Orthogonal Frequency Division Multiplexing (OFDM) for Wireless Communications

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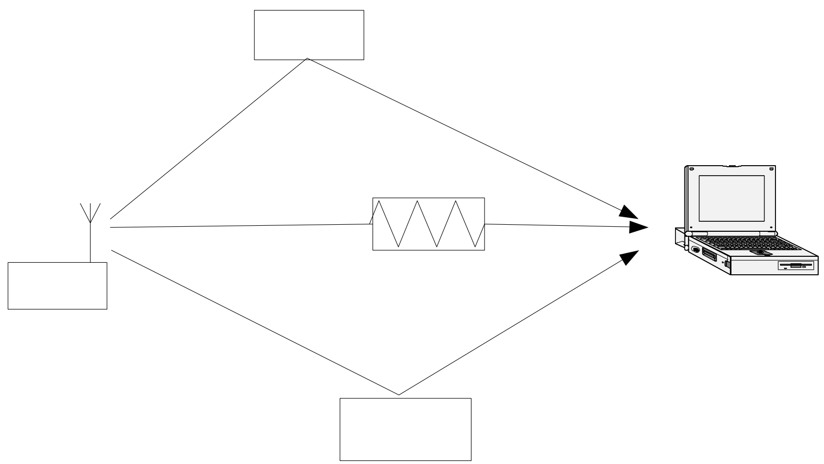
Outline

1. Wireless communications
   - Motivation
   - Issues
2. Introduction of OFDM
3. Peak power reduction
4. Synchronization
5. Channel estimation
6. Applications

Motivation of Wireless Communications

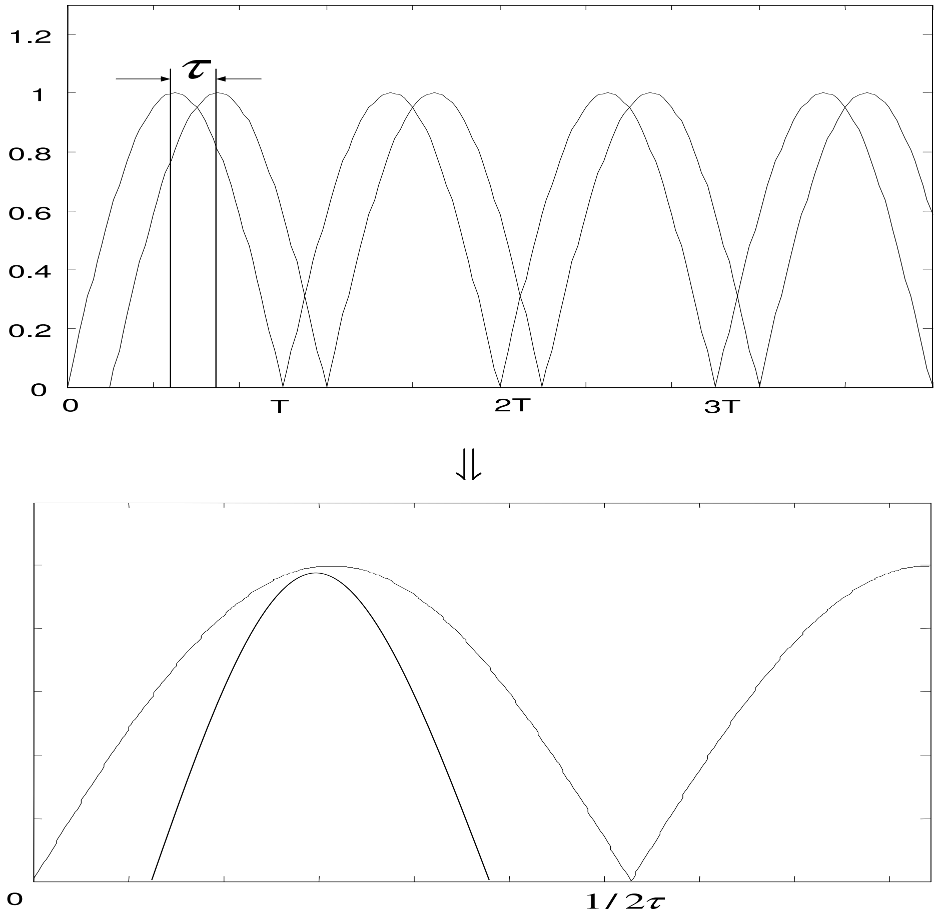
- High data rate wireless applications
  - Wireless LAN applications
  - 3G cellular systems
- High capacity
  - More users
  - More service
    - Voice: low data rate, low latency, low QoS
    - Data: high data rate, high latency, high QoS
    - Video stream: high data rate, low latency, high QoS

