CHAPTER 4

MULTI-CARRIER COMMUNICATION TECHNIQUES

4.1 INTRODUCTION

In this chapter first an overview of multi path propagation and its implication is presented. Next, an analytical model of the radio channel and its main characteristics: delay spread, coherence bandwidth, and Doppler shift are discussed. The need for a multi-carrier system and the basics of the two commonly used techniques: MC-CDMA and OFDMA is analyzed to provide the overview of the multi-carrier system. OFDMA is one of the most widely advocated multiple access technique for the next generation mobile networks. The discussion on OFDMA includes the system representation and a basic experiment to estimate the spectrum of OFDMA signal.

4.2 MULTIPATH PROPAGATION

Most cellular radio systems operate in urban areas where there is no direct line of sight path between the transmitter and receiver and where the presence of high buildings causes severe diffraction loss. Due to multiple reflections from various objects, the electromagnetic waves travel along different paths of varying lengths. The interaction between these waves causes multipath fading at a specific location, and strength of the wave decrease as the distance between transmitter and receiver increases.

In built up urban areas, there is very often no line of sight (LOS) path to the base station. This causes fading because the heights of the mobile
antennas are well below the height of the surrounding structures. Even when LOS exists, random phenomenon, such as, reflection, refraction, diffraction, absorption, or scattering deteriorate the signal and result in multiple reception of the signal with different delays and strength as shown in Figure 4.1. The signal received by a mobile at any point in space may consist of a large number of plane waves having randomly distributed amplitudes, phase, and angle of arrival. These multipath components combine vectorially at the receiver antenna and can cause the signal received by the mobile to fade. When a mobile user is stationary, the received signals are faded but constant in magnitude. On the other hand, when the mobile station is on the move, it experiences the fluctuation of the power of the received signal.

![Figure 4.1 Multipath propagation](image-url)
Multipath propagation causes frequency selective fading and intersymbol interference (ISI). The frequency selectivity results from destructive interference of transmitted signal with itself due to multipath reflections. It causes deep fading in some frequency components of the transmitted signal. ISI is due to the signal propagation through different paths and concurrent receptions of different transmitted signals. ISI is a form of distortion of a signal in which one symbol interferes with subsequent symbols as shown in Figure 4.2. Apart from multipath propagation, the inherent non-linear frequency response of a channel is another reason for ISI. In other words, imperfection in the overall frequency response of the system causes ISI. The ISI becomes a severe problem for broadband signal transmission, because the symbol length is short in time and ISI, symbol overlap will cause large errors in detection. Equalizer can help in combating ISI, but many times it becomes ineffective in multi carrier communication.

![ISI due to multipath propagation](image)

**Figure 4.2 ISI due to multipath propagation**

### 4.3 ANALYTICAL MODEL OF MULTIPATH RADIO CHANNEL

At the receiver, due to the presence of the multiple electromagnetic paths, more than one pulse is received, and each one of them arrives at different times. Even though, the electromagnetic signals travel at the speed of light, and since every path has a length different from that of the other ones, there are different air travelling times. A multipath channel can be represented as linear time variant filter as shown in Figure 4.3.
Let a band pass signal $x_b(t)$ with carrier frequency of $f_c$ to be transmit in the air be

$$x(t) = Re\{x_b(t)e^{j2\pi f_c t}\} \quad (4.1)$$

The transmit signal reaches the receiver through multiple paths where the $i^{th}$ path has an attenuation $\alpha_i$ and delay $\tau_i$. Now, the received signal is given by,

$$r(t) = \sum_{i=0}^{N_p-1} \alpha_i(t)x[t - \tau_i(t)] \quad (4.2)$$

Using (4.1) in the above equation, transmit baseband signal is,

$$r(t) = Re\left\{\sum_{i=0}^{N_p-1} \alpha_i(t)x_b[t - \tau_i(t)]e^{j2\pi f_c [t - \tau_i(t)]}\right\} \quad (4.3)$$

The baseband equivalent of the received signal is represented by

$$r_b(t) = \sum_{i=0}^{N_p-1} \alpha_i(t)e^{-j2\pi f_c \tau_i(t)}x_b[t - \tau_i(t)] \quad (4.4)$$

$$= \sum_{i=0}^{N_p-1} \alpha_i(t)e^{-j\theta_i(t)}x_b[t - \tau_i(t)] \quad (4.5)$$

where $\theta_i = 2\pi f_c \tau_i(t)$ is the phase of the $i^{th}$ path.
The impulse response is

\[ h_b(t) = r(t) = \sum_{i=0}^{N_p-1} \alpha_i(t) e^{-j\theta(t)} \] (4.6)

\( h_b(t) \) can be assumed as series impulses whose magnitudes and phase changes to represent multipath channel as shown in Figure 4.4.

