PC403 B. Tech Mini Project Report Implementation of an OFDM based Transmission System using USRP

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***Abstract*—OFDM is a method of encoding data on multiple carrier frequencies using IDFT. This report comprises of background on OFDM followed by implementation results. Motivation for using OFDM over conventional modulation is emphasized along with a few advantages. Digital implementation of an OFDM system is detailed. The principles of operation of a basic OFDM system are elaborated for both OFDM Transmitter and Receiver. OFDM symbol and frame are explained. Advantages of using a guard interval, specifically the cyclic prefix, at the beginning of OFDM symbol are studied. Inter Symbol Interference (ISI) and techniques to eliminate ISI are discussed. Pilot signals and Least Squares based Channel Estimation using scattered pilot distribution are investigated and also implemented in LabVIEW. Performance of channel estimation in a controlled channel environment with multipath is analysed in terms of both channel gains across frequencies and Bit Error Rate (BER). Simulation results of the implementation of OFDM system using USRP are also analysed for a transmitted grayscale image.**

I. Introduction

OFDM stands for Orthogonal Frequency Division Multiplexing. It has been adopted for various transmission systems such as Wi-Fi and forms the basis for 4G wireless communication systems. OFDM is basically a multi-carrier modulation technique. In single carrier modulation, the carrier occupies the entire communication bandwidth. On the other hand, in multi-carrier modulation, the available bandwidth is divided into sub-bands (say N) with each one corresponding to a subcarrier [1]. In OFDM, these N subcarriers at different frequencies are orthogonal. These closely spaced subcarriers are used to carry data on several parallel data streams using Inverse Discrete Fourier Transform (IDFT), thus rendering its implementation simple and cost-effective.

A significant advantage of OFDM over single-carrier modulation techniques is it's robustness to extreme channel conditions or frequency selective channels which may result from multipath fading. These channels have erratic power gains and frequency responses across the subcarriers [2]. Even though the data rates using OFDM are similar to those of conventional schemes, each subcarrier in OFDM is individually modulated at a low symbol rate. These low symbol rates enable the use of a guard interval which counters the fading caused due to multipath propagation [3]. Also, in OFDM, by choosing N to be sufficiently large, the narrowband sub-channels can be approximated as frequency-flat channels.

On the other hand, USRP stands for Universal Software Radio Peripheral. It is basically a Software Defined Radio (SDR) or a radio communication system where components such as modulators and filters are implemented digitally using software on a computer or an embedded system. All the simulations in this project have been implemented using NI LabVIEW 2015 on a Windows 7 PC.

II. OFDM - Working

OFDM pursues transmission over orthogonal complex exponential functions at different frequencies. The reason behind choosing complex exponentials for the transmission is based on the fact that they are indeed eigenfunctions to an LTI system. As the channel output is just a scaled version of the input, orthogonal complex exponentials remain orthogonal as they go through the channel [4]. These orthogonal subcarriers are generated using IDFT, which does the work of placing each stream on it's respective subcarrier and then combines the signals together. Orthogonality of subcarriers ensures there is no interference between any of the subcarriers.

A. *OFDM Transmitter*

In a typical digital implementation of an OFDM system, the input data bits are first mapped to data symbols, which are complex numbers corresponding to the modulation (QPSK, BPSK or others) constellation points. These complex data symbols are fed to an IFFT block of length equal to the number of subcarriers N and the output of IDFT is N orthogonal sinusoids at different frequencies. The IFFT block, thus, provides an effective way to modulate data symbols onto orthogonal subcarriers. The output of the IFFT block is referred to as an *OFDM Symbol* [1]. So, an OFDM symbol comprises of N orthogonal subcarriers with each of these subcarriers comprising a modulated data symbol.

To avoid Inter Symbol Interference (ISI), a *guard interval* is added at the beginning of every OFDM symbol before transmission [3]. This is done to ensure there is no interference between two adjacent OFDM symbols. Guard interval may be zero padded i.e. no waveform is transmitted in this duration or it may be a *cyclic prefix*. Cyclic prefix refers to prefixing a symbol with a repetition of it's end. It is preferred to zero padding as use of cyclic prefix enables the channel output

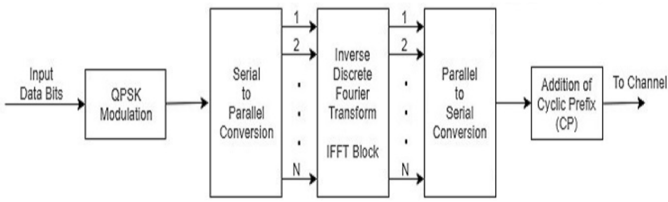

Fig. 1. Schematic of OFDM Transmitter using IDFT with cyclic prefix.

to be modeled as circular convolution as opposed to linear convolution of OFDM symbol and the impulse response of the channel. Duality of the time and frequency domains also facilitates easier techniques for channel estimation. Fig. 1 shows the schematic of an OFDM system transmitter. Transmission of OFDM symbols is usually organized in a frame structure with some preamble at the beginning for the purpose of synchronization. Thus, an *OFDM frame* generally consists a certain number of OFDM symbols based on the chosen frame length along with some preamble [5].

