Chapter 1
Introduction to Orthogonal Frequency Division Multiplexing Technique

Chapter 1

☞ **1 Introduction to Orthogonal Frequency Division Multiplexing (OFDM) Technique**

- **1.1 The History of OFDM**
- **1.2 OFDM and Multicarrier Transmission**
- **1.3 The Applications of OFDM**

Introduction

- **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.**
- **The basic principle of OFDM is to split a high-rate datastream into a number of lower rate stream that are transmitted simultaneously over a number of subcarriers.**
- **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.**

Introduction

- The employment of Discrete Fourier Transform to replace the banks of sinusoidal generator and the demodulation significantly reduced the implementation complexity of OFDM modems.
- Intersymbol interference is eliminated almost completely by introducing a guard time in every OFDM symbol.
- In the guard time , the OFDM symbol is cyclically extended to avoid intercarrier interference.

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].

The History of OFDM

- 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).
  - Wireless LAN [11-13,23-25]
    - HIPERLAN2 (European)
    - IEEE 802.11a (U.S.A)
    - IEEE 802.11g (U.S.A)
  - IEEE 802.16 Broadband Wireless Access System

The History of OFDM

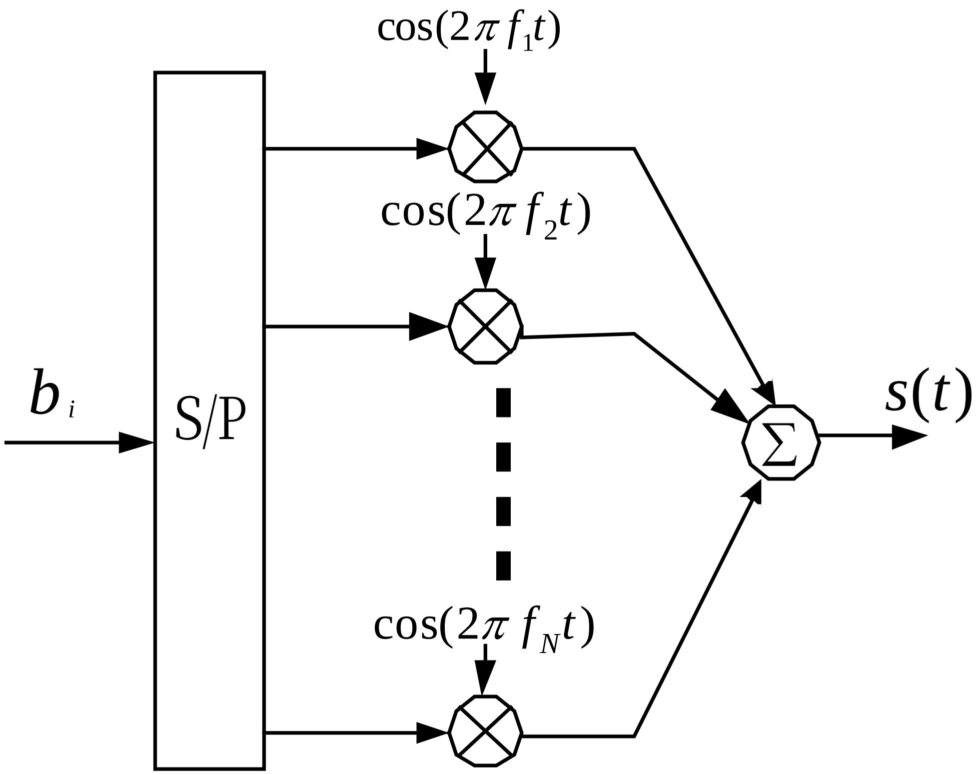
- **OFDM technique has been adopted as the new European DAB standard, and HDTV standard.**
- **A candidate of 4G mobile communication [27]**
- **OFDM/UWB (802.15.3a)**

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.

OFDM and Multicarrier Transmission

☞ Multicarrier Transmission



OFDM and Multicarrier Transmission -

Orthogonality

- **Time domain** — **Frequency domain**

$$\int_{-\infty}^{\infty} x_1(t)\, x_2^*(t)\, dt = 0 \quad \Leftrightarrow \quad \int_{-\infty}^{\infty} X_1(f)\, X_2^*(f)\, df = 0$$

