IMPLEMENTING OFDM IN TIME DOMAIN & FREQUENCY DOMAIN

Project Report submitted in partial fulfillment of the requirement for the degree of

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in

Electronics and Communication Engineering

By

Karan Gulati 061147

under the Supervision of

Mr.ALOK JOSHI

Jaypee University of Information Technology
Waknaghat, Solan - 173 234,Himachal Pradesh

CERTIFICATE

This is to certify that the project report entitled" **IMPLEMENTING OFDM IN TIME DOMAIN & FREQUENCY DOMAIN"** submitted by Karan Gulati in partial fulfillment for the award of degree of Bachelor of Technology in Electronics and Communication Engineering to Jaypee University of Information Technology, Waknaghat, Solan has been carried out under my supervision.

Date: 21-05-10

Mr. Alok Joshi
Sr. Lecturer

Certified that this work has not been submitted partially or fully to any other University or Institute for the award of this or any other degree or diploma

(Karan Gulati)
061147

Acknowledgement

Apart from the efforts, the success of any project depends largely on the encouragement and guidelines of many others. Therefore I take the opportunity to express my gratitude to the people who have been instrumental in the success completion of this project.

I would also like to show my greatest appreciation to my project guide **Mr. Alok Joshi** without whose able guidance, tremendous support and continuous motivation the project work would not be carried out satisfactory.

Special thanks to my project panel because it was their regular concern and appreciation that made this project carried out easily and satisfactory.

Date: 21.5.10

Karan Gulati

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ABSTRACT

Multi-carrier modulation, in particular Orthogonal Frequency Division Multiplexing (OFDM), has been successfully applied to a wide variety of digital communications applications over the past several years. Although OFDM has been chosen as the physical layer standard for a diversity of important systems, the theory, algorithms, and implementation techniques remain subjects of current interest.

The demand for high-speed mobile wireless communications is rapidly growing. OFDM technology promises to be a key technique for achieving the high data capacity and spectral efficiency requirements for wireless communication systems of the near future.

This report presents a better understanding of the basic priciples of OFDM. In interest of brevity, I have minimized treatment of more general communication issues. There exist many excellent texts on communication theory and technology. Only brief summaries of topics not specific to multicarrier modulation are presented in this book where essential.

Chapter 1 INTRODUCTION

1.1 OFDM History

The concept of using parallel data transmission by means of frequency division multiplexing (FDM) was published in mid 60s . Some early development can be traced back in the 50s. A U.S. patent was filled and issued in January, 1970. The idea was to use parallel data streams and FDM with overlapping subchannels to avoid the use of high speed equalization and to combat impulsive noise, and multipath distortion as well as to fully use the available bandwidth. The initial applications were in the military communications. In the telecommunications field, the terms of discrete multi-tone (DMT), multichannel modulation and multicarrier modulation (MCM) are widely used and sometimes they are interchangeable with OFDM. In OFDM, each carrier is orthogonal to all other carriers. However, this condition is not always maintained in MCM. OFDM is an optimal version of multicarrier transmission schemes.

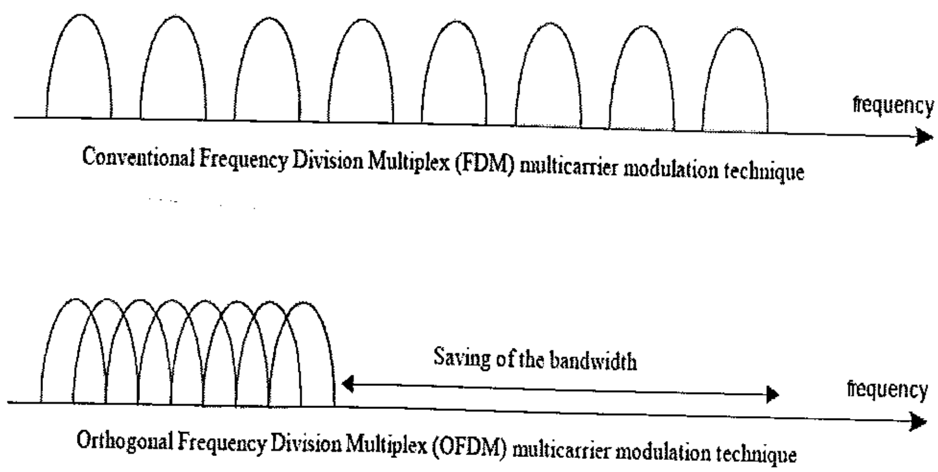


Fig. 1.1 Comparison of the bandwidth utilization for FDM and OFDM

For a large number of subchannels, the arrays of sinusoidal generators and coherent demodulators required in a parallel system become unreasonably expensive and complex. The receiver needs precise phasing of the demodulating carriers and sampling times in order to keep crosstalk between subchannels acceptable. Weinstein and Ebert [5] applied the discrete Fourier transform (DFT) to parallel data transmission system as part of the modulation and demodulation process. In addition to eliminating the banks of subcarrier oscillators and coherent demodulators required by FDM, a completely digital implementation could be built around special-purpose hardware performing the fast Fourier transform (FFT). Recent advances in VLSI technology enable making of high-speed chips that can perform large size FFT at affordable price.

In the 1980s, OFDM has been studied for high-speed modems, digital mobile communications and high-density recording. One of the systems used a pilot tone for stabilizing carrier and clock frequency control and trellis coding was implemented. Various fast modems were developed for telephone networks.

In 1990s, OFDM has been exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL, 1.6 Mb/s), asymmetric digital subscriber lines(ADSL, 1,536 Mb/s), very high-speed digital subscriber lines (VHDSL, 100 Mb/s), digital audiobroadcasting (DAB) and HDTV terrestrial broadcasting.

1.2 Qualitative description of OFDM

In multimedia communication, a demand emerges for high-speed, high-quality digital mobile portable reception and transmission. A receiver has to cope with a signal that is often weaker than desirable and that contains many echoes. Simple digital systems do not work well in the multipath environment.

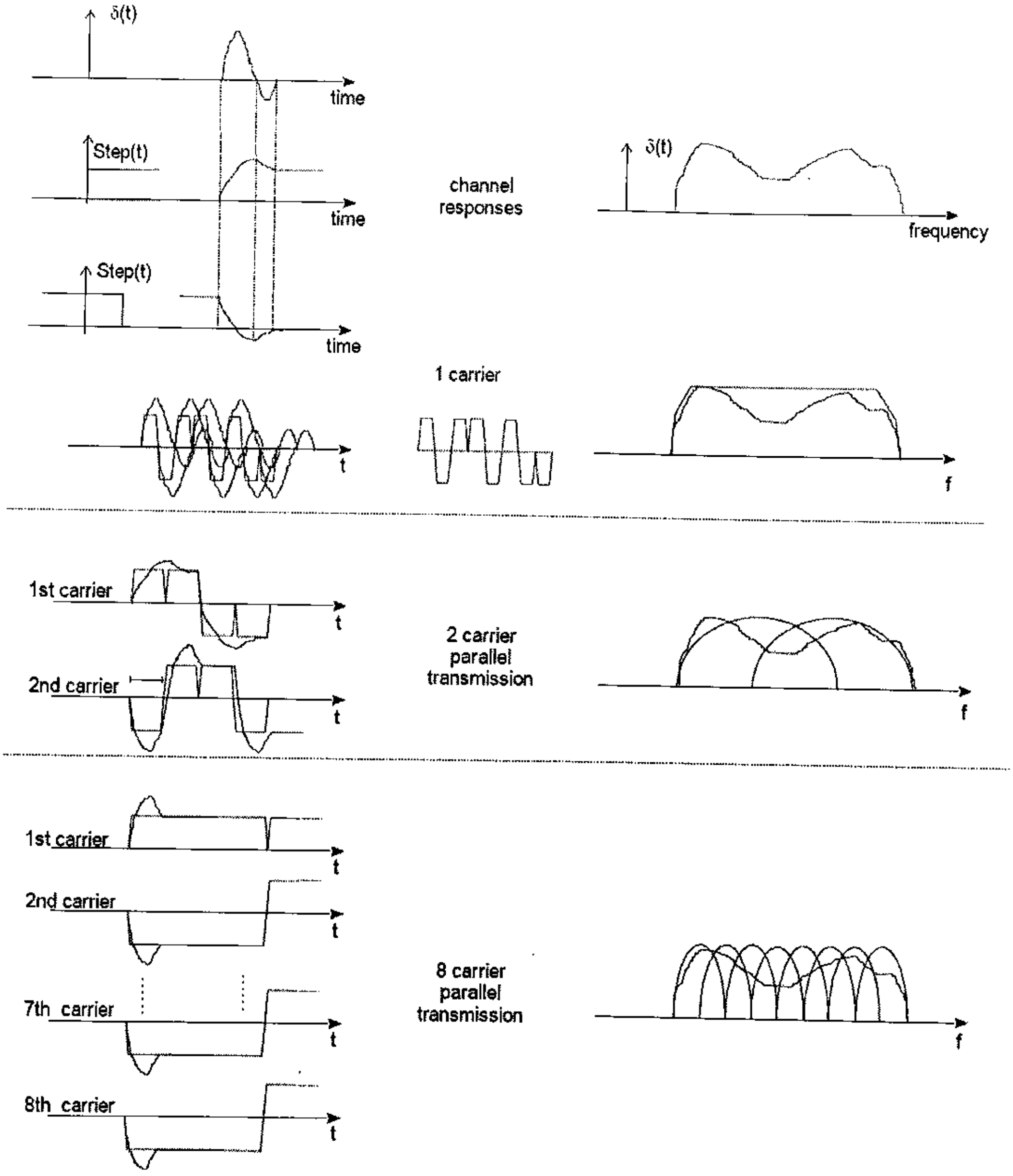


Fig 1.2 The effect of adopting a multicarrier system. For a given overall data rate, increasing the number of carriers reduces the data rate that each individual carrier must convey, and hence (for a given modulation system) lengthens the symbol period. This means that the intersymbol interference affects a smaller percentage of each symbol as the number of carriers and hence the symbol period increases

In a conventional serial data system, the symbols are transmitted sequentially, with the frequency spectrum of each data symbol allowed to occupy the entire available bandwidth. In a parallel data transmission system several symbols are transmitted at the same time, what offers possibilities for alleviating many of the problems encountered with serial systems.

In OFDM, the data is divided among large number of closely spaced carriers. This accounts for the "frequency division multiplex" part of the name. This is *not* a multiple access technique, sincethere is no common medium to be shared. The entire bandwidth is filled from a single source of data.Instead of transmitting in serial way, data is transferred in a parallel way. Only a small amount of the data is carried on each carrier, and by this lowering of the bitrate per carrier (not the total bitrate), the influence of intersymbol interference is significantly reduced. In principle, many modulation schemes could be used to modulate the data at a low bit rate onto each carrier

It is an important part of the OFDM system design that the bandwidth occupied is greater than the correlation bandwidth of the fading channel. A good understanding of the propagation statistics is needed to ensure that this condition is met. Then, although some of the carriers are degraded by multipath fading, the majority of the carriers should still be adequately received. OFDM can effectively randomize burst errors caused by Rayleigh fading, which comes from interleaving due to paralellisation. So, instead of several adjacent symbols being completely destroyed, many symbols are only slightly distorted. Because of dividing an entire channel bandwidth into many narrow subbands, the frequency response over each individual subband is relatively flat. Since each subchannel covers only a small fraction of the original bandwidth, equalization is potentially simpler than in a serial data system. A simple equalization algorithm can minimize mean-square distortion on each subchannel, and the implementation of differential encoding may make it possible to avoid equalization altogether .

This allows the precise reconstruction of majority of them, even without forward error correction (FEC).

In a classical parallel data system, the total signal frequency band is divided into N nonoverlapping frequency subchannels. Each subchannel is modulated with a separate symbol and, then, the N subchannels are frequency multiplexed. There are three schemes that can be used to separate the subbands:

1) Use filters to completely separate the subbands. This method was borrowed from the conventional FDM technology. The limitation of filter implementation forces the bandwidth of each subband to be equal to (1+a)fm, where a is the roll-off factor and fm is the Nyquist bandwidth. Another disadvantage is that it is difficult to assemble a set of matched filter when the number of carriers is large.

2) Use staggered QAM to increase the efficiency of band usage. In this way the individual spectra of the modulated carriers still use an excess bandwidth, but the are overlapped at the 3 dB frequency. The advantage is that the composite spectrum is flat. The separability or orthogonality is achieved by staggering the data (offset the data by half a symbol). The requirement for filter design is less critical than that for the first scheme.

3) Use discrete Fourier transform (DFT) to modulate and demodulate parallel data. The individual spectra are now *sinc* functions and are not band limited. The FDM is achieved, not by bandpass filtering, but by baseband processing. Using this method, both transmitter and receiver can be implemented using efficient FFT techniques that reduce the number of operations from N2 in DFT, down to NlogN.

OFDM can be simply defined as a form of multicarrier modulation where its carrier spacing is carefully selected so that each subcarrier is orthogonal to the other subcarriers. As is well known, orthogonal signals can be separated at the receiver by correlation techniques; hence, intersymbol interference among channels can be eliminated. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period.

1.3 Choice of the key elements

1.3.1 Useful symbol duration

The useful symbol duration T affects the carrier spacing and coding latency. To maintain the data throughput, a longer useful symbol duration results in increase of the number of carriers and the size of FFT (assuming the constellation is fixed). In practice, carrier offset and phase stability may affect how close two carriers can be placed. If the application is for the mobile reception, the carrier spacing must be large enough to make the Doppler shift negligible. Generally, the useful symbol duration should be chosen so that the channel is stable for the duration of a symbol.

1.3.2 Number of carriers

The number of subcarriers can be determined based on the channel bandwidth, data throughput and useful symbol duration.

$$N = 1/T$$

The carriers are spaced by the reciprocal of the useful symbol duration. The number of carriers corresponds to the number of complex points being processed in FFT. For HDTV applications, the number of subcarriers are in the range of several thousands, so as to accommodate the data rate and guard interval requirement.

1.3.3 Modulation scheme

The modulation scheme in an OFDM system can be selected based on the requirement of power or spectrum efficiency. The type of modulation can be specified by the complex number *d*n=*a*n+j*b*n , defined in section *The use of FFT in OFDM*. The symbols *a*n and *b*n can be selected to (±1, ±3) for 16QAM and ±1 for QPSK.

In general, the selection of the modulation scheme applying to each subchannel depends solely on the compromise between the data rate requirement and transmission robustness. Another advantage of OFDM is that different modulation schemes can be used on different subchannels for layered services.

1.3.4 Coded OFDM

By using frequency and time diversity OFDM provides a means to transmit data in a frequency selective channel. However, it does not suppress fading itself. Depending on their position in the frequency domain, individual subchannels could be affected by fading. This requires the use of channel coding to further protect transmitted data. Among those channel techniques, trellis coded modulation (TCM), combined with frequency and time interleaving is considered the most effective means for a selective fading channel.

