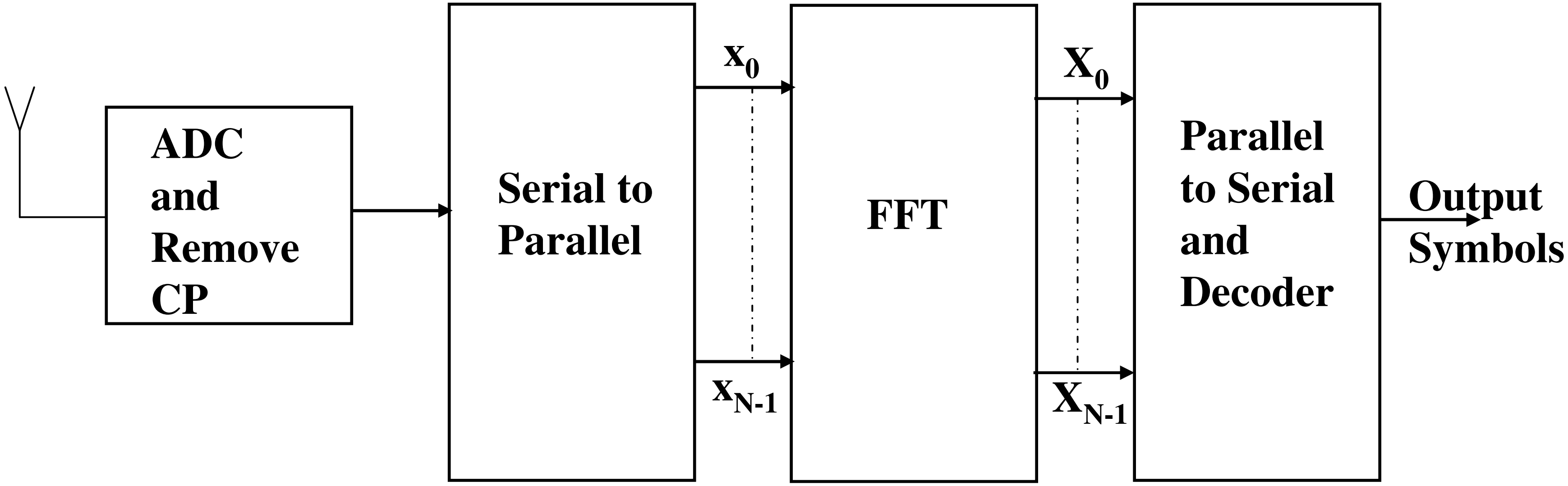




OFDM Transmitter



OFDM Receiver



Synchronization

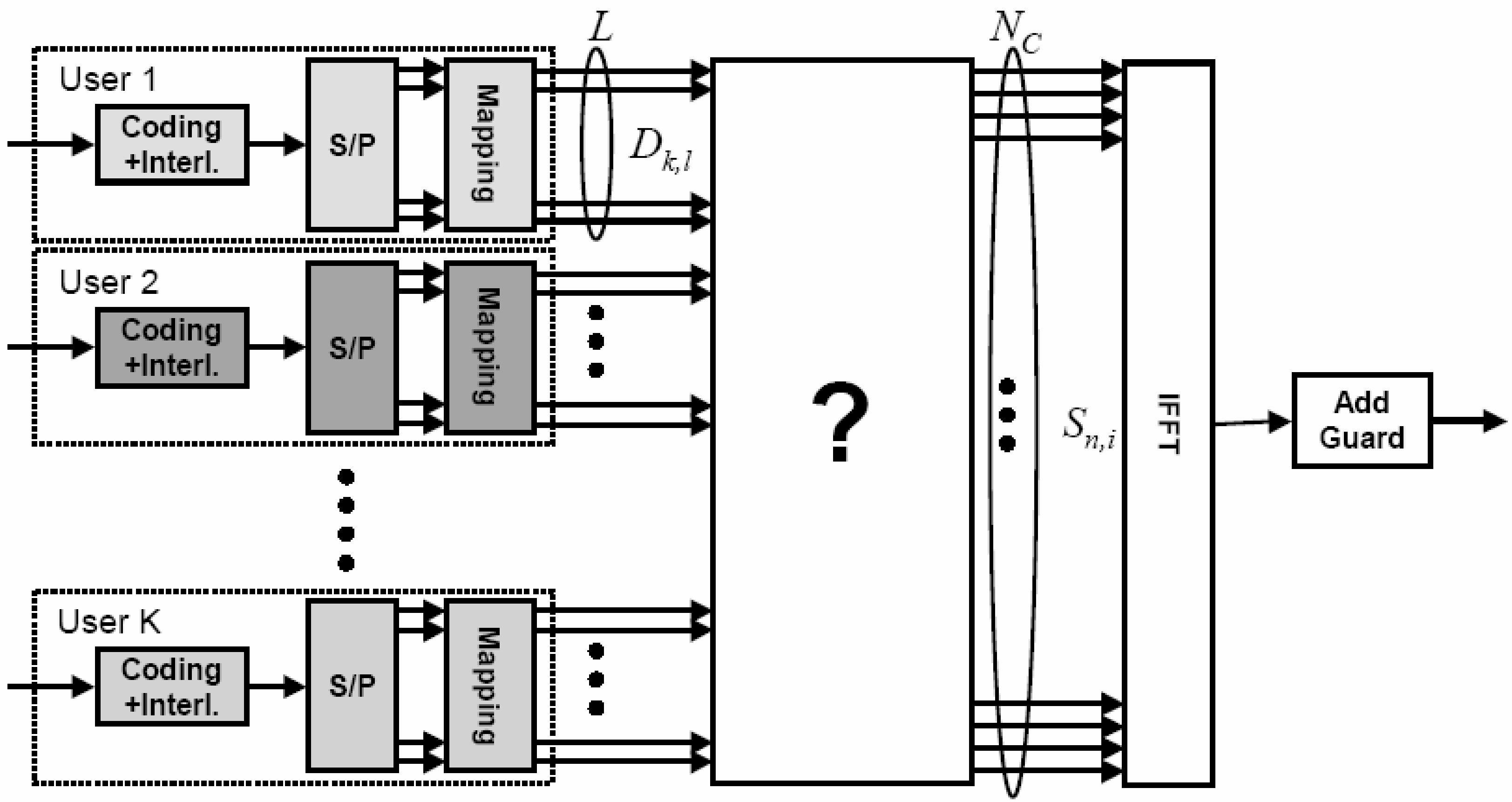
- Timing and frequency offset can influence performance.
- Frequency offset can influence orthogonality of subcarriers.
- Loss of orthogonality leads to Inter Carrier Interference.

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.

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