Introduction to Orthogonal Frequency Division Multiplexing Technique

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Introduction to Orthogonal Frequency Division Multiplexing (OFDM) Technique

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- The History of OFDM
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- The Applications of OFDM
  - DAB
  - HDTV
  - Wireless LAN
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  - IEEE 802.20
Because of its high-speed data transmission and effectiveness in combating the frequency selective fading channel, OFDM technique is widely used in wireless communication nowadays.

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier transmission technique, which divides the available spectrum into many subcarriers, each one being modulated by a low data rate stream.
OFDM can be viewed as either a modulation technique or a multiplex technique.

- **Modulation technique**
  - Viewed by the relation between input and output signals
- **Multiplex technique**
  - Viewed by the output signal which is the linear sum of the modulated signals
The employment of discrete Fourier transform to replace the banks of sinusoidal generator and the demodulation significantly reduces the implementation complexity of OFDM modems.
Intersymbol interference is eliminated almost completely by introducing a guard interval with zero padding in every OFDM symbol.

- **Guard interval with zero padding**

- The way to eliminate ISI
In the guard time, the OFDM symbol is cyclically extended to avoid intercarrier interference.

Guard interval with cyclic extension (cyclic prefix)
The way to avoid ICI

- Guard time
- FFT integration time = 1/carrier spacing
- OFDM symbol time
Introduction – FFT-based OFDM

- Serial Data Input
  - Serial-to-Parallel Converter
  - Signal Mapper
  - IFFT
  - Parallel-to-Serial Converter
  - Guard Interval Insertion
  - D/A & Low pass Filter
  - Up-Converter

- Serial Data Output
  - Parallel-to-Serial Converter
  - Signal Demapper
  - One-tap Equalizer
  - FFT
  - Serial-to-Parallel Converter
  - Guard Interval Removal
  - A/D
  - Down-Converter

- Fast Fourier Transform
- Guard Intervals
- Subchannels
- Frequency
- Time
- Channel
Introduction

- The advantages of OFDM
  - Immunity to delay spread and multipath
  - Resistance to frequency selective fading
  - Simple equalization
  - Efficient bandwidth usage

- The disadvantages of OFDM
  - Synchronization
  - Need FFT units at transmitter, receiver
  - Sensitive to carrier frequency offset
  - High peak to average power ratio
The History of OFDM

- The idea, which was proposed in mid-1960s, used parallel data transmission and frequency division multiplexing (FDM) [1,14].
- In the 1960s, the OFDM technique was used in several high-frequency military system
  - KINEPLEX [15]
  - ANDEFT [16]
  - KATHRYN [17]
The History of OFDM

- In 1971, Weinstein and Ebert applied the Discrete Fourier Transform (DFT) to parallel data transmission systems as part of modulation and demodulation process [1, 4, 18].
  - FFT-based OFDM

- In the 1980s, OFDM was studied for high-speed modems digital mobile communication, and high-density recording.
  - Pilot tone is used to stabilize carrier and frequency control
  - Trellis code is implemented
    - COFDM

- In 1980, Hirosaki suggested an equalization algorithm in order to suppress both intersymbol and intercarrier interference caused by the channel impulse response or timing and frequency errors [4, 19].

- In 1980, Hirosaki also introduced the DFT-based implementation of Saltzburg’s O-QAM OFDM system [4, 20].
In the 1990s, OFDM was exploited for wideband data communications [1-7]

- Mobile radio FM channels
- Fix-wire network [7,26]
  - High-bit-rate digital subscriber line (HDSL)
  - Asymmetric digital subscriber line (ADSL)
  - Very-high-speed digital subscriber line (VDSL)
- Digital audio broadcasting (DAB) [9,21]
- Digital video broadcasting (DVB)
- High-definition television (HDTV) terrestrial broadcasting [10,22]
  - There exist three mechanisms about the digital terrestrial television broadcasting system in European (COFDM), North America (8-VSB), and Japan (BST-OFDM).
  - HIPERLAN2 (European)
  - IEEE 802.11a (U.S.A)
  - IEEE 802.11g (U.S.A)
Now, OFDM technique has been adopted as the new European DAB standard, and HDTV standard.