TCM combines coding and modulation to achieve a high coding gain without affecting the bandwidth of the signal. In a TCM encoder, each symbol of *n* bits is mapped into constellation of *n+1* bits, using a set-partitioning rule. This process increases the constellation size and effectively adds additional redundancy to the signal. A TCM code can be decoded with a soft decision Viterbi decoding algorithm, which exploits the soft decision nature of the received signal. The coding gain for a twodimensional

TCM code over a Gaussian channel is about 3 dB for a bit error rate (BER) of 10-5. It should be mentioned that one of the advantages of OFDM is that it can convert a wideband frequency selective fading channel into a series of narrowband and frequency non-selective fading subchannels by using parallel and multicarrier transmission. Coding OFDM subcarriers sequentially by using specially designed TCM codes for frequency non-selective fading channel is the major reason for using the COFDM for terrestrial broadcasting. However, the search of the best TCM code is still ongoing.

Although trellis codes produce improvements in the signal-to-noise ratio (S/N), they do not perform well with impulsive or burst noise. In general, transmission errors have a strong time/frequency correlation. Interleaving plays an essential role in channel coding by providing diversity in the time domain. Interleaving breaks the correlation and enables the decoder to eliminate or reduce local fading throughout the band and over the whole depth of the time interleaving. Interleaving depth should be enough to break long straight errors.

1.3.5 Flexibility and scalability

Based on the information theory, the channel capacity is a function of the signal-to-noise ratio and channel bandwidth.

The concept of graceful degradation has been implemented in the analog TV systems. It is believed that the joint source/channel coding is the best way to achieve flexibility and scalability.

COFDM has been considered very flexible for the layered and scaleable transmission. Different groups of COFDM subchannels can be assigned to different orders of modulation, power levels, and channel coding schemes.

1.4 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

Orthogonal Frequency Division Multiplexing (OFDM) is an alternative wireless modulation technology to CDMA. OFDM has the potential to surpass the capacity of CDMA systems and provide the wireless access method for 4G systems.

OFDM is a modulation scheme that allows digital data to be efficiently and reliably transmitted over a radio channel, even in multipath environments. OFDM transmits data by using a large number of narrow bandwidth carriers. These carriers are regularly spaced in frequency, forming a block of spectrum. The frequency spacing and time synchronisation of the carriers is chosen in such a way that the carriers are orthogonal, meaning that they do not cause interference to each other. This is despite the carriers overlapping each other in the frequency domain. The name 'OFDM' is derived from the fact that the digital data is sent using many carriers, each of a different frequency (Frequency Division Multiplexing) and these carriers are orthogonal to each other, hence Orthogonal Frequency Division Multiplexing.

CHAPTER 2 BASIC PRINCLIPES OF OFDM

Modulation *- a mapping of the information on changes in the carrier phase, frequency or amplitude or combination.*

Multiplexing *- method of sharing a bandwidth with other independent data channels*

OFDM is a combination of modulation and multiplexing. Multiplexing generally refers to independent signals, those produced by different sources. So it is a question of how to share the spectrum with these users.

In OFDM the question of multiplexing is applied to independent signals but these independent signals are a sub-set of the one main signal. In OFDM the signal itself is first split into independent channels, modulated by data and then re-multiplexed to create the OFDM carrier.

Orthogonal Frequency Division Multiplexing (OFDM) is very similar to the wellknown and used technique of Frequency Division Multiplexing (FDM). OFDM uses the principles of FDM to allow multiple messages to be sent over a single radio channel. It is however in a much more controlled manner, allowing an improved spectral efficiency.

A simple example of FDM is the use of different frequencies for each FM (Frequency Modulation) radio stations. All stations transmit at the same time but do not interfere with each other because they transmit using different carrier frequencies. Additionally they are bandwidth limited and are spaced sufficiently far apart in frequency so that their transmitted signals do not overlap in the frequency domain.

At the receiver, each signal is individually received by using a frequency tuneable band pass filter to selectively remove all the signals except for the station of interest. This filtered signal can then be demodulated to recover the original transmitted information.

OFDM is different from FDM in several ways. In conventional broadcasting each radio station transmits on a different frequency, effectively using FDM to maintain a separation between the stations. There is however no coordination or synchronisation between each of these stations. With an OFDM transmission such as DAB, the information signals from multiple stations is combined into a single multiplexed stream of data.

This data is then transmitted using an OFDM ensemble that is made up from a dense packing of many subcarriers. All the subcarriers within the OFDM signal are time and frequency synchronised to each other, allowing the interference between subcarriers to be carefully controlled. These multiple subcarriers overlap in the frequency domain, but do not cause Inter-Carrier Interference (ICI) due to theorthogonal nature of the modulation. Typically with FDM the transmission signals need to have a large frequency guard-band between channels to prevent interference. This lowers the overall spectral efficiency. However with OFDM the orthogonal packing of the subcarriers greatly reduces this guard band, improving the spectral efficiency.

2.1 ORTHOGONALITY

Signals are orthogonal if they are mutually independent of each other. Orthogonality is a property that allows multiple information signals to be transmitted perfectly over a common channel and detected, without interference. Loss of orthogonality results in blurring between these information signals and degradation in communications. Many common multiplexing schemes are inherently orthogonal. Time Division Multiplexing (TDM) allows transmission of multiple information signals over a single channel by assigning unique time slots to each separate information signal. During each time slot only the signal from a single source is transmitted preventing any interference between the multiple information sources. Because of this TDM is orthogonal in nature. In the frequency domain most FDM systems are orthogonal as each of the separate transmission signals are well spaced out in frequency preventing interference.

Although these methods are orthogonal the term OFDM has been reserved for a special form of FDM. The subcarriers in an OFDM signal are spaced as close as is theoretically possible while maintain orthogonality between them.

OFDM achieves orthogonality in the frequency domain by allocating each of the separate information signals onto different subcarriers. OFDM signals are made up from a sum of sinusoids, with each corresponding to a subcarrier. The baseband frequency of each subcarrier is chosen to be an integer multiple of the inverse of the symbol time, resulting in all subcarriers having an integer number of cycles per symbol. As a consequence the subcarriers are orthogonal to each other. Figure 2.1 shows the construction of an OFDM signal with four subcarriers.

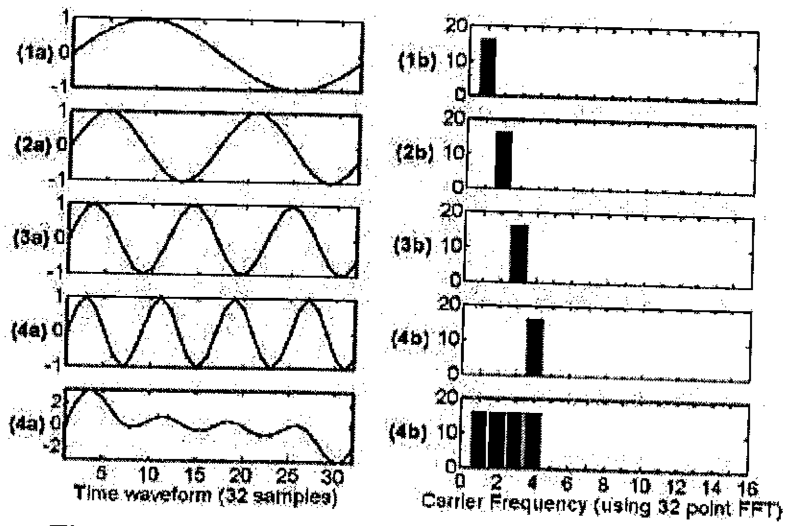


Figure 2.1 Time domain construction of an OFDM signal.

Sets of functions are orthogonal to each other if they match the conditions in equation 1. If any two different functions within the set are multiplied, and integrated over a symbol period, the result is zero, for orthogonal functions. Another way of thinking of this is that if we look at a matched receiver for one of the orthogonal functions, a subcarrier in the case of OFDM, then the receiver will only see the result for that function. The results from all other functions in the set integrate to zero, and thus have no effect.

$$\int_0^T s1(t)\, s2(t)\, dt = \begin{cases} C & i=j \\ 0 & i \neq j \end{cases} \qquad \text{..... Eqn 1}$$

2.1.1 The importance of being orthogonal

The main concept in OFDM is orthogonality of the sub-carriers. Since the carriers are all sine/cosine wave, we know that area under one period of a sine or a cosine wave is zero. This is easily shown in fig 2.1.1

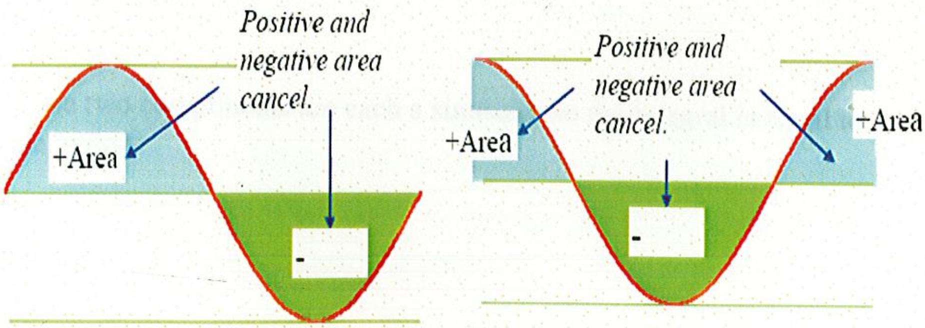


Fig 2.1.1 The area under a sine and a cosine wave over one period is always zero.

Let's take a sine wave of frequency m and multiply it by a sinusoid (sine or a cosine) of afrequency *n*, where both *m* and *n* are integers. The integral or the area under this product is given by

f(t) = sin mwt * sin nwt

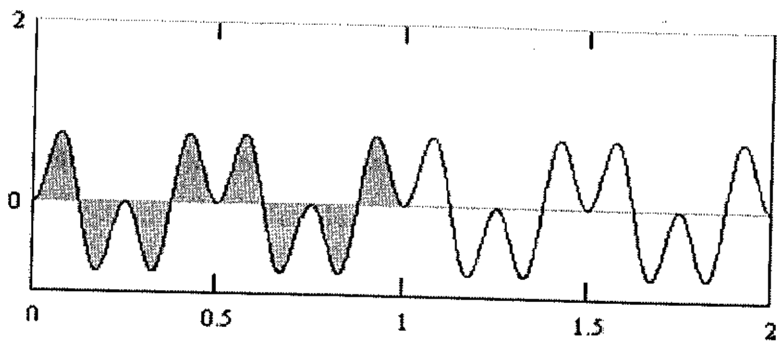


Fig 2.1.2 The area under a sine wave multiplied by its own harmonic is always zero

By the simple trigonometric relationship, this is equal to a sum of two sinusoids of frequencies
(n-m) and *(n+m)*

= 1/2cos(m-n) – 1/2cos(m+n)

These two components are each a sinusoid, so the integral is equal to zero over one period.

= 0 – 0

We conclude that when we multiply a sinusoid of frequency *n* by a sinusoid of frequency *m/n*, the area under the product is zero. In general for all integers *n* and *m*, sin *mx*, cos *mx*, cos *nx*,sin *nx* are all orthogonal to each other. These frequencies are called harmonics

.This idea is key to understanding OFDM. The orthogonality allows simultaneous transmission on a lot of sub-carriers in a tight frequency space without nterference from each other. In essencethis is similar to CDMA, where codes are used to make data sequences independent (also orthogonal) which allows many independent users to transmit in same space successfully.

2.2 FREQUENCY DOMAIN ORTHOGONALITY

Another way to view the orthogonality property of OFDM signals is to look at its spectrum. In the frequency domain each OFDM subcarrier has a sinc, *sin(x)/x,* frequency response, as shown in Figure 2-2. This is a result of the symbol time corresponding to the inverse of the carrier spacing. As far as the receiver is concerned each OFDM symbol transmitted for a fixed time (*TFFT*) with no tapering at the ends of the symbol. This symbol time corresponds to the inverse of the subcarrier spacing of *1/TFFT* Hz 1. This rectangular, boxcar, waveform in the time domain results in a *sinc* frequency response in the frequency domain. The *sinc* shape has a narrow main lobe, with many side-lobes that decay slowly with the magnitude of the frequency difference away from the centre. Each carrier has a peak at the centre frequency and nulls evenly spaced with a frequency gap equal to the carrier spacing.

The orthogonal nature of the transmission is a result of the peak of each subcarrier corresponding to the nulls of all other subcarriers. When this signal is detected using a Discrete Fourier Transform (DFT) the spectrum is not continuous as shown in Figure 2-2 (a), but has discrete samples. The sampled spectrum are shown as 'o's in the figure.

If the DFT is time synchronised, the frequency samples of the DFT correspond to just the peaks of the subcarriers, thus the overlapping frequency region between subcarriers does not affect the receiver. The measured peaks correspond to the nulls for all other subcarriers, resulting in orthogonality between the subcarriers.

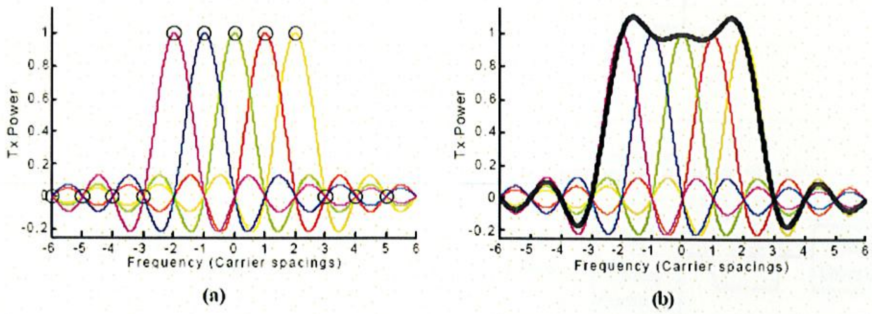


Fig 2.2 Frequency response of the subcarriers in a 5 tone OFDM signal

(a) shows the spectrum of each carrier, and the discrete frequency samples seen by an OFDM receiver. Note, each carrier is sinc, *sin(x)/x*, in shape. **(b)** Shows the overall combined response of the 5 subcarriers (thick black line).