- **Bandpass signal**

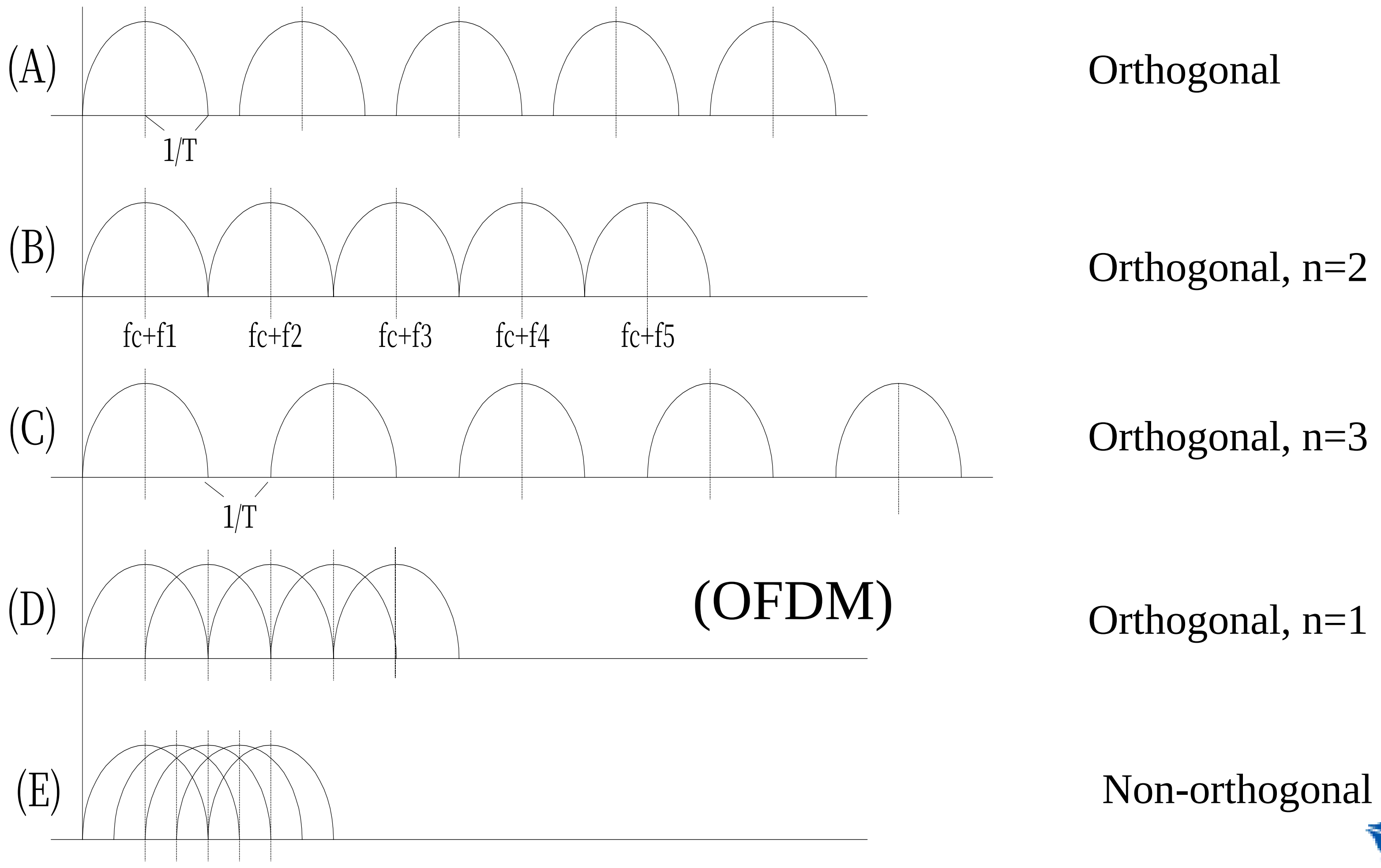
$$x_m(t) = \cos(2\pi(f_c + f_m)t) = \mathrm{Re}\left(e^{i2\pi(f_c+f_m)t}\right) = \mathrm{Re}\left(x_{lm}(t)\cdot e^{i2\pi f_c t}\right)$$

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

$$\gamma_{12} = \int_0^T e^{i2\pi f_1 t}\left(e^{i2\pi f_2 t}\right)^* dt = \int_0^T e^{i2\pi(f_1 - f_2)t} dt = \frac{\sin(\pi \Delta f T)}{\pi \Delta f} e^{i\pi \Delta f T}$$

if $\Delta f T = n$ **,*n* is non-zero integer, i.e.** $\Delta f = \frac{n}{T}$ **, then** $\gamma_{12} = 0$

OFDM and Multicarrier Transmission



OFDM and Multicarrier Transmission

- **Multicarrier CDMA**
  - **CDMA + OFDM**
  - **Three types of Multicarrier CDMA**
    - **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

- **High-frequency military system**
  - **KINEPLEX [15]**
  - **ANDEFT [16]**
  - **KATHRYN [17]**

