OFDM
OFDM

• OFDM was invented more than 40 years ago.
• OFDM has been adopted for several technologies:
  – IEEE 802.11a/g, IEEE 802.16a/d/m.
  – Digital Audio Broadcast (DAB).
  – Digital Video Broadcasting.
  – Wireless USB.
  – 4G: LTE, IEEE 802.11n, IEEE 802.16m, and IEEE 802.20.
OFDM

It distributes the data over a large number of carriers that are spaced apart at precise frequencies. This spacing provides the "orthogonality" in this technique which prevents the demodulators from seeing frequencies other than their own.
FDM and OFDM

- Frequency Division Multiplexing
- OFDM frequency dividing

EARN IN SPECTRAL EFFICIENCY
Generic Transmitter

FEC → Serial to Parallel → IFFT → Pulse shaper & DAC → Linear PA

- OFDM symbol
- add cyclic extension
- $f_c$
Generic Receiver

AGC

Sampler

Slot & Timing Sync.

FFT

P/S and Detection

Error Recovery

VCO

Freq. Offset Estimation

Coarse offset

fine offset

$\text{fc}$
One of the main reasons to use OFDM is to increase the robustness against frequency selective fading. In a single carrier system, a single fade can cause the entire link to fade, but in a multicarrier system only a small percentage of the subcarriers will be affected. FEC can then be used to correct few erroneous subcarriers.
Fading Channels

$|H(f)|$
Robustness in Fading Channels

$|H(f)|$

Subcarrier index
Uncoded OFDM

- $\text{Pe (single carrier)} = 10^{-2}$
- $\text{Pe}_1 = \text{Pe}_3 = 10^{-4}$
- $\text{Pe}_2 = 0.1$
- $\text{Pe}_{av} = \frac{(0.1 + 2 \times 10^{-4})}{3} \approx 0.033$
Coded Single carrier

- Using repetition code $r=1/3$:
- $P_e=0.01$
- $P_{eav}=0.01\times0.01\times0.99 \approx 3\times10^{-4}$
Coded OFDM (COFDM)

- Using repetition code:
  - $P_{e1}=P_{e3}=10^{-4}$
  - $P_{e2}=0.1$
  - $P_{eav}= 0.1*10^{-4}*10^{-4}$
    $+0.9*(10^{-4})^2$
    $+2*0.1*10^{-4}*(1-10^{-4})$
    $\approx 2*10^{-5}$
Advantages of OFDM

• OFDM is an efficient way to deal with multipath fading channels. For a given delay spread, the implementation complexity is significantly lower than that of a single carrier system with an equalizer.

• for slow channels, data rate for subcarriers can be adaptly changed according to SNR.

• OFDM is robust against narrow band interference.
Implementation Complexity

• Equalizer complexity grows quadratically with the BW delay-spread product ($N^2$)
• OFDM complexity grows only slightly faster than linear with the BW delay-spread product ($N \times \log_2(N)$)
Narrow-Band Interference

- Narrowband interference effect is treated similar to deep fading.
- It will only affect specific subcarriers which can be overcome by coding.
Disadvantages of OFDM

- OFDM is more sensitive to freq. offset.
- OFDM has large peak to average power ratio, which leads to reduce the power efficiency of RF amp’s.
- Sensitive to Doppler shift.
Frequency Offset

\[ a + jb \]

\[ e^{j2\pi f_t t} \]  \[ e^{-j2\pi f_r t} \]  \[ e^{j2\pi \Delta f t} \]  

Ideal, noiseless Channel

\[(a + jb)\]
Freq. Offset in OFDM
PDF of real(x)
Clipping (Power Amplifier)

\[ s(t) = s(t) - s(t) + L \cdot \text{CLIP} - L \cdot \text{CLIP} + L \cdot \text{CLIP} - L \cdot \text{CLIP} \]
OFDM signals in Multipath Fading Channels
OFDM Signal
OFDM Signal, Multiple Symbols
Multipath Fading channel
1 Symbol in fading channel
2 Symbols in fading channel