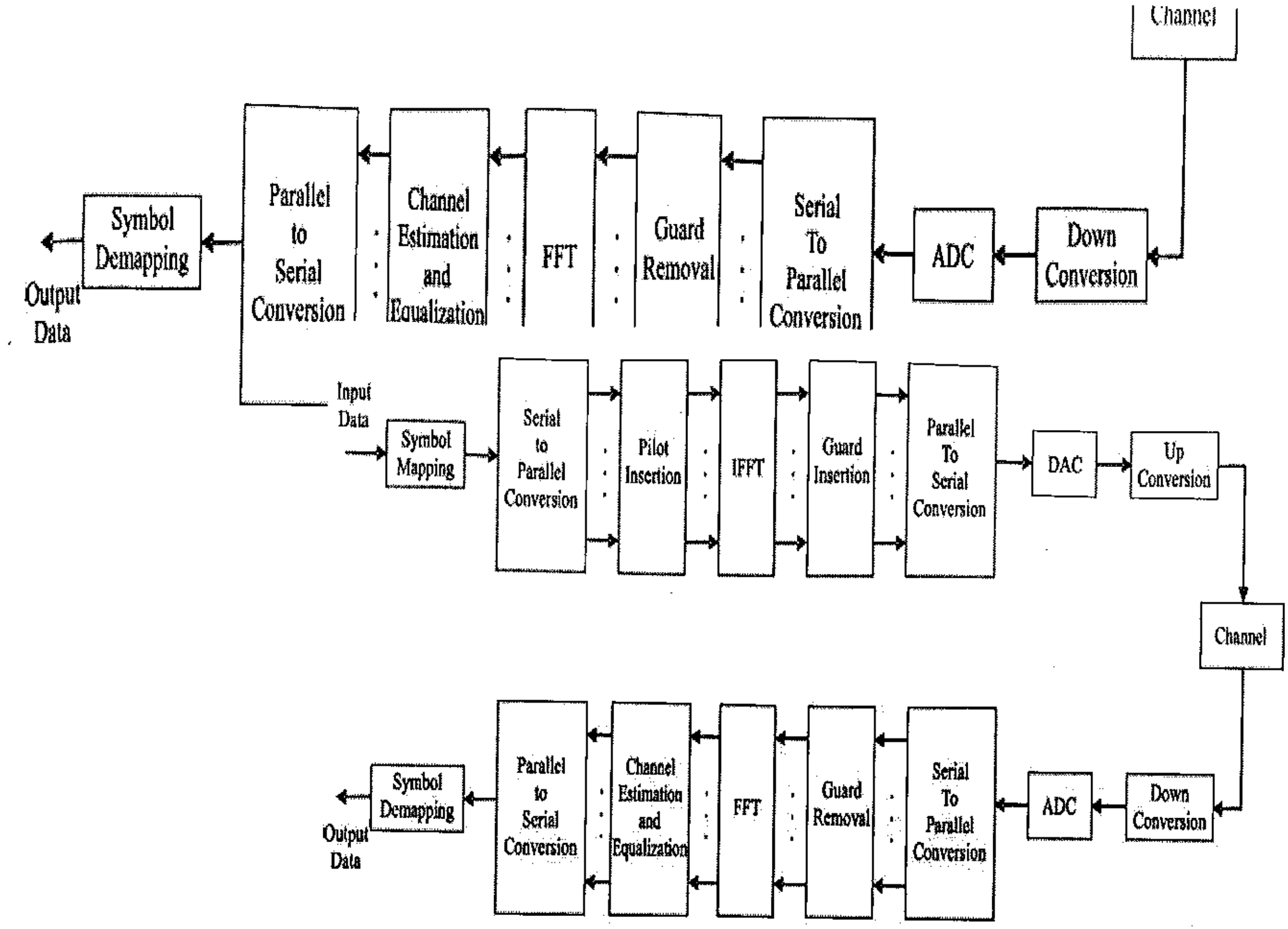


Fig 2.3 Block diagram showing a basic OFDM transceiver.

OFDM signals are typically generated digitally due to the difficulty in creating large banks of phase lock oscillators and receivers in the analog domain. Figure 2-3 shows the block diagram of a typical OFDM transceiver. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier 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.

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 analyse the signal in the frequency domain. The amplitude and phase of the subcarriers 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.

2.4 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 subcarriers. For example, for a subcarrier modulation of 16-QAM each subcarrier carries 4 bits of data, and so for a transmission using 100 subcarriers the number of bits per symbol would be 400.

For adaptive modulation schemes such as described in section 4.2, the modulation scheme used on each subcarrier can vary and so the number of bits per subcarrier also varies. As a result the serial to parallel conversion stage involves filling the data payload for each subcarrier. At the receiver the reverse process takes place, with the data from the subcarriers being converted back to the original serial data stream.

When an OFDM transmission occurs in a multipath radio environment, frequency selective fading can result in groups of subcarriers 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 neighbouring 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 randomising the subcarrier 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 randomisation of the location of the bit errors mproves the performance of the FEC and the system as a whole.

2.5 SUBCARRIER MODULATION

Once each subcarrier has been allocated bits for transmission, they are mapped using a modulation scheme to a subcarrier amplitude and phase, which is represented by a complex In-phase and Quadrature-phase (IQ) vector. Figure 2.4.1 shows an example of subcarrier modulation mapping. 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.

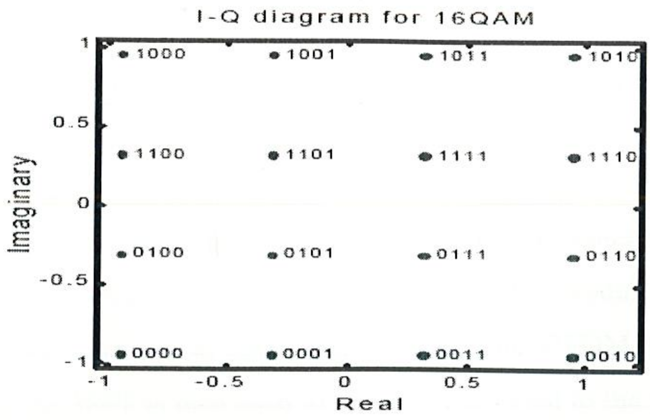


Fig 2.4.1 Example IQ modulation constellation. 16-QAM

In the receiver, mapping the received IQ vector back to the data word performs subcarrier demodulation. During transmission, noise and distortion becomes added to the signal due to thermal noise, signal power reduction and imperfect channel equalisation.

Figure 2.4.2 shows 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, making it cross over a decision boundary.

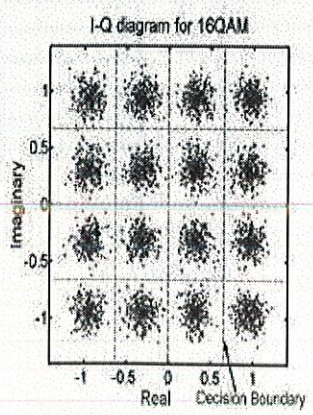


Fig 2.4.2 IQ plot for 16-QAM data with added noise.

2.6 FREQUENCY TO TIME DOMAIN CONVERSION

After the subcarrier modulation stage each of the data subcarriers is set to an amplitude and phase based on the data being sent and the modulation scheme; all unused subcarriers are set to zero. This sets up the OFDM signal in the frequency domain. An IFFT is then used to convert this signal to the time domain, allowing it to be transmitted. Figure 2-5 shows the IFFT section of the OFDM transmitter. In the frequency domain, before applying the IFFT, each of the discrete samples of the IFFT corresponds to an individual subcarrier. Most of the subcarriers are modulated with data.

The outer subcarriers are unmodulated and set to zero amplitude. These zero subcarriers provide a frequency guard band before the nyquist frequency and effectively act as an interpolation of the signal and allows for a realistic roll off in the analog anti-aliasing reconstruction filters.

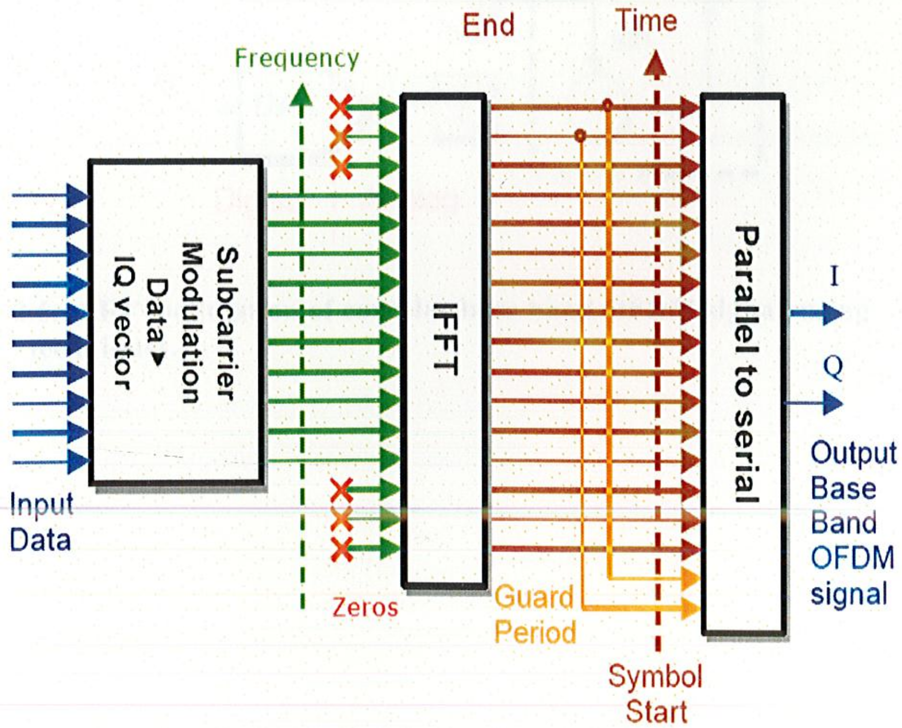


Fig 2.5 OFDM generation, IFFT stage

2.7 RF MODULATION

The output of the OFDM modulator generates a base band signal, which must be mixed up to the required transmission frequency. This can be implemented using analog techniques as shown in Figure 2.6.1 or using a Digital Up Converter as shown in Figure 2.6.2 Both techniques perform the same operation, however the performance of the digital modulation will tend to be more accurate due to improved matching between the processing of the I and Q channels, and the phase accuracy of the digital IQ modulator.

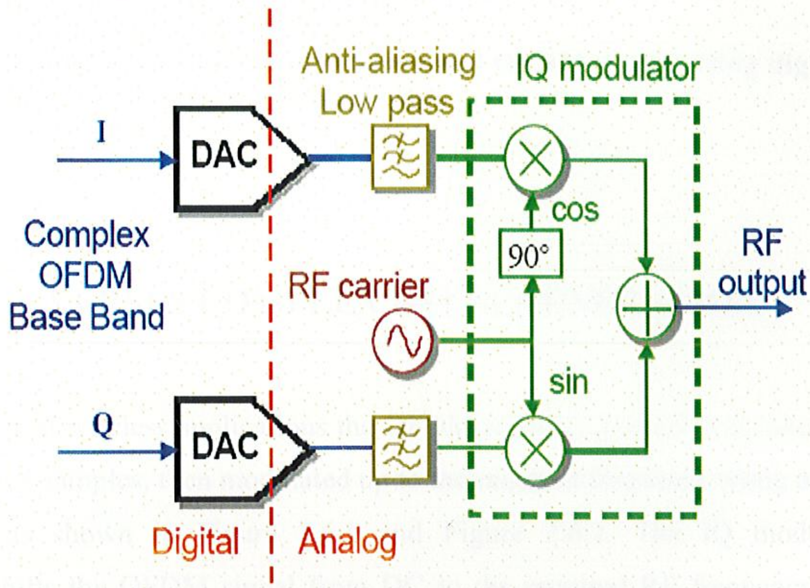


Figure 2.6.1 RF modulation of complex base band OFDM signal, using analog techniques.

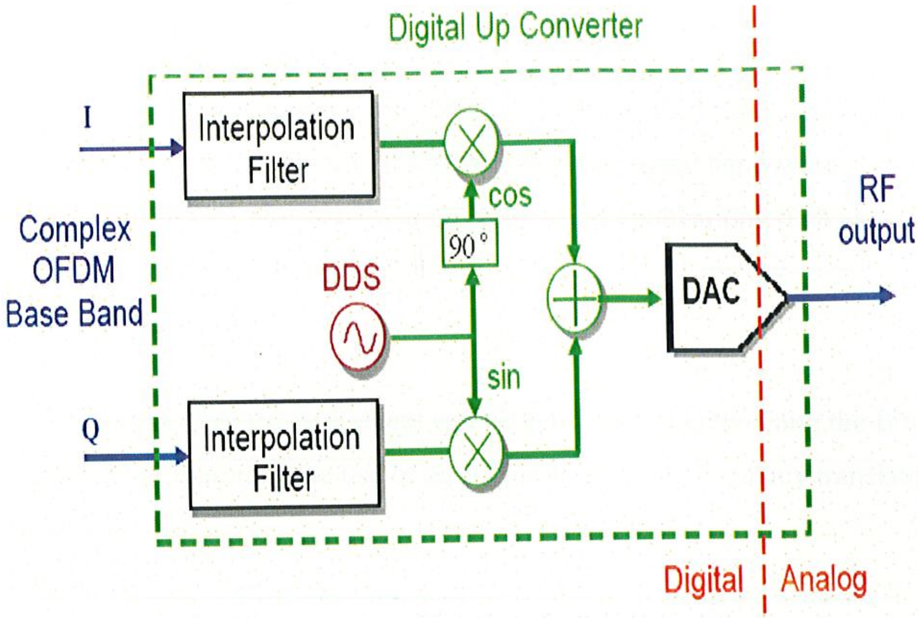


Fig 2.6.2 RF modulation of complex base band OFDM signal, using digital techniques. (DDS = Direct Digital Synthesis)

2.8 REAL VERSES COMPLEX OFDM GENERATION

For most wireless applications the OFDM signal is generated at base band using complex samples, then modulated up to the required frequency using an IQ modulator, as shown in Figure 2.6.1 and Figure 2.6.2. The IQ modulator frequency shifts the OFDM signal from DC to the required RF frequency, and converts thecomplex signal into a real signal. A transmitted RF signal is always a real signal as it is just a variation in field intensity. It is however possible to directly generate a real OFDM signal. This is useful in wired applications, such as ADSL. In these applications the transmitted signal is generally from just above DC to an upper limit determined by the required signal bandwidth. The required transmission signal is a real signal as only a single cable is used. If a complex signal were used then two wires would be needed, one for the real signal and one for the imaginary signal. A real signal is equivalent to a complex base band signal, centred on DC, mixed to the new centre frequency using an IQ modulator:

$$fc = W/2 + f_{off}$$

where *fc* is the frequency translation required to shift the complex base band signal to form the real OFDM signal, *W* is the signal bandwidth and *foff* is the offset from DC, also see Figure 2-9. In wired applications such as ASDL, the lower most subcarrier is offset from DC by a small amount compared with the signal bandwidth.

This means that the real signal can be generated directly using the IFFT stage instead of requiring the use of an IQ modulator for frequency translation.

