3

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING TECHNIQUES

3.1 INTRODUCTION

This chapter explains idea of OFDM, like, OFDM Transmitter and OFDM Receiver. OFDM (Orthogonal Frequency Division Multiplexing) is becoming new modulation technique for wireless communication because it can provide large data rates. In an OFDM, a large number of overlapping, orthogonal, narrow band sub-carriers are transmitted in parallel. These Carriers divide the available transmission bandwidth, and the separation of these sub carriers are such that there is a very compact spectral utilization. The OFDM is becoming popular due to its way of handling the multi-path interference at the receiver. Multi-path generates two effects (I) frequency selective fading (II) inter-symbol interference (ISI). The flatness of very narrow band channel overcomes the frequency selective Fading, while modulating symbols at a very low symbol rate makes the symbol much longer than channel impulse response and hence reduces ISI. Using powerful error correcting codes together with time and frequency interleaving yields more robustness against frequency selective fading and addition of extra guard interval between consecutive OFDM symbols can reduce effects of ISI even more.

Orthogonal Frequency Division Multiplexing is a scheme used in the area of high-data- rate mobile wireless communications such as cellular phones, DAB (Digital Audio Broadcasting). The expression digital communications in its basic form is the mapping of digital information into a waveform called a carrier signal, which is a transmitted electromagnetic pulse or wave at a steady base frequency of alternation on which information can be imposed by increasing signal strength, varying the base frequency, varying the wave phase, or other means. In this instance, Orthogonality is an implication of a definite and fixed relationship between all carriers in the collection. Multiplexing is the process of sending multiple signals or streams of information on a carrier at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end. Modulation is the addition of information to an electronic or optical signal carrier. Modulation can be applied to direct current (mainly by turning it on and off), to alternating current, and to optical signals. One can think of blanket waving as a form of modulation used in smoke signal transmission. In general, a channel is a separate path through which signals can flow. In optical fiber transmission using dense wavelength-division multiplexing, a channel is a separate wavelength of light within a combined, multiplexed light stream.

3.2 PRINCIPLES OF OFDM

The OFDM technology was mainly minimizing Inter-Symbol Interference, or ISI, due to multi-path. OFDM is a special form of Multi Carrier Modulation (MCM) in which sub-carriers are overlapped, so called Multi access. Multi carrier Modulation is the principle of transmitting data by dividing the stream into several bit streams, each of which has a much lower bit rate, and by using these sub-streams to modulate several carriers. This technique is being invented as the next generation transmission scheme for mobile wireless communications networks.

3.3 ORTHOGONALITY

Earlier, the application of OFDM was not very practical. This was because at that point, several banks of oscillators were needed to generate the carrier frequencies necessary for sub-channel transmission. Since the scheme was difficult to implement at that time. Orthogonal means right angles to each other. The term has been extended to general use, meaning the characteristic of being independent (relative to something else). It also can mean: non-redundant, non-overlapping, or irrelevant. Orthogonality is defined for both real and complex valued functions. The functions $\varphi_{f1}(t)$ and $\varphi_{f2}(t)$ are said to be orthogonal with respect to each other over the interval $x < t < y$ if they satisfy the condition

$$\int_x^y \phi_{f1}(t)\phi^*_{f2}(t)dt = 0 \text{, where f1 } \neq \text{f2.} \qquad (1)$$

3.4 GENERATION AND RECEPTION OF OFDM

OFDM signals are generated digitally due to requirement of large number of Oscillators. Figure: 3.1 is the block diagram of a typical OFDM transceiver. The transmitter section converts digital data to be transmitted, into a mapping of sub-carrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Discrete Fourier Transform (IDFT). The Inverse Fast Fourier Transform (IFFT) performs the same operations as an IDFT, except that it is much more computationally efficiency, and so is used in all practical systems. In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency.