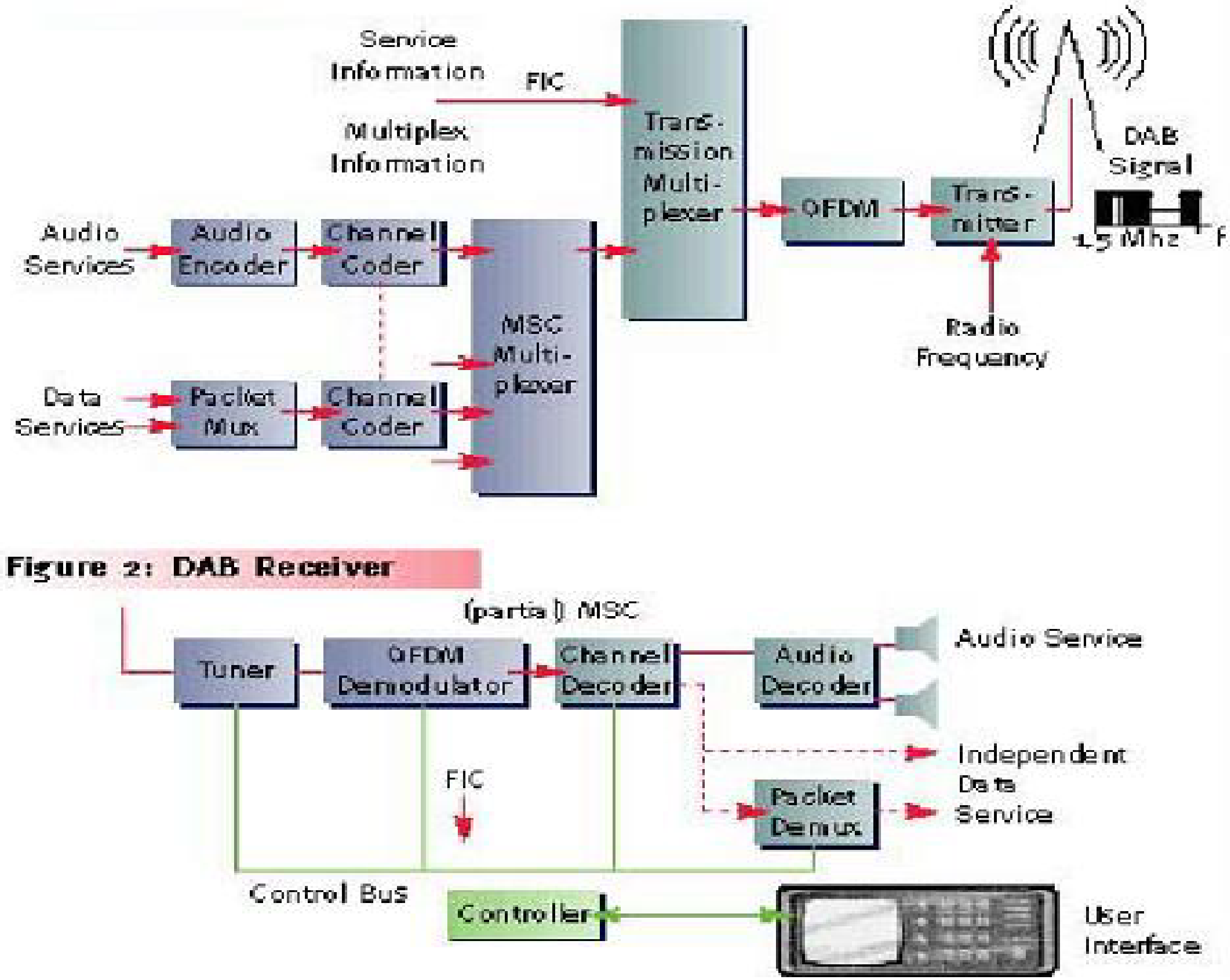
The Applications of OFDM - Fix-wire network

- **Fix-wire network [7,26]**
  - **High-bit-rate Digital Subscriber Line (HDSL)**
  - **Asymmetric Digital Subscriber Line (ADSL)**
  - **Very-high-speed Digital Subscriber Line (VDSL)**

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 - DAB



The Applications of OFDM - DAB

- **FIC:**
  - **Fast Information Channel, which carries control and service information.**
- **MSC**
  - **Main Service Channel, which carries the audio and data services.**
- **Multiplexer**
  - **A device which combines all audio and data services for modulation and transmission.**
- **OFDM**
  - **Orthogonal Frequency Division Multiplexing, the modulation technique which helps avoid multi-path fading in mobile communications. PCC : Punctured Convolutional Channel Code**