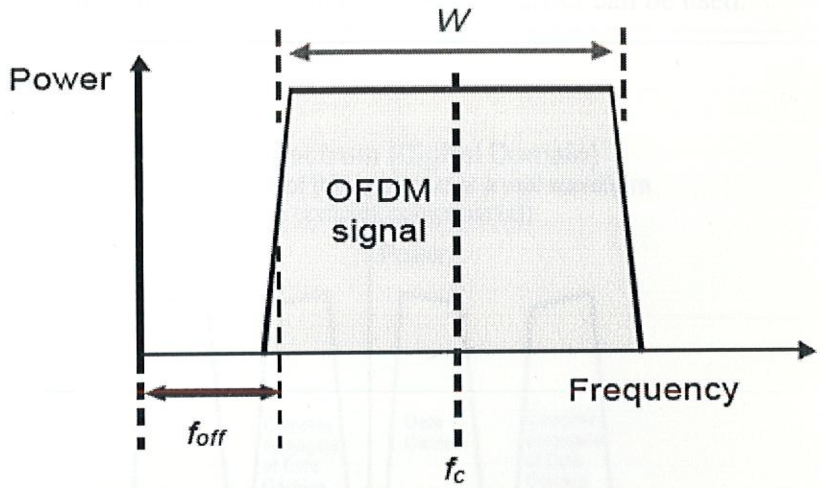
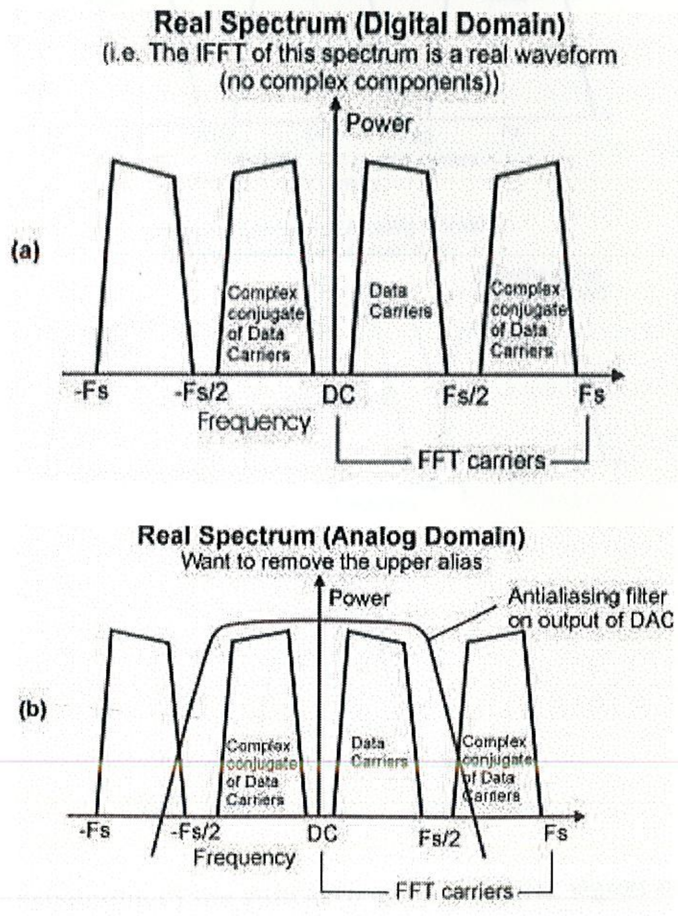


Fig DC offset OFDM signal, *W* - bandwidth, *foff* - frequency offset from DC, *fc* centre frequency.

Figure 2.10 shows the set up of the OFDM signal in the frequency domain for the generation of a real waveform. With a real waveform the useable bandwidth of the signal is only half the sampling frequency, and so to generate a real OFDM signal only one half of the available subcarriers can be used for data modulation. To create a real waveform the upper frequency bins of the IFFT must be set to the complex conjugate of the mirror of the lower half.

This can be contrasted with the construction of a complex base band OFDM signal as shown in Figure 2.11. In this case all of the frequency bins can be used for subcarrier modulation, with the main limitation being that the outer bins must be kept as zero to allow reconstruction of the analog signal, without aliasing occurring. In most applications the subcarrier corresponding to DC is not used. Its removal simplifies the implementation hardware. Most OFDM system currently using an analog base band the same as shown in Figure 2-7. In order for the DC subcarrier to be used it requires that the IQ outputs are DC coupled to the IQ mixer.

This is difficult to achieve in hardware as offset errors result in large errors in the generated IQ vector. Using AC coupling reduces the complexity of the implementation and so the DC subcarrier is usually not used. If digital modulation is used as shown in Figure 2-8 then the DC subcarrier can be used.



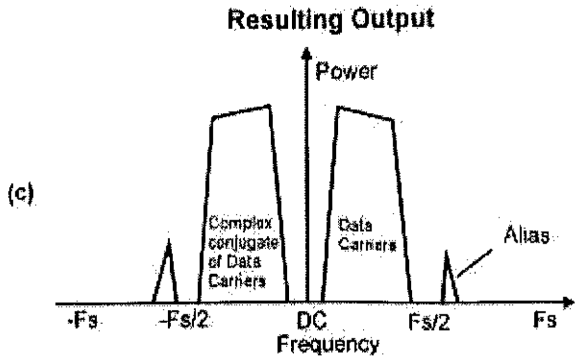


Fig 2.10 Construction of the subcarriers for generating a real output time domain waveform.

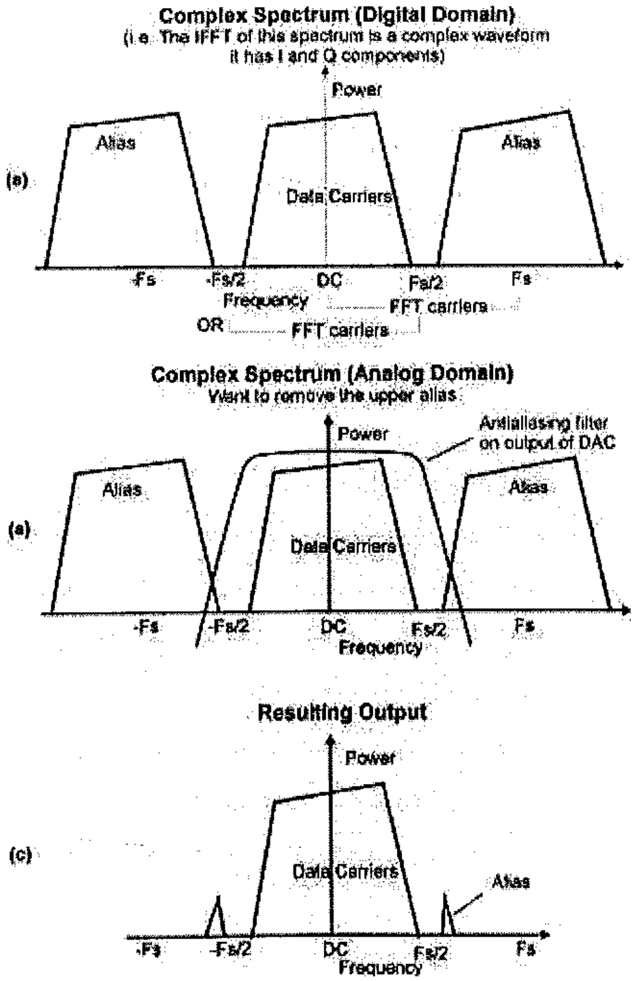


Fig 2.11 Construction of the subcarriers for complex signal representation of OFDM signals

2.9 GUARD PERIOD

For a given system bandwidth the symbol rate for an OFDM signal is much lower than a single carrier transmission scheme. For example for a single carrier BPSK modulation, the symbol rate corresponds to the bit rate of the transmission. However for OFDM the system bandwidth is broken up into *Nc* subcarriers, resulting in a symbol rate that is *Nc* times lower than the single carrier transmission. This low symbol rate makes OFDM naturally resistant to effects of Inter-Symbol Interference (ISI) caused by multipath propagation.

Multipath propagation is caused by the radio transmission signal reflecting off objects in the propagation environment, such as walls, buildings, mountains, etc. These multiple signals arrive at the receiver at different times due to the transmission distances being different. This spreads the symbol boundaries causing energy leakage between them.

The effect of ISI on an OFDM signal can be further improved by the addition of a guard period to the start of each symbol. This guard period is a cyclic copy that extends the length of the symbol waveform. Each subcarrier, in the data section of the symbol, (i.e. the OFDM symbol with no guard period added, which is equal to the length of the IFFT size used to generate the signal) has an integer number of cycles. Because of this, placing copies of the symbol end-to-end results in a continuous signal, with no discontinuities at the joins. Thus by copying the end of a symbol and appending this to the start results in a longer symbol time. Figure 2.8 shows the insertion of a guard period.

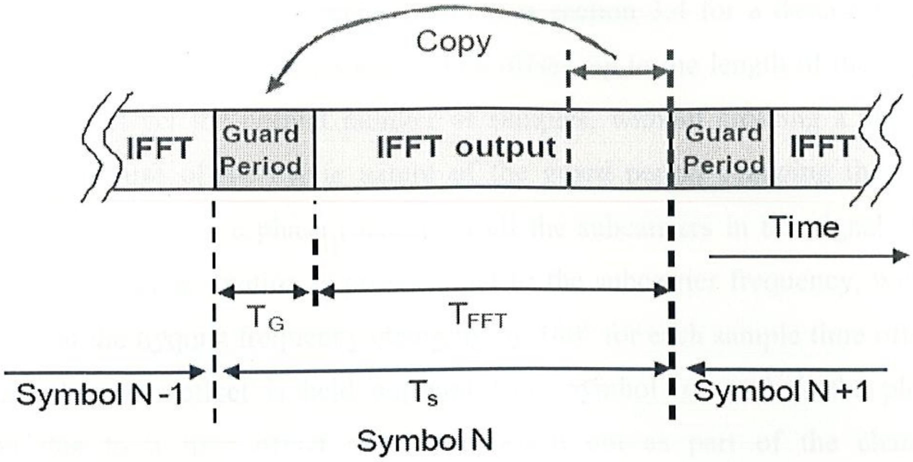


Fig 2.8 Addition of a guard period to an OFDM signal

The total length of the symbol is *Ts=TG + TFFT*, where *Ts* is the total length of the symbol in samples, *TG* is the length of the guard period in samples, and *TFFT* is the size of the IFFT used to generate the OFDM signal.

In addition to protecting the OFDM from ISI, the guard period also provides protection against time-offset errors in the receiver.

2.9.1 PROTECTION AGAINST TIME OFFSET

To decode the OFDM signal the receiver has to take the FFT of each received symbol, to work out the phase and amplitude of the subcarriers. For an OFDM system that has the same sample rate for both the transmitter and receiver, it must use the same FFT size at both the receiver and transmitted signal in order to maintain subcarrier orthogonality. Each received symbol has *TG + TFFT* samples due to the added guard period. The receiver only needs *TFFT* samples of the received symbol to decode the signal. The remaining *TG* samples are redundant and are not needed.

For an ideal channel with no delay spread (see section 3.4 for a description of delay spread) the receiver can pick any time offset, up to the length of the guard period, and still get the correct number of samples, without crossing a symbol boundary. Because of the cyclic nature of the guard period changing the time offset simply results in a phase rotation of all the subcarriers in the signal. The amount of this phase rotation is proportional to the subcarrier frequency, with a subcarrier at the nyquist frequency changing by 180° for each sample time offset. Provided the time offset is held constant from symbol to symbol, the phase rotation due to a time offset can be removed out as part of the channel equalisation. In multipath environments ISI reduces the effective length of the guard period leading to a corresponding reduction in the allowable time offset error.

2.9.2 PROTECTION AGAINST ISI

In an OFDM signal the amplitude and phase of the subcarrier must remain constant over the period of the symbol in order for the subcarriers to maintain orthogonality. If they are not constant it means that the spectral shape of the subcarriers will not have the correct *sinc* shape, and thus the nulls will not be at the correct frequencies, resulting in Inter-Carrier Interference. At the symbol boundary the amplitude and phase change suddenly to the new value required for the next data symbol. In multipath environments ISI causes spreading of the energy between the symbols, resulting in transient changes in the amplitude and phase of the subcarrier at the start of the symbol.

The length of these transient effects corresponds to the delay spread of the radio channel. The transient signal is a result of each multipath component arriving at slightly different times, changing the received subcarrier vector. Figure 2.8.1 shows this effect. Adding a guard period allows time for the transient part of the signal to decay, so that the FFT is taken from a steady state portion of the symbol.

This eliminates the effect of ISI provided that the guard period is longer than the delay spread of the radio channel. The remaining effects caused by the multipath, such as amplitude scaling and phase rotation are corrected for by channel equalisation.

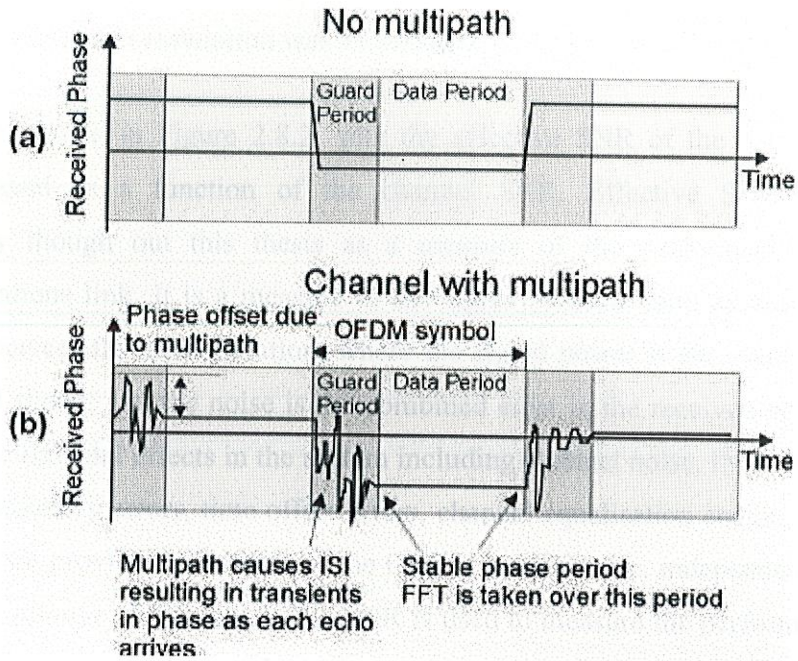


Fig 2.8.1 Function of the guard period for protecting against ISI.

The guard period protects against transient effects due to multipath, removing the effects of ISI, provided it is longer than the channel delay spread. This example shows the instantaneous phase of a single carrier for 3 symbols.

The addition of guard period removes most of the effects of ISI; however in practice, multipath components tend to decay slowly with time, resulting in some ISI even when a relatively long guard period is used.

Figure 2.8.3 shows the simulated performance of an OFDM system in the presence of static multipath. In this case the multipath impulse response followed an exponential decay with a time constant of 8 samples, resulting in an RMS delay spread of 3.5 samples. Each sample in the impulse response was complex and Gaussian distributed.

The RMS delay spread is a common parameter toestimate the spread of the multipath energy in time, and used to estimate the level of ISI in single carrier communications. Section 3.4 provides a more detailed description of RMS delay spread with typical values for a range of environments. A more appropriate measure is the time over which 99% of the total accumulated impulse energy arrived, which in this simulation was 16 samples.