Limitations of the Radio Environment



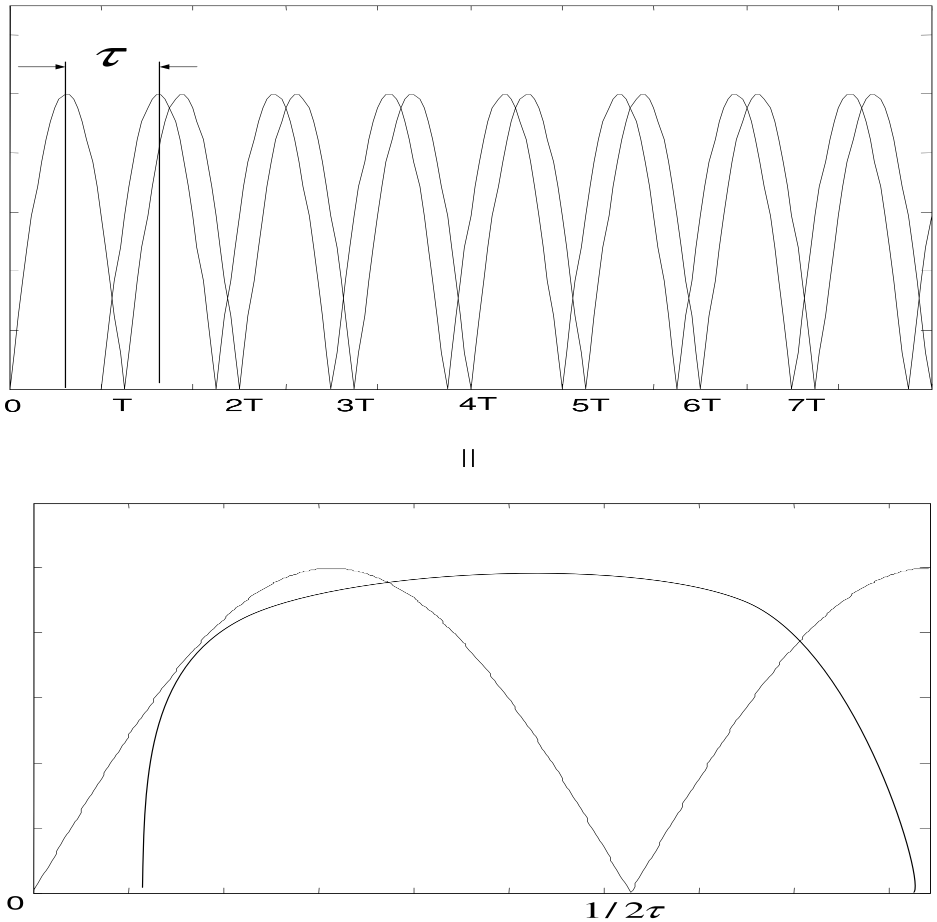
- Path loss
- Shadow fading
- Multipath
  - Delay spread
  - Frequency-selective fading
  - Doppler spread
- Interference

Small Delay Spread ⇒ Flat Fading



- Two ray model
- τ is the rms delay spread
- $\frac{\tau}{T}$ small
- Negligible intersymbol interference (ISI)
- Frequency flat fading

