Major Project Report On

DESIGN AND IMPLEMENTATION OF OFDM TRANSCEIVER

SUBMITTED IN THE PARTIAL FULFILLMENT FOR THE DEGREE OF

MASTER OF ENGINEERING

(ELECTRONICS & COMMUNICATION ENGG.)

(2004-2006)

SUBMITED BY

SATISH KUMAR

(25/ E&C/ 2004)

(UNIVESITY ROLL NO: 8736)

UNDER THE GUIDANCE OF

Dr. M.KULKARNI

(Astt. Prof.)

ELECTRONICS & COMMUNICATION ENGINEERING

***DEPATMENT OF* ELECTRONICS & COMMUNICATION ENGINEERING**

DELHI COLLEGE OF ENGINEERING

UNIVERSITY OF DELHI

BAWANA ROAD, NEW DELHI

CERTIFICATE

This is to certify that this thesis titled " **DESIGN AND IMPLEMENTATION OF OFDM TRANSCEIVER**" being submitted by **SATISH KUMAR (25/E&C/2004)** of Delhi College of Engineering in partial fulfilment of the requirements for the degree of **Master of Engineering** in Electronics and Communication Engineering is a bonafide work carried out under our guidance and supervision.

Dr. M.KULKARNI
Assistant Professor
Electronics & Communication
Engineering Deptt.
Delhi College of Engineering

ACKNOWLEDGEMENT

I am highly indebted and express my deep sense of gratitude to my worthy and reverend guide **Dr. M.KULKARNI, Assistant Professor**, Dept. of Electronics & communication Engineering, Delhi College of Engineering, New Delhi for this valuable guidance and help extended by this worthiness, which have enabled me to carried out the work successfully. His cooperation came forth to help me out of my difficulties before it was even called for by me. His precious suggestion and devotion have encouraged me all through to the advantage of making my carrier bright.

My family had a big role in ensuring that I successfully complete the project. Their constant encouragement and unwavering support have been a great source of strength for me. I am grateful to my friends for their valuable help and good wishes which went a long way in fulfilling this task.

SATISH KUMAR
Univ. R.No. 8736
Department of E&C Engg.
Delhi College of Engineering,

CONTENTS

Table of Contents

LIST OF FIGURES

List of Tables

ABSTRACT

Orthogonal frequency division multiplexing (OFDM) is becoming the chosen modulation technique for wireless communications. OFDM can provide large data rates with sufficient robustness to radio channel impairments. Many research centers in the world have specialized teams working in the optimization of OFDM for countless applications. The purpose of this thesis is to provide MatLab code to simulate the basic processing involved in the generation and reception of an OFDM signal in a physical channel and to provide a description of each of the steps involved. For this purpose, we shall use, as an example, one of the proposed OFDM signals of the Digital Video Broadcasting (DVB) standard for the European terrestrial digital television (DTV) service.

CHAPTER 1
INTRODUCTION

In an OFDM scheme, a large number of orthogonal, overlapping, narrow band sub-channels or subcarriers, transmitted in parallel, divide the available transmission bandwidth. The separation of the subcarriers is theoretically minimal such that there is a very compact spectral utilization. The attraction of OFDM is mainly due to how the system handles the multipath interference at the receiver. Multipath generates two effects: frequency selective fading and intersymbol interference (ISI). The "flatness" perceived by a narrow-band channel overcomes the former, and modulating at a very low symbol rate, which makes the symbols much longer than the channel impulse response, diminishes the latter. Using powerful error correcting codes together with time and frequency interleaving yields even more robustness against frequency selective fading and the insertion of an extra guard interval between consecutive OFDM symbols can reduce the effects of ISI even more. Thus, an equalizer in the receiver is not necessary.

1.1 Motivation

For the most part, Orthogonal Frequency Division Multiplexing (OFDM) is the standard being used throughout the world to achieve the high data rates necessary for data intensive applications that must now become routine.

This thesis enhances the throughput of an existing OFDM system by implementing DVB-T. The new system guarantees to reach a target performance over a slow time-varying fading channel. The system automatically switches from lower to higher modulation schemes on individual subcarriers, depending on the state of the quasi-stationary channel.

We designed this method in MAT lab codes.

CHAPTER 2
OFDM

2.1 Research Survey

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 sub channels 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. Weinstein and Ebert applied the discrete Fourier transform (DFT) to parallel data transmission system as part of the modulation and demodulation process. In the 1980s, OFDM has been studied for high-speed modems, digital mobile communications and high- density recording. Various fast modems were developed for telephone networks. In 1990s, OFDM has been exploited for wideband data communications over mobile radio FM channels, wireless LAN wireless multimedia communication , high-bit-rate digital subscriber lines (HDSL), asymmetric digital subscriber lines (ADSL), very high-speed digital subscriber lines (VHDSL), digital audio broadcasting (DAB) and HDTV terrestrial broadcasting.

2.2 OFDM Message

Orthogonal Frequency Division Multiplexing (OFDM) is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub carriers. Two signals are orthogonal if their dot product is zero. That is, if you take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. 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. As the sub carriers are orthogonal, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, allowing them to be spaced as close as theoretically possible. Mathematically, suppose we have a set of signals Ψ , where Ψp is the *p*-th element in the set. The signals are orthogonal if,

$$\int_a^b \Psi_p(t)\Psi_q^*(t)dt = \begin{cases} K & for\ p = q \\ 0 & for\ p \neq q \end{cases} \tag{2.1}$$

Where * indicates the complex conjugate and interval [a, b], is a symbol period**.** Since the carriers are orthogonal to each other the nulls of one carrier coincides with the peak of another sub carrier. As a result it is possible to extract the sub carrier of interest.

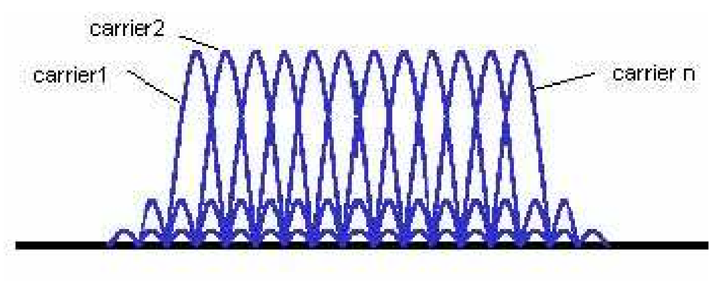

Figure 2.1 OFDM Spectrum

As the figure indicates the spectrum of carriers significantly over laps over the other carrier. This is contrary to the traditional FDM technique in which a guard band is provided between each carrier**.**

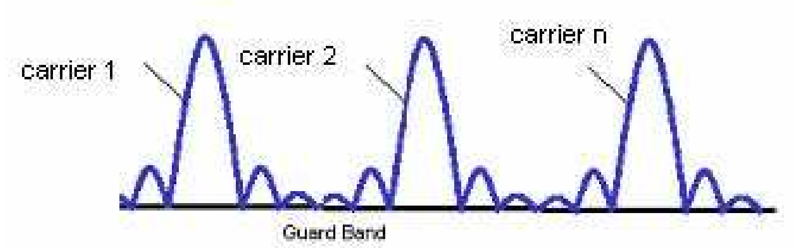

Figure 2.2 FDM Spectrum

From the figures illustrated, it is clear that OFDM is a highly efficient system and hence is often regarded as the optimal version of multi-carrier transmission schemes. The number of sub channels transmitted is fairly arbitrary with certain broad constraints, but in practical systems, sub channels tend to be extremely numerous and close to each other. For example the number of carriers in 802.11 wireless LAN is 48 while for Digital Video Broadcast (DVB) it is as high as 6000 sub carriers. If we consider a single OFDM carrier, we can model the transmitted pulse as a sinusoid multiplied by a RECT function. In the frequency domain, the resulting spectrum has a sin(x)/x shape centred at the carrier frequency as shown in the figure below.

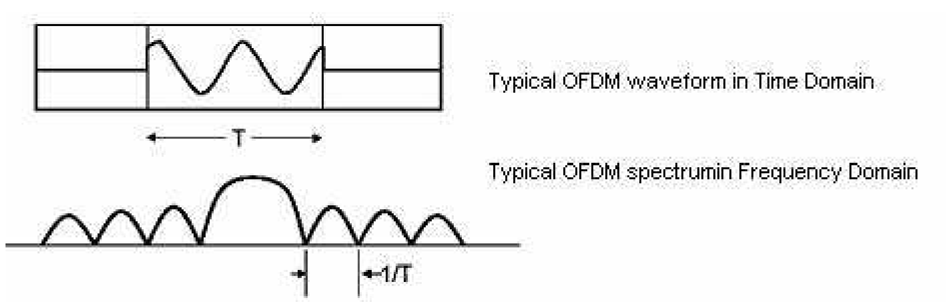

Figure 2.3 A Single carrier of OFDM

It is worth mentioning here that relative to single carrier Modulation technique SCM, the OFDM carriers occupy a significant amount of bandwidth of the spectrum relative to the symbol rate. This characteristic is not a problem given that the carriers overlap significantly. The slow sin (x)/x roll off, which implies a wider carrier bandwidth is only an issue at the edge of the channel spectrum. Standards like 802.11A, allow the RECT pulse to be modified such that the rising and falling edges are softer (Raised cosine) at the edge of their assigned spectrum. This helps constrain the spectrum without affecting data transmissions OFDM offers several advantages over single carrier system like better multi-path effect immunity, simpler channel equalization and relaxed timing acquisition constraints. But it is more susceptible to local frequency offset and radio front-end non-linearities. The frequencies used in OFDM system are orthogonal. Neighboring frequencies with overlapping spectrum can therefore be used. This results in efficient usage of BW. The OFDM is therefore able to provide higher data rate for the same BW.

2.3 ADVANTAGES AND DISADVANTAGES OF OFDM AS COMPARED TO SINGLE CARRIER MODULATION

2.3.1 ADVANTAGES

1. Makes efficient use of the spectrum by allowing overlap.
2. By dividing the channel into narrowband flat fading sub channel is more resistant to frequency selective fading than single carrier systems are.
3. Eliminates ISI and IFI through use of a cyclic prefix.
4. Using adequate channel coding and interleaving one can recover symbols lost due to the frequency selectivity of the channel.
5. Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems.
6. It is possible to use maximum likelihood decoding with reasonable complexity.
7. OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.

8. Is less sensitive to sample timing offsets than single carrier systems are.
9. Provides good protection against co channel interference and impulsive parasitic noise.

2.3.2 DISADVANTAGES:

1. The OFDM signal has a noise like amplitude with a very large dynamic range; therefore it requires RF power amplifiers with a high peak to average power ratio.
2. It is more sensitive to carrier frequency offset and drift than single carrier systems are due to leakage of the DFT.

2.4 OFDM SYSTEM MODEL

OFDM transmitters generate both the carrier and the data signal simultaneously with purely digital circuits residing in the specialized DSP (Digital Signal Processor) microchips. The specific process of digital signal generation used in OFDM is based on the series of mathematical computations known as an Inverse Fourier Transform, and the process results in the formation of a complex modulated waveform at the output of the transmitter. The incoming serial data is first converted from serial to parallel and grouped into x bits each to form a complex number. The complex numbers are modulated in a base band fashion by the IFFT and converted back to serial data for transmission. A guard interval is inserted between symbols to avoid intersymbol interference (ISI) caused by multipath distortion. The discrete symbols are converted to analog and low pass filtered for RF up-conversion. The receiver performs the inverse process of the transmitter. One tap equalizer is used to correct channel distortion. The tap coefficients of the filter are calculated based on channel information.

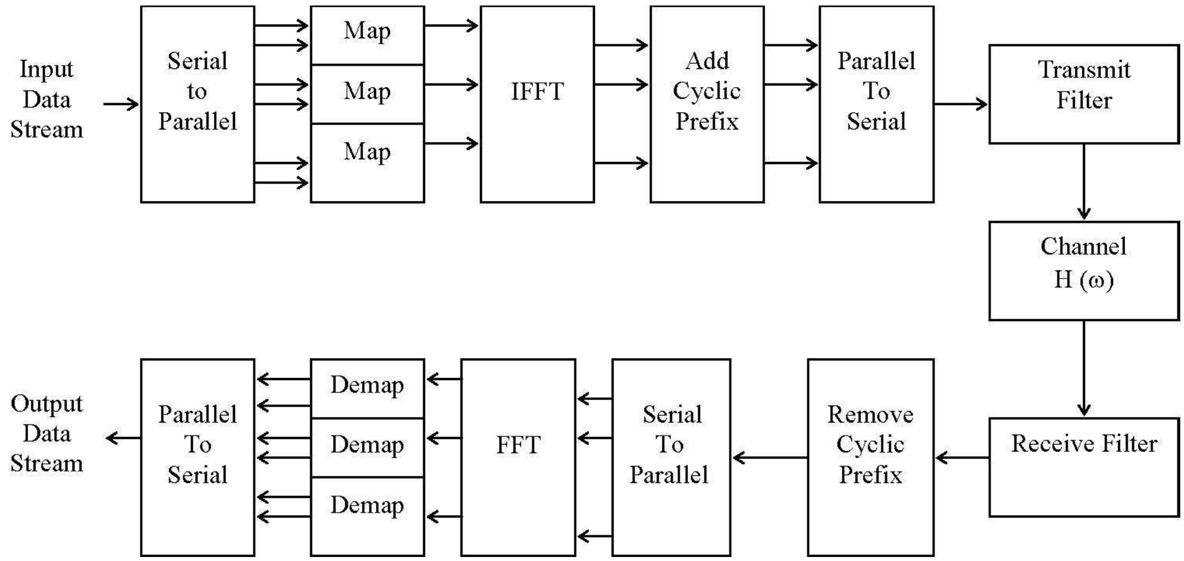

Figure 2.4 OFDM System model

2.5 Interference

In a multipath environment, different versions of the transmitted symbol reach the receiver at different times. This is due to the fact that different propagation paths exist between transmitter and receiver. As a result, the time dispersion stretches a particular received symbol into the one following it. This symbol overlap is called inter-symbol interference, or ISI. It also is a major factor in timing offset. One other form of interference is inter-carrier interference or ICI. In OFDM, successful demodulation depends on maintaining orthogonality between the carriers. We demodulate a specific subcarrier N at its spectral peak, meaning that all the other carriers must have a corresponding zero spectra at the N_{th} center frequency (frequency domain perspective). Frequency offsets lead to this criterion not being met. This condition can seriously hinder the performance of our OFDM system. Figure 2.2 below shows that when the decision is not taken at the correct center frequency (i.e. peak) of carrier considered, adjacent carriers factor in the decision making, thus reducing the performance of the system.