The results shown in Figure 2.8.2 plot the effective SNR of the demodulated OFDM signal as a function of the channel SNR. Effective SNR is used extensively though out this thesis as a measure of the performance of the communications link. It is a measure of the signal to noise ratio as seen by the OFDM receiver after demodulation, where the signal power is the magnitude of the wanted signal, and the noise is the combined error in the received signal due to all the detrimental effects in the system including channel noise, IMD, filtering, ISI, ICI, frequency errors, time offset errors, channel equalisation errors, etc. The effective SNR provides a measure of the OFDM performance, independent of the modulation scheme. Traditionally the BER is used to measure the performance of a link, however in this thesis OFDM is considered the work with a large number of modulation schemes making BER a poor method of measurement. The BER of any particular modulation scheme can be estimated from the effective SNR by finding the BER of the modulation scheme in an AWGN channel with a SNR equal to the effective SNR.

Figure 2.8.2 shows the effect of multipath on the OFDM transmission. Ideally the effective SNR should follow the channel SNR, however detrimental effects such as ISI lead to degraded performance. We can see from the results that as the length of the guard period is increased the maximum effective SNR improves. For example, the effective SNR of the OFDM signal only reaches a maximum of 15 dB when the guard period length is 4 samples in length, but reaches 25 dB when a guard period of 16 samples is used. This is a result of more of the ISI energy being removed by the guard period. This shows that having a guard period (16 samples) that is more than four times the multipath RMS delay spread (3.5 samples) still results in significant ISI.

The low effective SNR for when the guard period was a similar length to the channel RMS delay spread is fine for robust modulation schemes such as BPSK and QPSK, but is insufficient for higher spectral efficiency modulation schemes such as 64-QAM and 256-QAM. Traditionally the RMS delay spread has been used as a measure of ISI and the allowable symbol rate in a multipath environment. However if a higher spectral efficiency is required a more appropriate measure is needed.

To achieve very high spectral efficiencies an effective SNR of greater than 35 dB must be able to be reached. In this case it required a guard period of at least 64 samples in length. This length of the guard period corresponds to the time it took for the impulse energy to decay to –35 dBc. Thus if we require a SNR of 25 dB then we have a guard period that is at least long enough to remove all impulse reflections that are stronger than –25 dBc.

The last two results in the simulation show the performance when using a guard period of 64 samples, with an IFFT size of 128, and 512. In the 128-point IFFT simulation, 80 subcarriers were used while in the 512-point simulation, 320 subcarriers were used, making the bandwidth of both systems the same. In order for the OFDM carriers to remain orthogonal to each other, the channel response must be approximately flat over the bandwidth of each subcarrier (see section 3.7.1). The simulation using 320 subcarriers divides the channel response using finer subcarriers, and hence the variation of the channel fading over their bandwidth of each subcarrier is more constant, improving the performance. The effective SNR for the 128 IFFT size is not limited by the guard period, but instead by poor channel equalisation caused by an insufficient number of subcarriers. For OFDM to operate effectively, the frequency response must be approximately flat over the bandwidth of a subcarrier. If insufficient subcarriers are used then the frequency response changes too rapidly, leading to degraded performance.

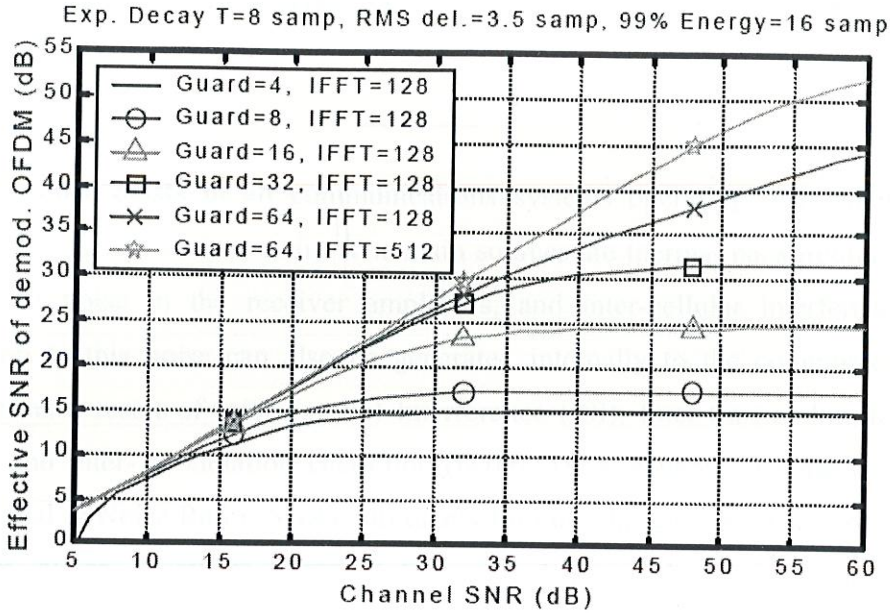


Fig 2.8.2 Effectiveness of adding a guard period for removal of ISI.

2.9.3 GUARD PERIOD OVERHEAD AND SUBCARRIER SPACING

Adding a guard period lowers the symbol rate, however it does not affect the subcarrier spacing seen by the receiver. The subcarrier spacing is determined by the sample rate and the FFT size used to analyse the received signal.

$$\Delta f = F_s / N_{FFT} \qquad \text{...... Eqn 2.8.3}$$

In Equation 2.8.3, Δf is the subcarrier spacing in Hz, Fs is the sample rate in Hz, and $NFFT$ is the size of the FFT. The guard period adds time overhead, decreasing the overall spectral efficiency of the system.

2.10 EFFECT OF ADDITIVE WHITE GAUSSIAN NOISE ON OFDM

Noise exists in all communications systems operating over an analog physica channel, such as radio. The main sources are thermal background noise, electrical noise in the receiver amplifiers, and inter-cellular interference. In addition to this noise can also be generated internally to the communications system as a result of Inter-Symbol Interference (ISI), Inter-Carrier Interference (ICI), and Inter- Modulation Distortion (IMD). These sources of noise decrease the Signal to Noise Ratio (SNR), ultimately limiting the spectral efficiency of the system. Noise, in all its forms, is the main detrimental effect in most radio communication systems. It is therefore important to study the effects of noise on the communications error rate and some of the trade offs that exists between the level of noise and system spectral efficiency.

Most types of noise present in radio communication systems can be modelled accurately using Additive White Gaussian Noise (AWGN). This noise has a uniform spectral density (making it white), and a Gaussian distribution in amplitude (this is also referred to as a normal distribution or bell curve).

Thermal and electrical noisefrom amplification, primarily have white Gaussian noise properties, allowing them to be modelled accurately with AWGN. Also most other noise sources have AWGN properties due to the transmission being OFDM. OFDM signals have a flat spectral density and a Gaussian amplitude distribution provided that the number of carriers is large (greater than about 20 subcarriers), because of this the inter-cellular interference from other OFDM systems have AWGN properties. For the same reason ICI, ISI, and IMD also have AWGN properties for OFDM signals.

2.10.1 MODULATION SCHEMES

Digital data is transferred in an OFDM link by using a modulation scheme on each subcarrier. A modulation scheme is a mapping of data words to a real (In phase) and imaginary (Quadrature) constellation, also known as an IQ constellation. For example 256-QAM (Quadrature Amplitude Modulation) has 256 IQ points in the constellation (see Table 2-2(h)), constructed in a square with 16 evenly spaced columns in the real axis and 16 rows in the imaginary axis. The number of bits that can be transferred using a single symbol corresponds to log2(M), where M is the number of points in the constellation, thus 256-QAM transfers 8 bits per symbol. Each data word is mapped to one unique IQ location in the constellation. The resulting complex vector $I + j \times Q$, corresponds to an amplitude of $\sqrt{I^2 + Q^2}$ and a phase of Ð($I + j \times Q$) where $j = \sqrt{-1}$.

Increasing the number of points in the constellation does not change the bandwidth of the transmission, thus using a modulation scheme with a large number of constellation points, allows for improved spectral efficiency. For example 256-QAM has a spectral efficiency of 8 b/s/Hz, compared with only 1 b/s/Hz for BPSK. However, the greater the number of points in the modulation constellation, the harder they are to resolve at the receiver. As the IQ locations become spaced closer together, it only requires a small amount of noise to cause errors in the transmission. This results in a direct trade off between noise tolerance and the spectral efficiency of the modulation scheme and was summarised by Shannon's Information Theory, which states that the maximum capacity of a channel of bandwidth W, with a signal power of S, perturbed by white noise of average power N, is given by

$$C = W \log_2(1 + S/N)$$

The spectral efficiency of a channel is a measure of the number of bits transferred per second for each Hz of bandwidth and thus the spectral efficiency *SE* is given by

$$SE = C / W = \log2(1 + S/N)$$

where both the signal and noise is linear scale, and the spectral efficiency is measured in b/s/Hz. If the SNR is significantly higher than one then each doubling of the signal power (a 3 dB increase) the ideal spectral efficiency increases by 1 b/s/Hz.

2.10.2 OFDM VERSES SINGLE CARRIER TRANSMISSION

The BER of an OFDM system is dependent on several factors, such as the modulation scheme used, the amount of multipath, and the level of noise in the signal. However if we look at the performance of OFDM with just AWGN then the performance of OFDM is exactly the same as that of a single carrier coherent transmission using the same modulation scheme.

If we look at just a single OFDM subcarrier (since the subcarriers are orthogonal to each other, this does not effect the performance in any way) then this is exactly the same as a single carrier transmission that is quadrature modulated with no band pass filtering. The transmitted amplitude and phase is held constant over the period of the symbol and is set based on the modulation scheme and the transmitted data. This transmitted vector is then updated at the start of each symbol. This results in a *sinc* frequency response, which is the required response for OFDM.

The optimal receiver for such a single carrier transmission is to use a coherent matched receiver, which can be implemented by mixing the signal to DC using an IQ mixer. This results in an IQ output that describes the amplitude and phase of the received modulated carrier. The amplitude and phase of the transmitted signal is constant over the symbol period, and so the optimal method of removing the most noise from the signal is to use an integrate-and-dump filter. This filter averages the received IQ vector over the entire symbol, then performs IQ demodulation on the average.

The demodulation of an OFDM signal is performed in exactly the same manner. In the receiver a FFT is used to estimate the amplitude and phase of each subcarrier. The FFT operation is exactly equivalent to IQ mixing each of the subcarriers to DC then applying an integrate-and-dump over the number of samples in the FFT. From this we can see that the FFT performs the same operation as the matched receiver for the single carrier transmission, except now for a bank of subcarriers.

From this we can conclude that in AWGN, OFDM will have the same performance as a single carrier transmission with no band limiting.

However, most propagation environments suffer from the effects of multipath propagation. For a given fixed transmission bandwidth, the symbol rate for a single carrier transmission is very high, where as for an OFDM signal it is N times lower, where N is the number of subcarriers used. This lower symbol rate results in a lowering of the ISI. In addition to lowering of the symbol rate, OFDM systems can also use a guard period at the start of each symbol. This guard period removes any ISI shorter than its length. If the guard period is sufficiently long, then all the ISI can be removed.

Multipath propagation results in frequency selective fading (see section 3.6 for more details) that leads to fading of individual subcarriers.

Most OFDM systems use Forward Error Correction to compensate for the subcarriers that suffer from severe fading. The adaptive modulation scheme proposed in section 4.2 matches the modulation scheme of each subcarrier to its SNR. The additional spectral efficiency of those subcarriers that have a SNR greater than the average (due to constructive interference) tends to compensate for subcarriers that are subjected to fading (destructive interference). As a result of this the performance of such an OFDM system in a multipath environment is similar to its performance in an AWGN channel. The performance of the OFDM system will be primarily determined by the noise seen at the receiver. However, the performance of a single carrier transmission will degrade rapidly in the presence of multipath.

2.10.3 MODULATION LIMITATIONS OF SYSTEMS

Most current mobile communication systems, specifically GSM, IS-95, and 3rd Generation Systems, only use modulation schemes with a high noise tolerance, such as BPSK, QPSK or similar. This results in a low spectral efficiency, but gives improved robustness. These systems use fixed modulation schemes due to the problems with obtaining a high SNR.

The symbol rate of single carrier systems has to be high if they are to obtain a high bit rate, and as a result, systems such as GSM require complex equalisation (up to 4 symbol periods) to cope with multipath propagation. GSM systems are designed to cope with a maximum delay spread of 15 ms, which corresponds to the typical delay spread experienced at a transmission distance of 30 - 35 km. The symbol rate for GSM is 270 kHz corresponding to a symbol period of 3.7 ms, thus ISI caused by the multipath spans over 4 symbol periods.

This would normally completely destroy the transmitted information, but is recovered in practice by using complex adaptive equalisation. Although this works for robust modulation schemes such as Gaussian Minimum Shift Keying (GMSK) as used in the GSM system, it is difficult to successfully apply to higher modulation schemes, as the residual errors in the equalisation will cause a high error rate.

In DS-CDMA systems the problem is not primarily limited by multipath, but instead inter-user interference. DS-CDMA systems utilise the fact that by spreading the userinformation over a wide bandwidth it allows multiple users to transmit at the same frequency [26], [27]. Each of these users spread the information signal by multiplying it by a unique higher speed Pseudo Random Sequence (PRS). At the receiver the signal from each user is extracted by multiply the by the same PRS and integrating over the period of an information symbol. This process is however nonorthogonal in the reverse link, resulting in users appearing as noise to each other. The system capacity is maximised when the number of users is maximised, resulting in very high levels of noise. This results in the system typically operating at an Energy per Bit to Noise Ratio (EBNR) of around 5 - 8 dB after demodulation. This rules out the use of high spectral efficiency modulation schemes since the SNR is too low.

OFDM on the other hand, minimises both of these effects. Multipath is minimised by using a low symbol rate and the use of a guard period. Equalisation of the channel can be easily achieved through the use of pilot symbols and or pilot tones. This type of equalisation is accurate and results in minimal residual error, thus allowing a high average SNR. Additionally, users in OFDM are kept orthogonal to each other, by use of time division multiplexing or synchronised frequency division multiplexing minimising inter-user interference. Both these advantages mean that a high effective channel SNR can be maintained even in a multiuser, multipath environment. This potential for a high SNR means that high modulation schemes can be used in OFDM systems, allowing for improved system spectral efficiency.

Additionally each subcarrier can be allocated a different modulation scheme based on the measured channel conditions. These measurements can be easily obtained as part of the channel equalisation step, allowing subcarriers to be dynamically allocated modulation schemes based on the SNR of each subcarrier. These variations in SNR arise due to interference, transmission distance, frequency selective fading, etc. This technique is known as adaptive modulation and is presented in section 4.2 Those subcarriers with a low SNR can be allocated to use BPSK (1 b/s/Hz) or to transmit no data at all. Subcarriers with a high SNR can transmit higher modulation schemes such as 256-QAM (8 b/s/Hz) allowing a higher system throughput.

The modulation allocation is flexible in OFDM systems allowing them to be optimised to local current conditions, rather than having to always use a low modulation scheme just to ensure the system operates during worst-case conditions.