Large Delay Spread ⇒ Frequency-Selective Fading



- Two ray model
- τ is the rms delay spread
- $\frac{\tau}{T}$ large
- Significant intersymbol interference (ISI)
- Frequency selective fading

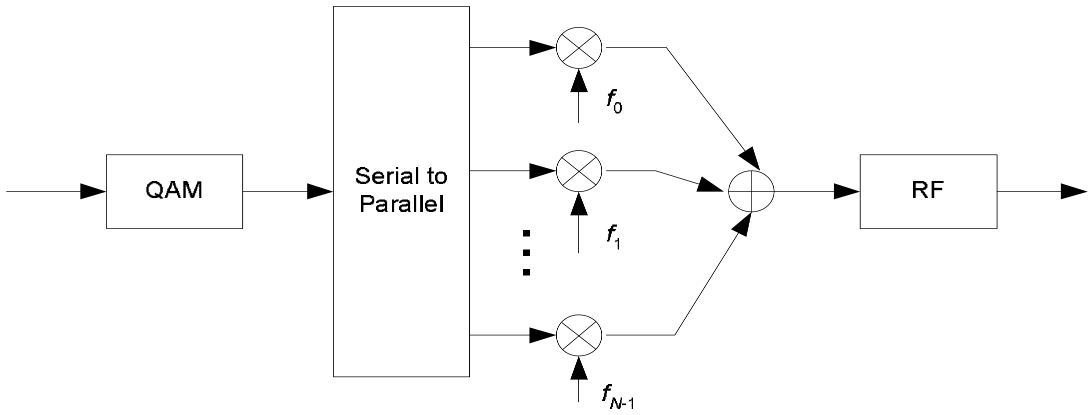
Bit Rate Limitations

	τ	Maximum Bit Rate
Mobile (rural)	25 μs	8 kbps
Mobile (city)	2.5 μs	80 kbps
Microcells	500 ns	400 kbps
Large Building	100 ns	2 Mbps