Similar to linear time invariant systems, the multipath phenomenon can be characterized by the channel system function \( H(f) \), which is the Fourier transform of the impulse response \( h(t) \).

\[ H(f) = F[h(t)] = \int_{-\infty}^{\infty} h(t) e^{-j2\pi ft} dt = \sum_{i=0}^{N_p-1} \alpha_i e^{j\omega t} e^{-j2\pi f\tau_i} \] (4.7)

\[ \tau_0, \tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \ldots, \tau_{N-1} \]

**Figure 4.4 Multi path impulse response**

The channel transfer characteristic thus obtained has a typical appearance of a sequence of peaks and valleys (also called notches); it can be shown that, on average, the distance (in Hz) between two consecutive valleys (or two consecutive peaks), is roughly inversely proportional to the multipath time as shown in Figure 4.5.
4.3.1 Rayleigh Fading Model

The Rayleigh channel is normally viewed as a suitable approach to model the wireless communication medium when analyzing radio wave propagation performance for areas such as cellular communications in a well built-up urban environment where there are many reflections from buildings, etc.

This model is particularly useful in scenarios where the signal may be considered to be scattered between the transmitter and receiver. In this form of scenario, there is no single signal path that dominates and a statistical approach is required to the analysis of the overall nature of the radio communications channel.

A Rayleigh channel models assume that the magnitude of a signal that has passed through a transmission medium will vary randomly, or fade, according to a Rayleigh distribution. The probability density function of a Rayleigh fading channel is defined as follows (Jean-Paul Linnartz 2004).

\[
f_{\rho}(\rho) = f_{\rho}(\sqrt{2\rho}) \left| \frac{d\rho}{dp} \right| = \frac{1}{\sigma^2} e^{\frac{-\rho}{\sigma^2}}
\]  

\((4.8)\)
where, $p$ is instantaneous power and is related to signal amplitude $a$ as

$$p = \frac{1}{2}a^2$$  \hfill (4.9)

To represent the simulation process more rigorous, sometimes the AWGN model is mixed with Rayleigh channel.

### 4.3.2 AWGN Noise Model

The additive white Gaussian noise (AWGN) model is one in which the information is given as a single impairment: a linear addition of wideband or white noise with a constant spectral density and a Gaussian distribution of noise samples. The model does not account for the phenomena of fading, frequency selectivity, interference, nonlinearity or dispersion. Wideband Gaussian noise comes from many natural sources, such as the thermal vibrations of atoms in antennas (referred to as thermal noise), shot noise, black body radiation from the earth and other warm objects, and from celestial sources such as the Sun.

The AWGN can be represented by

$$\sigma^2 = \frac{W N_0}{N}$$  \hfill (4.10)

where $W$ is the total bandwidth, $N_0$ is the noise spectral density, $N$ is total subcarriers.

### 4.4 CHARACTERISTICS OF FADEING CHANNEL

The effects of fading channel depend on some channel characteristics such as delay spread, coherence bandwidth, and Doppler spread (Lee 2008). These characteristics and their relative importance are explained below.
4.4.1 Delay Spread

As the number of scatters in the vicinity of mobile unit increases, the received discrete pulses become a continuous signal pulse with a pulse length of $\Delta$, and it is called the delay spread.

A delay model (distribution of delay spread) can be expressed as (Lee 2008)

$$p(T_i) = \frac{1}{\Delta} exp \left(\frac{T_i}{\Delta}\right) \tag{4.11}$$

where $T_i$ is the time delay of $i^{th}$ wave arrival.

4.4.2 Coherence Bandwidth

The presence of time delays in two fading signals that are closely spaced in frequency can cause the two signals to become correlated. The frequency spacing that allows this condition to prevail is dependent upon the delay spread $\Delta$, and this frequency interval is called the coherence bandwidth ($B_c$).

For a frequency of the phase modulated signal based on phase correlation of 0.5, the coherence bandwidth $B_c$ is given by (Lee 2008)

$$B_c = \frac{1}{4\pi\Delta} \tag{4.12}$$

where $\Delta$ is the delay spread.