Symbol 1

Symbol 2

ISI
Effect of Multipath Fading Channel

- OFDM deals with multipath delay spread by dividing the i/p data stream in $N_s$ subcarriers, the symbol duration is made $N_s$ times larger which also reduces the relative multipath delay spread, relative to the symbol time by the same factor.
Guard Time

Guard time
Guard Time removes ISI
Effect of guard time

- To eliminate ISI completely a guard time is introduced for each OFDM signal. The guard time is chosen larger than the expected delay spread such that multipath component for one symbol can’t interfere with the next symbol.
Inter-Carrier Interference (ICI)
Adding Cyclic Extension
Cyclic Prefix in Fading channel
Cyclic prefix removes ICI
CP removes ICI

• The guard time could consist of no signal. However the problem of ICI (Inter-Carrier Interference) would arise. ICI is the cross talk between different subcarriers which means they are no longer orthogonal.

• To eliminate ICI, OFDM symbols are cyclically extended in the guard time. This ensures that delayed replicas of the OFDM symbol always have an integer # of cycles within the FFT interval.

• Energy is wasted in the cyclic prefix samples.
Subcarrier 1 Signals

![Graph showing three signals: Main Path, 2nd path, Sum. The graph plots frequency on the x-axis and amplitude on the y-axis. The signals are labeled and differentiated by color.](image)
Channel estimation

• The multipath components of every subcarrier adds in the presence of CP to form a signal with the same frequency but with different phase and amplitude.

• Channel estimation is used to estimate the channel effects which can be easily compensated for, in order to receive the signal correctly.
OFDM Block diagram
OFDM Frame Structure

Figure 110—OFDM training structure
AGC

• AGC’s function is to set the gain used by the ADC such that the input signal dynamic range spans the ADC range

• AGC function is typically divided into two “modes” of operation
  – Fast AGC: as soon as the energy is detected
  – Slow AGC: during the preamble
AGC (cont.)

• AGC design is tightly coupled with the RF Rx chain
• If a filter is needed in the Rx chain, two measurement points will be needed
Packet Detection

• A state diagram usually describes how packet detection and timing acquisition takes place
• Energy detection as well as correlation are the main components that are used
Frequency Offset ($\Delta f$) Effects

- Frequency offset up to ±20 ppm is allowed, Tx Rx offset of 40 ppm is possible.
- It causes two problems,
  - Carrier frequency offset
  - Sampling frequency offset

\[ s(t)e^{j\omega t} \times s(t)e^{-j\delta \omega t} \rightarrow A/D \]

\[ s(t)e^{-j\omega (\delta)} t \rightarrow f_s(1+\delta) \]
$\Delta f$ Estimation

• As recommended by the standard, the frequency offset estimation is performed in two steps
  – Coarse frequency offset estimation
  – Fine frequency offset estimation
$(\Delta f)$ Estimation: Frame Structure

![Diagram of OFDM training structure](image)

**Figure 110—OFDM training structure**
Channel Estimation

• To estimate the channel taps between the transmitter and receiver
• We estimate the channel taps in the frequency domain
• This is typically performed in the frequency domain by dividing the “received” preamble by the “transmitted” preamble

\[ \text{FFT} \rightarrow \frac{\text{RX preamble}}{\text{TX preamble}} \rightarrow \text{Initial channel estimate} \]
FFT/IFFT

- The FFT is a standard mathematical block
- Several techniques to implement the FFT exist
- This block is a computationally intensive block, and a thorough design review has to be carried out between the baseband and RTL groups
Scrambler

• Generates scrambling sequence that scrambles bits in the “DATA” field.
• Generated using feedback shift register.
De-Scrambler

- Inverse of the Scrambling process in the transmitter.
- Main issue: Synchronize the sequence generator at the transmitter and receiver. (Done through the service field)
Interleaver