A candidate of 4G mobile communication [27]

OFDM/UWB (802.15.3a)

IEEE 802.16 broadband wireless access system

IEEE 802.20 mobile broadband wireless access (MBWA)
OFDM and Multicarrier Transmission

- **OFDM** is a special case of multicarrier transmission, where a single data stream is transmitted over a number of lower rate subcarrier\([1,4]\).

- **Single carrier transmission**
  - The concept of single-carrier is that each user transmits and receives data stream with only one carrier at any time.

- **Multicarrier transmission**
  - The concept of multi-carrier transmission is that a user can employ a number of carriers to transmit data simultaneously.
Single and multicarrier transmission

Single carrier transmission

Multicarrier carrier transmission

\[ b_i \rightarrow \cos(2\pi f_i t) \rightarrow s(t) \]

\[ b_i \rightarrow S/P \rightarrow \sum \rightarrow s(t) \]

\[ \cos(2\pi f_1 t) \]

\[ \cos(2\pi f_2 t) \]

\[ \cos(2\pi f_N t) \]
Orthogonality

- Time domain
  \[ \int_{-\infty}^{\infty} x_1(t) x_2(t)^* dt = 0 \iff \int_{-\infty}^{\infty} X_1(f) X_2(f)^* df = 0 \]

- Bandpass signal

\[
x_m(t) = \cos(\pi (f_c + f_m) t) \quad \Re e^{i2\pi(f + f_m)t}
\]

where \( x_{lm}(t) = e^{i2\pi f_m t} \) is the equivalent lowpass signal of \( x_m(t) \)

\[
\gamma_{12} = \int_{0}^{T} e^{i2\pi f_1 t} (e^{i2\pi f_2 t})^* dt = \int_{0}^{T} e^{i\pi (f_1 f_2) t} dt = \frac{\sin(\pi\Delta f T)}{\pi\Delta f} e^{i\pi\Delta f T}
\]

if \( \Delta f \cdot T = n \), \( n \) is a non-zero integer, i.e. \( \Delta f = \frac{n}{T} \), then \( \gamma_{12} = 0 \)
OFDM and Multicarrier Transmission

(A) Orthogonal

(B) Orthogonal, $n=3$

(C) Orthogonal, $n=2$

(D) Orthogonal, $n=1$

(E) Non-orthogonal
**OFDM and Multicarrier Transmission**

Time domain  Frequency domain

**subcarrier** $f_1$

**subcarrier** $f_2$

**subcarrier** $f_3$

**subcarrier** $f_4$
OFDM and Multicarrier Transmission

- Multicarrier CDMA system
  - CDMA + OFDM system
  - Three types of Multicarrier CDMA system
    - MC-CDMA system
    - Multi-carrier DS-CDMA system
    - Multi-tone CDMA system
**Multicarrier CDMA system**

- **Frequency domain spreading**
  - **MC-CDMA system**
    - The spreading operation in the frequency domain
    - It spreads the original data streams using a given spreading code, and then modulates a different subcarriers with each chip.
### Time domain spreading

- **Multi-carrier DS-CDMA system**
- **Multi-tone CDMA system**

  - The spreading operation in the time domain
  - It spreads the serial-to-parallel (s/p) converted data streams using a given spreading code, and then modulates a different subcarrier with each data stream.
The Applications of OFDM

- DAB
- HDTV
- Wireless LAN
- IEEE 802.16
- IEEE 802.20
The Applications of OFDM - DAB

- Digital Audio Broadcasting (DAB) [9,21]
  - DAB is a digital technology offering considerable advantages over today's FM radio, both to listeners and broadcasting.
  - DAB's flexibility will also provide a wider choice of programs, including many not available on FM.
  - A single station might offer its listeners a choice of mono voice commentaries on three or four sporting events at the same time, and then combine the bitstreams to provide high-quality sound for the concert which follows.
The Applications of OFDM - HDTV

