Introduction to OFDM

- Basic idea
  » Using a large number of parallel narrow-band sub-carriers instead of a single wide-band carrier to transport information

- Advantages
  » Very easy and efficient in dealing with multi-path
  » Robust against narrow-band interference

- Disadvantages
  » Sensitive to frequency offset and phase noise
  » Peak-to-average problem reduces the power efficiency of RF amplifier at the transmitter

- Adopted for various standards
  – DSL, 802.11a, DAB, DVB
Multipath can be described in two domains: time and frequency

Time domain: Impulse response
- Sinusoidal signal as input
- Impulse response
- Sinusoidal signal as output

Frequency domain: Frequency response
- Frequency response

Modulation techniques: monocarrier vs. multicarrier

Channel
- B
- Pulse length ~ 1/B
- Data are transmitted over only one carrier

Drawbacks
- Selective Fading
- Very short pulses
- ISI is comparatively long
- EQs are then very long
- Poor spectral efficiency because of band guards

To improve the spectral efficiency:
- Eliminate band guards between carriers
- Use orthogonal carriers (allowing overlapping)

Advantages
- Flat Fading per carrier
- N long pulses
- ISI is comparatively short
- N short EQs needed
- Poor spectral efficiency because of band guards

Furthermore
- It is easy to exploit Frequency diversity
- It allows to deploy 2D coding techniques
- Dynamic signalling

Similar to FDM technique
- B
- Pulse length ~ N/B
- Data are shared among several carriers and simultaneously transmitted
Orthogonal Frequency Division Modulation

Data coded in frequency domain

Transformation to time domain: each frequency is a sine wave in time, all added up.

Receive

Time-domain signal

Frequency-domain signal

Decode each frequency bin separately

Channel frequency response

OFDM uses multiple carriers to modulate the data

Features
- No intercarrier guard bands
- Controlled overlapping of bands
- Maximum spectral efficiency (Nyquist rate)
- Easy implementation using IFFTs
- Very sensitive to freq. synchronization

Modulation technique
A user utilizes all carriers to transmit its data as coded quantity at each frequency carrier, which can be quadrature-amplitude modulated (QAM).
OFDM Modulation and Demodulation using FFTs

Data coded in frequency domain: one symbol at a time

Data in time domain: one symbol at a time

P/S
Parallel to serial converter

Transmit time-domain samples of one symbol

Receive time-domain samples of one symbol

S/P
Serial to parallel converter

Decode each frequency bin independently

Loss of orthogonality (by frequency offset)

Transmission pulses
\[ \psi_k(t) = \exp(j2\pi ft/T) \]

Reception pulse with offset \( \delta \)
\[ \psi_{k+m}(t) = \exp(j2\pi f(t+m\delta/T)) \] \( \cos |\delta| \leq 1/2 \)

Interference between channels \( k \) and \( k+m \)

\[ I_m(\delta) = \int_0^T \exp(j2\pi ft/T) \exp(-j2\pi f(t+m\delta/T)) dt = \frac{T(1-\exp(-j2\pi \delta))}{j2\pi (m+\delta)} \]

Summing up
\[ \sum_m E_m(\delta) = (T^2) \sum_m \left| \frac{\sin(\pi \delta m)}{\pi m} \right|^2 \]

\( N \gg 1 \) \( (N > 5 \text{ is enough}) \)

Practical limit

Loss of orthogonality (time)

Let us assume a misadjustment:

\[ X_i = c_0 \int_{-T/2}^{T/2} y_k(t) y_l^*(t-t) \, dt - T/2 + c_1 \int_c^T y_k(t) y_l^*(t-t) \, dt \]

Then

\[ \begin{cases} \sin \frac{\pi m}{N} & \text{if } m \neq k \setminus i, \\ 0 & \text{if } m = k \setminus i, \end{cases} \]

Or approximately, when \( t \ll T \):

\[ \left| X_i \right| = \frac{2 \sin \frac{\pi m}{N}}{T} \approx \frac{2 \sin \frac{\pi m}{N}}{T} \]

In average, the interfering power in any carrier is

\[ \frac{\left| X_i \right|^2}{T} \approx \frac{1}{2} \left( \frac{1}{N} \right)^2 \frac{1}{2} \left( \frac{1}{T} \right)^2 \]

ICI due to loss of orthogonality

\[ ICI = 20 \log \left( \frac{2 \sin \frac{\pi m}{N}}{T} \right), \quad t \ll T \]

Per carrier

ICI for 16 carriers

Incl. a “cyclic prefix”

To combat the time dispersion: including ‘special’ time guards in the symbol transitions

Furthermore it converts Linear conv. = Cyclic conv.