The Applications of OFDM - DAB

- **Packet Mux**
  - **Combines several 'service components' (stock-market updates, weather forecasts, paging messages, etc.) into a single data service for transmission.**
- **Packet Demux**
  - **Deconstructs the single service data into separate services upon reception.**

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.**

The Applications of OFDM - Wireless LANs

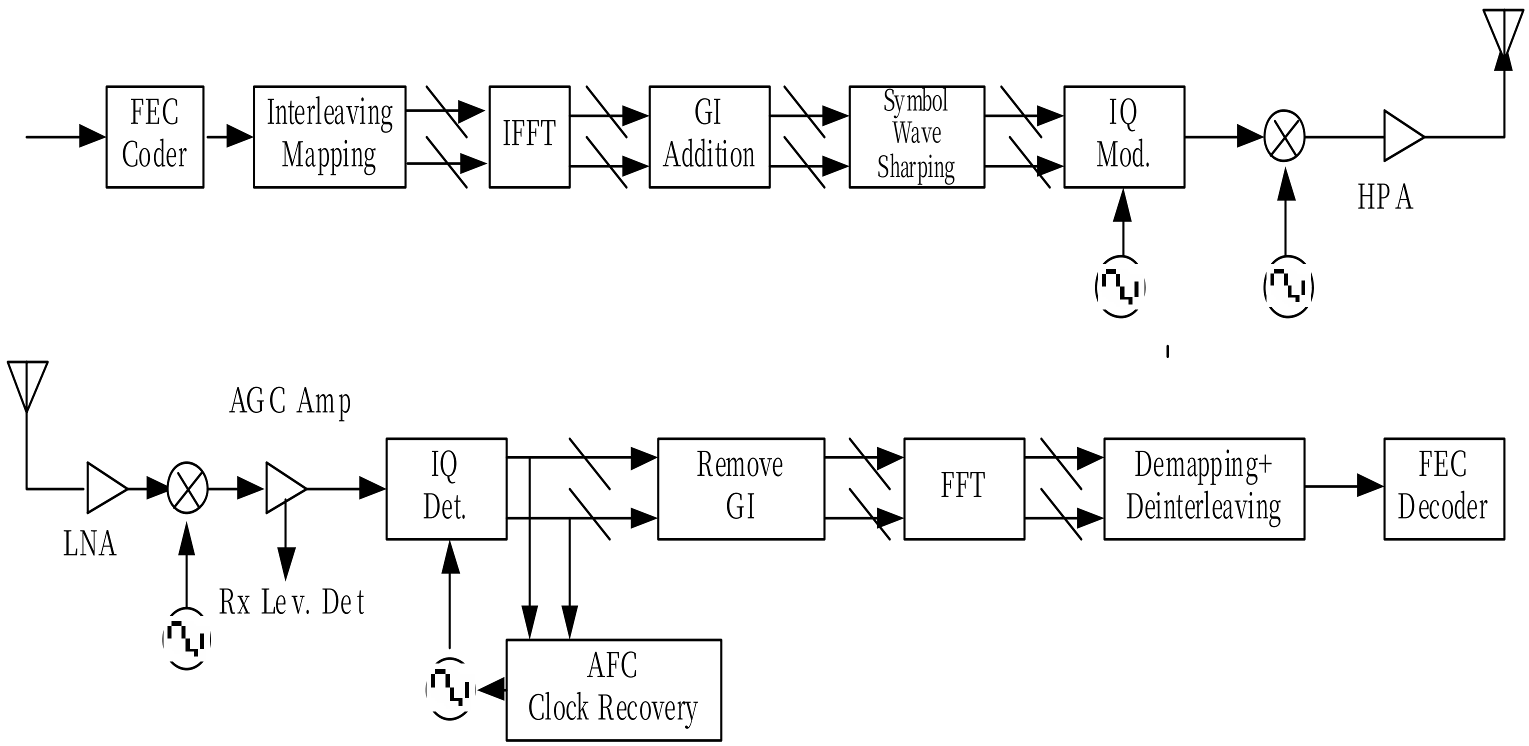
- **Wireless LANs [11-13,23-25]**
  - **HIPERLAN2 (European)**
  - **IEEE 802.11a (U.S.A)**
  - **IEEE 802.11g (U.S.A)**

The Applications of OFDM - Wireless LANs HIPERLAN2

- 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.