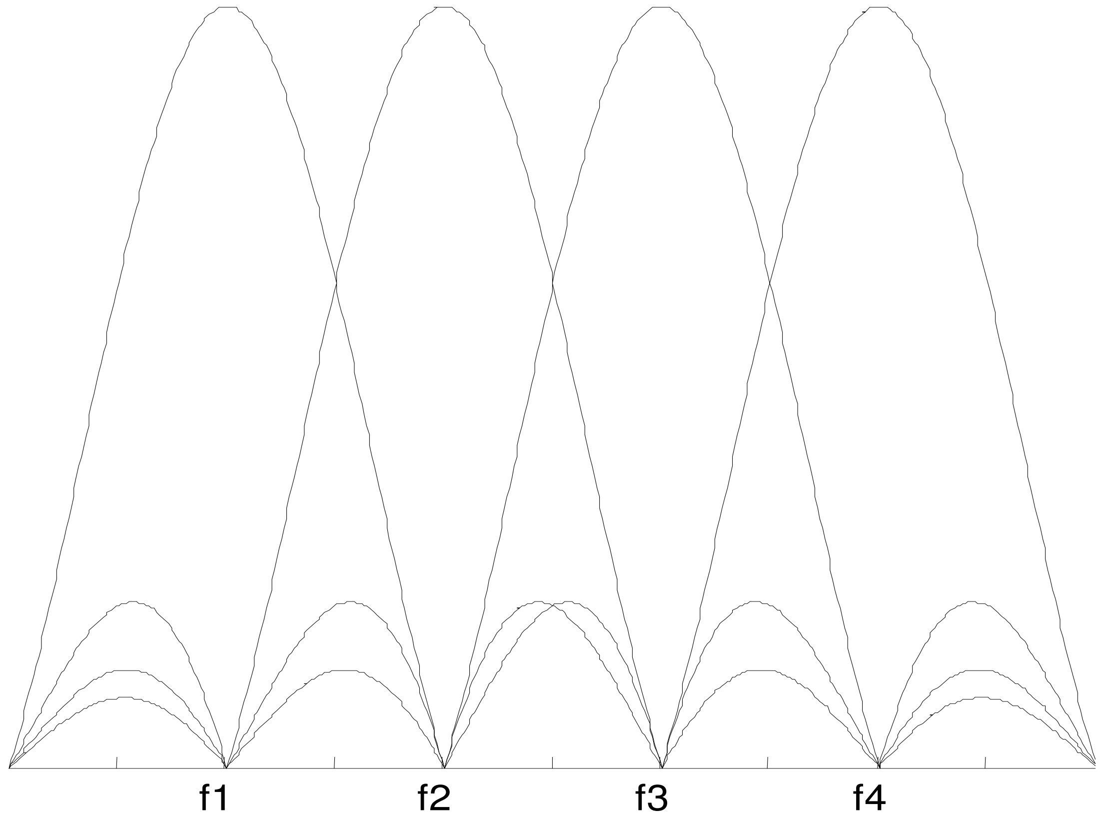
Introduction to OFDM

- Multicarrier
- OFDM
- Impairments
- Alternative forms

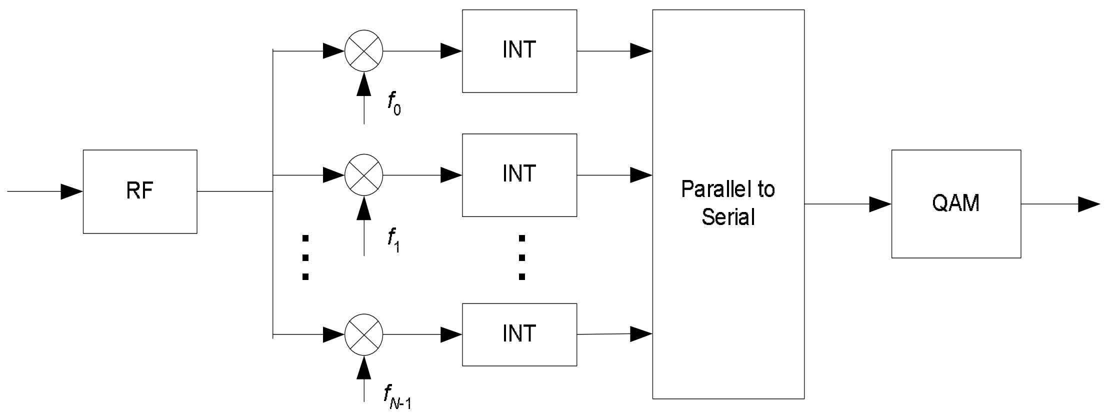
OFDM Transmitter



OFDM Frequency Domain



OFDM Receiver



Advantages of OFDM

- Spectral efficiency
  - The orthogonal subchannels are spaced 1/T Hz apart and overlap in frequency
- Simple implementation
  - IFFT/FFT pair
  - ADC/DAC pair
- Mitigation of ISI
  - Cyclic prefix/suffix guard interval

Disadvantages of OFDM

- Peak to average power ratio (PAPR) is high
  - High power transmitter amplifiers need linearlization
  - Low noise receiver amplifiers need large dynamic range
- Capacity and power loss due to guard interval
  - Bandwidth and power loss due to the guard interval can be significant
  - The guard interval consumes 20% of the bandidth and transmit power in IEEE802.11a
- Frequency offsets and phase noise sensitivity
  - Phase noise is especially acute at high carrier frequencies

Sample Design

- Goal
  - Transmit 1.2 Mb/s using QPSK with B = 800 kHz bandwidth channel
  - Delay span up to 20 μsec
- Design
  - Assume a guard interval $T_g = 40\mu\text{sec}$
  - OFDM symbol duration $T_s = 1/\Delta f = 160\mu\text{sec}$
  - OFDM block length $T_f = T_s + T_g = 200\mu\text{sec}$
  - $\Delta f = 1/T_s = 6.25kHz \Rightarrow N = B/\Delta f = 128$ subchannels
  - Assuming 4 guard channels on each end, there are 120 data subchannels, each transmitting 2 bits in 200 μsec

$$R_b = \frac{120 \times 2\text{bits}}{200\mu\text{sec}} = 1.2\text{Mbits/sec}$$

Application: 802.11a (I)