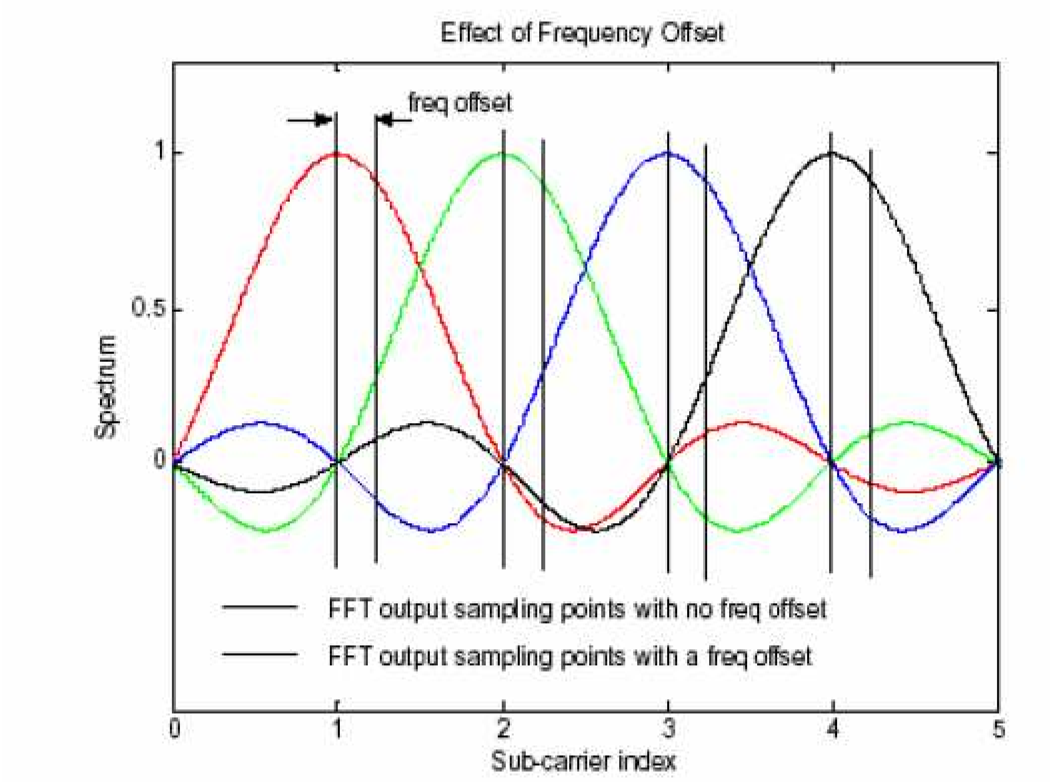

Figure 2.5 Effect of Frequency Offset (maintaining orthogonality)

2.6 The Cyclic Prefix

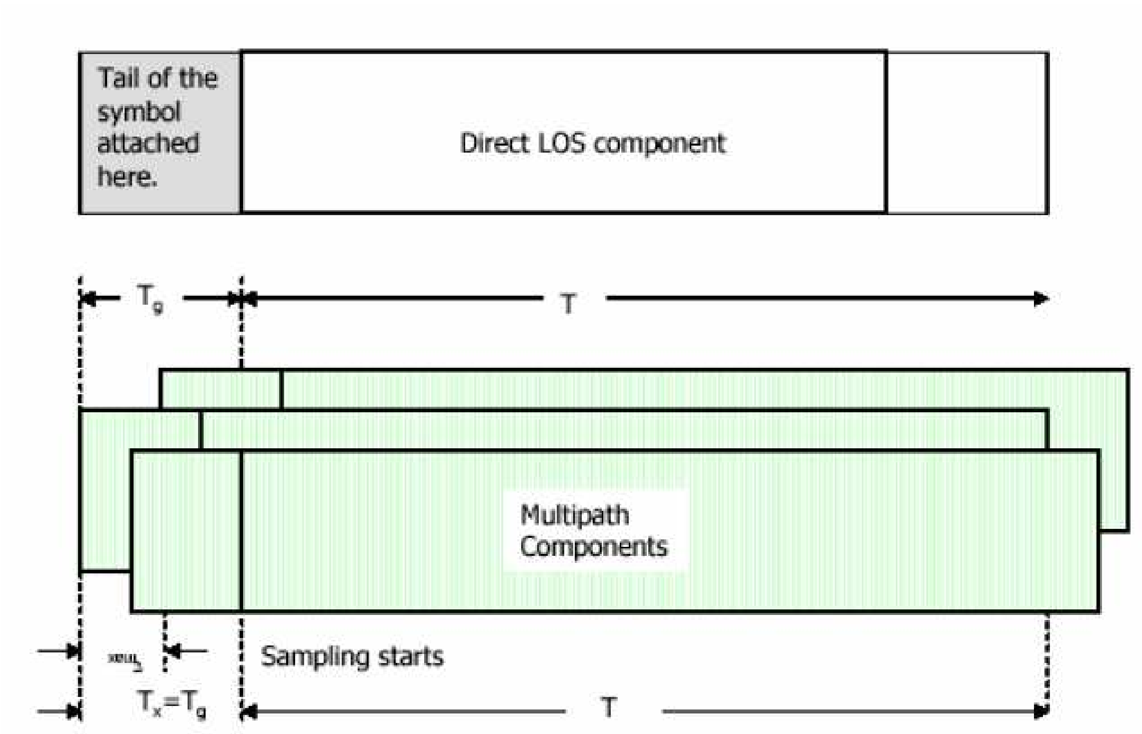

Figure 2.6 Cyclic prefix

The cyclic prefix (CP) is a copy of the last η samples from the IFFT, which are placed at the beginning of the OFDM symbol. There are two reasons to insert a CP:

1. The convolution between the data and the channel impulse response will act like a circular convolution instead of a linear one. Circular convolution makes equalization easier.

2. Interference from the previous symbol will only affect the CP, which is discarded in the receiver.

Both reasons assume that the CP is longer than the channels impulse response. If the CP is shorter than the impulse response, the convolution will not be circular and intersymbol interference will occur. However, if the number of samples in the CP is large, the data transmission rate will decrease significantly, since the CP does not carry any useful data. The data rate will decrease with the factor R as $R = N = (N + \eta)$. Thus, it is important to chose the minimum possible CP to maximize the systems efficiency.

OFDM demodulation must be synchronized both in the time domain as well as in the frequency domain. Engineers have found a way to ensure that goal by adding a guard time in the form of a cyclic prefix (CP) to each OFDM symbol. The CP consists in duplicates of the end samples of the OFDM message relocated at the beginning of the FDM symbol. This increase the length T_{sym} of the transmit message without altering its frequency spectrum.

$$T_{sym} = CP + T_{data} N \tag{2.2}$$

where T_{data} is the duration of one data symbol, and N the number of carriers. The receiver is set to demodulate over a complete OFDM symbol period, which maintains orthogonality. As long as the CP is longer than the channel delay spread, τ_{max}, the system will not suffer from ISI. The CP is to be added after the FFT operation at the transmitter and removed prior to demodulation. The figure below whose the deteriotiation in performance when the CP is closely matched by the delay spread. The signal constellation is less tightly grouped, no doubt a sign of less than accurate decoding.

2.7 Multipath Challenges

In OFDM-based WLAN architecture, as well as many other wireless systems, multipath distortion is a key challenge. This distortion occurs at a receiver when objects in the environment reflect a part of the transmitted signal energy. Figure 2.7 illustrates one such multipath scenario from a WLAN environment.

Figure 2.7 Multipath reflections, such as those shown here, create ISI problems in OFDM receiver designs.

Multipath reflected signals arrive at the receiver with different amplitudes, different phases, and different time delays. Depending on the relative phase change between reflected paths, individual frequency components will add constructively and destructively. Consequently, a filter representing the multipath channel shapes the frequency domain of the received signal. In other words, the receiver may see some frequencies in the transmitted signal that are attenuated and others that have a relative gain. In the time domain, the receiver sees multiple copies of the signal with different time delays. The time difference between two paths often means that different symbols will overlap or smear into each other and create inter-symbol interference (ISI). Thus, designers building WLAN architectures must deal with distortion in the demodulator. Recall that OFDM relies on multiple narrowband subcarriers. In multipath environments, the subcarriers located at frequencies attenuated by multipath will be received with lower signal strength. The lower signal strength leads to an increased error rate for the bits transmitted on these weakened subcarriers. Fortunately for most multipath environments, this only affects a small number of subcarriers and therefore only increases the error rate on a portion of the transmitted data stream. Furthermore, the robustness of OFDM in multipath can be dramatically improved with interleaving and error correction coding. Let's look at error correction and interleaving in more detail.

2.8 Error Correction & Interleaving

Error correcting coding builds redundancy into the transmitted data stream. This redundancy allows bits that are in error or even missing to be corrected. The simplest example would be to simply repeat the information bits. This is known as a repetition code and, while the repetition code is simple in structure, more sophisticated forms of redundancy are typically used since they can achieve a higher level of error correction. For OFDM, error correction coding means that a portion of each information bit is carried on a number of subcarriers; thus, if any of these subcarriers has been weakened, the information bit can still arrive intact.

Interleaving is the other mechanism used in OFDM system to combat the increased error rate on the weakened subcarriers. Interleaving is a deterministic process that changes the order of transmitted bits. For OFDM systems, this means that bits that were adjacent in time are transmitted on subcarriers that are spaced out in frequency. Thus errors generated on weakened subcarriers are spread out in time, i.e. a few long bursts of errors are converted into many short bursts. Error correcting codes then correct the resulting short bursts of errors.

2.9 Handling ISI

The time-domain counter part of the multipath is the ISI or smearing of one symbol into the next. OFDM gracefully handles this type of multipath distortion by adding a "guard interval" to each symbol. This guard interval is typically a cyclic or periodic extension of the basic OFDM symbol. In other words, it looks like the rest of the symbol, but conveys no 'new' information. Since no new information is conveyed, the receiver can ignore the guard interval and still be able to separate and decode the subcarriers. When the guard interval is designed to be longer than any smearing due to the multipath channel, the receiver is able to eliminate ISI distortion by discarding the unneeded guard interval. Hence, ISI is removed with virtually no added receiver complexity.

It is important to note that discarding the guard interval does have an impact on the noise performance since it reduces the amount of energy available at the receiver for channel symbol decoding. In addition, it reduces the data rate since no new information is contained in the added guard interval. Thus a good system design will make the guard interval as short as possible while maintaining sufficient multipath protection. Why don't single carrier systems also use a guard interval? Single carrier systems could remove ISI by adding a guard interval between each symbol. However, this has a much more severe impact on the data rate for single carrier systems than it does for OFDM. Since OFDM uses a bundle of narrowband subcarriers, it obtains high data rates with a relatively long symbol period because the frequency width of the subcarrier is inversely proportional to the symbol duration. Consequently, adding a short guard interval has little impact on the data rate. Single carrier systems with bandwidths equivalent to OFDM must use much shorter duration symbols. Hence adding a guard interval equal to the channel smearing has a much greater impact on data rate.

2.10 Frequency Interleaving

DAB also uses frequency interleaving, a similar technique to time interleaving but applied to the sub-carriers centre frequencies in the RF spectrum instead. The data stream from the studio is deliberately not modulated serially onto sub-carriers across the frequency range, but instead in a more random way. Multipath and other forms of selective fading generally affect a relatively narrow part of the RF multiplex bandwidth at any one time so frequency interleaving would tend to average out 'bursts' of errors resulting from these.

2.11 Single Frequency Networks

A major advantage of DAB over FM is the provision of single frequency networks (SFNs). Provided the transmitters are synchronized, the multiplex licence holder may operate several in a relatively small geographic area at the same multiplex frequency without any destructive interference occurring at the receiver. SFNs allow substantial service areas to be built up steadily and efficiently as the network develops, funding allows and frequency spectra become available. Compared to FM where service areas operating at the same carrier frequency cannot overlap, a typical DAB network will comprise several relatively low powered closely spaced transmitters operating at the same multiplex frequency. This saves frequency spectrum, reduces the complexity and cost of the transmitter hardware and avoids the need for frequent re-tuning of mobile receivers as they move about within the network. It also means that each transmitter has a smaller audience, thus mitigating the service loss should a transmitter fail. Because of this synchronization, receivers which are located in places where the service areas of two or more transmitters overlap will interpret one of the signals as a slightly delayed version of the other, effectively an apparent deliberate multipath interference. The actual delays will depend on the radio path geometry and any extra delays that may be added artificially when the network is commissioned. Within the receiver then a relatively simple form of delay filtering may be applied to extract the desired data.

2.12 Coding

Coding refers to convolutional coding and means that the original data carried over the multiplex is deliberately manipulated by splitting it into small blocks and adding some intelligently designed redundant information to each, thus generating a data 'overhead'. The overhead bits added to each block are determined according to rules applied to the true data content of the block. After demodulation at the receiver the digital signal processor examines both the actually received data and overhead bits and regenerates what it believes to be the original data based on a set of statistical rules known as an algorithm. The regenerated data may include a number of data bit corrections. The algorithm used in DAB is known as a Viterbi algorithm, and is an example of a maximum likelihood algorithm. This works by maintaining a history of demodulated bit sequences, building up a view of their probabilities and then using these to finally select either a 0 or 1 for the bit under consideration. This type of coding is also known as an example of forward error correction (FEC).

2.13 The importance of coding

The distribution of the data over many carriers means that selective fading will cause some bits to be received in error while others are received correctly. By using an error-correcting code, which adds extra bits at the transmitter, it is possible to correct many or all of the bits that were incorrectly received. The information carried by one of the degraded carriers is corrected, because other information, which is related to it by the error-correcting code, is transmitted in a different part of the multiplex (and, it is
hoped, will not suffer from the same deep fade). This accounts for the “coded” part of the name COFDM.

2.14 Channel encoder

The incoming data are encoded to reduce the bit error rate (BER). The idea is to insert controlled redundancy in order to correct errors that are introduced by the channel.

2.15 Mapper

The mapper converts input data into complexed valued constellation points, according to a given constellation. Typical constellations for wireless applications are, BPSK, QAM, and 16 QAM, see Figure 3. In Figure 3, I is the in-phase component and Q is the quadrature component. The amount of data transmitted on each subcarrier depends on the constellation, e.g. BPSK and 16QAM

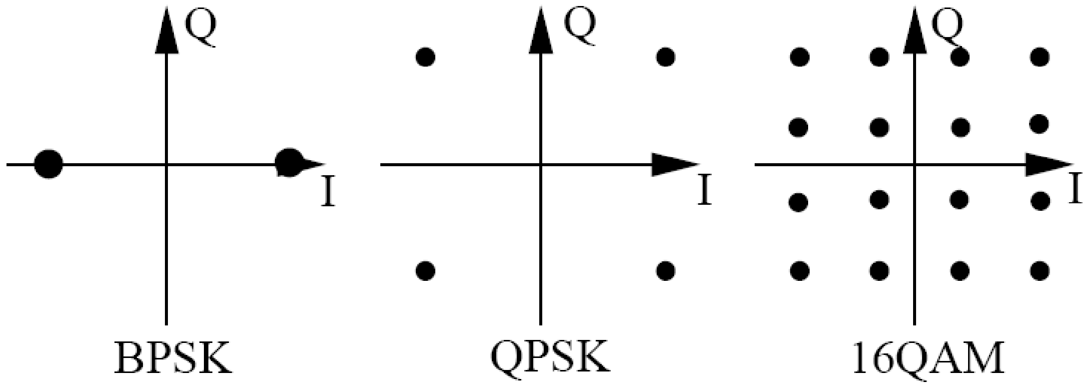

Figure 2.8 Typical constellations for wireless applications

Transmit one and four data bits per subcarrier, respectively. Which constellation to chose depends on the channel quality. In a high interference channel a small constellation like BPSK is favourable, since the required signal to noise ratio (SNR) in the receiver is low, whereas in a low interference channel a larger constellation is more beneficial due to the higher bit rate. Three examples of how the constellations can be chosen are;

1. Only one constellation is included, which is often the case in low-end transmitters. How to choose the included constellation is a design decision, depending on the delay and multipath propagation situation.

2. More than one constellation is included, but only one constellation is used per OFDM frame, which is the case in the Hiperlan/2 and IEEE 802.11a standards. The choice of constellation can be based on measurements of the BER.

3. More than one constellation is included, where each subcarrier can use a different constellation. This is called bit loading. Bit-loading algorithms base the choice of constellation on the frequency response in each subcarrier. A subcarrier with high SNR will get a larger constellation and vice versa [3]. Thus a flexible transmitter must provide the user with the possibility to use one of several constellations for each subcarrier.

The mapper is designed to be used with a bit-loading algorithm. The included constellations are no modulation (ZERO), BPSK, QPSK, 8PSK, 16QAM, and 64QAM. The ZERO constellations do not contain any data, but is included for unused subcarriers. That can be subcarriers with very low SNR and subcarriers at the fringes of the spectrum, where a spectrum- shaping filter ruins them. The DC subcarrier is sometimes also unused, because all offset errors in the IFFT will end up in this component. Constellations larger than 64QAM are not likely to be used in a wireless system, due to the high SNR required at the receiver side.

2.16 The use of the FFT in OFDM

The main reason that the OFDM technique has taken a long time to become a prominence has been practical. It has been difficult to generate such a signal, and even harder to receive and demodulate the signal. The hardware solution, which makes use of multiple modulators and demodulators, was
somewhat impractical for use in the civil systems. The ability to define the signal in the frequency domain, in software on VLSI processors, and to generate the signal using the inverse Fourier transform is the key to its current popularity. The use of the reverse process in the receiver is essential if cheap and reliable receivers are to be readily available. Although the original proposals were made a long time ago [5], it has taken some time for technology to catch up. At the transmitter, the signal is defined in the frequency domain. It is a sampled digital signal, and it is defined such that the discrete Fourier spectrum exists only at discrete frequencies. Each
OFDM carrier corresponds to one element of this discrete Fourier spectrum. The amplitudes and phases of the carriers depend on the data to be transmitted. The data transitions are synchronized at the carriers, and can be processed together, symbol by symbol.

2.17 IFFT

The Inverse Fast Fourier Transform (IFFT) transforms the signals from the frequency domain to the time domain. In 1973 it was discovered that the FFT could be used in multicarrier systems like OFDM [4]. However, it was not until 1989 with the introduction of the CP that OFDM was established.

The number of subcarriers, N, determines how many sub-bands the available spectrum is split into. The more subcarriers used the less overhead is introduced by the CP, see section 2.4. Contrary to this the sub-band must be much wider than the Doppler frequency to remain orthogonal [6].

In other words the faster the terminal moves, the fewer subcarriers can be used and the more overhead is introduced. The crest factor, the ratio between the peak and the average amplitude of the OFDM symbol, will also limit the maximum number of sub carriers that can be used. A high N will give a high crest factor, which will cause linearity problems in the power amplifier [7]. Another drawback with using a large number of subcarriers is that more hardware will be required to perform the IFFT and the latency through the

hardware will increase. The latency can be critical if the transmitter is used in a real-time application. Thus, for the system to be efficient, the number of subcarriers has to be adjusted over time.

2.18 OFDM APPLICATION

1. DAB - OFDM forms the basis for the Digital Audio Broadcasting (DAB) standard in the European market.
2. ADSL - OFDM forms the basis for the global ADSL (asymmetric digital subscriber line) standard.
3. Wireless Local Area Networks - development is ongoing for wireless point-to-point and point-to-multipoint configurations using OFDM technology.

4. In a supplement to the IEEE 802.11 standard, the IEEE 802.11 working group published IEEE 802.11a, which outlines the use of OFDM in the 5.8-GHz band.