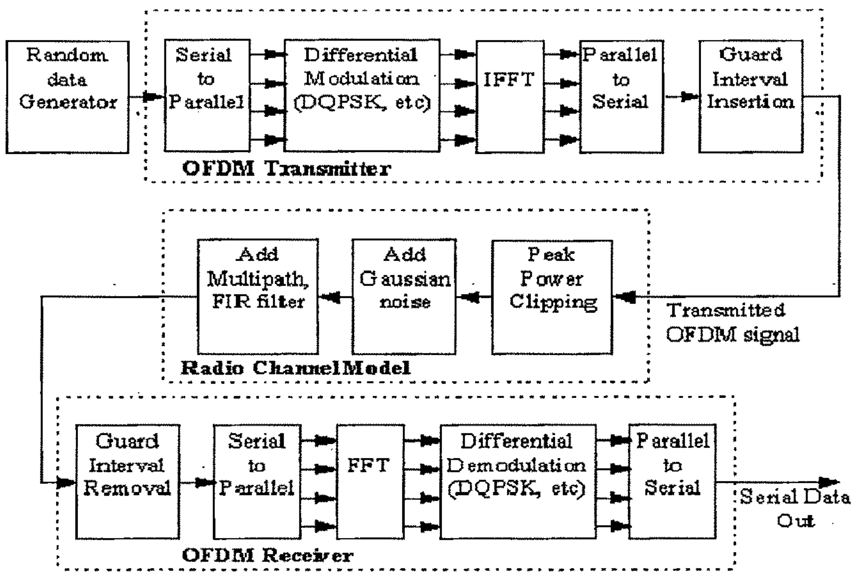

Figure: 3.1 Block diagram showing a basic OFDM transceiver

The receiver performs the reverse operation of the transmitter, mixing the RF signal to base band for processing, then using a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the sub-carriers is then picked out and converted back to digital data. The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably.

3.5 OFDM CARRIERS

OFDM is a special form of MCM and the OFDM time domain waveforms are chosen such that mutual orthogonality is ensured even though sub-carrier spectra may over-lap. With respect to OFDM, it can be stated that orthogonality is an implication of a definite and fixed relationship between all carriers in the collection. It means that each carrier is positioned such that it occurs at the zero energy frequency point of all other carriers. The *sinc* function, exhibits this property and it is used as a carrier in an OFDM system.

3.6 SERIAL TO PARALLEL CONVERSION

Data to be transmitted is typically in the form of a serial data stream. In OFDM, each symbol typically transmits 40 - 4000 bits, and so a serial to Parallel conversion stage is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol. The data allocated to each symbol depends on the modulation scheme used and the number of sub-carriers. For example, for a sub-carrier modulation of 16-QAM each sub-carrier carries 4 bits of data, and so for a transmission using 100 sub-carriers the number of bits per symbol would be 400, the modulation scheme used on each sub-carrier can vary and so the number of bits per sub-carrier also varies. As a result the serial to parallel conversion stage involves filling the data payload for each sub-carrier. At the receiver the reverse process takes place, with the data from the sub-carriers being converted back to the original serial data stream. When an OFDM transmission occurs in a multi-path radio environment, frequency selective fading can result in groups of sub-carriers being heavily attenuated, which in turn can result in bit errors. These nulls in the frequency response of the channel can cause the information sent in neighboring carriers to be destroyed, resulting in a clustering of the bit errors in each symbol. Most Forward Error Correction (FEC) schemes tend to work more effectively if the errors are spread evenly, rather than in large clusters, and so to improve the performance most systems employ data scrambling as part of the serial to parallel conversion stage. This is implemented by randomizing the sub-carrier allocation of each sequential data bit. At the receiver the reverse scrambling is used to decode the signal. This restores the original sequencing of the data bits, but spreads clusters of bit errors so that they are approximately uniformly distributed in time. This randomization of the location of the bit errors improves the performance of the FEC and the system as a whole.

3.7 OFDM MODULATION

In general, the OFDM signal can be represented as the sum of 'N' separately modulated orthogonal sub-carriers.