The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ **IEEE 802.11a Standard [25]**



The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ Timing-related parameters

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})
Δ_F: Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)
T_{FFT}: IFFT/FFT period	3.2 μs ($1/\Delta_F$)
$T_{PREAMBLE}$: PLCP preamble duration	16 μs ($T_{SHORT} + T_{LONG}$)
T_{SIGNAL}: Duration of the SIGNAL BPSK-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_{SYM}: Symbol interval	4 μs ($T_{GI} + T_{FFT}$)
T_{SHORT}: Short training sequence duration	8 μs ($10 \times T_{FFT}/4$)
T_{LONG}: Long training sequence duration	8 μs ($T_{GI2} + 2 \times T_{FFT}$)

The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ **Convolutional Encoder**

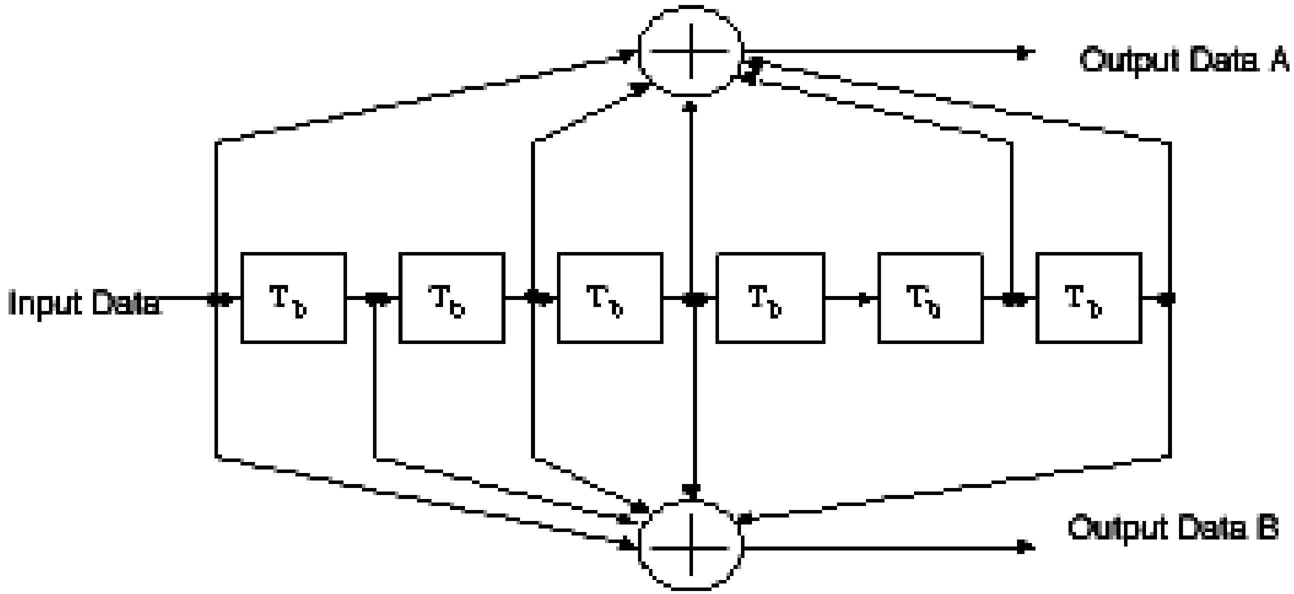


Figure 114—Convolutional encoder (k = 7)

NCCU
Wireless Comm. Lab.

The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

Data Interleaving

- The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers.
- The second ensures that adjacent coded bits are mapped alternately onto less and more significant bits of the constellation and long runs of low reliability bits are avoided.
- Let k be the index of the coded bit before the first permutation, i be the index after the first permutation, and j be the index after the second permutation, just prior to modulation mapping.
- Formula $i=(N_{CBPS}/16)\ (k \bmod 16) + \text{floor}(k/16),\ k=0,1,\ \ldots,\ N_{CBPS}-1$
- The formula of second permutation is
- $j=s^*\ \text{floor}(i/s)+(i+N_{CBPS}\ -\text{floor}(16^*I/N_{CBPS}))\bmod s,\ i=0,1,\ \ldots,\ N_{CBPS}-1$
- Where $s=\max(N_{BPSC}/2,1)$, N_{BPSC} is the number of coded bits per subcarrier