High-definition Television (HDTV) Terrestrial Broadcasting [10,22]

- Commercial television station is first published by England.
- There exist three mechanisms about the digital terrestrial television broadcasting system in European (COFDM), North America (8-VSB), and Japan (BST-OFDM).
  - The European introduces the COFDM modulation scheme into the system structure.
  - American develops the system based on 8-level vestigial side-band (8-VSB) modulation scheme.
  - Japan is zealous to develop the band segmented transmission Orthogonal Frequency Division Multiplexing (BST-OFDM) system, which nature is based on COFDM modulation scheme.
Wireless LANs [11-13, 23-25]

- HIPERLAN2 (European)
- IEEE 802.11a (U.S.A)
- IEEE 802.11g (U.S.A)
ETSI has developed a new WLAN technology called HiperLAN type 2 (HiperLAN2)[23].

HiperLAN2 provides:

- High and scalable capacity as the number of users increase in the system
- Managed bandwidth with predictable performance for each user and application
- Robust protocols that also optimize the overall throughput of the available radio resource, making it the most spectrum-efficient WLAN technology operating at 5 GHz
- A high level of security
- QoS capabilities to support virtually any type of service or application
- Ease-of-use through a set of auto-configuration tools.
- HiperLAN2 standard achieves its 54 Mbps data rate through an OFDM technique.
IEEE 802.11a, 1999

- 5GHz band
- Orthogonal frequency division multiplexing (OFDM)
- 6Mbps to 54Mbps

<table>
<thead>
<tr>
<th>Data rate (Mbits/s)</th>
<th>Modulation</th>
<th>Coding rate (R)</th>
<th>Coded bits per subcarrier (N_{BPSC})</th>
<th>Coded bits per OFDM symbol (N_{CBPS})</th>
<th>Data bits per OFDM symbol (N_{DBPS})</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>
IEEE 802.11g [28]

- IEEE 802.11g will use the same 2.4 GHz radio spectrum as current 802.11b equipment, but with the higher data rates, packet structure, and modulation technology of 802.11a.
- IEEE 802.11g standard achieves its 54 Mbps data rate through a OFDM technique.
- IEEE 802.11b and IEEE 802.11g are operated in the same 2.4 GHz frequency band. When their devices are used in the same area, they will coexist, sharing the airspace between them.
Operational modes

- **802.11b Mode**
- **OFDM Mode** (Support of 6, 12 and 24 Mbit/s data rates is mandatory)
- **PBCC-22 and PBCC-33 Modes (Optional)**
- **CCK-OFDM Modes (Optional)**

<table>
<thead>
<tr>
<th>模式</th>
<th>資料速率 (Mbit/s)</th>
<th>調變技術</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>1, 2, 5.5, 11</td>
<td>DSSS, CCK, PBCC</td>
</tr>
<tr>
<td>OFDM</td>
<td>6, 9, 12, 18, 24, 36, 48, 54</td>
<td>OFDM</td>
</tr>
<tr>
<td>PBCC-22 and PBCC-33</td>
<td>2, 5.5, 11, 22, 33</td>
<td>DSSS, PBCC</td>
</tr>
<tr>
<td>CCK-OFDM</td>
<td>6, 9, 12, 18, 24, 36, 48, 54</td>
<td>DSSS, OFDM</td>
</tr>
</tbody>
</table>
The Applications of OFDM – Wireless LANs

IEEE 802.11a/b/g Standards

- **Maximum Data rate**
  - **IEEE 802.11a**
    - 54 Mbps
    - For example, an 802.11a network, which broadcasts on the 5GHz frequency band, supports 12 simultaneous channel (in North American).
      - maximum data rate 12*54=648 Mbps.
  - **IEEE 802.11b**
    - 11Mbps
    - For example, a standalone 802.11b network supports three non-overlapping channel (worldwide), each with a peak data rate of 11 Mbps.
      - maximum data rate 3*11=33 Mbps.
  - **IEEE 802.11g**
    - 54 Mbps
    - For example, an 802.11g installation supports three channels, each with a peak rate of 54 Mbps.
      - maximum data rate 3*54=162 Mbps.
  - **Mixed mode**
The Applications of OFDM - Wireless LANs
IEEE 802.11a/b/g Standards