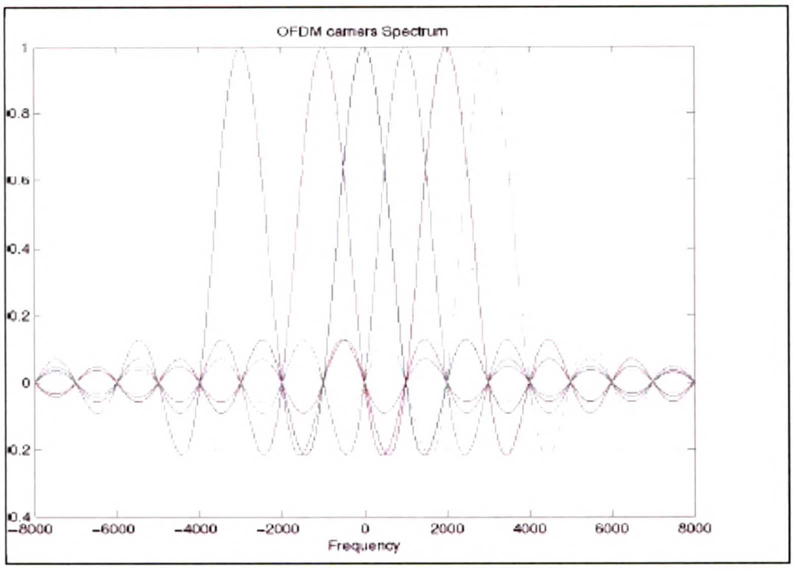

Figure: 3.2 Sub-carriers in the OFDM Spectrum

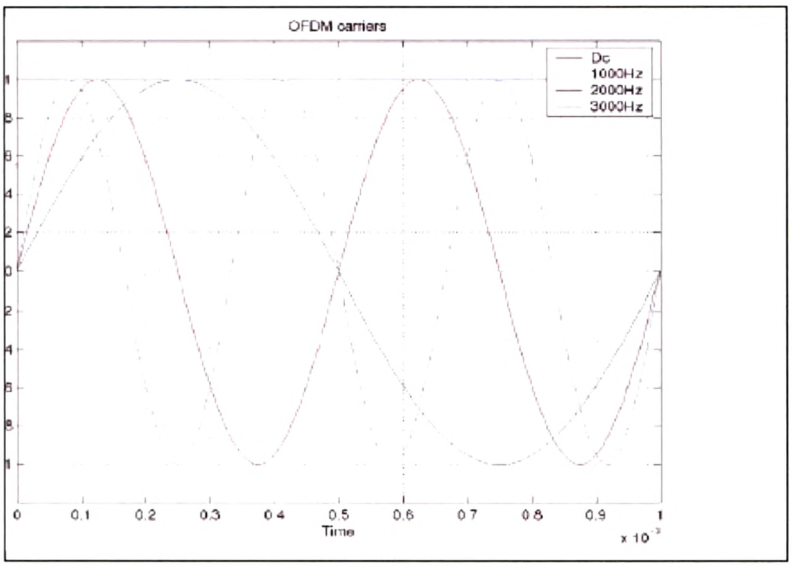

Figure: 3.3 Sub-carriers within an OFDM Symbol (Time Domain)

$$s(t) = \sum_{n=-\infty}^{\infty} \sum_{k=0}^{N-1} d_{n,k}\, g_k(t - nTs) \tag{2}$$

Where $g_k(t)$, $k = 0,1,..., N -1$, represent the 'N' carriers and are given by,

$$g_k(t) = e^{j2\pi fkt}, t \in [t, Ts) \tag{3}$$

In above equation, dn, k stands for the symbol that modulates the k^th carrier in the nth signaling interval and each signaling interval is of duration Ts. From this equation, 'N' symbols are transmitted in Ts time interval. The symbol sequence dn, k is obtained by converting a serial symbol sequence of rate N/Ts (symbol duration = Ts/N) into 'N' parallel symbol sequences of rate 1/Ts (each with symbol duration Ts). As mentioned previously, the sub-carrier frequencies satisfy the following requirement

$$f_k = f_o + \frac{k}{Ts}, k = 1,2,\ldots, N-1 \tag{4}$$

Figures: 3.2, 3.3 illustrate the time domain and frequency domain representation of the 'N' orthogonal sub-carriers in an OFDM symbol. The signal transmitted in the 'n'^th signaling interval (of duration Ts) is defined as the 'n'^th OFDM frame, i.e,

$$F_n(t) = \sum_{k=0}^{N-1} d_{n,k}\, g_k(t - nTs) \tag{5}$$

The 'n'th OFDM frame $F_n(t)$ consists of 'N' symbols, each modulating one of the 'N' orthogonal sub-carriers as shown figure: 3.4. From equations (4), (5) we see that 'N' modulators and 'N' demodulators are required at the transmitter and the receiver respectively. The number of sub-carriers 'N' in OFDM systems is usually of the order of 100's implying that the transmitter and receiver blocks become bulky and expensive to build. Also the oscillators (for generating the carrier frequencies) have temperature instability and other problems.