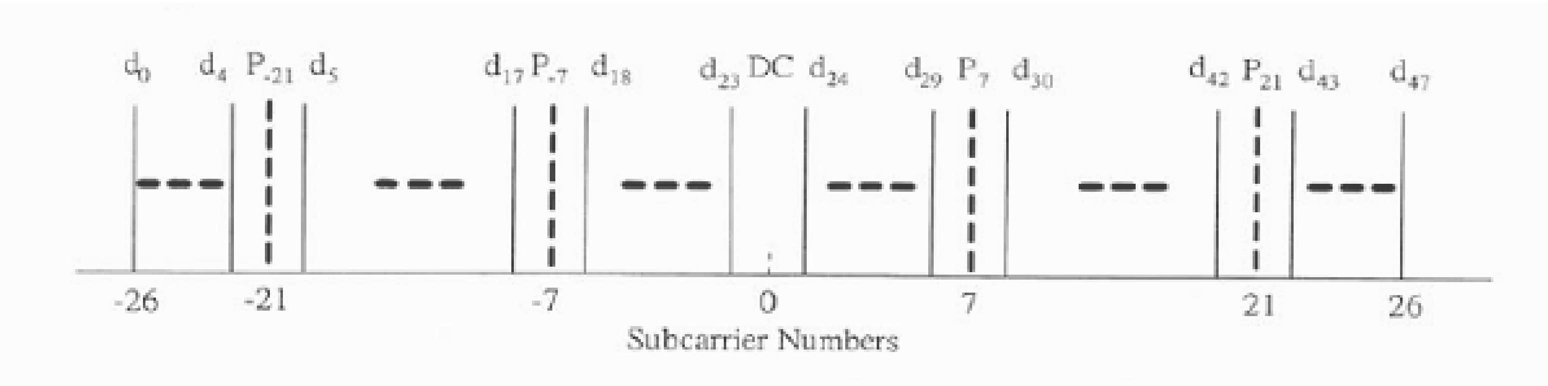
The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ IEEE 02.11a OFDM Modulation

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ **80211a subcarrier allocation**



The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ **OFDM PHY frequency channel plan**

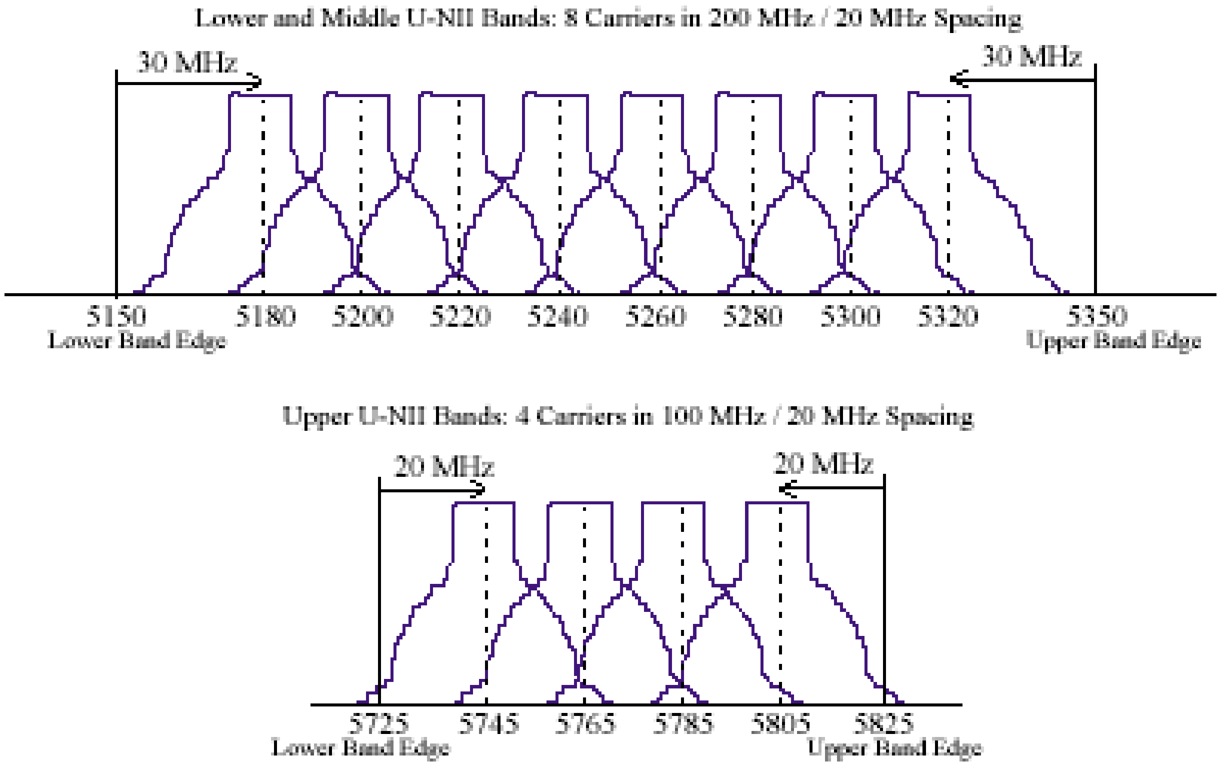


Figure 119—OFDM PHY frequency channel plan for the United States

The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ **Transmit spectrum mask**