2.19 MATHEMATICAL ANALYSIS

With an overview of the OFDM system, it is valuable to discuss the mathematical definition of the modulation system. It is important to understand that the carriers generated by the IFFT chip are mutually orthogonal. This is true from the very basic definition of an IFFT signal, as we will derive now. This will allow us to understand how the signal is generated and how receiver must operate. Mathematically, each carrier can be described as a complex wave:

$$s_c(t) = A_c(t)e^{j\left[\omega_c t+\phi_c(t)\right]} \tag{2.3}$$

The real signal is the real part of sc (t). $A_c(t)$ and $\varphi_c(t)$, the amplitude and phase of the carrier, can vary on a symbol-by-symbol basis. The values of the parameters are constant over the symbol duration period *t*. OFDM consists of many carriers. Thus the complex signals *s (t)* is represented by:

$$s_s(t) = \frac{1}{N}\sum_{n=0}^{N-1} A_N(t)e^{j\left[\omega_n t+\phi_n(t)\right]} \tag{2.4}$$

Where,

$$\omega_n = \omega_0 + n\Delta\omega$$

This is of course a continuous signal. If we consider the waveforms of each component of the signal over one symbol period, then the variables $A_c(t)$ and $\varphi_c(t)$ take on fixed values, which depend on the frequency of that particular carrier, and so can be rewritten:

$$\phi_n(t) \Rightarrow \phi_n$$
$$A_n(t) \Rightarrow A_n$$

If the signal is sampled using a sampling frequency of 1/T, then the resulting signal is represented by:

$$s_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n e^{j[(\omega_0 + n\Delta\omega)kT + \phi_n]} \tag{2.5}$$

At this point, we have restricted the time over which we analyze the signal to N samples. It is convenient to sample over the period of one data symbol. Thus we have a relationship: t=NT If we now simplify 3, without a loss of generality by letting ω0=0, then the signal becomes:

$$s_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n e^{j\phi_n} e^{j(n\Delta\omega)kT} \tag{2.6}$$

Now Eq. (2.6) can be compared with the general form of the inverse Fourier transform:

$$g(kT) = \frac{1}{N}\sum_{n=0}^{N-1} G\left(\frac{n}{NT}\right) e^{j2\pi nk/N} \tag{2.7}$$

In Eq. (2.6), the function $A_n e^{j\phi_n}$ is no more than a definition of the signal in the sampled frequency domain, and s (kT) is the time domain representation. Eq. (2.6) and (2.7) are equivalent if:

$$\Delta f = \frac{\Delta\omega}{2\pi} = \frac{1}{NT} = \frac{1}{\tau}$$

This is the same condition that was required for orthogonality Thus, one consequence of maintaining orthogonality is that the OFDM signal can be defined by using Fourier transform procedures.

CHAPTER 3
OFDM TRANSMISSION

A block diagram of the European DVB-T standard is shown in Figure 3.1. Most of the processes described in this diagram are performed within a digital signal processor (DSP), but the aforementioned drawbacks occur in the physical channel; i.e., the output signals of this system. Therefore, it is the purpose of this project to provide a description of each of the steps involved in the generation of this signal and the Matlab code for their simulation. In other words, this thesis will concentrate only in the blocks labeled OFDM, D/A, and Front End of Figure 3.1. We only have transmission regulations in the DVB-T standard since the reception system should be open to promote competition among receivers' manufacturers. We shall try to portray a general receiver system to have a complete system description.

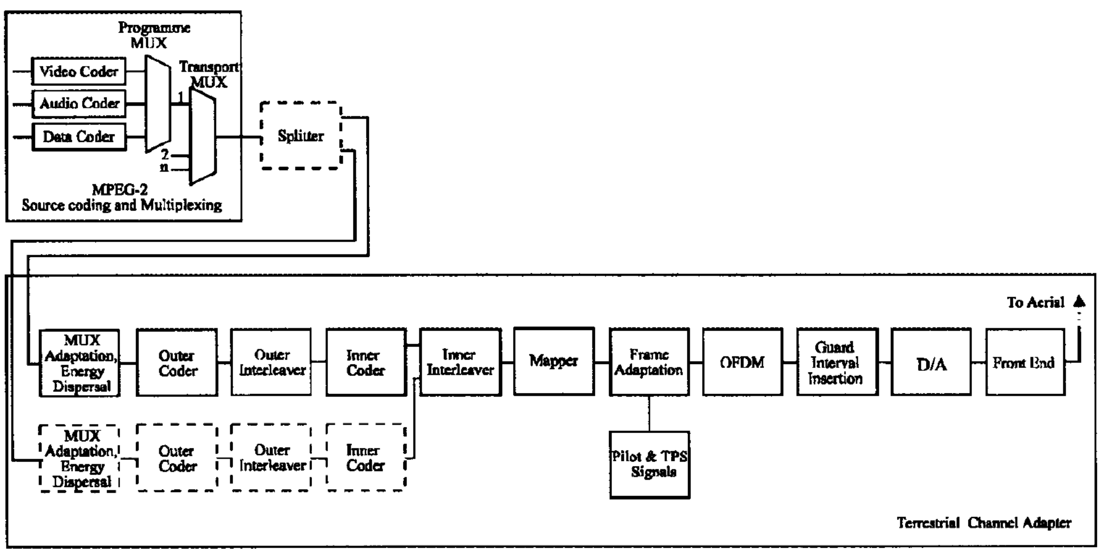

Figure 3.1: DVB-T transmitter

3.1 DVB-T Example

A detailed description of OFDM can be found in [2] where we can find the expression for one OFDM symbol starting at $t=t_s$ as follows:

$$s(t)=\mathrm{Re}\left\{\sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2}\exp\left(j2\pi\left(f_c-\frac{i+0.5}{T}\right)(t-t_s)\right)\right\},\ t_s\le t\le t_s+T$$
$$s(t)=0,\ t<t_s\ \wedge\ t>t_s+T \tag{3.1}$$

where d_i are complex modulation symbols, N_s is the number of subcarriers, T the symbol duration, and f_c the carrier frequency. A particular version of (3.1) is given in the DVB-T standard as the emitted signal. The expression is

$$s(t)=\mathrm{Re}\left\{e^{j2\pi f_c t}\sum_{m=0}^{\infty}\sum_{l=0}^{67}\sum_{k=K_{min}}^{K_{max}} c_{m,l,k}\cdot\Psi_{m,l,k}(t)\right\} \tag{3.2}$$

Where

$$\Psi_{m,l,k}(t)=\begin{cases} e^{j2\pi\frac{k'}{T_U}(t-\Delta-l\cdot T_S-68\cdot m\cdot T_S)} & (l+68\cdot m)\cdot T_S\le t\le(l+68\cdot m+1)\cdot T_S \\ 0 & \text{else}\end{cases} \tag{3.3}$$

Where:

K denotes the carrier number;

l denotes the OFDM symbol number;

m denotes the transmission frame number;

K is the number of transmitted carriers;

T_S is the symbol duration;

T_U is the inverse of the carrier spacing;

Δ is the duration of the guard interval;

fc is the central frequency of the radio frequency (RF) signal;

k' is the carrier index relative to the center frequency, $K' = K - (K_{max} + K_{min})/2$;

$C_{m,0,k}$ complex symbol for carrier k of the Data symbol no.1 in frame number m;

$C_{m,1,k}$ complex symbol for carrier k of the Data symbol no.2 in frame number m;

……

$C_{m,67,k}$ complex symbol for carrier k of the Data symbol no.68 in frame number m;

It is important to realize that (3.2) describes a working system, i.e., a system that has been used and tested since March 1997. Our simulations will focus in the 2k mode of the DVB-T standard. This particular mode is intended for mobile reception of standard definition DTV. The transmitted OFDM signal is organized in frames. Each frame has duration of T_F, and consists of 68 OFDM symbols. Four frames constitute one super-frame. Each symbol is constituted by a set of K=1,705 carriers in the 2k mode and transmitted with a duration T_S. A useful part with duration T_U and a guard interval with a duration Δ compose T_S. The specific numerical values for the OFDM parameters for the 2k mode are given in Table 1.

The next issue at hand is the practical implementation of (3.2). OFDM practical implementation became a reality in the 1990's due to the availability of DSP's that made the Fast Fourier Transform (FFT) affordable [3]. Therefore, we shall focus the rest of the report to this implementation using the values and references of the DVB-T example. If we consider (3.2) for the period from t = 0 to t = T_S we obtain:

Table 1: Numerical values for the OFDM parameters for the 2k mode

Parameter	**2k mode**
Elementary period T	7/64µs
Number of carriers K	1,705
Value of carrier number K_{min}	0
Value of carrier number K_{max}	1,704
Duration T_U	224 µs
Spacing between carriers K_{min} and K_{max}(K-1)/T_U	7.61 MHz
Carrier spacing 1/T_U	4,464 Hz
Allowed guard interval Δ /T_U	1/4 1/8 1/16 1/32
Duration of symbol part T_U	2,048xT 224 µs
Duration of guard interval Δ	512xT 256xT 128xT 64xT 56 µs 28 µs 14µs 7µs
Symbol duration T_S= Δ +T_U	2,560xT 2,304xT 2,176xT 2,112xT 280 µs 252µs 238µs 231µs

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{k=K_{min}}^{K_{max}} c_{0,0,k} e^{j2\pi k'(t-\Delta)/T_U} \right\} \qquad (3.4)$$

with $k' = k - (K_{max} + K_{min})/2.$

There is a clear resemblance between (3.4) and the Inverse Discrete Fourier Transform (IDFT):

$$x_n = \frac{1}{N}\sum_{q=0}^{N-1} X_q e^{j2\pi\frac{nq}{N}} \tag{3.5}$$

Since various efficient FFT algorithms exist to perform the DFT and its inverse, it is a convenient form of implementation to generate N samples x_n corresponding to the useful part, T_U long, of each symbol. The guard interval is added by taking copies of the last $N\Delta/T_U$ of these samples and appending them in front. A subsequent up-conversion then gives the real signal s(t) centered on the frequency f_c .

3.2 FFT Implementation

The first task to consider is that the OFDM spectrum is centered on f_c ; i.e., subcarrier 1 is7.61/2 MHz to the left of the carrier and subcarrier 1,705 is7.61/2 MHz to the right. One simple way to achieve the centering is to use a 2N-IFFT [2] and T/2 as the elementary period. As we can see in Table **1**, the OFDM symbol duration, TU, is specified considering a 2,048-IFFT (N=2,048); therefore, we shall use a 4,096-IFFT. A block diagram of the generation of one OFDM symbol is shown in Figure 3.1 where we have indicated the variables used in the MatLab code. The next task to consider is the appropriate simulation period. T is defined as the elementary period for a base band signal, but since we are simulating a pass band signal, we have to relate it to a time-period, 1/Rs, that consider at least twice the carrier frequency. For simplicity, we use an integer relation, R_s=40/T. This relation gives a carrier frequency close to 90 MHz, which is in the range of a VHF channel five, a common TV channel in any city. We can now proceed to describe each of the steps specified by the encircled letters in Figure 3.1.

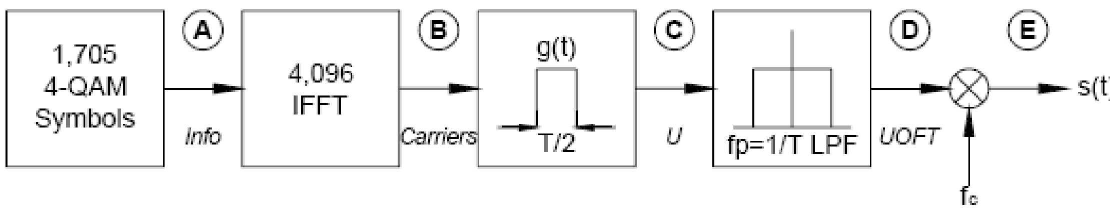

Figure 3.2 OFDM symbol generation simulations.

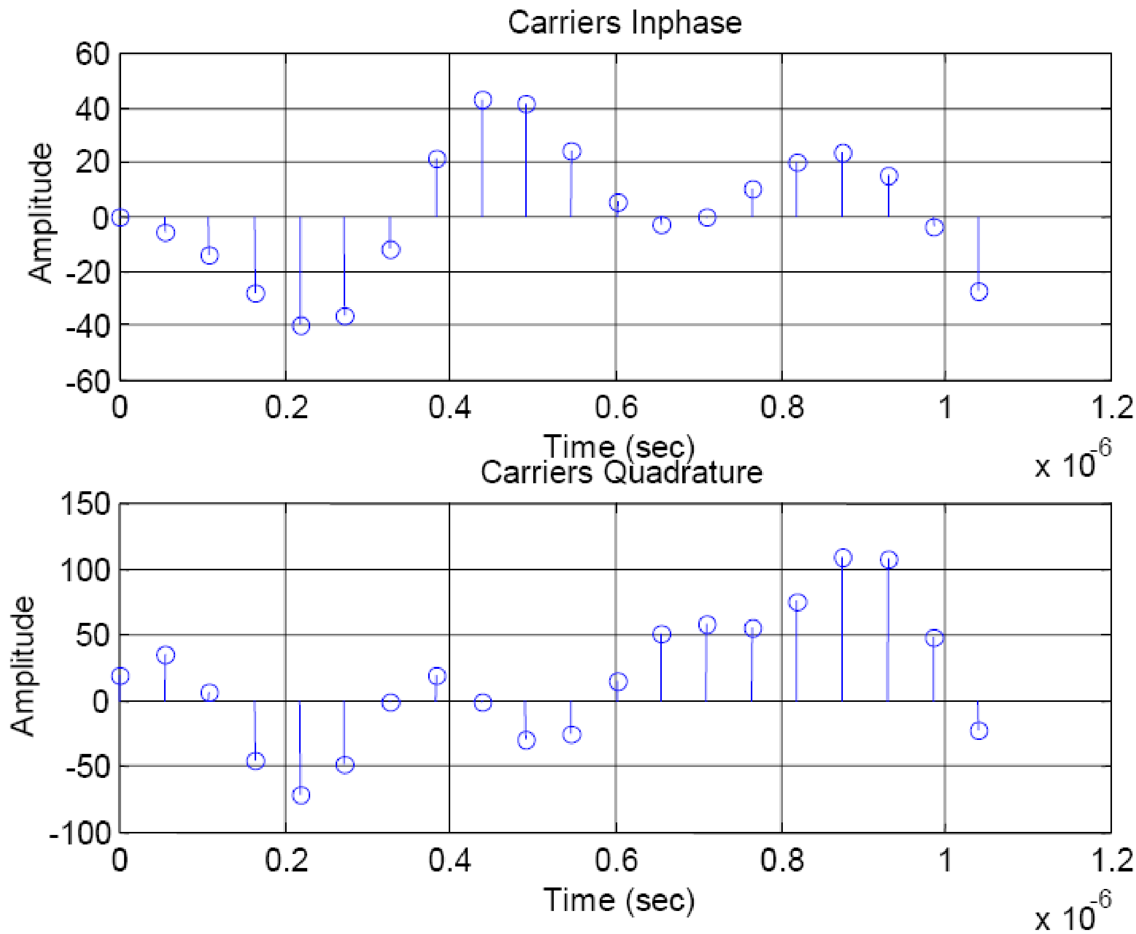

Figure 3.3 Time response of signal carriers at (B)

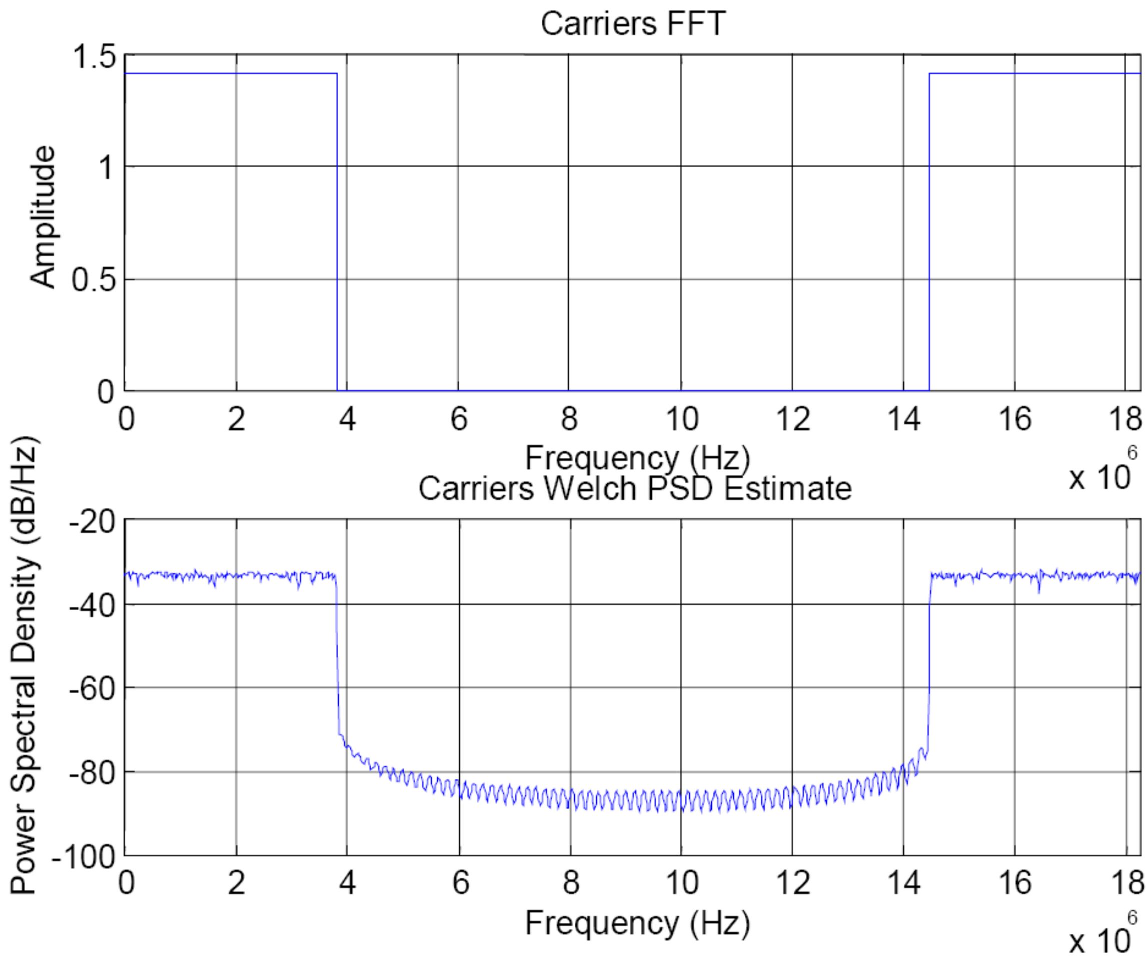

Figure 3.4 Frequency responses of signal carriers at (B)

As suggested in [2], we add 4,096-1,705=2,391 zeros to the signal *info* at (A) to achieve over-sampling, 2X, and to center the spectrum. In Figure 3.2 and Figure 3.3, we can observe the result of this operation and that the signal carriers uses T/2 as its time period. We can also notice that carriers are the discrete time baseband signal. We could use this signal in baseband discrete-time domain simulations, but we must recall that the main OFDM drawbacks occur in the continuous time domain; therefore, we must provide a simulation tool for the latter. The first step to produce a continuous-time signal is to apply a transmit filter, g(t), to the complex signal carriers. The impulse response, or pulse shape, of g (t) is shown in Figure 3.4.