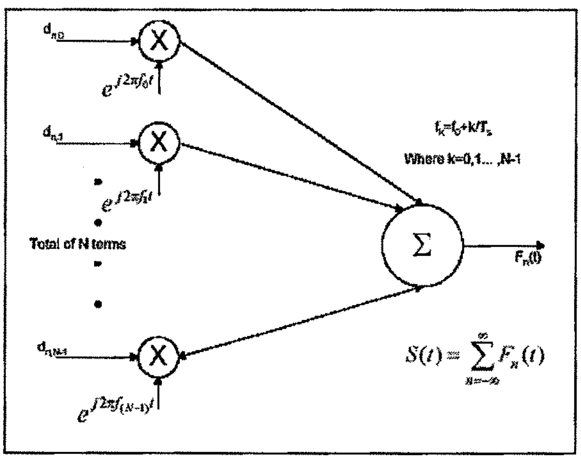

Figure: 3.4 OFDM Modulation- Block Diagram

The Discrete Fourier Transform is used to solve the modulation and demodulation complexities discussed above. The following discussion is modulation process can be achieved by the IFFT operation.

The OFDM frame represented by equation (4) at a rate 'N/Ts', the resulting discrete-time signal is

$$F_n^m = \sum_{k=0}^{N-1} d_{n,k} g_k(t-nTs) @ t = (n+\frac{m}{N})Ts, m = 0,1,...,N-1 \quad (6)$$

Expanding the above equation,

$$F_n^m = e^{j2\pi f_0 \frac{m}{N}Ts} \sum_{k=0}^{N-1} d_{n,k} e^{j2\pi \frac{mk}{N}}, m = 0,1,...,N-1 \quad (7)$$

Assume, $f_0=0$ then the above equation reduces to

$$F_n^m = \sum_{k=0}^{N-1} d_{n,k} e^{j2\pi \frac{mk}{N}}, m = 0,1,...,N-1 \quad (8)$$

The above equation can be expressed in terms of the IFFT as,

$$F_n^m = N \bullet IFFT(d_{n,k}) \quad (9)$$

Applying the FFT operation on both sides of the above equation,

$$FFT(F_n^m) = N \bullet FFT(IFFT(d_{n,k})) = d_{n,k} \quad (10)$$

Thus the OFDM modulation and demodulation can be accomplished using the computationally efficient operations IFFT and FFT respectively.

3.8 OFDM DEMODULATION

Since the carriers are orthogonal with each other, it follows that the scalar product

$$\prec g_k(t), g_i(t) \succ_{Ts} = \int_{Ts} g_k(t), g_i^*(t)dt = Ts\delta(k-i) \quad (11)$$

Thus, the Orthogonality of the carriers can be used to demodulate each of the sub-carriers (without Inter-Carrier Interference) as follows

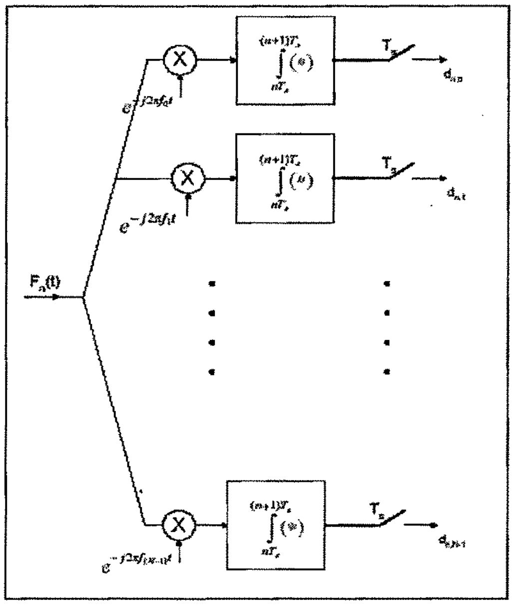

Figure: 3.5 OFDM Demodulation - Block Diagram

$$d'_{n,k} = \frac{1}{Ts}\int_{nTs}^{(n+1)Ts} S\,(t)\,g_k(t)dt \qquad (12)$$

If there is zero Inter-Frame Interference, then the above expression reduces to

$$d'_{n,k} = \frac{1}{Ts}\int_{nTs}^{(n+1)Ts} F_n(t)\,g_k(t)dt = d_{n,k} \qquad (13)$$

Thus perfectly demodulate each sub-carrier in the transmitted signal and get back the transmitted symbol sequence as shown figure: 3.5