(Method: overlap-save)

CP functions:

- It accommodates the decaying transient of the previous symbol
- It avoids the initial transient reaches the current symbol
Cyclic Prefix

802.11a System Specification

- Sampling (chip) rate: 20MHz
- Chip duration: 50ns
- Number of FFT points: 64
- FFT symbol period: 3.2μs
- Cyclic prefix period: 16 chips or 0.8μs
  - Typical maximum indoor delay spread < 400ns
  - OFDM frame length: 80 chips or 4μs
  - FFT symbol length / OFDM frame length = 4/5
- Modulation scheme
  - QPSK: 2bits/sample
  - 16QAM: 4bits/sample
  - 64QAM: 6bits/sample
- Coding: rate ½ convolutional code with constraint length 7
Frequency diversity using coding

**Random errors:** primarily introduced by thermal and circuit noise.

**Channel-selected errors:** introduced by magnitude distortion in channel frequency response.

Errors are no longer random. Interleaving is often used to scramble the data bits so that standard error correcting codes can be applied.

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Spectrum Mask

- Requires extremely linear power amplifier design.
Adjacent Channel and Alternate Channel Rejection

<table>
<thead>
<tr>
<th>Date rate</th>
<th>Minimum Sensibility</th>
<th>Adjacent Channel Rejection</th>
<th>Alternate Channel rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Mbps</td>
<td>-82 dBm</td>
<td>16 dB</td>
<td>32 dB</td>
</tr>
<tr>
<td>12 Mbps</td>
<td>-79 dBm</td>
<td>13 dB</td>
<td>29 dB</td>
</tr>
<tr>
<td>24 Mbps</td>
<td>-74 dBm</td>
<td>8 dB</td>
<td>24 dB</td>
</tr>
<tr>
<td>36 Mbps</td>
<td>-70 dBm</td>
<td>4 dB</td>
<td>20 dB</td>
</tr>
<tr>
<td>54 Mbps</td>
<td>-65 dBm</td>
<td>0 dB</td>
<td>15 dB</td>
</tr>
</tbody>
</table>

• Requires joint design of the anti-aliasing filter and ADC.

OFDM Receiver Design

Yun Chiu, Dejan Markovic, Haiyun Tang, Ning Zhang
EE225C Final Project Report, 12 December 2000
OFDM System Block Diagram

Synchronization

- Frame detection
  
  - Frequency offset compensation
    \[ e^{j2\pi f_s t} \]

- Sampling error
  - Usually less 100ppm and can be ignored
    - 100ppm = off 1% of a sample every 100 samples
System Pilot Structure

IEEE 802.11a OFDM Txer
Short & Long Preambles

Short Preamble

Long Preamble

Period = 16 Chips

Period = 64 Chips

Correlation of Short Preamble

Correlation

Fine Timing

Auto-Correlation

Coarse Timing
Synchronization

From AGC

Moving Auto-Corr. Unit

Σ

Moving SP Corr. Unit

Short Preamble (LUT)

Impairments: Multi-Path Channel

Ch. Impulse Response

Auto-Correlation w/ Multi-Path Channel Response.
Impairments: Frequency Offset

Fine Frequency Offset Est.
Coarse-Fine Joint Estimation & Decision Alignment Error Correction

![Diagram of Coarse-Fine Joint Estimation & Decision Alignment Error Correction](image)

Frequency Offset Compensation

![Diagram of Frequency Offset Compensation](image)
### Performance Summary

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sub-carriers</td>
<td>48 data +4 pilot</td>
</tr>
<tr>
<td>OFDM symbol freq.</td>
<td>4 μs</td>
</tr>
<tr>
<td>Modulation Scheme</td>
<td>BPSK up to 64-QAM</td>
</tr>
<tr>
<td>Sampling clock freq.</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Sync. Frame Start Accuracy</td>
<td>≤ 8 chips (CP = 16 chips)</td>
</tr>
<tr>
<td>Freq. Offset Est. Range</td>
<td>± 5π = ± 100ppm @ 5.8 GHz</td>
</tr>
<tr>
<td>Freq. Offset Est. Accuracy</td>
<td>1% (@ 15dB SNR)</td>
</tr>
<tr>
<td>Critical path delay</td>
<td>12.7 ns</td>
</tr>
<tr>
<td>Silicon area</td>
<td>397,080 μm²</td>
</tr>
<tr>
<td>Total power consumption</td>
<td>3.4 mW @ 20 MHz</td>
</tr>
</tbody>
</table>