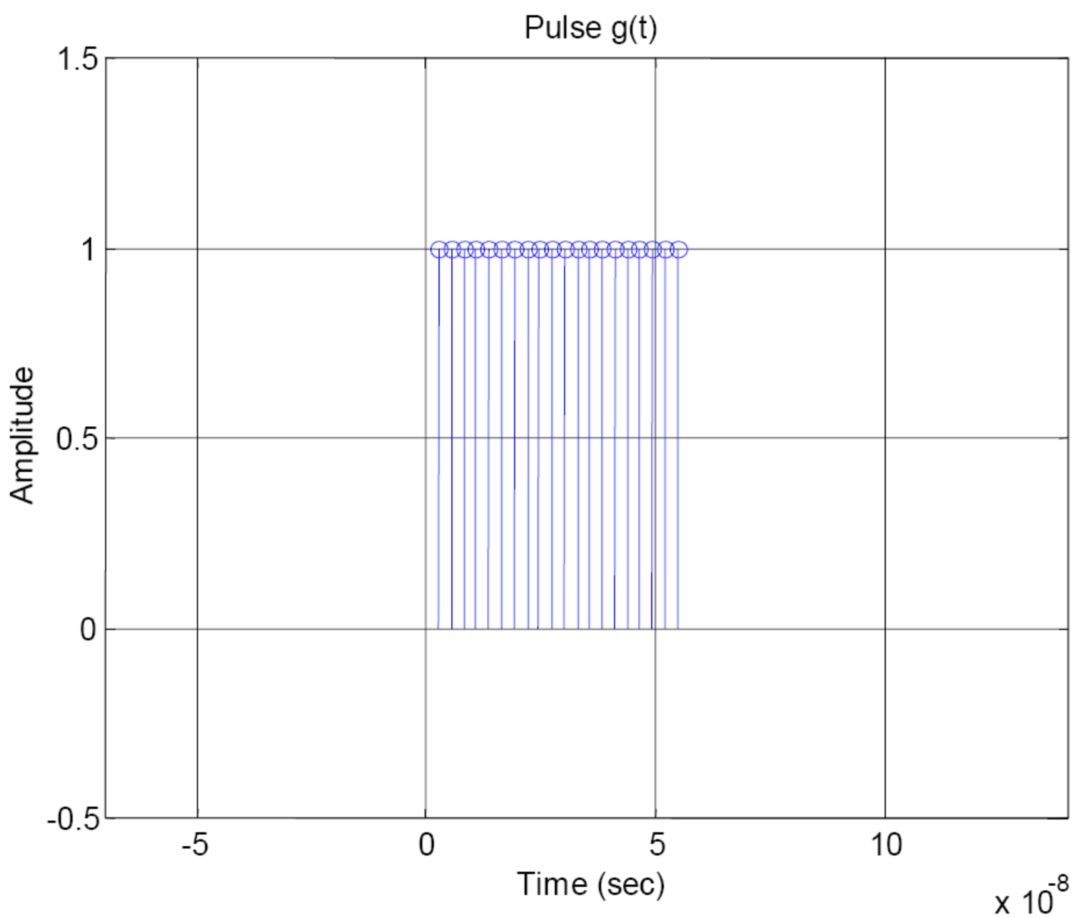

Figure 3.5 Pulse shape g(t)

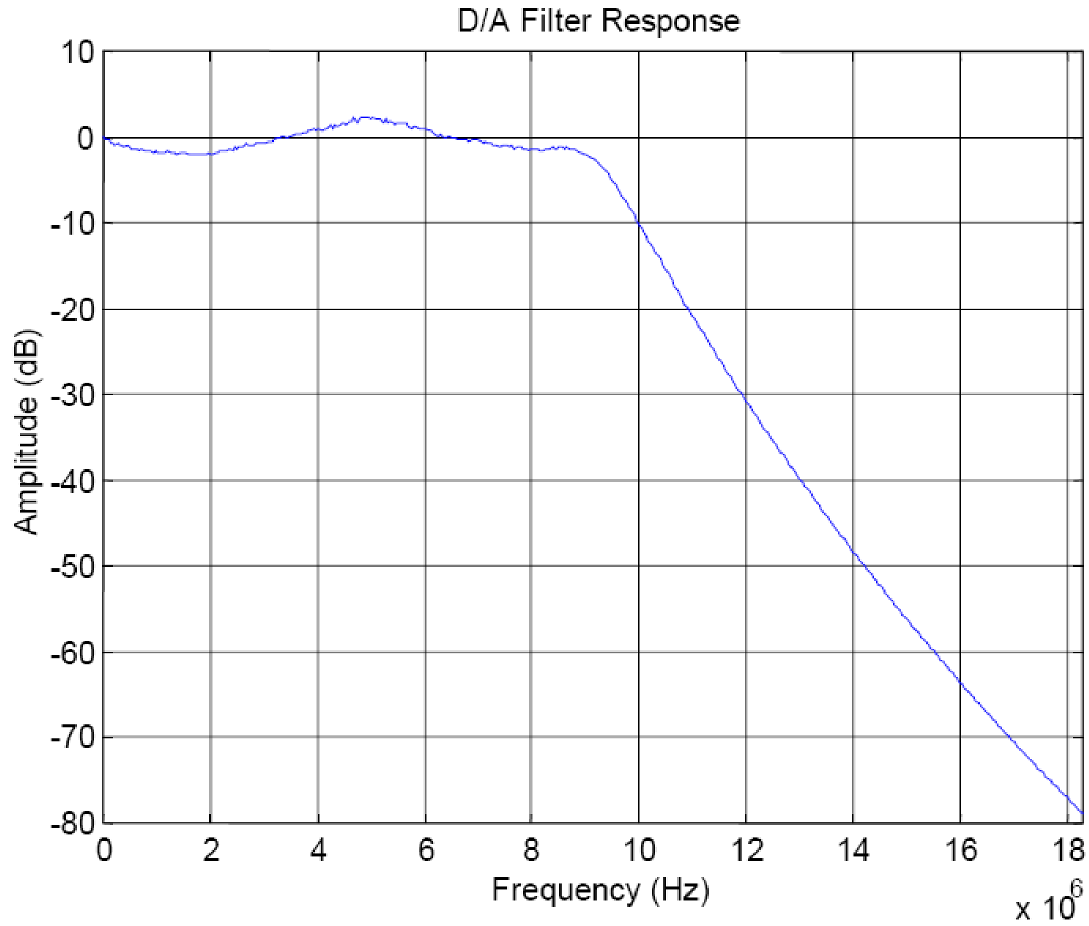

Figure 3.6 D/A filter response

The output of this transmit filter is shown in Figure 3.6 in the time-domain and in Figure 3.7 in the frequency-domain. The frequency response of Figure 3.7 is periodic as required of the frequency response of a discrete-time system [4], and the bandwidth of the spectrum shown in this figure is given by Rs. U(t).s period is 2/T, and we have (2/T=18.286)-7.61=10.675 MHz of transition bandwidth for the reconstruction filter. If we were to use an N-IFFT, we would only have (1/T=9.143)- 7.61=1.533 MHz of transition bandwidth; therefore, we would require a very sharp roll-off, hence high complexity, in the reconstruction filter to avoid aliasing.

The proposed reconstruction or D/A filter response are shown in Figure 3.5. It is a Butterworth filter of order 13 and cut-off frequency of approximately 1/T. The filter's output is shown in Figure 3.8 and Figure 3.9. The first thing to notice is the delay of approximately $2x10^{-7}$produced by the filtering process. Aside of this delay, the filtering performs as expected since we are left with only the baseband spectrum. We must recall that subcarriers 853 to 1,705 are located at the right of 0 Hz, and subcarriers 1 to 852 are to the left of 4 fc Hz.

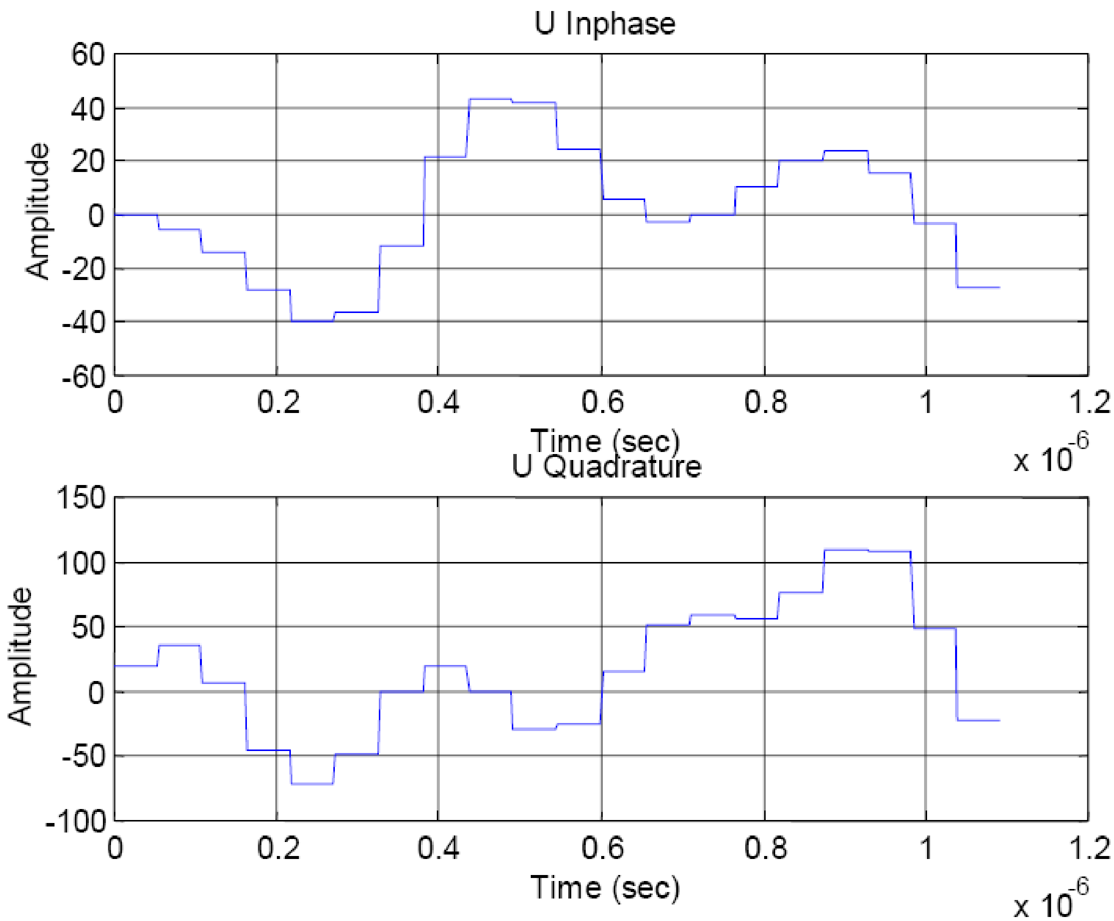

Figure 3.7: Time response of signal *U* at (C)

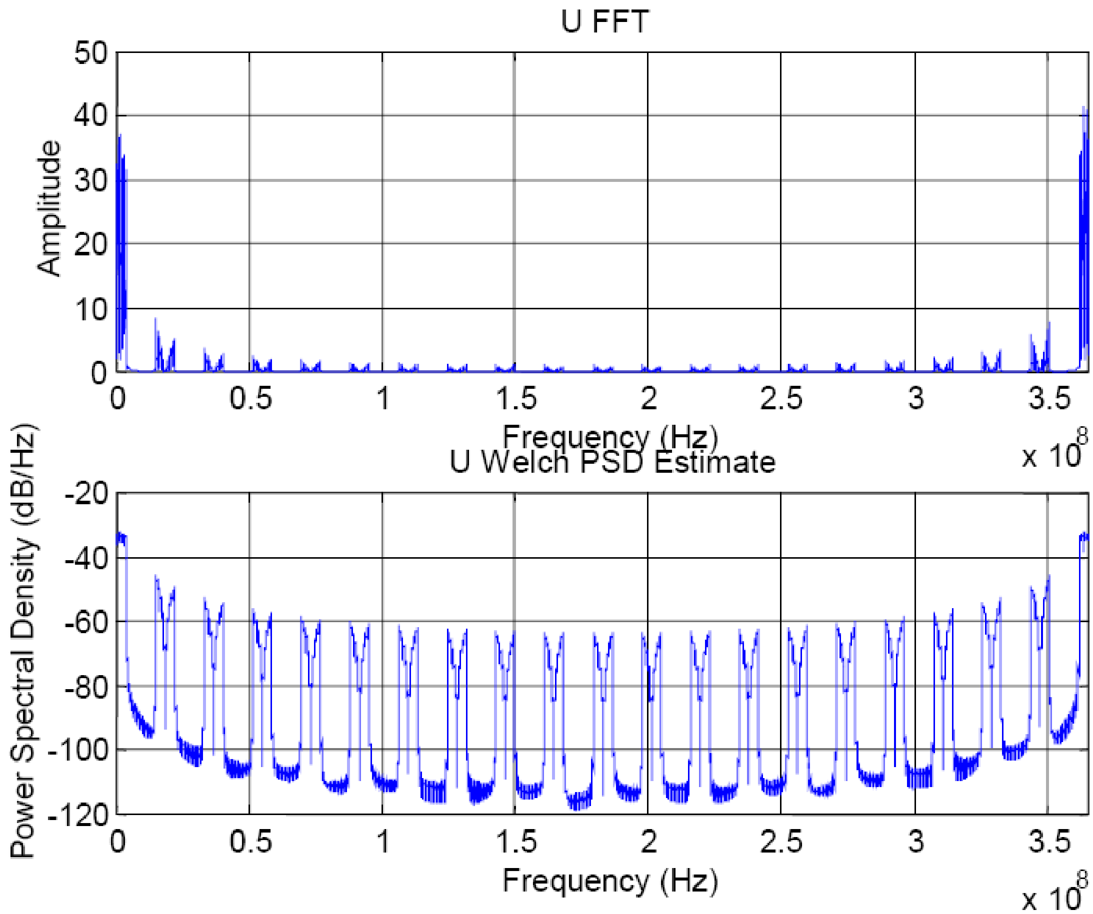

Figure 3.8 Frequency response of signal *U* at (C)