4.4.3 Doppler Shift

One crucial parameter in the adaptation of wireless systems is the maximum Doppler shift (spread). It provides information about the fading rate of the channel. The Doppler shift is the change in frequency of a wave for an observer moving relative to the source of the waves. The phase change in
the received signal due to the difference in path length can be given by (Rappaport 2008)

\[ \Delta \phi = \frac{2\pi \Delta l}{\lambda} = \frac{2\pi \nu \Delta t}{\lambda} \cos\theta \quad (4.13) \]

where \( \nu \) is the velocity of mobile, \( \Delta l \) is the difference in path length travelled by the wave from source \( S \) to the mobile at point \( x \) and \( y \) i.e \( \Delta l = d \cos\theta = \nu \Delta t \cos\theta \) and \( \Delta t \) is the time required for the mobile to travel from \( x \) to \( y \).

The apparent change in frequency, or Doppler shift is given by \( f_d \), where (Rappaport 2008)

\[ f_d = \frac{1}{2\pi} \frac{\Delta \phi}{\Delta t} = \frac{\nu \cos\theta}{\lambda} \quad (4.14) \]

Figure 4.6 and Figure 4.7 are the results of experiments conducted to study the effect of Doppler shift on received power in Rayleigh fading channel. These Doppler shifts correspond to velocities of about 6km/h and 60km/h respectively at 2.4 GHz.

Clearly, the Doppler shift has a significant role on the fluctuation of received power by a mobile station. In particular, in the deep fades the signal strength can drop by a factor of several thousands (30-45 dB). Estimating it is a complex process and requires an advance setup. It has been observed that if the signal bandwidth is much greater than the maximum Doppler shift, then the effects of Doppler spread are negligible at the receiver.

Doppler information can help in the selection of appropriate transmission characteristics to combat inter-carrier interference including proper channel estimators to enhance reception. In particular, a power control update approach can be applied to adjust the interleaving length to reduce reception delays and so on. Communication systems should work in a wide range of channel states, such as Mobile user’s velocities from 0 to 250 km/h and delay spreads from 0 to 20\( \mu \)s (Cai et al 2003, Tevfik Yucek 2005).
Figure 4.6 Rayleigh fading with a maximum Doppler shift of 10Hz

Figure 4.7 Rayleigh fading with a maximum Doppler shift of 100Hz.
4.5 NEED FOR MULTI-CARRIER COMMUNICATION

As discussed earlier, the channel response is never flat in practice, but if a wideband channel is divided into a number of narrowband sub channels, the frequency response can considered nearly flat in a particular band. In other words the multi-carrier communication becomes a natural choice for the provision of robustness against frequency selective fading. This technique divides a bit stream in to $N$ sub streams each of different frequency gains to support heterogeneous requirement of users in a cell. The channel error gets reduced as the broadband channel becomes $N$ narrowband sub channels as shown in Figure 4.8.

![Figure 4.8 Downlink scenario in a typical cell](image)

Further an adaptive resource allocation strategy can be implemented for the efficient management of subcarrier which allows increased system capacity and improved quality of service support.
4.6 MULTI-CARRIER COMMUNICATION TECHNIQUES

Multi-carrier modulation (MCM) is a method of transmitting data by splitting it into several components and sending each of these components over separate carrier signals. The individual carriers have narrow bandwidth, but the composite signal can have broad bandwidth. The advantages of MCM include relative immunity to fading caused by transmission over more than one path at a time (multipath fading), less susceptibility than single-carrier systems to interference caused by impulse noise, and enhanced immunity to inter-symbol interference. Broadly, there are two popular multi-carrier multiple access techniques:

i. Multi-carrier code division multiple access (MC-CDMA)
ii. Orthogonal frequency division multiple access (OFDMA)

4.6.1 Multi-Carrier Code Division Multiple Access

The MC-CDMA spreads each user symbol in the frequency domain. That is, each user symbol is carried over multiple parallel subcarriers, but it is phase shifted (typically 0 or 180 degrees) according to a code value. The code values differ per subcarrier and per user. The receiver combines all subcarrier signals by weighing these to compensate varying signal strengths and undo the code shift. The receiver can separate signals of the different users, because these have different (e.g. orthogonal) code values. Since each data symbol occupies a much wider bandwidth (in hertz) than the data rate (in bit/s), a signal-to-noise-plus-interference ratio of less than 0 dB is feasible. One way of interpreting MC-CDMA is to regard it as a direct-sequence CDMA signal (DS-CDMA) which is transmitted after it has been fed through an inverse FFT (Fast Fourier Transform). It is easier to implement for high data rate services than DS-CDMA by the increased signaling interval. The salient features of MC-CDMA systems are:
• Suitable for indoor wireless environment: small delay spread and small Doppler spread