3.9 GUARD INTERVAL AND CYCLIC EXTENSION

OFDM system is an effective way that deals with multi-path delay spread. In a single carrier system, inter-symbol interference (ISI) is still a problem in an OFDM system. To eliminate ISI almost completely, the concept of guard interval is introduced for each OFDM symbol. The guard interval must be chosen larger than the maximum delay spread, such that the multi-path component from one OFDM symbol cannot interfere with the next symbol. However, the problem of inter-carrier interference (ICI) would occur when the guard interval is empty. ICI is cross talk between different sub-carriers, which means they are no longer orthogonal. When the receiver tries to demodulate the data from sub-carrier 1, some interference form sub-carrier 2 is contained. To combat ICI, the OFDM symbol is cyclically extend in the guard interval, and it protecting against ISI shown in. This ensures that delayed replicas of the OFDM symbol always has an integer number of circles with OFDM data interval, as long as the delay is smaller than the guard interval.

Cyclic extension has two types: Cyclic Prefix and Cyclic Suffix (see Figure: 3.6). A cyclic prefix is a copy of the last part of the OFDM symbol to its front end; a cyclic suffix is a copy of the first part of the OFDM symbol to its tail.

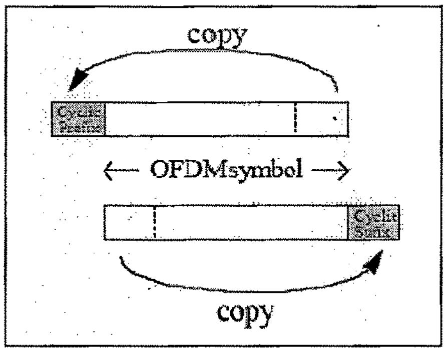

Figure: 3.6 cyclic extension types

3.10 SUB-CARRIER MODULATION

Once each sub-carrier has been allocated bits for transmission, they are mapped using a modulation scheme to a sub-carrier amplitude and phase, which is represented by a complex In-phase and Quadrature-phase (IQ) vector. This example shows 16-QAM, which maps 4 bits for each symbol. Each combination of the 4 bits of data corresponds to a unique IQ vector, shown as a dot on the figure. A large number of modulation schemes are available allowing the number of bits transmitted per carrier per symbol to be varied.

In the receiver, mapping the received IQ vector back to the data word performs sub-carrier demodulation. During transmission, noise and distortion becomes added to the signal due to thermal noise, signal power reduction and imperfect channel equalization. Figure: 3.7 show an example of a received 16-QAM signal with a SNR of 18 dB. Each of the IQ points is blurred in location due to the channel noise. For each received IQ vector the receiver has to estimate the most likely original transmission vector. This is achieved by finding the transmission vector that is closest to the received vector. Errors occur when the noise exceeds half the spacing between the transmission IQ points, it cross over a decision boundary.

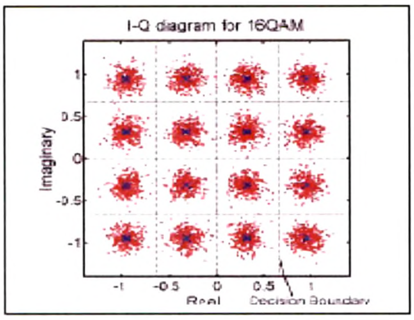

Figure: 3.7 IQ plot for 16-QAM data with added noise

3.11 ADVANTAGES OF OFDM

OFDM has several advantages over single carrier modulation systems and these make it a viable alternative for CDMA in future wireless networks. In this section, discussing some of the advantages

3.11.1 Multi-path Delay Spread Tolerance

OFDM is highly immune to multi-path delay spread that causes inter-symbol interference in wireless channels. Since the symbol duration is made larger (by converting a high data rate signal into 'N' low rate signals), the effect of delay spread is reduced by the same factor. Also by introducing the concepts of guard time and cyclic extension, the effects of inter-symbol interference (ISI) and inter-carrier interference (ICI) is removed completely.

3.11.2 Immunity to Frequency selective fading Channels

If the channel undergoes frequency selective fading, then complex equalization techniques are required at the receiver for single carrier modulation techniques. But in the case of OFDM the available bandwidth is split among many orthogonal narrowly spaced sub-carriers. Thus the available channel bandwidth is converted into many narrow flat- fading sub-channels. Hence it can be assumed that the sub-carriers experience flat fading only, though the channel gain/phase associated with the sub-carriers may vary. In the receiver, each sub-carrier just needs to be weighted according to the channel gain/phase encountered by it. Even if some sub-carriers are completely lost due to fading, proper coding and interleaving at the transmitter can recover the user data.