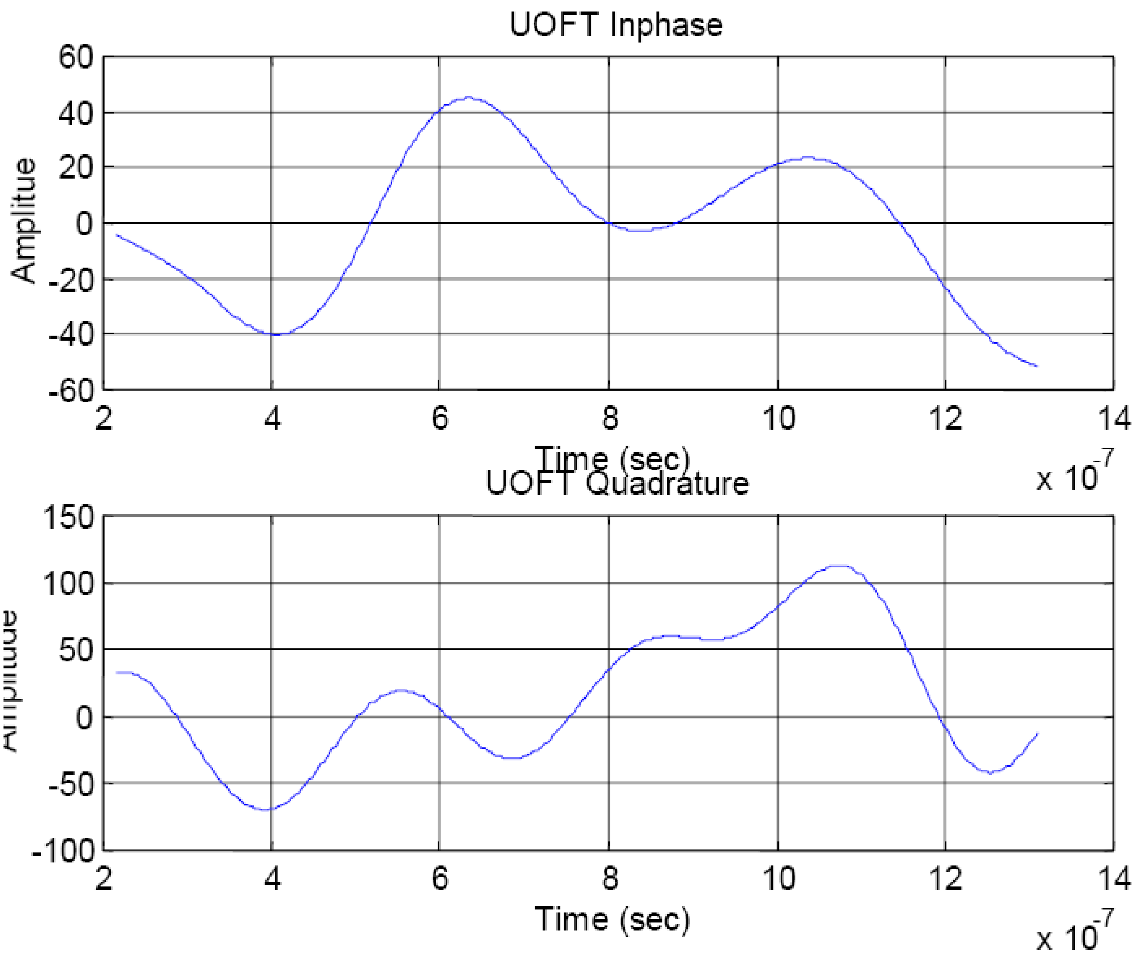

Figure 3.9 Time response of signal *UOFT* at (D)

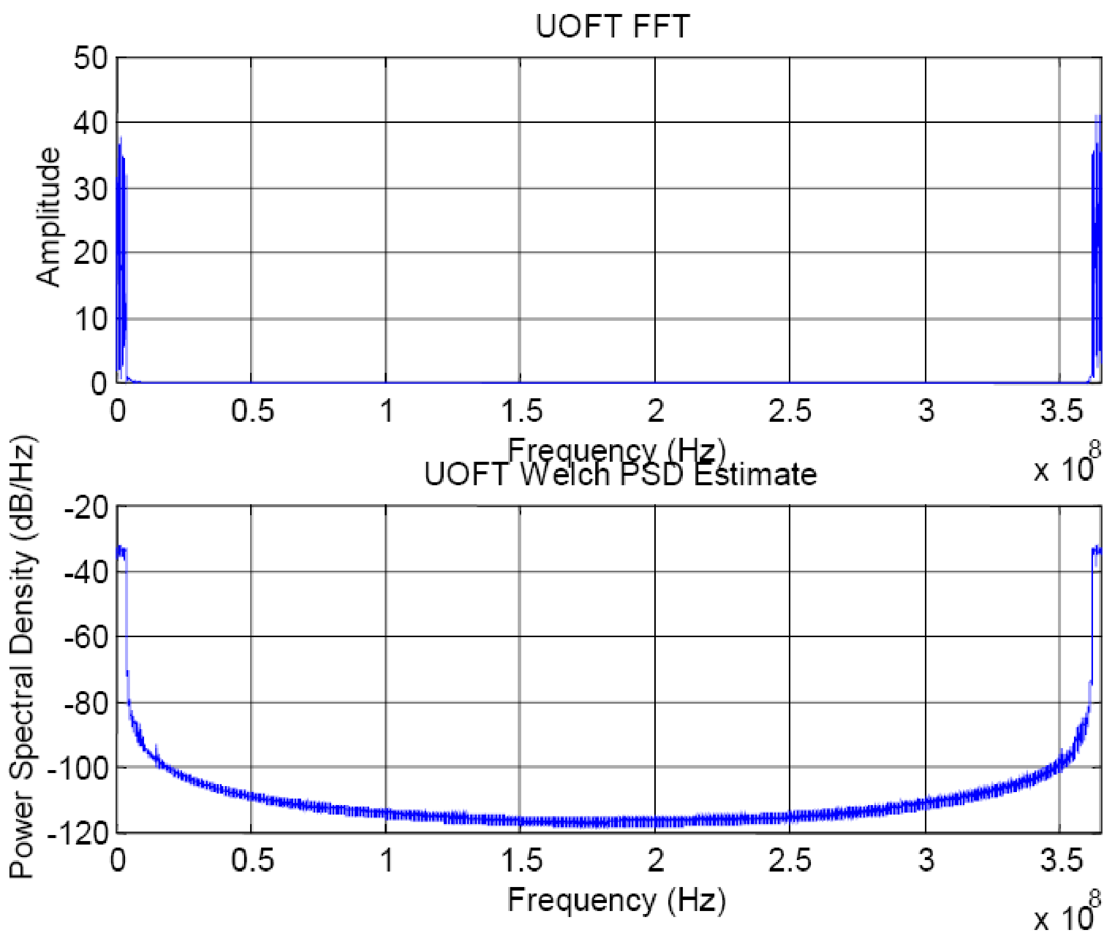

Figure 3.10 Frequency response of signal UOFT at (D)

The next step is to perform the quadrature multiplex double-sideband amplitude modulation of uoft (t). In this modulation, an in-phase signal $m_I(t)$ and a quadrature signal $m_g(t)$ are modulated using the formula.

$$s(t) = m_I(t)\cos(2\pi f_c t) + m_Q(t)\sin(2\pi f_c t) \tag{3.6}$$

Equation (3.4) can be expanded as follows:

$$\begin{aligned} s(t) = &\sum_{k=K_{min}}^{K_{max}} \mathrm{Re}\left(c_{0,0,k}\right)\cos\left[2\pi\left(\left(\frac{\left(k-\frac{K_{max}+K_{min}}{2}\right)}{T_U}+f_c\right)t-\frac{\Delta}{T_U}\right)\right] \\ &-\sum_{k=K_{min}}^{K_{max}} \mathrm{Im}\left(c_{0,0,k}\right)\sin\left[2\pi\left(\left(\frac{\left(k-\frac{K_{max}+K_{min}}{2}\right)}{T_U}+f_c\right)t-\frac{\Delta}{T_U}\right)\right] \end{aligned} \tag{3.7}$$

where we can define the in-phase and quadrature signals as the real and imaginary parts of $C_{m,l,k}$ the 4-QAM symbols, respectively.

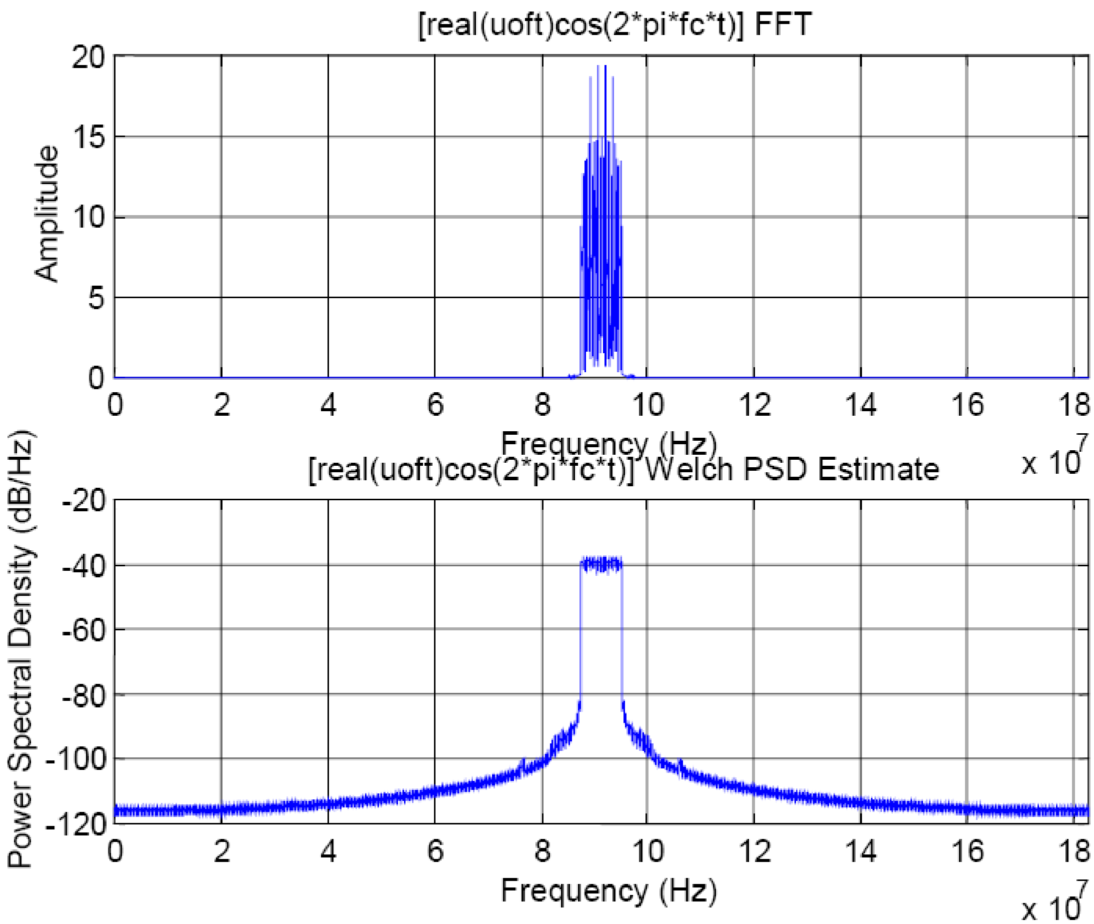

Figure 3.11 $uoft_I(t)\cos(2\pi f_c t)$ frequency response

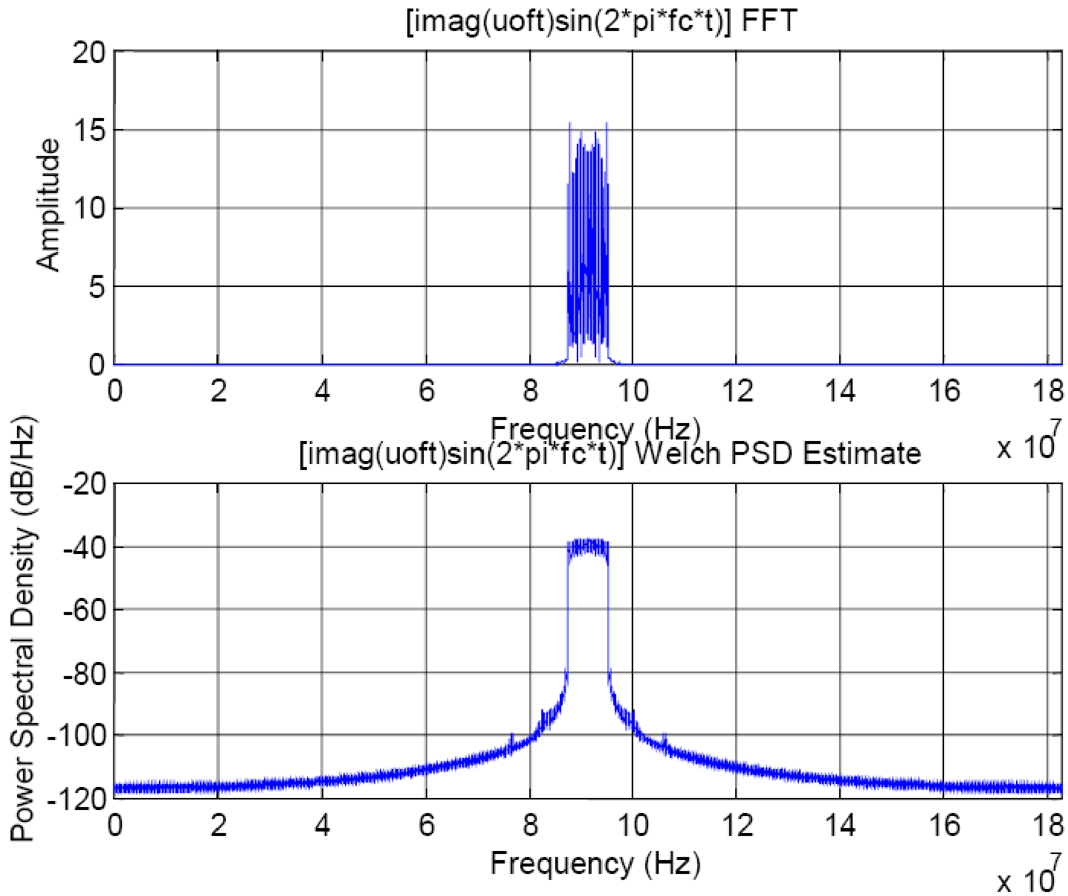

Figure 3.12 uoft$_Q$ (t) sin (2π f$_c$ t) frequency response

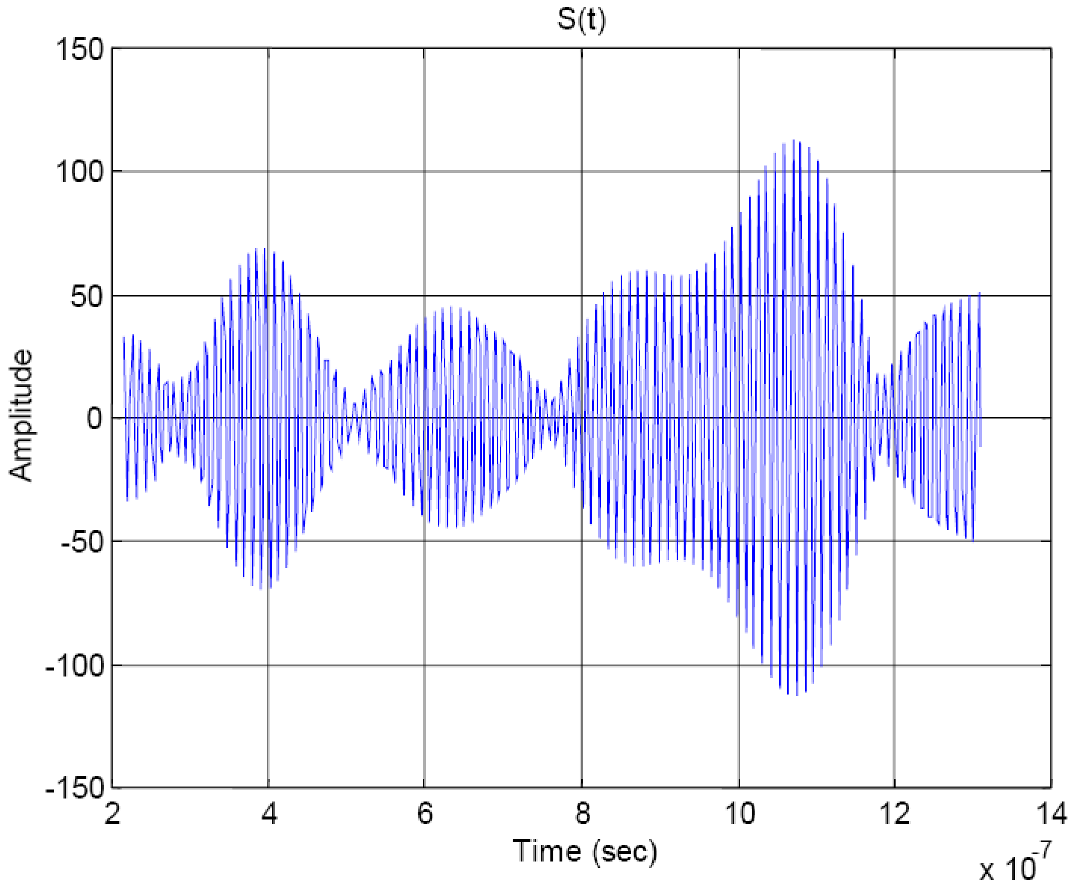

Figure 3.13 Time response of signal s(*t)* at (E)