- 5 GHz U-NII (Unlicensed National Information Infrastructure) band
- 6, 9, 12, 18, 24, 36, and 48 Mbps
- Modulation: BPSK, QPSK, 16 QAM, 64 QAM
- Error correcting code: (133, 171) convolutional code with variant coding rate
- 64 point FFT/IFFT
- 52 subcarriers

Application: 802.11a (II)

Parameter	**Value**
N_{SD}: Number of data subcarriers	48
N_{SP}: Number of pilot subcarriers	4
N_{ST}: Number of subcarriers, total	52 ($= N_{SD} + N_{SP}$)
Δf: Subcarrier frequency spacing	0.3125 MHz (= 20 MHz / 4)
T_{FFT}: IFFT/FFT perios	3.2 μs ($= 1/\Delta f$)
$T_{PREAMBLE}$: PLCP preamble duration	16 μs ($= T_{SHORT} + T_{LONG}$)
T_{SIGNAL}: Duration of the OFDM symbol	4.0 μs ($= T_{GI} + T_{FFT}$)
T_{GI}: GI duration	0.8 μs ($= T_{FFT}/4$)
T_{GI2}: Training symbol GI duration	1.6 μs ($= T_{FFT}/2$)
T_{SHORT}: Short training sequence duration	8 μs ($= 10 \times T_{FFT}/4$)
T_{LONG}: Long training sequence duration	16 μs ($= T_{GI} + 2 \times T_{FFT}$)

Application: ADSL

- Coexistence with traditional telephone service
- Private line with high SNR
- Harmful cross talk
- Asymmetric user model: Up to 1.5 Mbps download/Up to 128 kbps uploading
- Upload: 25 kHz – 200 kHz/Download: 200 kHz – 1.1 MHz
- Error correcting code: convolutional codes concatenated with Reed-Solomon codes
- DMT (discrete multi-tone): a different name of OFDM
- Dynamic channel load assignment
- Echo cancellation for wider download bandwidth

Frequency Offset

- Time domain expression

$$x(t) = \sum_{k=0}^{N-1} a[k]\, e^{j2\pi(k\Delta f - \delta f)t}, \quad 0 \le t \le T_s$$

- Frequency domain expression
  - Attenuation + phase
  - Interchannel interference (ICI)

$$\begin{aligned}
\hat{a}[k] &= \text{DFT}\{x[n]\} = \underbrace{C[k,k]\, a[k]}_{\text{attenuation \& rotation}} + \underbrace{\sum_{n \ne k} C[n,k]\, a[n]}_{\text{ICI}} \\
C[k,k] &= \text{sinc}\left(\pi \frac{\delta f}{\Delta f}\right) e^{j\pi \frac{\delta f}{\Delta f}} \\
C[n,k] &= \text{sinc}\left[\pi\left(n - k - \frac{\delta f}{\Delta f}\right)\right] e^{j\pi\left(n-k-\frac{\delta f}{\Delta f}\right)}
\end{aligned}$$