3.11.3 High Spectral Efficiency

OFDM achieves high spectral efficiency by allowing the sub-carriers to overlap in the frequency domain. At the same time, to facilitate inter-carrier interference free demodulation of the sub-carriers, the sub-carriers are made orthogonal to each other. If the number of sub-carriers in 'N', the total bandwidth required is

$$BW_{total} = \frac{N+1}{Ts} \qquad (14)$$

For large values of N, the total bandwidth required can be approximated as

$$BW_{total} \approx \frac{N}{Ts} \qquad (15)$$

On the other hand, the bandwidth required for serial transmission of the same data is

$$BW_{total} \approx \frac{2N}{Ts} \qquad (16)$$

Thus we achieve a spectral gain of nearly 100% in OFDM compared to the single carrier serial transmission case.

3.11.4 Efficient Modulation and Demodulation

Modulation and Demodulation of the sub-carriers is done using IFFT and FFT methods respectively, which are computationally efficient. By performing the modulation and demodulation in the digital domain, the need for highly frequency stable oscillators is avoided.

3.11.5 Frequency Diversity

A technique, MC-CDMA, which is based on a combination of DS-CDMA and OFDM, has been introduced recently

3.12 APPLICATIONS OF OFDM

Orthogonal Frequency Division Multiplexing is a new technology whose applications just being explored. The primary applications are in multimedia push technology and in wireless LAN.

3.12.1 Wireless LAN Applications

3.12.1.1 HIPERLAN/2

HIPERLAN/2 is a Wireless LAN application defined by the ETSI. HIPERLAN/2 handles data rates between 6 Mbit/s to 54 Mbit/s. HIPERLAN/2 provide a DLC layer on top of which an IP based broadband network can be implemented. The PHY layer of HIPERLAN/2 is based on the Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme. The Numerical Values of OFDM parameters in HIPERLAN are given in Table: 3.1:

Parameters	**Value**
Sampling rate fs=1/T	20 MHz
Symbol part duration TU	64*T 3,2 μs
Cyclic prefix duration	16*T, 0,8 μs (mandatory); 8*T, 0,4 μs (optional)
Symbol interval TS	80*T, 4,0 μs (TU+ TCP) ; 72*T, 3,6 μs (TU+ TCP)
Number of data sub-carriers NSD	48
Number of pilot sub-carriers NSP	4
Sub-carrier spacing Δf	0,3125 MHz (1/TU)
Spacing between the two outmost sub-carriers	16,25 MHz (NST * Δf)

Table: 3.1 HiperLAN/2 Parameters

3.12.1.2 IEEE 802.11

The IEEE 802.11 committee has a standard similar to the HIPERLAN its OFDM parameters are as shown.

3.12.2 Digital Audio Broadcasting (DAB)

Digital Audio Broadcasting is a new multimedia push technology, with a good sound quality and better spectrum efficiency. This is achieved by the use of OFDM technology. The DAB system samples audio at a sample rate of 48 kHz and a resolution of 22bits. Then the data is compressed to between 32 and 384 Kbps. A rate ¼ convolution code is used with constraint length 7. The total data rate is about 2.2Mbps. The frame time is 24ms. QPSK modulation is performed at the transmitter.

The advantage of using OFDM for DAB is that the OFDM suffers very little from delay spread and also that the OFDM system has high spectral efficiency.

3.12.3 Digital Video Broadcasting (DVB-T)

Digital Video Broadcasting (DVB) is an ETSI standard for broadcasting Digital Television over satellites, cables and thorough terrestrial (wireless) transmission. Terrestrial DVB operates in either of 2 modes called 2k and 8k modes with 1705 carriers and 6817 carriers respectively.

3.13 SUMMARY

In this chapter we discuss different types of technique Orthogonal Frequency Division Multiplexing. OFDM is becoming 4th Generation technique for their high rata rates transmission, and its ability to overcome Multi-path Fading. We have discuss OFDM transmission and OFDM receiver technique, their detection and its different types of parameters such as FFT size, IFFT size, Guard band, etc. Finally we discuss OFDM advantages and limitations and their recent application.