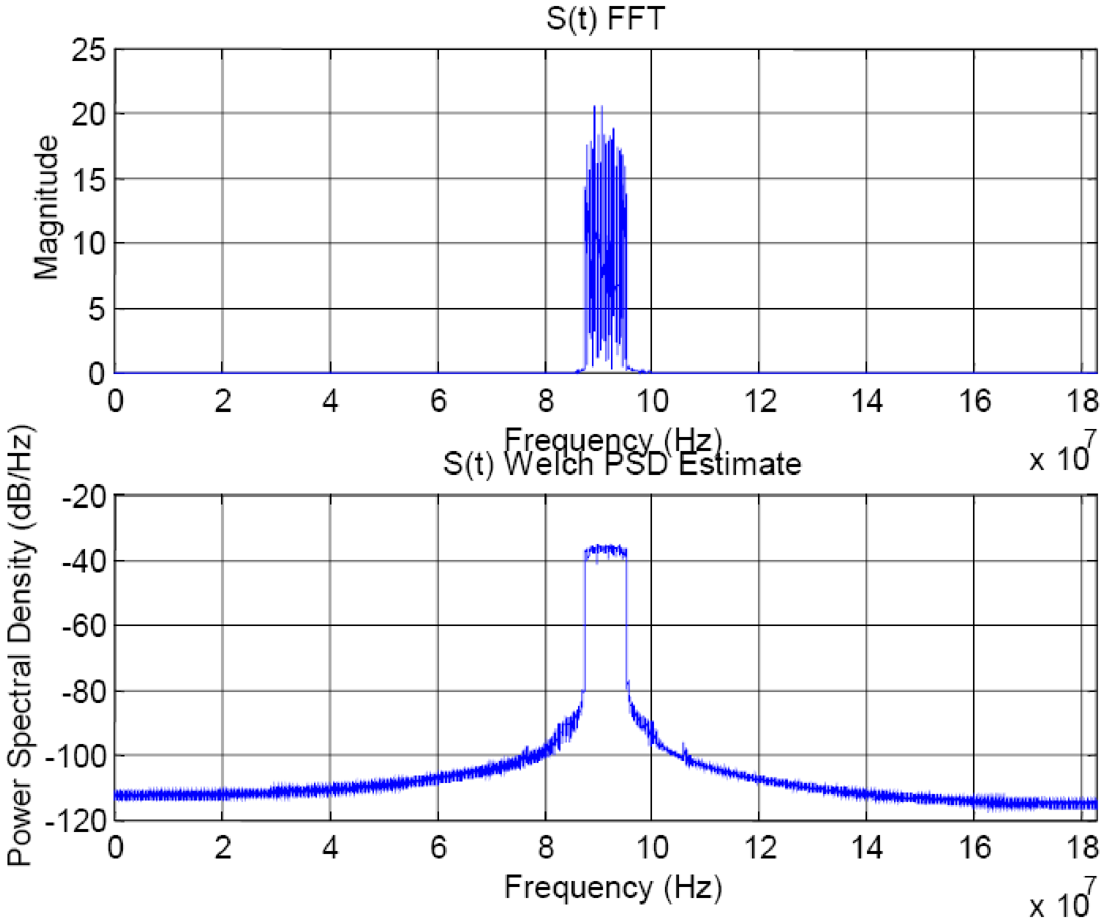

Figure 3.14 Frequency response of signal s(t) at (E)

The corresponding operation for the IFFT process is

$$s(t) = uoft_I(t)\cos(2\pi f_c t) - uoft_Q(t)\sin(2\pi f_c t). \tag{3.8}$$

The frequency responses of each part of (3.8) are shown in Figure 3.10 and Figure 3.11 respectively. The time and frequency responses for the complete signal, s(t), are shown in Figure 3.12 and in Figure 3.13. We can observe the large value of the aforementioned PAR in the time response of Figure 3.12.

Finally, the time response using a direct simulation of (3.4) is shown in Figure 3.14, and the frequency responses of the direct simulation and 2N-IFFT implementation are shown in Figure 3.15. The direct simulation requires a considerable time (about 10 minutes in a Sun Ultra 5,333 MHz); therefore, a practical application must use the IFFT/FFT approach. A direct comparison of Figure 3.12 and Figure 3.14 shows differences in time alignment and amplitude, and a study of the frequency responses shown in Figure 3.15 reveals amplitude variations but closely related spectra. We could not expect an identical signal since we obtain different results from a 1,705-IFFT vs. a 4,096-IFFT using the same input data.

s(t) (eq.3.4) Amplitude

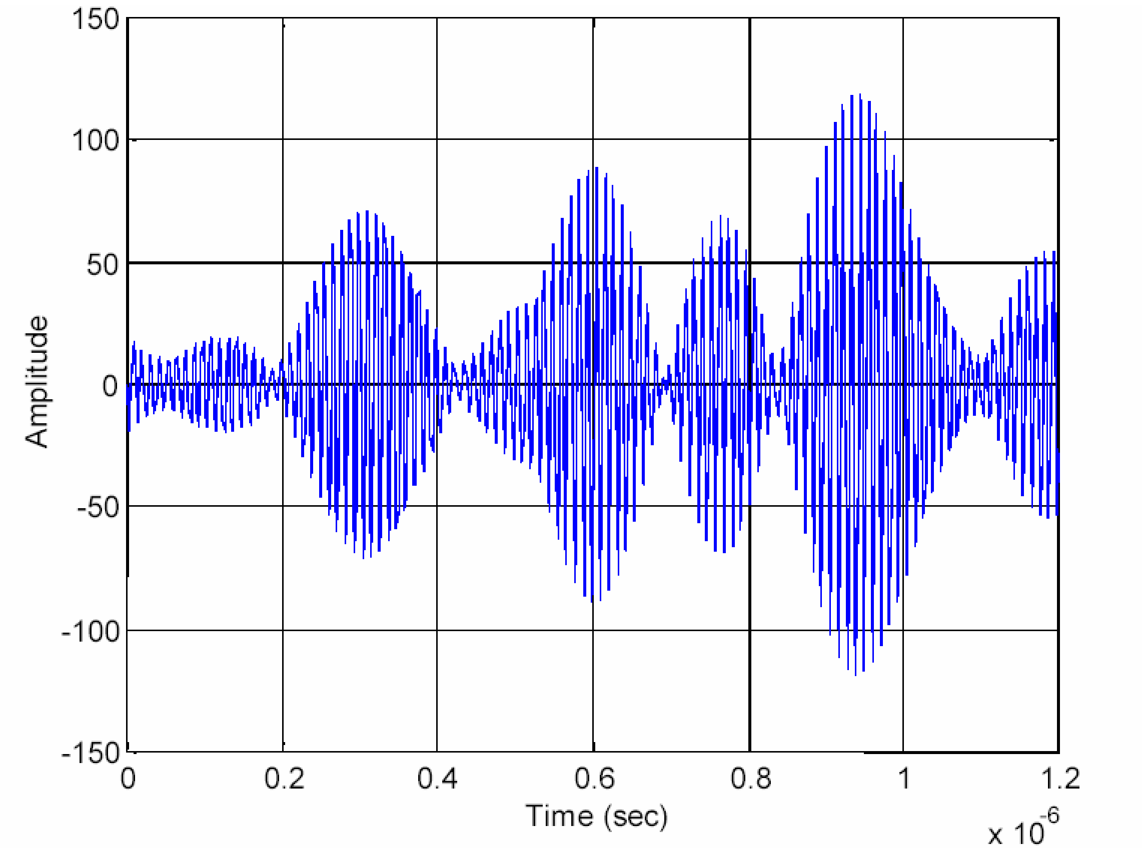

Figure 3.15 Time response of direct simulation of (3.4)

(3.4) vs. IFFT Welch PSD Estimate

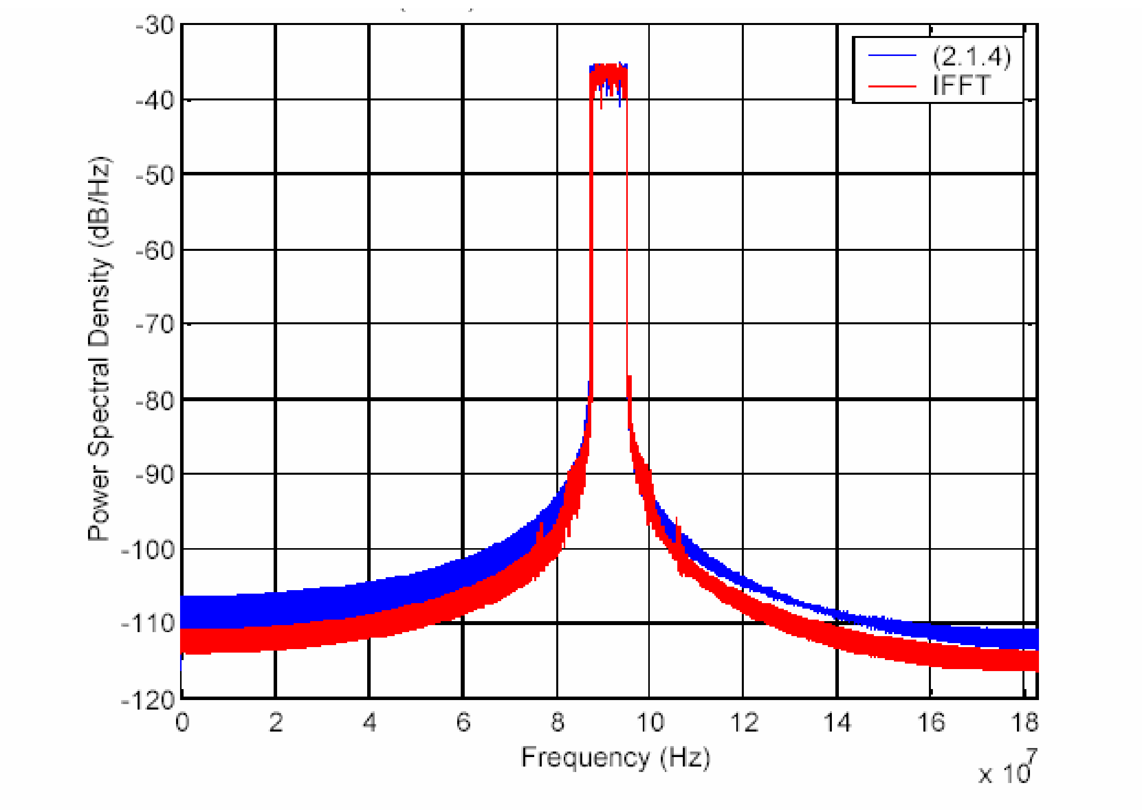

Figure 3.16 Frequency response of direct simulation of (3.4) and IFFT

CHAPTER 4
OFDM RECEPTION

As we mentioned before, the design of an OFDM receiver is open; i.e., there are only transmission standards. With an open receiver design, most of the research and innovations are done in the receiver. For example, the frequency sensitivity drawback is mainly a transmission channel prediction issue, something that is done at the receiver; therefore, we shall only present a basic receiver structure in this report. A basic receiver that just follows the inverse of the transmission process is shown in Figure 4.1.

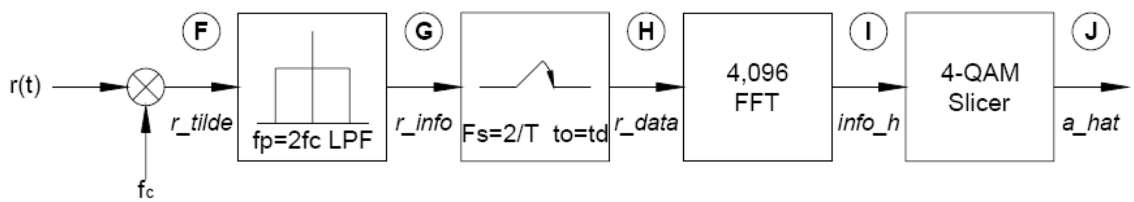

Figure 4.1 OFDM reception simulations

OFDM is very sensitive to timing and frequency offsets [2]. Even in this deal simulation environment, we have to consider the delay produced by the filtering operation. For our simulation, the delay produced by the reconstruction and demodulation filters is about td=64/Rs. This delay is enough to impede the reception, and it is the cause of the slight differences we can see between the transmitted and received signals (Figure 3.3 vs. Figure 4.7 for example). With the delay taken care of, the rest of the reception process is straightforward. As in the transmission case, we specified the names of the simulation variables and the output processes in the reception description of Figure 4.1. The results of this simulation are shown in Figures 4.2 to 4.9.

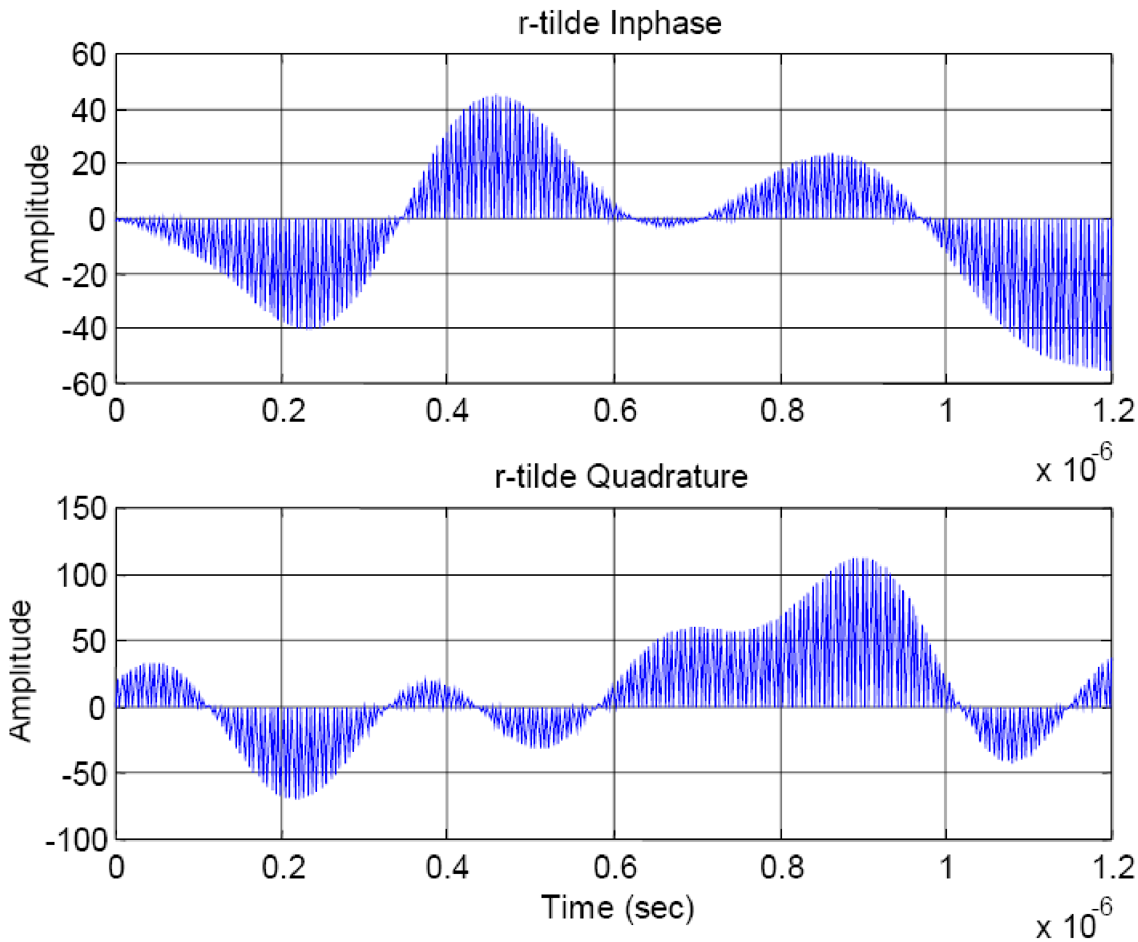

Figure 4.2 Time response of signal r_tilde at (F)