- The interleaver rearranges the bits such that the $k$th received bit is generated at the $j$th order.
- The relation between $k$ and $j$ is given through an intermediate variable $i$ as follows

$$i = \frac{N_{CBPS}}{16} (k \mod 16) + \left\lfloor \frac{k}{16} \right\rfloor, \quad k = 0, 1, \ldots, N_{CBPS} - 1$$

$$j = s \left\lfloor \frac{i}{s} \right\rfloor + \left( i + N_{CBPS} - \left\lfloor \frac{16i}{N_{CBPS}} \right\rfloor \right) \mod s, \quad i = 0, 1, \ldots, N_{CBPS} - 1.$$  

where $s = \max\left(\frac{N_{CBPS}}{2}, 1\right)$ and $\lfloor x \rfloor$ means integer part of $x$.  

$N_{CBPS}$: number of coded bits per OFDM symbol
Interleaver (cont.)

• Interleaving process is performed using read/write table.

• Input bits are written horizontally into the rows of a 2-dimensional array, starting from the top row.

• Output bits are read from the array vertically from the columns, starting from the left column.
De-Interleaver

- Performs inverse of interleaving process at the transmitter.
- The de-interleaving formulas are similar to the ones presented for the interleaving process and could be found at the IEEE 802.11a standard document.
Symbol Mapping

- The Symbol mapping block receives number of bits at a time (depends on the modulation scheme; BPSK, QPSK, 16-QAM, 64-QAM) and generates the complex number that corresponds to the constellation point to be transmitted.
- The output is given by
  \[ d_{out} = (I_{out} + j Q_{out}) K \]

  Where \( K \) is a normalization factor used to keep a constant average transmitted power for all modulation schemes.
Symbol De-Mapper

- The Symbol De-mapping block produces soft values (as opposed to hard decisions) for transmitted bits.
Convolution Encoding and Puncturing

• Basic encoder: rate $\frac{1}{2}$ with constraint length 7.
• To increase code rate to 2/3 or 3/4, puncturing is used.
• Ex: for rate 2/3, the puncturing block throws away the fourth of its input.
De-Puncturing

• Performs inverse of puncturing process at the transmitter.
• How? Insert absolute zeros at the locations of the punctured bits.
Viterbi Decoder

• Used to produce estimates of the information bits
• An important parameter to be determined is the number of bits to represent every bit at the input of the decoder.
Example

• Design an OFDM system, with the following requirements:
  – Bit Rate: 20 Mbps
  – Tolerable Delay spread 200 ns
  – Bandwidth <15MHz

Find: Symbol time, Guard time, subcarrier spacing, number of subcarriers and FFT size, and modulation order.
Guard time

• The first step is to design the guard interval to mitigate the delay spread.
• We take the guard time $T_G = 4 \times \text{rms delay spread}$
  \[= 4 \times 200 \text{ns} = 0.8 \text{ usec} \]
Symbol duration

- In order to lose less than 1dB in the guard time, the useful symbol time is take 5 times the guard time
  
  \[ T_u = 5 \times T_G = 5 \times 0.8 = 4 \text{ usec} \]

- The symbol duration is
  
  \[ T_u + T_G = 4.8 \text{ usec} \]
Symbol construction

CP1  Symbol 1  CP2  Symbol 2
0.8  4.0usec
More parameters

• Subcarrier spacing \( f_1 \) = \( \frac{1}{T_u} \) = 250 KHz
• Maximum number of subcarriers = \( \frac{BW}{f_1} \)
  = \( \frac{15}{0.25} \) = 60 subcarriers
• Number of bits per symbol
  = \( 4.8 \times 20 \times 10^6 \) = 96 bits/symbol
• Number of bits per subcarrier = \( \frac{96}{60} \) = 1.6
More parameters

- Choose number of bits per subcarrier = 2
- Number of used subcarriers is 96/2 = 48 subcarrier
- FFT size = $2^N$ = 64, 48 data symbols, 4 pilots and 12 zeros (like WiFi)
- Modulation QPSK
THE END