2.10.4 COHERENT MODULATION

Coherent modulation is achieved by transmitting the IQ constellation data vectors with absolute phase angles, i.e. if BPSK was used then 0° or 180° would be transmitted. At the receiver it would compare the received phase to 0° or 180°. Phase rotations and amplitude scaling (important for QAM), greatly increase the error rate,or completely destroy all communications. This problem is however overcome by using channel equalisation to remove this scaling of the channel before demodulation. The phase rotation of the channel and the amplitude scaling is measured using pilot symbols and pilot tones, which contain a known IQ transmission vector. In a static channel with no movement, the response of the channel will be constant, and thus once measured and corrected for, data can be sent reliably.

However in most applications radio channels are non-static. Frequency selective fading cause complete fades in the spectrum approximately once every wavelength of movement, causing the response of the channel to change rapidly during movement. Tracking of the channel requires continual updates in the channel equalisation, thus regular pilot symbols/tones must be inserted into the transmission. The greater the number of pilot signals the faster the channel tracking rate, however this also causes significant overhead.

2.10.5 **DIFFERENTIAL PHASE MODULATION**

Another common method for subcarrier modulation is to send the data differentially. Instead of each symbol being independent of each other, the transmitted information is sent as a difference between symbols vectors. Differential Phase Shift Keying (DPSK) is the most common method of sending differential information. Instead of mapping data to an absolute phase angle, as in the case of coherent modulation, DPSK maps the data to a phase difference between symbols. The transmitted phase corresponds to the cumulative sum of the phase differences.

For example, fordifferential QPSK each symbol transmits 2 bits of information, corresponding to 4 different phase differences. Table 2.9.5 shows the IQ diagram for coherent QPSK. D-QPSK has the same IQ diagram except that each data combination corresponds toa phase difference. The most obvious method for allocating word combinations to phase differences, is to linearly map the binary word combinations to a linear phase difference, as shown in Table 2-3. For example, if the data to be transmitted is {1,0 1,1 0,0 0,1} then the differential phase would be {180°, 270°, 0°, 90°}, thus if the starting phase is 0° then the transmitted phase would be {180°, 180°+270° = 90°, (90°+0°) = 90°, (90°+90°) = 180°}.

In a noisy channel phase errors can result in the received phase being closer to the next or previous phase difference combinations, causing a symbol error. The number of bits in error depends on the data word mapping. Linear mapping is not optimal as a wrap around error from 270° to 0° causes a double bit error (1,1) to (0,0). By using gray coding, the number of bit errors can be reduced by ensuring that the phasedifference combinations that are closest to each other, only differ by a single bit in the data word.

Data Word	Phase Difference (linear mapping)	Phase Difference (gray coding)
0,0	0°	0°
0,1	90°	90°
1,0	180°	270°
1,1	270°	180°

Table 2.9.5 Phase mapping for differential QPSK.

Differential modulation has the advantage of cancelling out channel phase rotations, eliminating the need for additional channel equalisation. Additionally the phase tracking of the channel is effectively updated at the symbol rate, thus tracking the channel very quickly. Differential modulation is thus highly suited to mobile communication. The disadvantage of differential modulation is the limited range of modulation schemes, and that it requires about 3 dB higher SNR than coherent modulation. The output symbol phase corresponds to the phase difference between the present and previous symbols, and as a result the symbol noise is doubled (degrading the performance by 3 dB) compared with the phase noise of a single symbol (as used in coherent modulation).

2.10.6 DIFFERENTIAL QAM

Differential mapping can be applied to QAM modulation, with some limitations. For differential modulation to work, the mapping of the data to modulation domain must wrap. For example with differential PSK the transmitted phase is found by mapping each data word to a phase from 0 to 2p, then integrating this mapping from symbol to symbol. The phase wraps in a circular fashion as it is constrained to the range 0 to 2p. The receiver decodes the phase by taking the phase difference between symbols. To achieve this type of mapping with a QAM scheme the input data can be split into two data streams of N/2 bits each per symbol, where N is the number of bits per symbol. The number of bits per symbol must be even and so this mapping can only be done for square QAM mapping such as 16-QAM, 64-QAM, etc. Each N/2 bit data stream is mapped to the (I) real and (Q) imaginary axes to form the resulting transmitted vector. Because the signal is differential modulated each axis is modulo integrated from symbol to symbol. Figure 2.9.6.1 shows an example of differential QAM. If we examine just one axis, then if the data to be transmitted was: {1, 2, 0, 3, 1}, and we started with a reference of 0, then the differentially encoded signal can be found by taking the cumulative sum of the data words {1, 3, 3, 6, 7} then modulo wrapping it to the bounds 0 to 3, resulting in {1, 3, 3, 2, 3}. The receiver decodes this by taking the difference, {1, 2, 0, -1, 1}, remembering that the reference at the start was 0, then wrapping from 0 to 3, resulting in {1, 2, 0, 3, 1}.

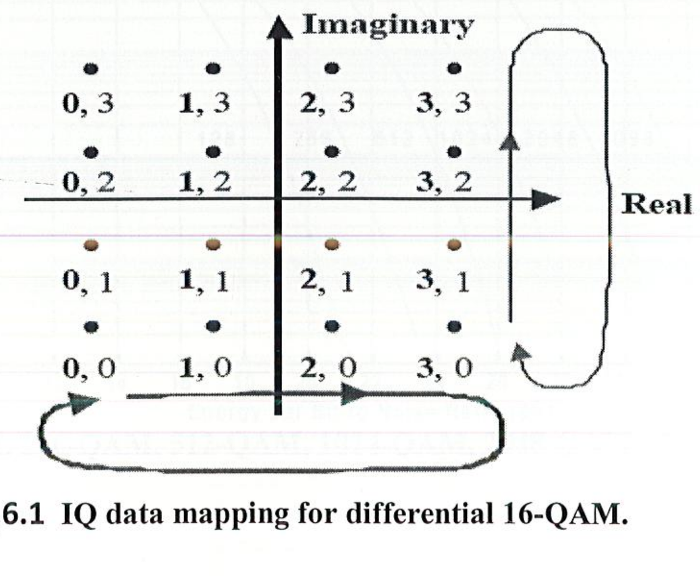
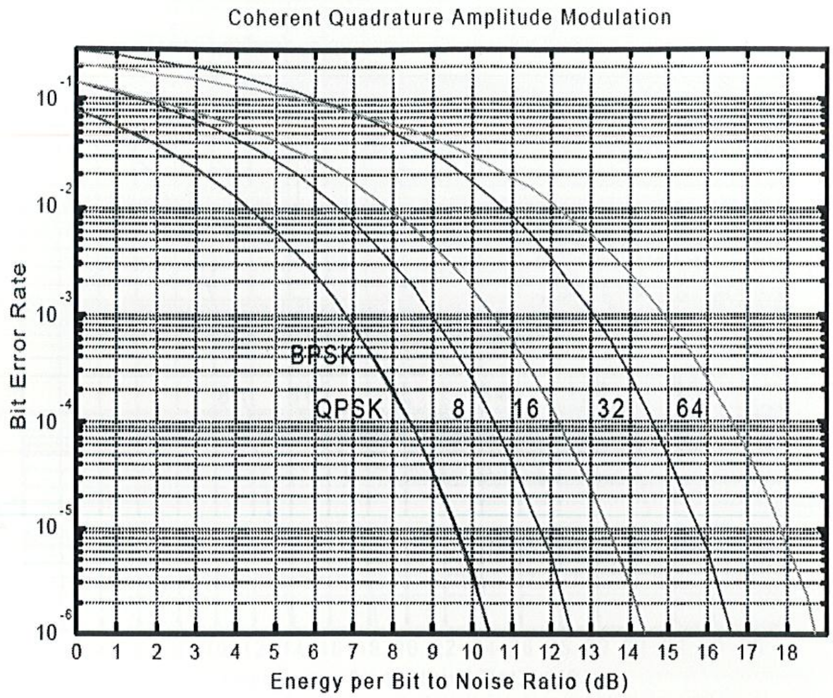
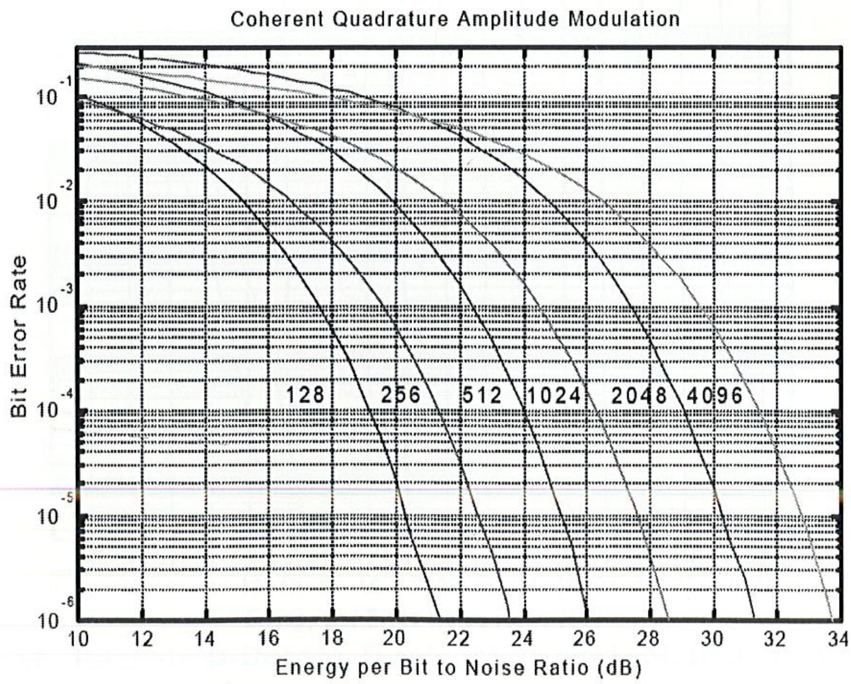


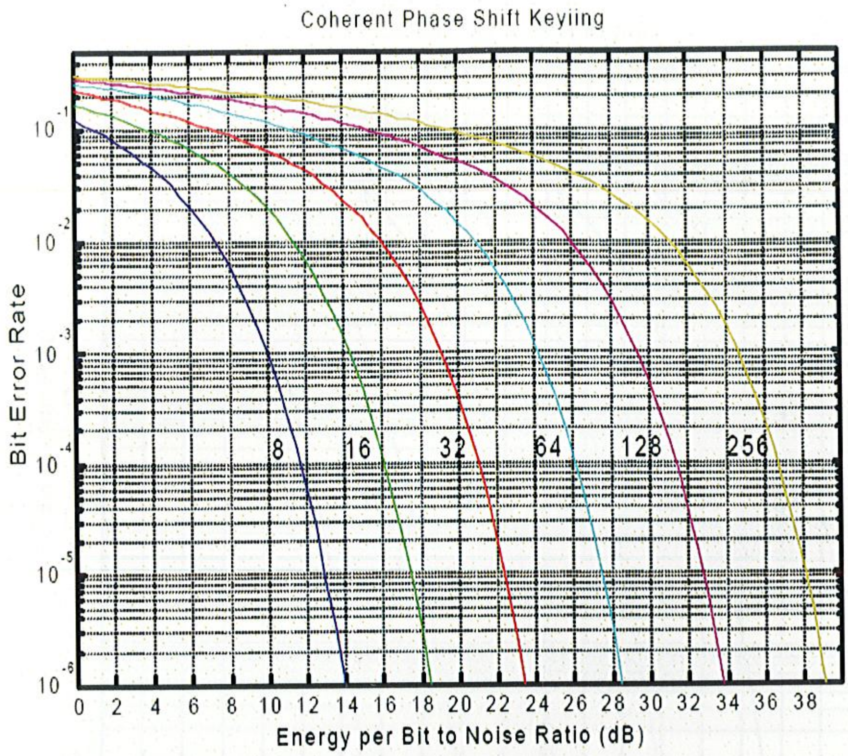
Fig 2.9.6.1 IQ data mapping for differential 16-QAM.



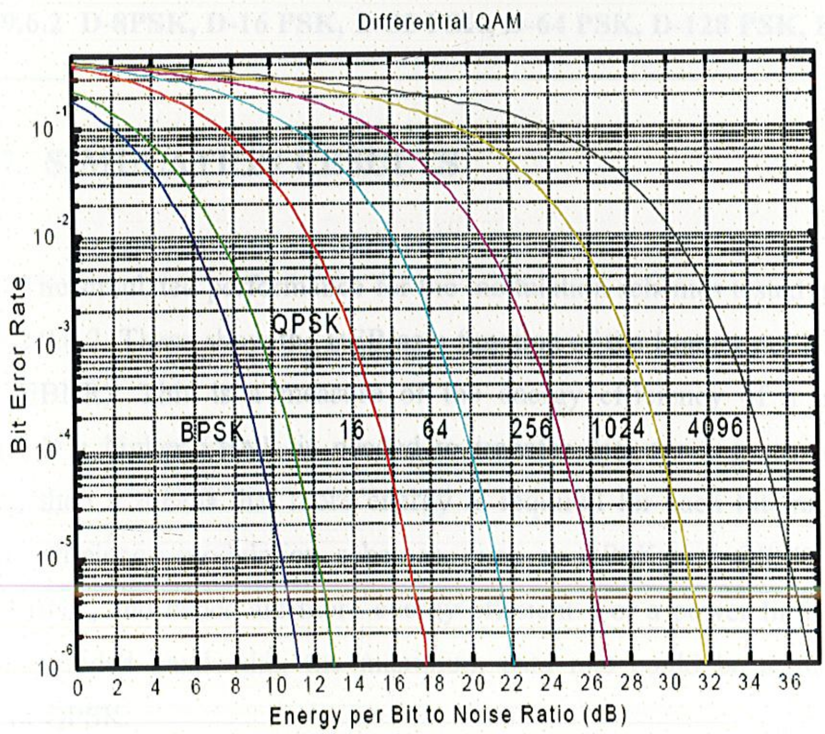
BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM
Note: BPSK and QPSK have the same EBNR performance.