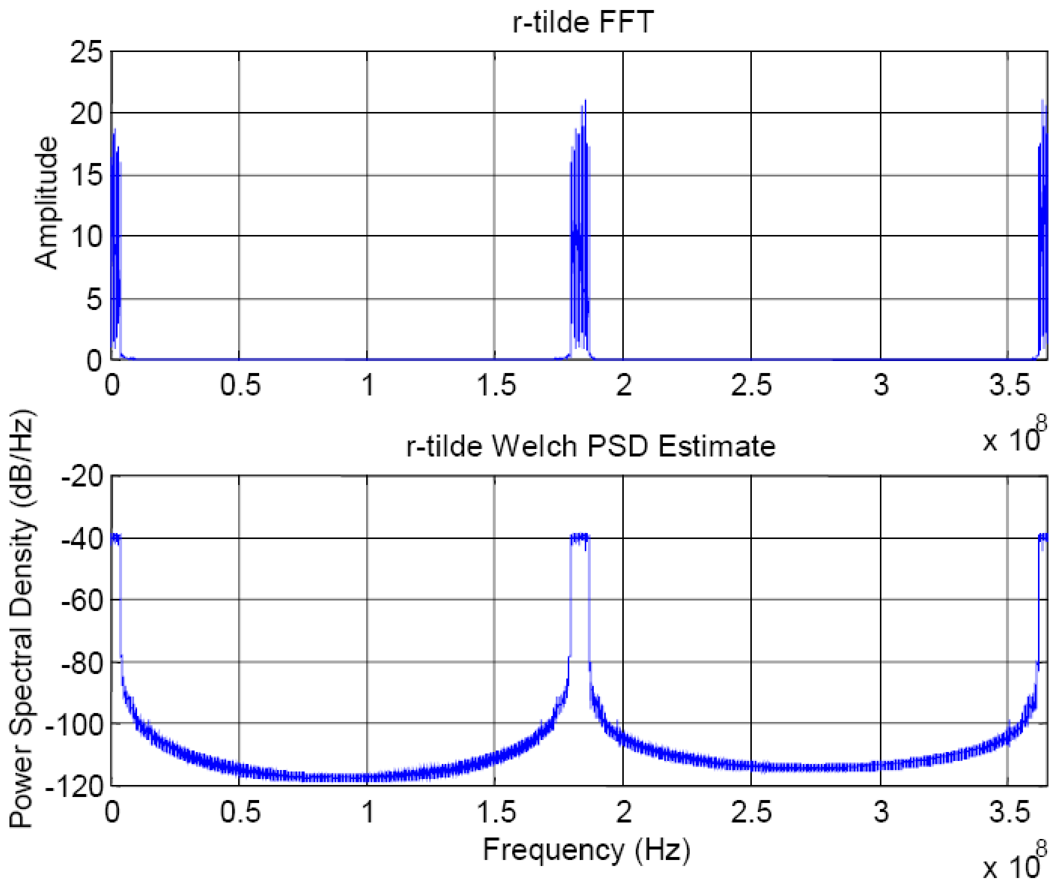

Figure 4.3 Frequency response of signal r_tilde at (F)

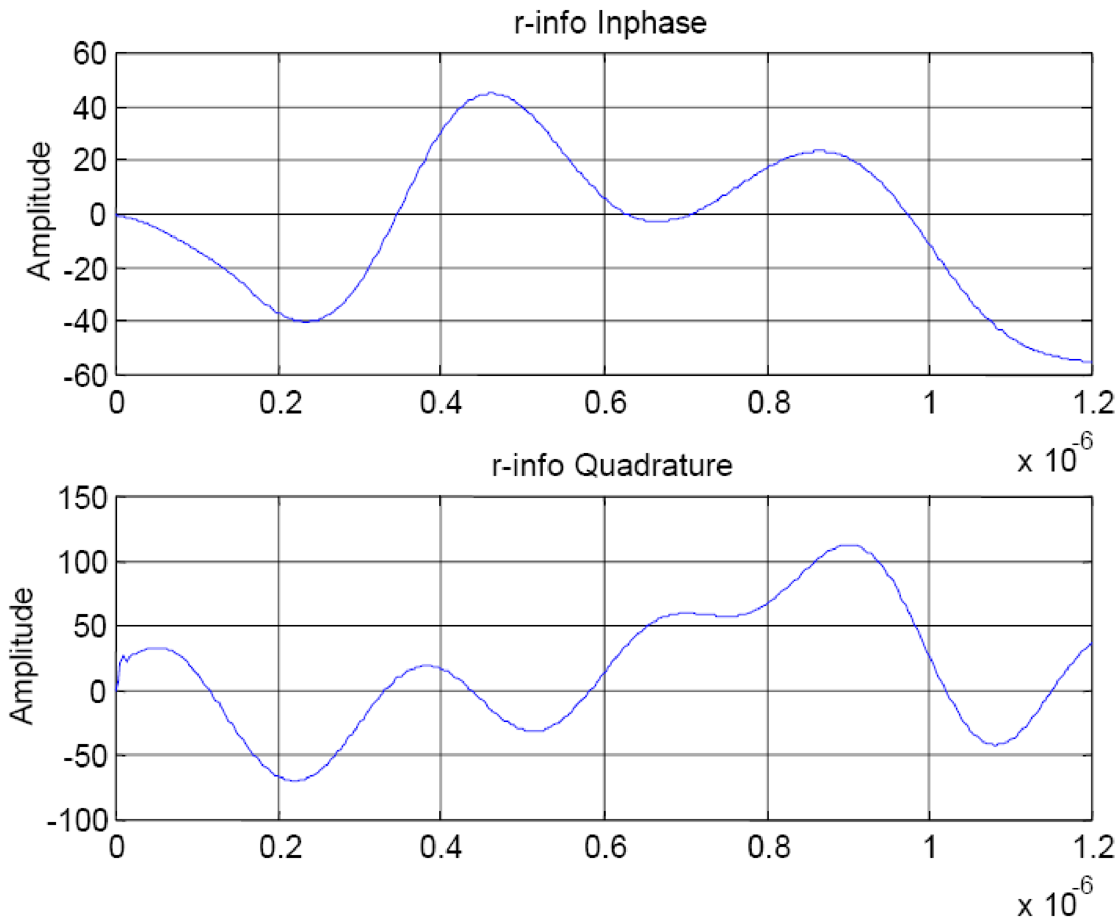

Figure 4.4: Time response of signal r_info at (G)

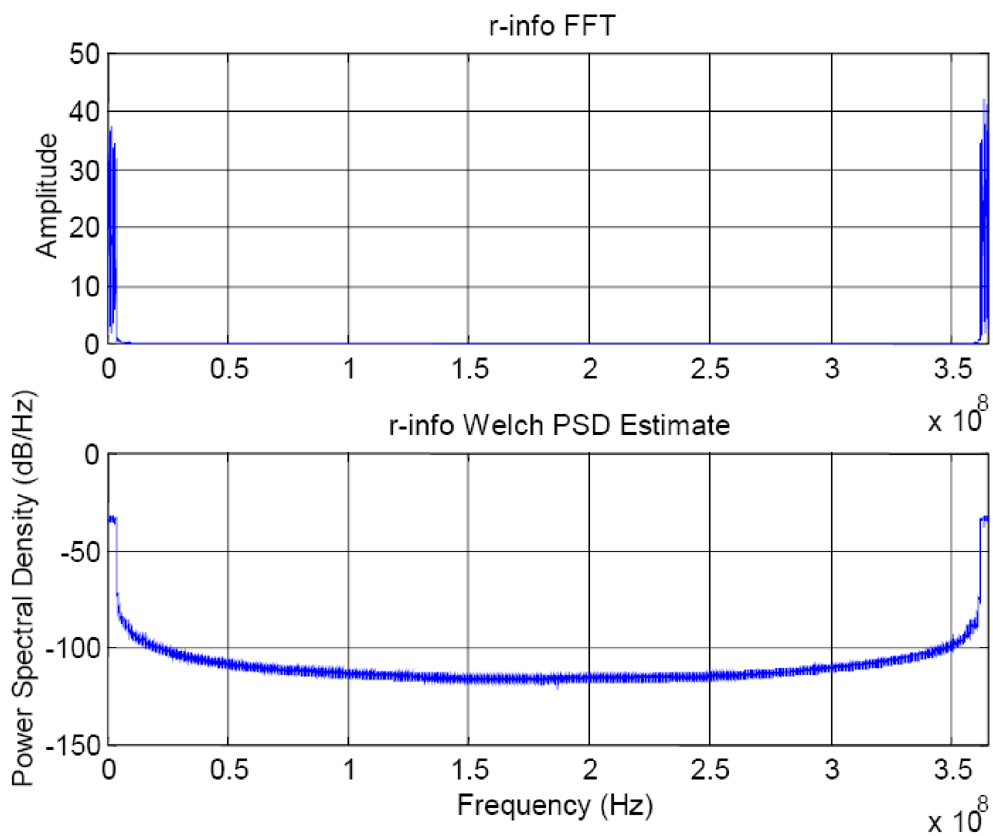

Figure 4.5 Frequency response of signal r_info at (G)

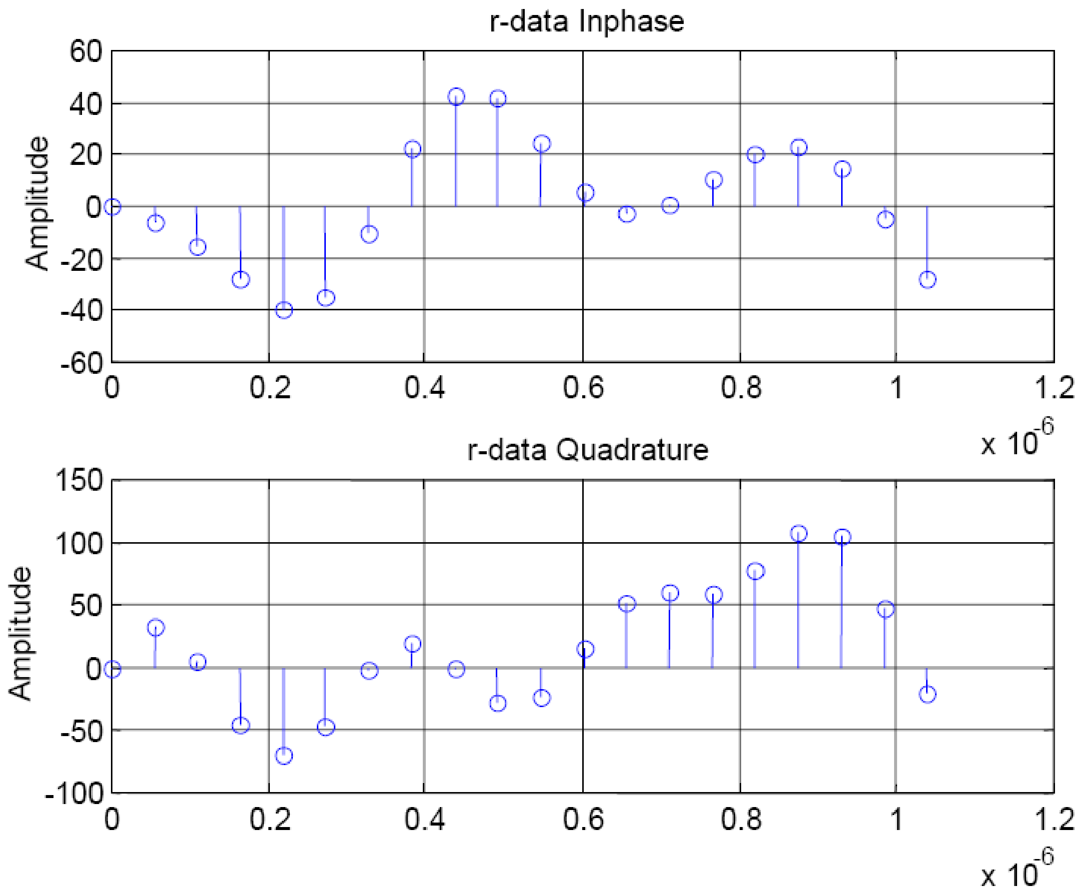

Figure 4.6 Time response of signal r_data at (H)

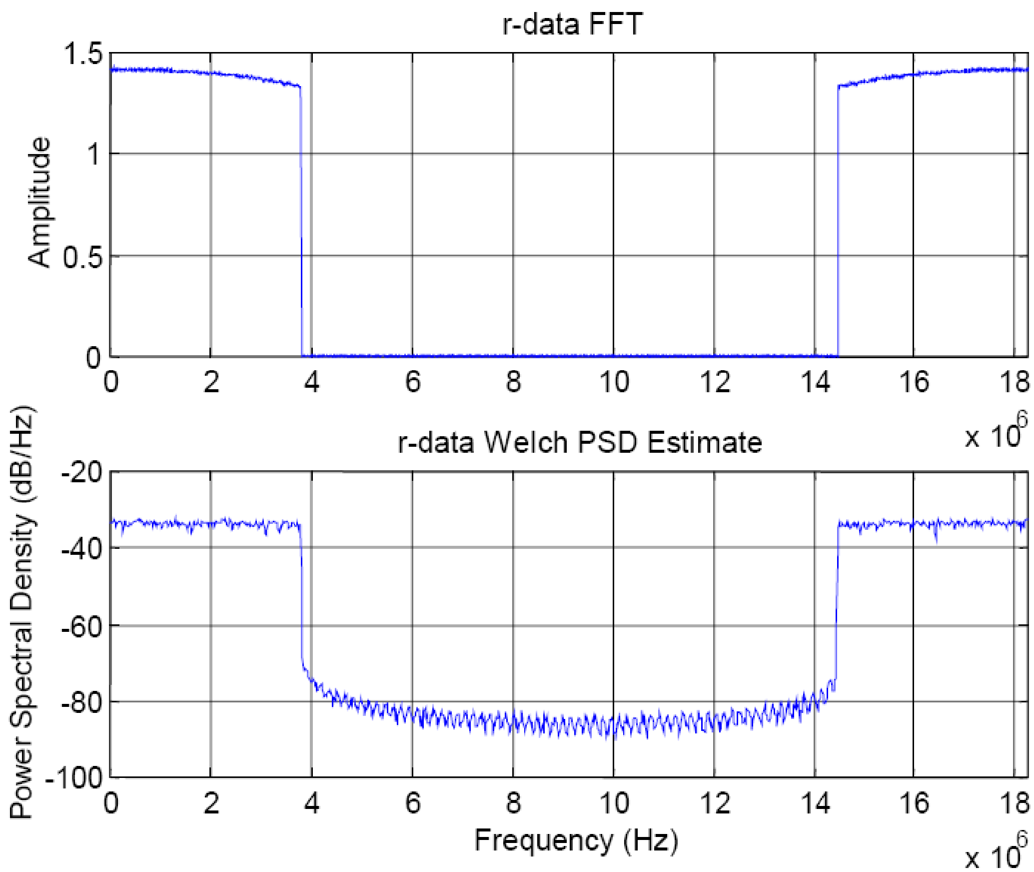

Figure 4.7: Frequency response of signal r_data at (H)