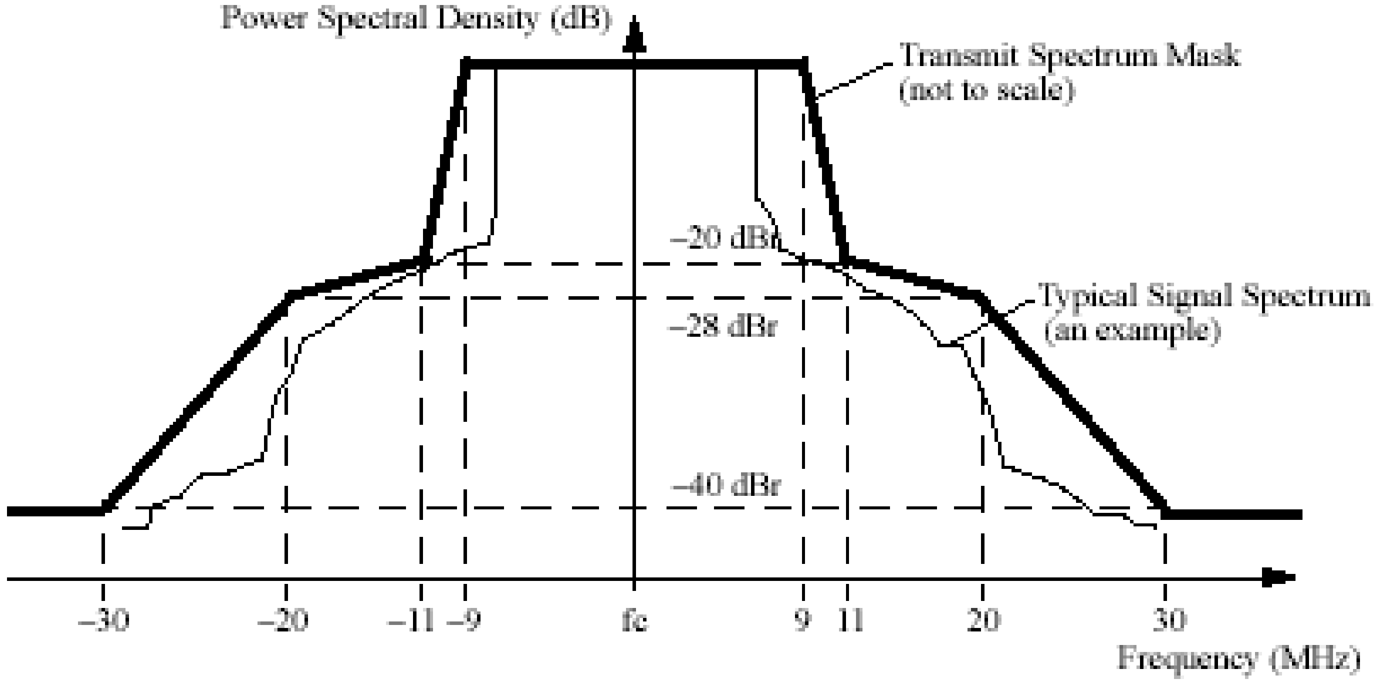


Figure 120—Transmit spectrum mask

The Applications of OFDM - Wireless LANs IEEE 802.11a Standard

☞ **OFDM PHY characteristics**

Characteristics	Value
aSlotTime	9 μs
aSIFSTime	16 μs
aCCATime	< 4 μs
aRxTxTurnaroundTime	< 2 μs
aTxPLCPDelay	Implementation dependent
aRxPLCPDelay	Implementation dependent
aRxTxSwitchTime	<< 1 μs
aTxRampOnTime	Implementation dependent
aTxRampOffTime	Implementation dependent
aTxRFDelay	Implementation dependent
aRxRFDelay	Implementation dependent
aAirPropagationTime	<< 1 μs
aMACProcessingDelay	< 2 μs
aPreambleLength	20 μs
aPLCPHeaderLength	4 μs
aMPDUMaxLength	4095
aCWmin	15
aCWmax	1023

The Applications of OFDM - Wireless LANs IEEE 802.11g Standard

- **IEEE 802.11g [28]**
  - **IEEE 802.11g will use the same 2.4GHz 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 2.4GHz frequency band. When their devices are used in the same area, they will coexist, sharing the airspace between them.**

The Applications of OFDM - Wireless LANs IEEE 802.11g Standard

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)