128-QAM, 256-QAM, 512-QAM, 1024-QAM, 2048-QAM, 4096-QAM



8-PSK, 16-PSK, 32-PSK, 64-PSK, 128-PSK, 256-PSK



D-BPSK, D-QPSK, D-16QAM, D-64QAM, D-256QAM, D-1024QAM, D-4096QAM

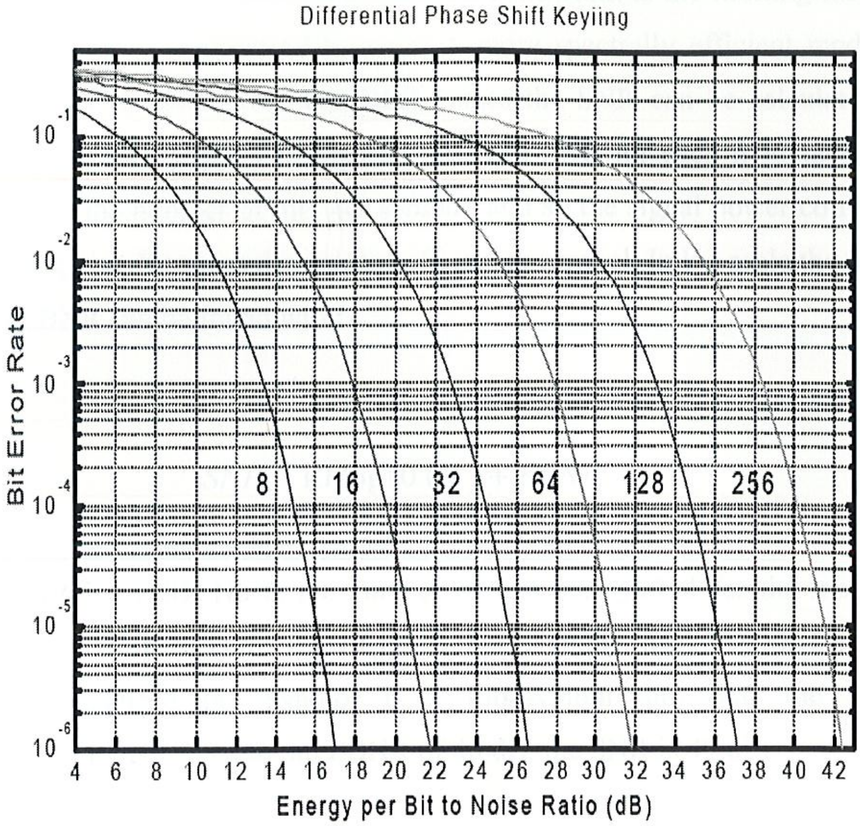


Fig 2.9.6.2 D-8PSK, D-16 PSK, D-32 PSK, D-64 PSK, D-128 PSK, D-256PSK

2.10.7 SIMULATION RESULTS

The simulated performance for the modulation schemes tested is shown in Figure 2.9.6.2. These show the BER as a function of the Energy per Bit to Noise Ratio (EBNR). This is a measure of the energy efficiency of a modulation scheme. If a higher EBNR is needed to transfer data for a given modulation scheme, then it means that more energy is required for each bit transfer. Low spectral efficiency modulation schemes, such as BPSK and QPSK, require a lower EBNR, and hence are more energy efficient. For a power limited system, with unbounded bandwidth, the maximum data rate could be achieved using BPSK or QPSK.

However, in most applications the available bandwidth is the limiting factor and so the data rate is maximised by using a more spectrally efficient modulation schemes such as 256-QAM. The BER verses the SNR can be calculated from EBNR shown on the plots in Figure 2-30. The SNR for each modulation takes into account the number of bits per symbol, and so the signal power corresponds to the energy per bit times the number of bits per symbol. In log scale the SNR for a given EBNR can be found with:

$$SNR = 10\ \log10\ (\mathrm{N}\ ) + EBNR$$

where SNR is in dB, Nb is the number of bits per symbol for the modulation scheme and EBNRdB is the EBNR in dB. For example, for 256-PSK the number of bits transferred per symbol is 8 bits/symbol and thus the SNR is 10.log10(8)+EBNR, thus for an EBNR of 40 dB, the SNR is 49 dB.

Figure 2.9.7 shows a comparison between all of the modulation schemes simulated. It shows the required SNR for a fixed BER of 1′10-5. Coherent QAM performs best requiring the least SNR, while differential PSK is the worst. Also shown is Shannon's limit, which represents the lowest possible SNR for a given spectral efficiency over which zero error communications can occur.

In order for a communication system to approach Shannon's limit powerful forward error correction coding techniques must be used. For the BER shown coherent QAM is approximately 7.5 dB worse than Shannon's limit. For QAM the required SNR for a fixed BER increases by approximately 3 dB for each additional 1 b/s/Hz in spectral efficiency, which matches the same slope as Shannon's limit. In comparison, for PSK the required SNR increases by 6 dB for each addition 1 b/s/Hz resulting in the capacity of PSK modulation techniques being approximately half that of QAM for the same SNR.

The low efficiency of PSK is a result of under utilisation of the IQ vector space. PSK only uses the phase angle to convey information, with amplitude being ignored. QAM uses both amplitude and phase for information transfer and so is more efficient.

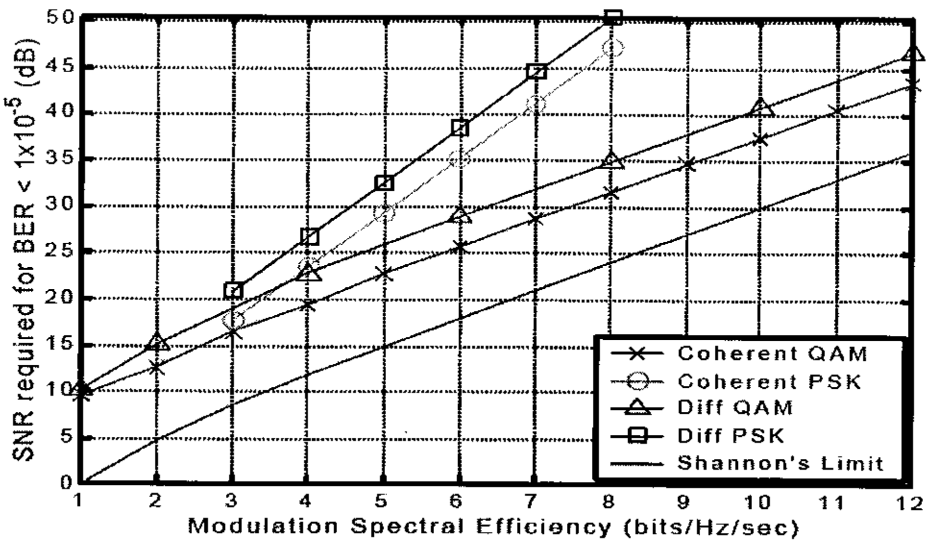


Fig 2.9.7 Effectiveness of adding a guard period for removal of ISI.

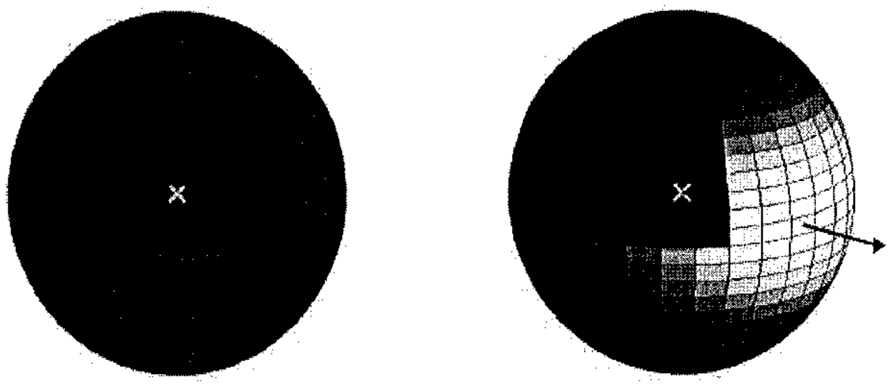
CHAPTER 3 RADIO PROPAGATION

Radio propagation effects such as path loss, frequency selective fading, Doppler spread and multipath delay-spread limit the effectiveness of wireless communications. An understanding of radio propagation is needed before different forms of multiuser OFDM can be discussed. This chapter provides a review of wellknown propagation effects and extends these to look at the effects on wide bandwidth transmissions. This chapter includes an experimental investigation of small-scale frequency selective fading of multipath environments. It looks at the variation of the multipath fading with small changes in space. This work was needed to allow different user allocation schemes, such as adaptive subcarrier modulation, to be investigated. This work provides insight into how fast radio channels change with space and time. Although there has been extensive work done on narrow band radio modelling, not much work has been done on wide band modelling (10 - 100 MHz bandwidth). Most models in literature are based on statistical results, making them of little use for investigating user allocation schemes in an OFDM system. For this the clustering of the frequency fading and change with space is needed to decide how subcarrier hopping systems will work. This work is very important for OFDM systems development because it provides a deterministic relationship between frequency selective fading and space (movement)

3.1 PATH LOSS AND ATTENUATION

During propagation, radio signals weaken with distance. This is due to the wave front of the radio signal expanding and thus reducing in power density. In free space, the propagating wave expands as a sphere and thus the power density reduces in proportion to the surface area of this sphere. If the signal is transmitted using a directional antenna, the signal still expands as a sphere, except that the energy density is concentrated to one or more areas

If we transmitted the same energy from an omnidirectional as a direction antenna, the integrated energy over the surface area of the RF sphere, the energy would be the same. Figure 3-1 shows an expanding RF pulse, if we were to imagine a sinusoidal transmission (single frequency) it would be continuous stream of expanding spheres, with the power of these following a sinusoid waveform.



(a) **(b)**

Figure 3-1, Expanding RF pulse from a central transmitter.

The transmitter is shown as an **X** in the cut away section. (a) For an omnidirectional antenna, the energy density is even in all directions. (b) For a high gain antenna, the energy is concentrated in one direction; it still however expands as a sphere.

The area of a sphere is proportional to the radius squared, and thus in free space the RF field strength reduces proportionally with distance squared. Equation (3-1) calculates the received power over transmission in free space.

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi R} \right)^2$$

....Eqn 3.1

Where *Pr*is the received signal power (watts), *Pt* is the transmitted power (watts), *Gr* gain of the receive antenna with respect to an isotropic antenna, *Gt* gain of the transmitter antenna, *l* wavelength of the RF carrier (m), and *R* is the transmission distance in metres.

Free space propagation is very predictable, and can be used to accurately model satellite communications and directional links with no obstructions, such as shortrange microwave directional point-to-point links. However for most terrestrial communications such as mobile phones and wireless LAN systems, the environment is much more complex making propagation modelling much more difficult.

3.2 FADING

The received signal exhibits fluctuation in signal level called fading. Fluctuations in signal level is composed of two componbents: *Macroscopic fading* represents the long term variation of the received signal power level, while *Microscopic* fading represents short term variation. Macroscopic Fading caused by shadowing effect of building or natural features and is determined by the local means experimentally. Microscopic Fading refers to the rapid fluctuations of the received signal in space, time & frequency and is caused by the signal scattering off objects between the transmitter and receiver.

3.2.1 SHORT TERM FADING

In a multipath environment, the received signal fades with distance due to the changing phase of the multipath components. Short term fading is caused by the interference (constructive or destructive) that result from the combination of multiple received waves. As the receiver or transmitter are moved in space the relative phase between the different multipath components change, causing the interference to also change, resulting in fades in the received signal power. At certain locations, the signal can suffer almost compete cancellation of the signal, resulting in a deep null inthe signal. These nulls can be as much as 30 dB. Nulls occur approximately at intervals of the RF wavelength (30 cm for 1 GHz transmission).

The rate of fading with distance is usually measured using the coherence distance. This is a measure of the distance over which the radio channel experiences comparable or correlated fading.

3.2.2 FREQUENCY SELECTIVE FADING

Multipath also causes fading changes with frequency. This is due to the phase response of the multipath components varying with frequency. The received phase, relative to the transmitter, of a multipath component corresponds to the number of wavelengths the signal has travelled from the transmitter. The wavelength is inversely proportional to frequency and so for a fixed transmission path the phase will change with frequency. The path distances of each of the multipath component is different and so results in a different phase change. Figure 3.2.1 shows an example two-path transmission. Path 1 is a direct signal and has a transmission distance of 10 m, while the second path is a reflection with a longer transmission distance of 25 m. For a wavelength of 1 m each path is an integer number of wavelengths hence the phase change from transmitter to receiver will be 0° for each path. At this frequency, the two paths will reinforce each other. If we change the frequency to have a wavelength of 0.9 m then path 1 will be 10/0.9 = 11.111λ, or a phase of 0.111 × 360° = 40°, while second path will be 25/0.9 = 27.778λ, a phase of 0.778 × 360° = 280°. This makes the two paths out of phase, which results in a reduction in the signal amplitude at this frequency.

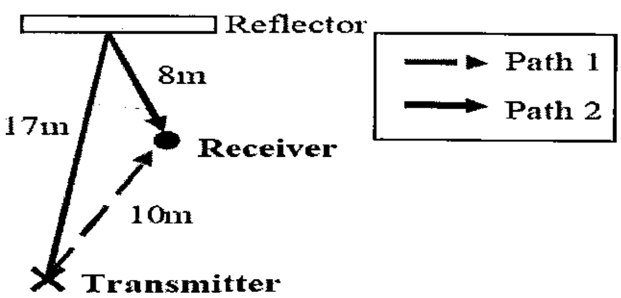


Figure 3.2.1 , Two path transmission to demonstrate frequency selectiv fading.

The rate of phase rotation is proportional to the path distance of each multipath component. For environments with a large number of multipath components, this results in complex variations in the fading verses frequency. Figure 3.2.2 shows an example of measured frequency selective fading within an indoor environment. The signal power varies by more than 25 dB with frequency, showing that at certain frequencies near complete signal cancellation is occurring. The frequency selective fading characteristics of a channel can be summarised by the correlation bandwidth of the channel. This is the approximate maximum bandwidth or frequency interval over which the fading is similar and correlated. The exact correlation bandwidth depends on the required level of correlation. The correlation bandwidth is inversely proportional to the channel delay spread.

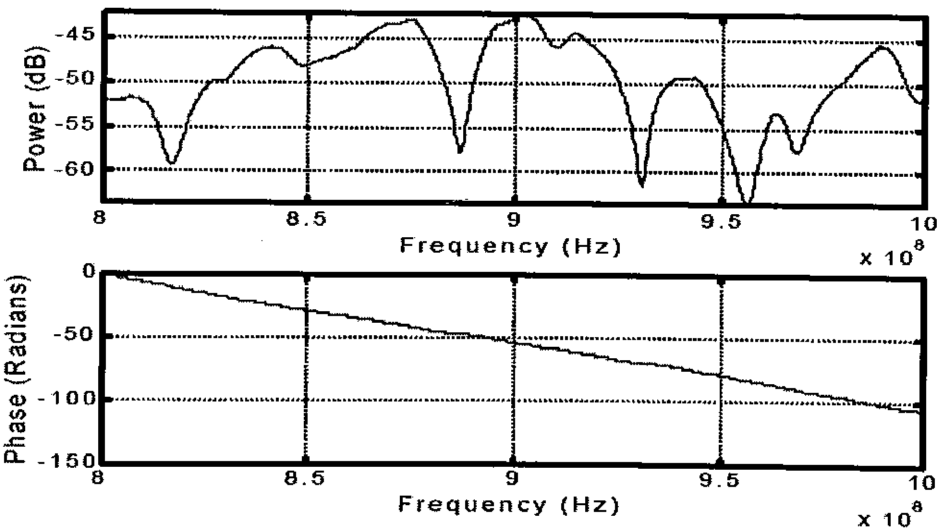


Figure 3.2.2, Frequency selective fading for a short indoor link.

3.3 Delay spread

You are driving in rain, and the car in front splashes a bunch of water on you. What do you do? You move further back, you put a little distance between you and the front car, far enough so that the splash won't reach you. If we equate the reach of splash to delay spread of a splashed signal then we have a better picture of the phenomena and how to avoid it.