Peak to Average Power Ratio

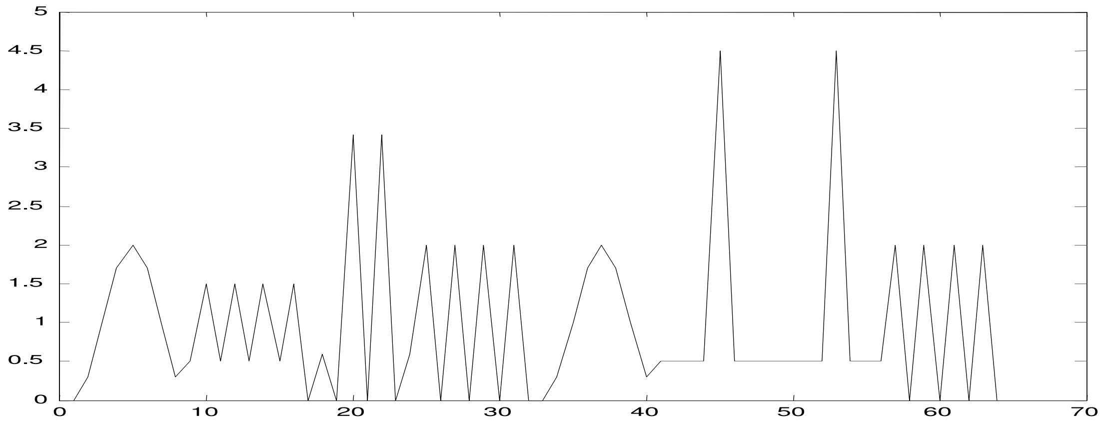


Figure 1: A sample OFDM symbol

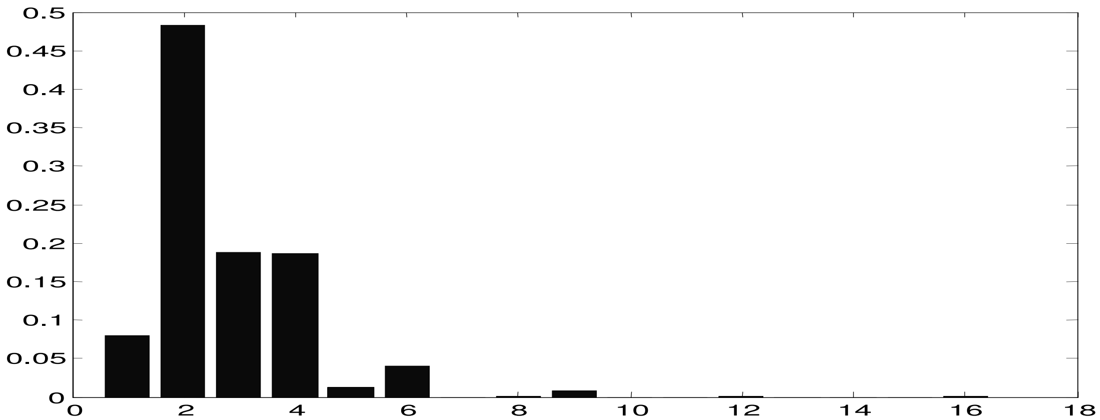


Figure 2: Statistics of OFDM PAPR values. $N = 64$

- Definition

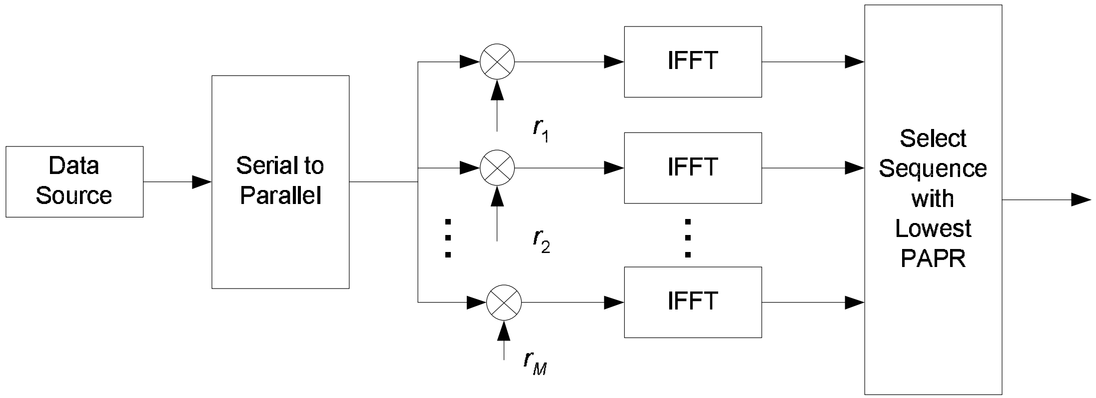
$$R = \frac{\max\limits_{0<t<T_{FFT}} |x(t)|^2}{P_{avg}} = N$$

- For $N = 128$, $R = 21$ dB.
- Large PAPR
  - In-band noise $\Rightarrow$ increases BER
  - Spectral spreading $\Rightarrow$ ICI
- PAPR could be large
  - We need to be very smart to solve this problem.
- Large PAPR does not appear frequently
  - Just ignore it!