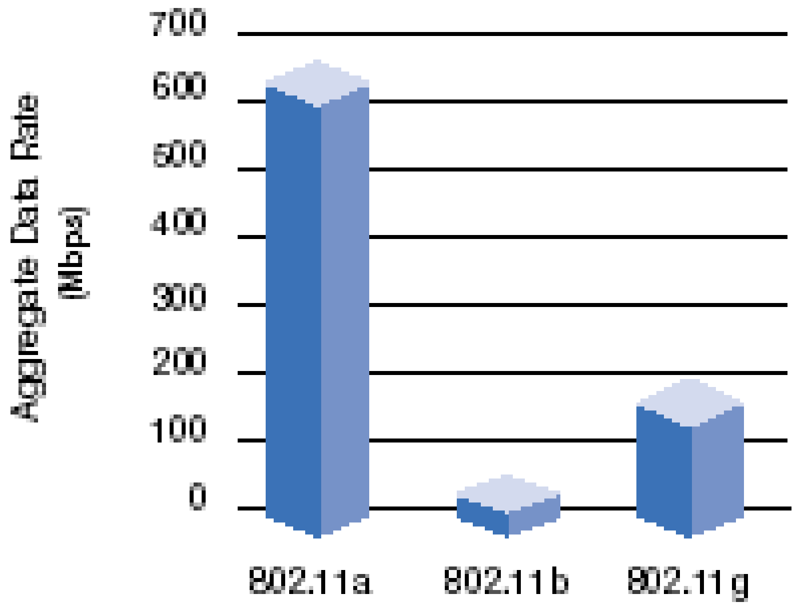
模式	資料速率(Mbit/s)	調變技術
802.11b	1, 2, 5.5, 11	DSSS, CCK, PBCC
OFDM	6, 9, 12, 18, 24, 36, 48, 54	OFDM
PBCC-22 and PBCC-33	2, 5.5, 11, 22, 33	DSSS, PBCC
CCK-OFDM	6, 9, 12, 18, 24, 36, 48, 54	DSSS, OFDM

The Applications of OFDM - Wireless LANs IEEE 802.11a/b/g Standards

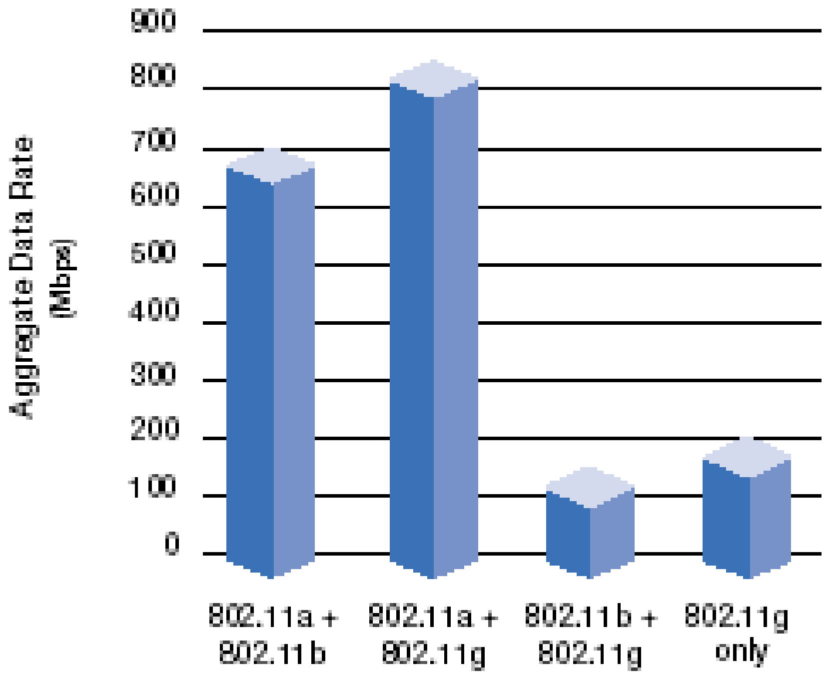
- **Maximum Data rate**
  - **IEEE 802.11a**
    - **54 Mbps**
    - **For example, an 802.11a network, which broadcasts on the 5GHz frequency band, supports 12 simultaneous channel (in North American).**
      - **maximum data rate 12*54=648 Mbps.**
  - **IEEE 802.11b**
    - **11Mbps**
    - **For 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

The Applications of OFDM – IEEE 802.16

- 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.
  - It provides a pool of bandwidth, shared automatically amongst the users. Demand from different users is often statistically of low correlation, allowing the BWA network to deliver significant
  - The range of applications is very wide and evolving quickly. It includes voice, data and entertainment services of many kinds.

The Applications of OFDM – IEEE 802.16

- **The IEEE 802.16 standard should provides the solution to access systems based on DSL, cable, and eventually fiber optics.**
- **The background of technologies and standards are followed by a primer on OFDM and its basic advantages and trade-offs.**

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