• Fading resistance using frequency diversity

• Possibility of quasi-synchronous operation in reverse link

• DS-CDMA has energy loss due to the limited number of rake receivers while MC-CDMA gathers nearly all energy scattered in subcarriers.

Problems in MC-CDMA:

• High Peak-to-Mean Envelope Power Ratio
  • Nonlinear amplification - spurious power
  • Power inefficient

• Sensitive to carrier frequency offset: Difficult to deploy for high speed vehicles

• Sensitive to phase noise

• Low frequency reuse factor than DS-CDMA.

4.6.2 Orthogonal Frequency Division Multiple Access

The key concept in OFDMA is to split a wide band signal into several orthogonal narrow band signals for transmission. In other words, instead of transmitting a volume of bits over a short time duration and a wide frequency band, it is transmitted over a long time duration and several narrow frequency bands. For this purpose, a baseband high data rate stream is divided into $K$ parallel low data rate streams in an OFDMA transmitter as shown in Figure 4.9. They are then modulated using an adaptive modulation technique, called $M$-ary - quadrature amplitude modulation (M-QAM) with orthogonal sub-carriers by IFFT and the addition of guard interval greater than the delay spread between the OFDM symbols to eliminate ISI. A cyclic extension of the
OFDM symbol, called cyclic prefix, is inserted in the guard interval. The OFDM symbols are modulated by a carrier frequency after passing a parallel to serial converter.

The channel estimation information is estimated at the receiver and fed back to the transmitter for adaptive transmission schemes, such as adaptive modulation, channel coding, and power allocation.

![OFDMA transmitter and receiver](image)

**Figure 4.9 OFDMA transmitter and receiver**

The cyclic prefix is in fact a circular convolution in the discrete-time domain which is equivalent to multiplication in the discrete frequency domain. To be precise, suppose \( x_k \) is a length of \( P \) sequence. Its circular convolution with another sequence \( h_k \) where \( k \) varies from 0 to \( N_{cp}-1 \) is defined as

\[
y_k = x_k \otimes h_k = \sum_{l=0}^{P-1} h_l x_{(k-l)\mod P} = \sum_{l=0}^{P-1} x_l h_{(k-l)\mod P} \quad (4.15)
\]

This is the same as periodically extending \( h_l \) and \( x_l \) to form the periodic sequences \( h_l \) and \( x_k \), and then summing \( h_l x_{(k-l)} \) over one period of \( P \) samples.
At the receiver after removing cyclic prefix, the $N$-point FFT is computed, and then demodulated using $M$-QAM. Finally sets of parallel data are converted back serially before passing it to the channel decoder and hence to the destination. Thus the OFDMA allows multiple users to transmit simultaneously on the different subcarriers per OFDM symbol.

Let $s_{n,i}$ be the $n^{th}$ block user data to be transmitted on the $i^{th}$ subchannel, then the $T_s$ shift orthogonal complex baseband signal transmitted can be represented as (Ye Geoffrey Li and Gordon Stuber 2006)

$$s(t) = \sum_{n=-\infty}^{+\infty} \sum_{i=0}^{N-1} s_{n,i} e^{j2\pi f_i (t-nT_s)}$$

(4.16)

The received signal can be represented by

$$x(t) = s(t) + n(t)$$

(4.17)

where $n(t)$ is additive white Gaussian noise.

To decode the input data, the received signal is processed as

$$X_{n,i} = \int_{-\infty}^{\infty} x(t) e^{-j2\pi f_i (t-nT_s)} dt$$

(4.18)

Due to the orthogonality of $T_s$ shift complex function, eqn. (4.18) becomes

$$X_{n,i} = s_{n,i} + N_{n,i}$$

(4.19)

where

$$N_{n,i} = \int_{-\infty}^{\infty} n(t) e^{-j2\pi f_i (t-nT_s)} dt$$

(4.20)
Adaptive modulation allows higher capacity or reduced spectrum consumption that will be required for the delivery of next-generation high bandwidth services. M-QAM is the modulation scheme used in OFDMA system implementation where $M$ is the order of modulation. $M$ can be varied as per channel conditions like SINR, BER. If the channel condition is good i.e., SINR value is high, that subcarrier can be effectively utilized by transmitting the data at high modulation order thereby pumping more data in the corresponding carrier. Also $M$ can be decreased when the link budget of a system is no longer sufficient, typically during a rain fade. This modulation shift results in an improved link budget, still allowing the system to operate at a lower throughput.