Reduce PAPR I: Clipping and Filtering

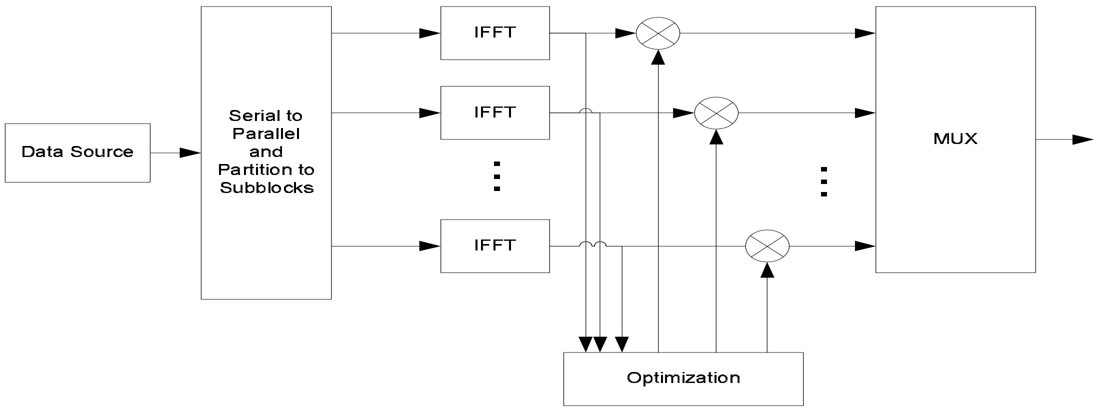
- Deliberate clipping will reduce peak value, but will result in spectral spreading (ICI) and in-band distortion (BER).
- Filtering is required to minimize spectral spreading. $\Rightarrow$ peak regrowth

Reduce PAPR II: Selective Mapping



- Multiply data signal by M different sequences, $r_1, \cdots, r_M$
- Convert each data sequence into the time-domain with an N-point IFFT
- Select sequence for transmission with the smallest PAPR

Reduce PAPR III: Partial Transmit Sequence



- Divide the OFDM tones into M clusters
- Convert each cluster into the time-domain using an N-point IFFT
- Combine the M output sequences to minimize the PAPR

Synchronization

- Pilot-based methods
  - Non-OFDM-based pilot symbols (e.g., null, chirp, ...)
  - OFDM-based pilot symbols ⇒ inefficient
- Non-pilot-based methods
  - Most are based on the redundancy in the cyclic prefix
  - Works well in AWGN
  - Degrades quickly in time dispersion environment

Channel Estimation

- Coherent detection
- Equalization
- Pilot-symbol-aided estimation

Summary

- High-bit-rate wireless data is desirable, but the radio environment puts an upper limit on the achievable bit rte.
- OFDM, by transmitting data over many narrow subchannels, can overcome the bit rate limit.
- However, to realize an OFDM system, several practical issues must be addressed, including PAPR, frequency offset and timing mismatch, and channel estimation.
- Several promising solutions have been proposed for all of these problems.
- OFDM is currently a very popular choice for future wireless applications, including wireless LANs, cellular and PCS data, and pssibly 4G systems.

Other Research Topics

- MIMO OFDM
- Multiple acess OFDM (OFDMA)
  - Uplink
  - Receiver structure
  - Interference cancellation
- MAC layer issues
  - Dynamic channel assignment
- Multicarrier CDMA