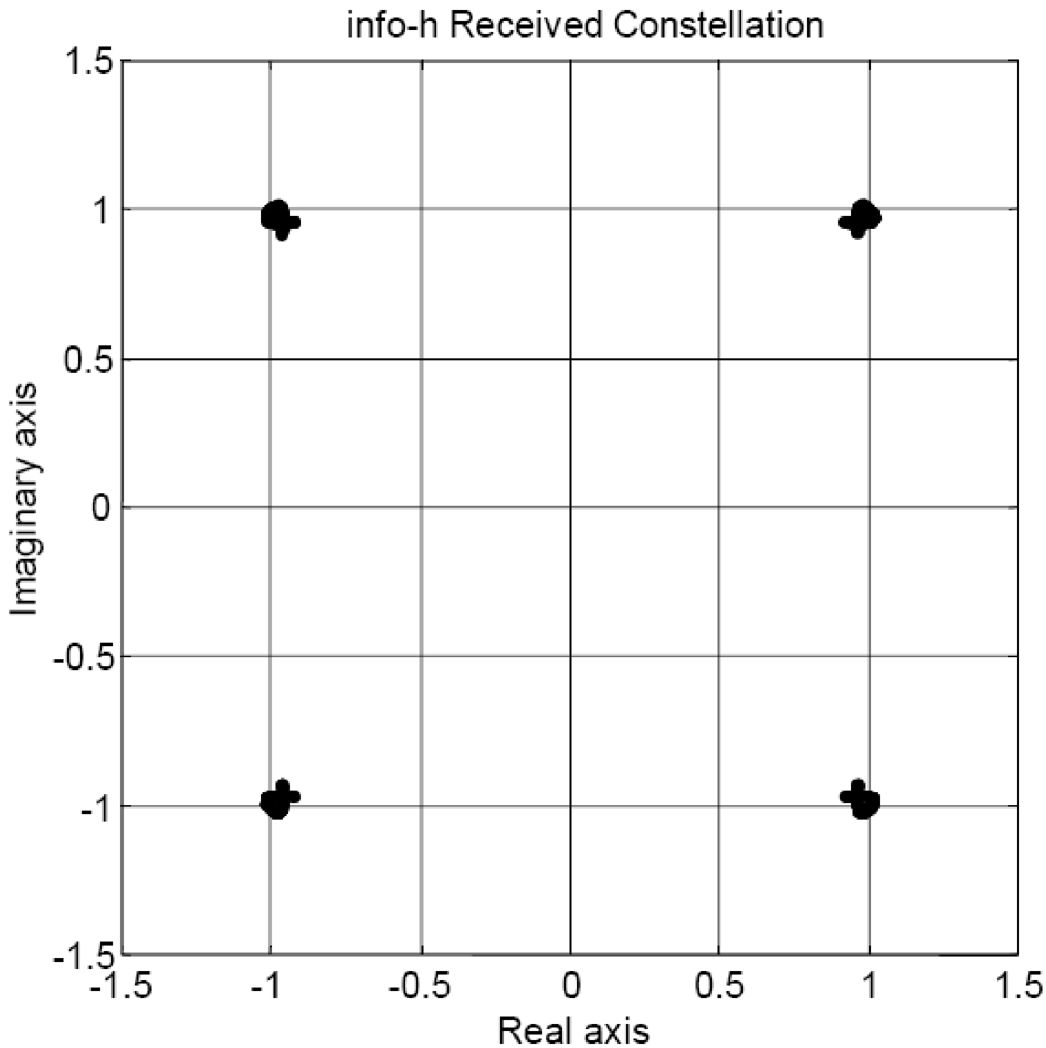

Figure 4.8: info_h constellation

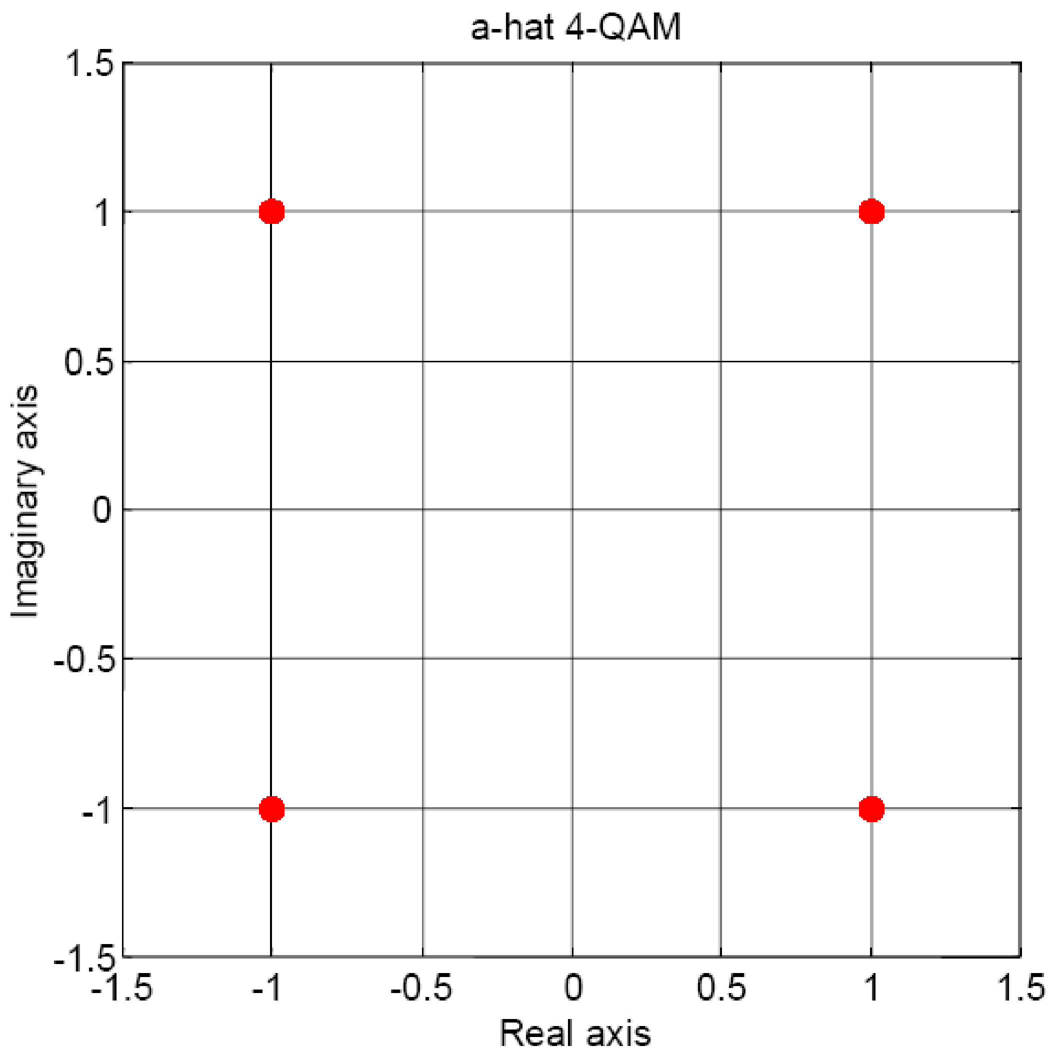

Figure 4.9: a_hat constellation

APPENDIX

OFDM Transmission

```
%DVB-T 2K Transmission
%The available bandwidth is 8 MHz
%2K is intended for mobile services
clear all;
close all;
%DVB-T Parameters
Tu=224e-6; %useful OFDM symbol period
T=Tu/2048; %baseband elementary period
G=0; %choice of 1/4, 1/8, 1/16, and 1/32
delta=G*Tu; %guard band duration
Ts=delta+Tu; %total OFDM symbol period
Kmax=1705; %number of subcarriers
Kmin=0;
FS=4096; %IFFT/FFT length
q=10; %carrier period to elementary period ratio
fc=q*1/T; %carrier frequency
Rs=4*fc; %simulation period
t=0:1/Rs:Tu;
%Data generator (A)
M=Kmax+1;
rand('state',0);
a=-1+2*round(rand(M,1)).'+i*(-1+2*round(rand(M,1))).';
A=length(a);
info=zeros(FS,1);
info(1:(A/2)) = [ a(1:(A/2)).']; %Zero padding
```

```
info((FS-((A/2)-1)):FS) = [ a(((A/2)+1):A).'];
%Subcarriers generation (B)
carriers=FS.*ifft(info,FS);
tt=0:T/2:Tu;
figure(1);
subplot(211);
stem(tt(1:20),real(carriers(1:20)));
subplot(212);
stem(tt(1:20),imag(carriers(1:20)));
figure(2);
f=(2/T)*(1:(FS))/(FS);
subplot(211);
plot(f,abs(fft(carriers,FS))/FS);
subplot(212);
pwelch(carriers,[],[],[],2/T);
% D/A simulation
L = length(carriers);
chips = [ carriers.';zeros((2*q)-1,L)];
p=1/Rs:1/Rs:T/2;
g=ones(length(p),1); %pulse shape
figure(3);
stem(p,g);
dummy=conv(g,chips(:));
u=[dummy(1:length(t))]; % (C)
figure(4);
subplot(211);
plot(t(1:400),real(u(1:400)));
subplot(212);
plot(t(1:400),imag(u(1:400)));
```

```
figure(5);
ff=(Rs)*(1:(q*FS))/(q*FS);
subplot(211);
plot(ff,abs(fft(u,q*FS))/FS);
subplot(212);
pwelch(u,[],[],[],Rs);
[b,a] = butter(13,1/20); %reconstruction filter
[H,F] = FREQZ(b,a,FS,Rs);
figure(6);
plot(F,20*log10(abs(H)));
uoft = filter(b,a,u); %baseband signal (D)
figure(7);
subplot(211);
plot(t(80:480),real(uoft(80:480)));
subplot(212);
plot(t(80:480),imag(uoft(80:480)));
figure(8);
subplot(211);
plot(ff,abs(fft(uoft,q*FS))/FS);
subplot(212);
pwelch(uoft,[],[],[],Rs);
%Upconverter
s_tilde=(uoft.').*exp(1i*2*pi*fc*t);
s=real(s_tilde); %passband signal (E)
figure(9);
plot(t(80:480),s(80:480));
figure(10);
subplot(211);
%plot(ff,abs(fft(((real(uoft).').*cos(2*pi*fc*t)),q*FS))/FS);
```

```
%plot(ff,abs(fft(((imag(uoft).').*sin(2*pi*fc*t)),q*FS))/FS);
plot(ff,abs(fft(s,q*FS))/FS);
subplot(212);
%pwelch(((real(uoft).').*cos(2*pi*fc*t)),[],[],[],Rs);
%pwelch(((imag(uoft).').*sin(2*pi*fc*t)),[],[],[],Rs);
pwelch(s,[],[],[],Rs);
```

OFDM Reception

```
%DVB-T 2K Reception
clear all;
close all;
Tu=224e-6; %useful OFDM symbol period
T=Tu/2048; %baseband elementary period
G=0; %choice of 1/4, 1/8, 1/16, and 1/32
delta=G*Tu; %guard band duration
Ts=delta+Tu; %total OFDM symbol period
Kmax=1705; %number of subcarriers
Kmin=0;
FS=4096; %IFFT/FFT length
q=10; %carrier period to elementary period ratio
fc=q*1/T; %carrier frequency
Rs=4*fc; %simulation period
t=0:1/Rs:Tu;
tt=0:T/2:Tu;
%Data generator
sM = 2;
[x,y] = meshgrid((-sM+1):2:(sM-1),(-sM+1):2:(sM-1));
alphabet = x(:) + 1i*y(:);
N=Kmax+1;
```

```
rand('state',0);
a=-1+2*round(rand(N,1)).'+i*(-1+2*round(rand(N,1))).';
A=length(a);
info=zeros(FS,1);
info(1:(A/2)) = [ a(1:(A/2)).'];
info((FS-((A/2)-1)):FS) = [ a(((A/2)+1):A).'];
carriers=FS.*ifft(info,FS);
%Upconverter
L = length(carriers);
chips = [ carriers.';zeros((2*q)-1,L)];
p=1/Rs:1/Rs:T/2;
g=ones(length(p),1);
dummy=conv(g,chips(:));
u=[dummy; zeros(46,1)];
[b,aa] = butter(13,1/20);
uoft = filter(b,aa,u);
delay=64; %Reconstruction filter delay
s_tilde=(uoft(delay+(1:length(t))).').*exp(1i*2*pi*fc*t);
s=real(s_tilde);
%OFDM RECEPTION
%Downconversion
r_tilde=exp(-1i*2*pi*fc*t).*s; %(F)
figure(1);
subplot(211);
plot(t,real(r_tilde));
axis([0e-7 12e-7 -60 60]);
grid on;
figure(1);
subplot(212);
```

```
plot(t,imag(r_tilde));
axis([0e-7 12e-7 -100 150]);
grid on;
figure(2);
ff=(Rs)*(1:(q*FS))/(q*FS);
subplot(211);
plot(ff,abs(fft(r_tilde,q*FS))/FS);
grid on;
figure(2);
subplot(212);
pwelch(r_tilde,[],[],[],Rs);
%Carrier suppression
[B,AA] = butter(3,1/2);
r_info=2*filter(B,AA,r_tilde); %Baseband signal continuous-time (G)
figure(3);
subplot(211);
plot(t,real(r_info));
axis([0 12e-7 -60 60]);
grid on;
figure(3);
subplot(212);
plot(t,imag(r_info));
axis([0 12e-7 -100 150]);
grid on;
figure(4);
f=(2/T)*(1:(FS))/(FS);
subplot(211);
plot(ff,abs(fft(r_info,q*FS))/FS);
grid on;
```

```
subplot(212);
pwelch(r_info,[],[],[],Rs);
%Sampling
r_data=real(r_info(1:(2*q):length(t)))... %Baseband signal, discretetime
+1i*imag(r_info(1:(2*q):length(t))); % (H)
figure(5);
subplot(211);
stem(tt(1:20),(real(r_data(1:20))));
axis([0 12e-7 -60 60]);
grid on;
figure(5);
subplot(212);
stem(tt(1:20),(imag(r_data(1:20))));
axis([0 12e-7 -100 150]);
grid on;
figure(6);
f=(2/T)*(1:(FS))/(FS);
subplot(211);
plot(f,abs(fft(r_data,FS))/FS);
grid on;
subplot(212);
pwelch(r_data,[],[],[],2/T);
%FFT
info_2N=(1/FS).*fft(r_data,FS); % (I)
info_h=[info_2N(1:A/2) info_2N((FS-((A/2)-1)):FS)];
%Slicing
for k=1:N,
a_hat(k)=alphabet((info_h(k)-alphabet)==min(info_h(k)-alphabet)); %
(J)
```

```
end;
figure(7)
plot(info_h((1:A)),'.k');
title('info-h Received Constellation')
axis square;
axis equal;
figure(8)
plot(a_hat((1:A)),'or');
title('a_hat 4-QAM')
axis square;
axis equal;
grid on;
axis([-1.5 1.5 -1.5 1.5]);
```

Eq. (3.4) vs. IFFT

```
%DVB-T 2K signal generation Eq. (2.1.4) vs. 2N-IFFT
clear all;
close all;
Tu=224e-6; %useful OFDM symbol period
T=Tu/2048; %baseband elementary period
G=0; %choice of 1/4, 1/8, 1/16, and 1/32
delta=G*Tu; %guard band duration
Ts=delta+Tu; %total OFDM symbol period
Kmax=1705; %number of subcarriers
Kmin=0;
FS=4096; %IFFT/FFT length
q=10; %carrier period to elementary period ratio
fc=q*1/T; %carrier frequency
Rs=4*fc; %simulation period
```

```
a=-1+2*round(rand(M,1)).'+i*(-1+2*round(rand(M,1))).';
A=length(a);
info = [ a.'];
tt=0:1/Rs:Ts;
TT=length(tt);
k=Kmin:Kmax;
for t=0:(TT-1); % Eq. (2.1.4)
phi=a(k+1).*exp((1j*2*(((t*(1/Rs))-delta))*pi/Tu).*((k-(Kmax-Kmin)/2)));
s(t+1)=real(exp(1j*2*pi*fc*(t*(1/Rs))).*sum(phi));
end
infof=zeros(FS,1);
infof(1:(A/2)) = [ a(1:(A/2)).'];
infof((FS-((A/2)-1)):FS) = [ a(((A/2)+1):A).'];
carriers=FS.*ifft(infof,FS); % IFFT
%Upconverter
L = length(carriers);
chips = [ carriers.';zeros((2*q)-1,L)];
p=1/Rs:1/Rs:T/2;
g=ones(length(p),1);
dummy=conv(g,chips(:));
u=[dummy(1:TT)];
[b,a] = butter(13,1/20);
uoft = filter(b,a,u);
s_tilde=(uoft.').*exp(1i*2*pi*fc*tt);
sf=real(s_tilde);
figure(1);
plot(tt,s,'b',tt,sf,'g');
figure(2);
```

```
pwelch(s,[],[],[],Rs);
hold on;
pwelch(sf,[],[],[],Rs);
hold off;
```

REFERENCES

[1] ETS 300 744, "Digital broadcasting systems for television, sound and data services; framing structure, channel coding, and modulation for digital terrestrial television,. European Telecommunication Standard, Doc. 300 744, 1997.

[2] R. V. Nee and R. Prasad, OFDM Wireless Multimedia Communications, Norwood, MA: Artech House, 2000.

[3] J. A. C. Bingham, "Multi-carrier modulation for data transmission: An idea whose time has come", IEEE Communications Magazine, vol.28, no. 5, pp. 5-14, May 1990.

[4] A. V. Oppenheim and R. W. Schafer, Discrete-Time Signal Processing, Englewood Cliffs, NJ: Prentice Hall, 1989

[5] http://www.sce.carleton.ca/~hazyl/MEng/index.html (Master’s Thesis)

[6] http://ludo.jcu.edu.au/eric/thesis/Thesis.htm (Ph.D Dissertation)

[7] http://wireless.per.nl/telelearn/ofdm/ (Online-presentation by r.Linnartz)

[8] http://www.sss-mag.com/ofdm.html (Interview with Dr. Zaghloul of Wi-Lan)

[9] http://www.bwif.org/ (Broadband Wireless Internet Forum)

[10] http://www.ofdm-forum.com/

[11] http;//www.comlextorial.com

ABBREVATIONS

APP: A Posteriori Probabilities

AWGN: Additive White Gaussian Noise

BCJR: Bahl, Cocke, Jelinek and Raviv,

BER: Bit Error Rate

BPS: Bit Per Symbol

BPSK: Binary Phase Shift Keying

CIR: Channel Impulse Response

CP: Cyclic Prefix

DFT: Discrete Fourier Transform

FFT: Fast Fourier Transform

FDM: Frequency Division Multiplexing

FER: Frame Error Rate

FSM: Finite Sequence Machine

IDFT: Inverse Discrete Fourier Transform

IFFT: Inverse Fast Fourier Transform

ICI: Inter Carrier Interference

ISI: Inter Symbol Interference

LLR: Loglikelyhood Ratios

LOS: Line Of Sight

MAP: Maximum a Posterior Algorithm

MLSE: Maximum Likelihood Sequence Estimatiuon

MPSK: Multiple Phase Shift Keying

MQM: Multiple Quadrature Amplitude Modulation

OFDM: Orthogonal frequency Division Multiplexing

PAPR: Peak to Average Power Ratio

PDF: Probability Density Function

PDP: Power Delay Profile

PSK Phase Shift Keying

PTS: Partial Transmit Sequences

QAM: Quadrature Amplitude Multiplexing

QPSK: Quadrature Phase shift keying

PSAM: Pilot Symbol Aided Modulation

PSK Phase Shift Keying

SLM: Selective Mapping

SNR: Signal to noise ration

SISO: Soft Input, Soft Output

SOVA: Soft Output Viterbi Algorithm

TR: Tone Reservation

WLAN: Wireless Local Area Network

ZF: Zero Forcing

16-QAM: 16 –state Quadrature Amplitude Modulation

64-QAM: 64 –state Quadrature Amplitude Modulation