4.6.3 Advantages of OFDMA

The use of a large number of slow rate streams, which are carried by narrow band sub-carriers, increases robustness against frequency selective fading and immunity against impulsive noise. As bandwidth of sub-carrier is narrow, the fading that they experience is flat. Also, due to enlarging symbols duration in time domain, the OFDMA symbol duration is much larger than multipath delay dispersion, which eliminates ISI. Thus elimination of ISI removes the requirements for equalization and reduces the complexity of an OFDMA receiver. Orthogonality means sub-carriers are independent and each one can be adaptively coded and modulated. With orthogonal sub-carriers, there is no need for guard band between subcarriers, due to orthogonality property the peak of one sub-carrier occurs when other sub-carriers are at zero as shown in Figure 4.10.
4.6.4 OFDMA Signals and its Spectrum

Although the diagram in Figure 4.10 can be used to explain the fundamental features of OFDMA signal in frequency domain, in practice the actual spectrum looks different. The following is input specification corresponding to an OFDMA system that has been used to generate OFDM signals and its spectrum. The objective of Figure 4.11 and Figure 4.12 is to visualize the OFDMA signal by means of basic system parameters.

Symbol rate 1000 Hz
No of samples per symbol 2. Symbol rate
Types of symbol (M) 4
Transmitted data symbol 2048
No of frames 16
Data symbol per frame 64
IFFT 128
Guard interval length 16
Symbol with GI insertion 144
Figure 4.11 OFDM signal in time domain

Figure 4.12 Spectrum of an OFDM signal
4.7 MC-CDMA vs. OFDMA

A major benefit of the OFDM is the robustness against multipath propagation channels and, therefore, high data rate transmissions are possible. Furthermore, OFDM is a low-complex technique to modulate multiple subcarriers in a bandwidth-efficient way. The assignment of one or several subcarriers to each user in an OFDM system leads to the multiple access scheme OFDMA. Contrary to OFDMA, the multi-carrier code division multiple access (MC-CDMA) scheme transmits in parallel chips of a spread data symbol on different subcarriers. In OFDMA, user-data symbols are allocated directly to channel resources and therefore offer no diversity without channel coding but adaptive transmission is possible. In contrast, an MC-CDMA transmission scheme spreads the user data symbol energy over all channel resources and therefore offers diversity.

MC-CDMA system uses scramble code, and the interference transmitted from the other adjacent sector antennas is treated as a random noise in a receiver. On the other hand, in the OFDMA system with scheduling algorithm, it is possible to assign the subcarriers per sector antenna that no double allocation of subcarriers between the sectors occurs.

4.8 SUMMARY

Multipath propagation is a natural property of wireless communication channel. It causes frequency selective fading and ISI which limits the broadband data communication. Multi-carrier communication system enhances system capacity while combating with these phenomenons.

Rayleigh channel is a model that can be used to describe the form of fading that occurs when multipath propagation exists, and in many instances cellular systems being used in a dense urban environment fall into
this category. Although there are many channel parameters like delay spread, and coherence band width that characterize the wireless channel, the higher value of Doppler shift greatly affects the received wireless signal. In the deep fades due to Doppler shift of 10-100Hz in the Rayleigh channel at 2.4 GHz the signal strength drop by a factor of several thousand or 30-40 dB. Knowledge of Doppler spread can improve detection and aid into transmission optimization in both physical layer and higher levels of the protocol stack.

The multi-carrier systems are more flexible for resource allocation and shows higher spectrum utilization due to the use of subcarriers and hence it is highly suitable for the next generation network. Out of the two basic multiple access schemes, i.e., MC-CDMA and OFDMA, the OFDMA shows greater flexibility. Though the cyclic prefix helps in combating ISI, it is an overhead on wireless communication. In other words, part of the system capacity is wasted in carrying cyclic prefix data.