Increase distance from car in front to avoid splash. The reach of splash is same as the delay spread of a signal. In composite, these splashes become noise and affect the beginning of the next symbol.

To mitigate this noise at the front of the symbol, we will move our symbol further away from the region of delay spread as shown below. A little bit of blank space has been added between symbols to catch the delay spread.

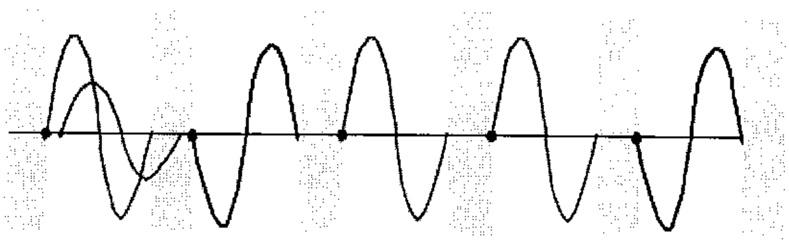


Fig 3.3.1 – Move the symbol back so the arriving delayed signal peters out in the gray region. No interference to the next symbol!

But we can not have blank spaces in signals. This is won't work for the hardware which likes to crank out signals continuously. So it's clear we need to have something there. Why don't we just let the symbol run longer as a first choice?

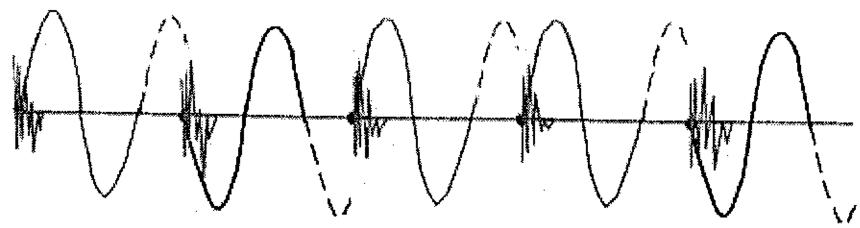


Fig. 3.3.2 – If we just extend the symbol, then the front of the symbol which is important to us since it allows figuring out what the phase of this symbol is, is now corrupted by the "splash".

We extend the symbol into the empty space, so the actual symbol is more than one cycle.

But now the start of the symbol is still in the danger zone, and this start is the most important thing about our symbol since the slicer needs it in order to make a decision about the bit. We do not want the start of the symbol to fall in this region, so lets just slide the symbol backwards, so that the start of the original symbol lands at the outside of this zone. And then fill this area with something.

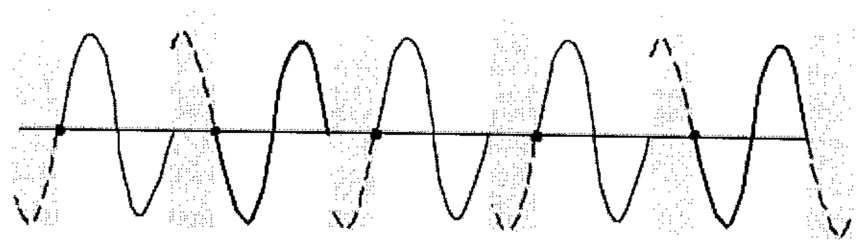


**Fig. 3.3.3 – If we move the symbol back and just put in convenient filler in this area, then not only we
have a continuous signal but one that can get corrupted and we don't care since we will just cut it out
anyway before demodulating.**

Slide the symbol to start at the edge of the delay spread time and then fill the guard space with a copy of what turns out to be tail end of the symbol.

1. We want the start of the symbol to be out of the delay spread zone so it is not corrupted and

2. We start the signal at the new boundary such that the actual symbol edge falls out side this zone.

We will be extending the symbol so it is 1.25 times as long, to do this, copy the back of the symbol and glue it in the front. In reality, the symbol source is continuous, so all we are doing is adjusting the starting phase and making the symbol period longer. But nearly all books talk about it as a copy of the tail end. And the reason is that in digital signal processing, we do it this way.

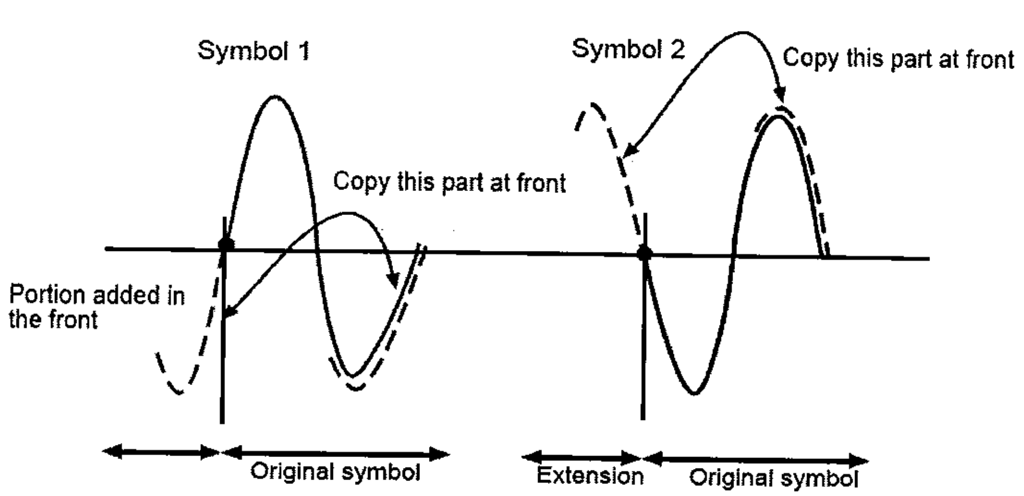


Fig. 3.3.4– Cyclic prefix is this superfluous bit of signal we add to the front of our precious cargo, the symbol.

This procedure is called adding a cyclic prefix. Since OFDM, has a lot of carriers, we would do this to each and every carrier. But that's only in theory. In reality since the OFDM signal is a linear combination, we can add cyclic prefix just once to the composite OFDM signal. The prefix is any where from 10% to 25% of the symbol time.

CHAPTER 4 PROPERTIES OF OFDM

4.1 Spectrum and performance

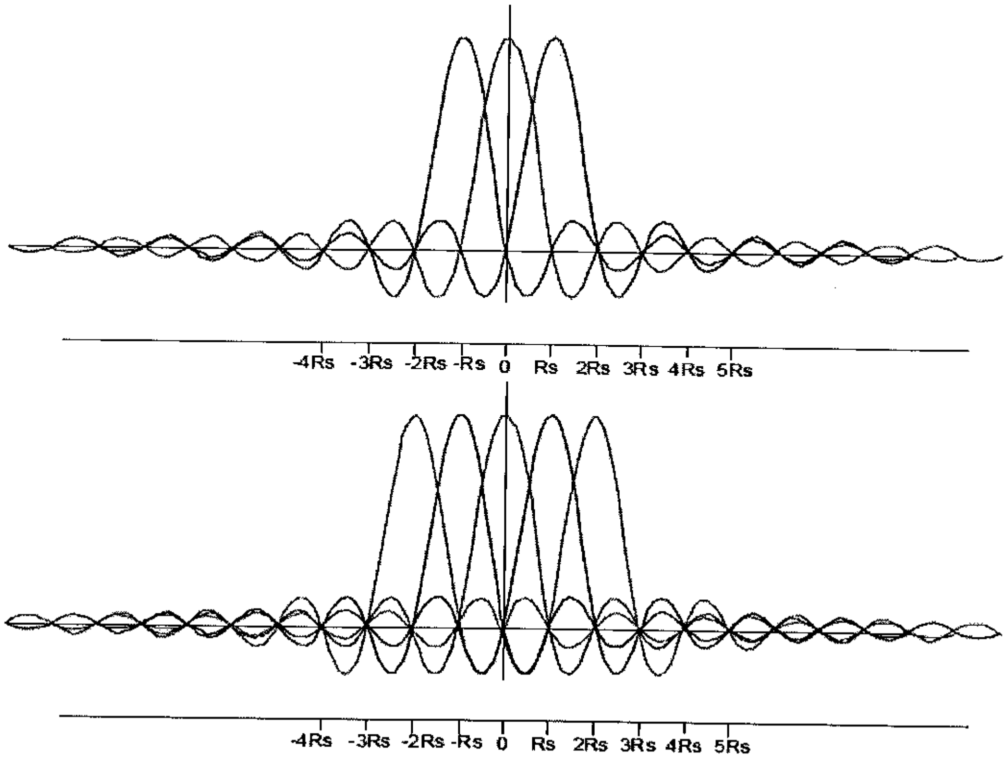


Fig. 4.1 – The spectrum of an OFDM signal (without addition of cyclic prefix) is much more bandwidth efficient than QPSK.

Unshaped QPSK signal produces a spectrum such that its bandwidth is equal to (1+ α)Rs. In OFDM, the adjacent carriers can overlap in the manner shown here. The addition of two carriers, now allows transmitting 3Rs over a bandwidth of -$2R_s$ to $2R_s$ or total of 4Ts. This gives a bandwidth efficiency of 4/3 Hz per symbol for 3 carriers and 6/5 for 5 carriers.

As more and more carriers are added, the bandwidth approaches,

(N+1)/N bits per Hz

So the larger the number of carriers, the better. Here is a spectrum of an OFDM signal. Note that the out of band signal is down by 50 dB without any pulse shaping.

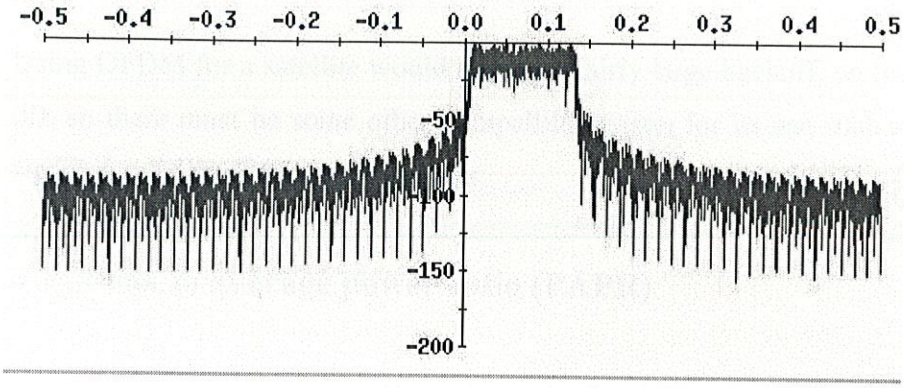


Fig. 4.2 – the spectrum of an OFDM signal with 1024 sub-carriers

Compare this to the spectrum of a QPSK signal, not how much lower the sidebands are for OFDM and how much less is the variance.

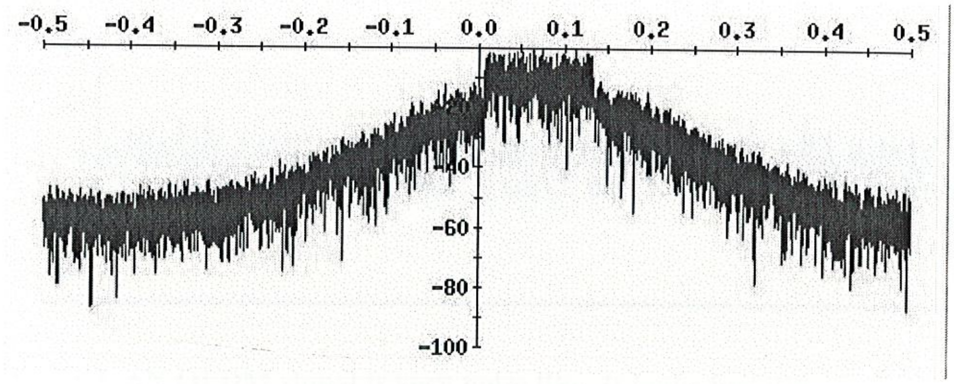


Fig. 4.3 – the spectrum of a QPSK signal

4.2 Bit Error Rate performance

The BER of an OFDM is only exemplary in a fading environment. We would not use OFDM is a straight line of sight link such as a satellite link. OFDM signal due to its amplitude variation does not behave well in a non-linear channel such as created by high power amplifiers on board satellites

Using OFDM for a satellite would require a fairly large backoff, on the order of 3 dB, so there must be some other compelling reason for its use such as when the signal is to be used for a moving user.

4.3 Peak to average power ratio (PAPR)

If a signal is a sum of N signals each of max amplitude equal to 1 v, then it is conceivable that we could get a max amplitude of N that is all N signals add at a moment at their max points. The PAPR is defined as

$$R = \frac{|x(t)|^2}{P_{avg}}$$

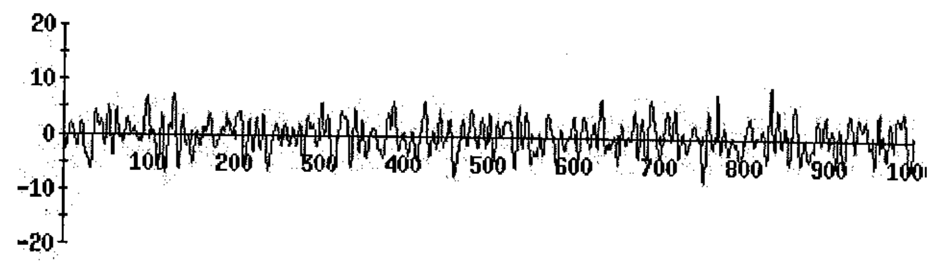


Fig. 4.3 AN OFDM signal is very noise like. It looks just like a composite multi-FDM signal

4.4 Synchronization.

The other problem is that tight synchronization is needed. Often pilot tones are served in the sub- carrier space. These are used to lock on phase and to equalize the channel.

4.5 Coding

The sub-carriers are typically coded with Convolutional coding prior to going through IFFT. The coded version of OFDM is called COFDM or Coded OFDM.

4.6 Parameters of real OFDM

The OFDM use has increased greatly in the last 10 years. It is now proposed for radio broadcasting such as in Eureka 147 standard and Digital Radio Mondiale (DRM). OFDM is used for modem/ADSL application where it coexists with phone line. For ADSL use, the channel, the phone line, is filtered to provide a high SNR. OFDM here is called Discrete Multi Tone (DMT.) OFDM is also in use in your wireless internet modem and this usage is called 802.11a. Let's take a look at some parameters of this application of OFDM. The summary of these are given below.

Data rates

    6 Mbps to 48 Mbps

Modulation

    BPSK, QPSK, 16 QAM and 64 QAM

Coding

    Convolutional concatenated with Reed Solomon

FFT size

64 with 52 sub-carriers uses, 48 for data and 4 for pilots.

Subcarrier frequency spacing

20 MHz divided by 64 carriers or .3125 MHz

FFT period

Also called symbol period, 3.2 μsec = $1/\Delta f$

Guard duration

One quarter of symbol time, 0.8 μsec

Symbol time

4 μsec

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