Maximum Theoretical Data Rate

Mixed-Mode Data Rate vs. 802.11g Data Rate

54 Mbps IEEE 802.11 Wireless LAN at 2.4 GHz
Deploying standards-based Wireless LAN solutions
December 2002 Intel white paper
IEEE 802.16 broadband wireless access system [29]

- Broadband wireless access (BWA) is a term referring to a range of fixed radio systems, used primarily to convey broadband services between users’ premises and core networks.
- The term “broadband” is usually taken to mean the capability to deliver significant bandwidth to each user (in ITU terminology, greater than around 1.5 Mbps, though many BWA networks support significantly higher data rates).
- A typical BWA network supports connection to many user premises within a radio coverage area.
- The IEEE 802.16 standard should provide the solution to access systems based on DSL, cable, and eventually fiber optics.
- The applications of IEEE 802.16
  - The range of applications is very wide and evolving quickly. It includes voice, data and entertainment services of many kinds.
IEEE 802.16 wireless MAN background
- Target: FBWA (fixed broadband wireless access)
- Fast local connection to network
- Project development since 1998
The Applications of OFDM - IEEE 802.16

802.16 bit rate and channel size

<table>
<thead>
<tr>
<th>Channel Width (MHz)</th>
<th>Symbol Rate (Msym/s)</th>
<th>QPSK bit rate (Mbps)</th>
<th>16-QAM bit rate (Mbps)</th>
<th>64-QAM bit rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>96</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>28</td>
<td>22.4</td>
<td>44.8</td>
<td>89.6</td>
<td>134.4</td>
</tr>
</tbody>
</table>
IEEE 802.20 mobile broadband wireless access

Mission

- The mission of IEEE 802.20 is to develop the specification for an efficient packet based air interface that is optimized for the transport of IP based services.
- The goal is to enable worldwide deployment of affordable, ubiquitous, always-on and interoperable multi-vendor mobile broadband wireless access networks that meet the needs of business and residential end user markets.
IEEE 802.20 mobile broadband wireless access

- MBWA Scope
  - Specification of physical and medium access control layers of an air interface for interoperable mobile broadband wireless access systems, operating in licensed bands below 3.5 GHz, optimized for IP-data transport, with peak data rates per user in excess of 1 Mbps.
  - It supports various vehicular mobility classes up to 250 Km/h in a MAN environment and targets spectral efficiencies, sustained user data rates and numbers of active users that are all significantly higher than achieved by existing mobile systems.

- The applications of MBWA
  - This allows applications including, but not limited to, video, full graphical web browsing, e-mail, file uploading and downloading without size limitations (e.g., FTP), streaming video and streaming audio, IP multicast, telematics, location based services, VPN connections, VoIP, instant messaging and on-line multiplayer gaming.
The Applications of OFDM – IEEE 802.20


16/17
IEEE 802.20 mobile broadband wireless access

- Peak data rates
  - These peak data rate targets are independent of channel conditions, traffic loading, and system architecture.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.25 MHz</td>
</tr>
<tr>
<td>Downlink</td>
<td>Uplink</td>
</tr>
<tr>
<td>Peak User Data Rate</td>
<td>4.5 Mbps</td>
</tr>
</tbody>
</table>

### IEEE 802.20 mobile broadband wireless access

- **Peak data rates**
  - These peak data rate targets are independent of channel conditions, traffic loading, and system architecture.
Introduction to Orthogonal Frequency Division Multiplexing Technique

Readings

References


References

- [22] Digital broadcasting systems for television, sound and data services. European Telecommunication Standard, prETS 300 744 (Draft, version 0.0.3), Apr. 1996.
References