B. Wireless Channel

In wireless transmissions, there may be a delay spread introduced due to the channel as multipath increases. As OFDM symbols are transmitted one by one, the multipath delay spread results in a symbol spreading out and interfering with the succeeding symbol, thus changing it's amplitude and phase. This is known as Inter Symbol Interference (ISI) [3]. As already discussed, this can be eliminated by adding cyclic prefix of duration more than the multipath delay spread of the channel to OFDM symbols before transmission across the channel. However, an immediate and obvious consequence of this approach is a reduction in data rates.

In order to evaluate the performance of channel estimation and to make BER measurements in a controlled environment, a frequency selective channel is implemented by modeling it as a multi-tap channel [2]. Frequency selectivity of the channel is directly proportional to the number of channel taps.

C. OFDM Receiver

Synchronization is first performed to detect the preamble and precisely determine the starting location of the transmitted OFDM frame. In OFDM, the baseband signal with modulated symbols is transmitted after performing IDFT. The reverse operation of DFT is performed at the receiver. The first part of the received OFDM output symbol corresponds to the cyclic prefix and may be subjected to ISI from preceding symbol. Consequently, DFT is performed only after the cyclic prefix is removed. Assuming the length of cyclic prefix to be $L-1$, the OFDM symbol with cyclic prefix has a length of $N+L-1$ and thus the received OFDM output also has a length of $N+L-1$. The first $L-1$ values of this output are removed before taking the DFT as these correspond to the cyclic prefix [4]. Taking DFT of this signal gives the modulated data, which is mapped back to the input bits based on the type of modulation used to encode the data originally as in Fig. 2.

Channel gains across the subcarriers in a controlled environment can be found out conceptually by taking the DFT (length N) of the zero-padded channel impulse response. To find out the channel gains practically, channel estimation is usually performed at the receiver.

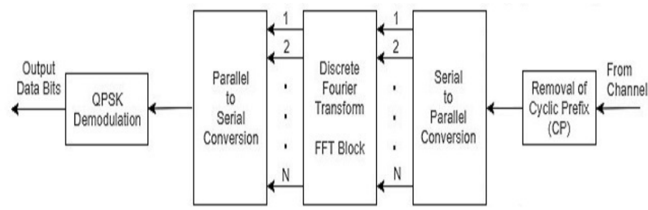

Fig. 2. Schematic of OFDM Receiver using DFT (right to left).

III. PILOT-BASED CHANNEL ESTIMATION

A dynamic estimation of channel is necessary before the demodulation of OFDM signal as the channel may sometimes be highly frequency selective. This can be achieved by inserting pilot tones into the OFDM symbols before transmission. A pilot signal is an unmodulated reference signal which is transmitted along with data symbols for channel estimation.

As a wireless channel is doubly spread, the pilots can be scattered across both time and frequency dimensions as shown in Fig. 3. The first plot shows *block-type* pilot distribution, where the pilots are inserted into all subcarriers of OFDM symbols with a specific period. On the other hand, the second plot shows *comb-type* pilot distribution, where the pilots are inserted into certain subcarriers of all OFDM symbols [6]. The former pattern of pilot distribution is used for the estimation of a slow varying channel and works well for a highly frequency selective channel whereas the latter is used for the estimation of a fast varying channel and works well only for moderately frequency selective channels.

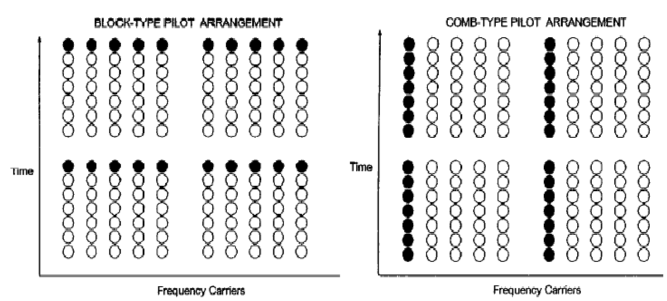

Fig. 3. Block-Type Pilot Distribution & Comb-Type Pilot Distribution, with the darkened circles representing pilot tones and others representing the data.

Most of the times in practice, however, a *scattered* pilot distribution, Fig. 4, is used for channel estimation, where the pilots following a specific pattern are scattered in both time and frequency directions [5]. Even though a good channel estimation can be made, transmission efficacy is reduced due to the required overhead of the pilot tones. Least Squares (LS) technique is often used for channel estimation when pilot symbols are used. Channel response is first estimated

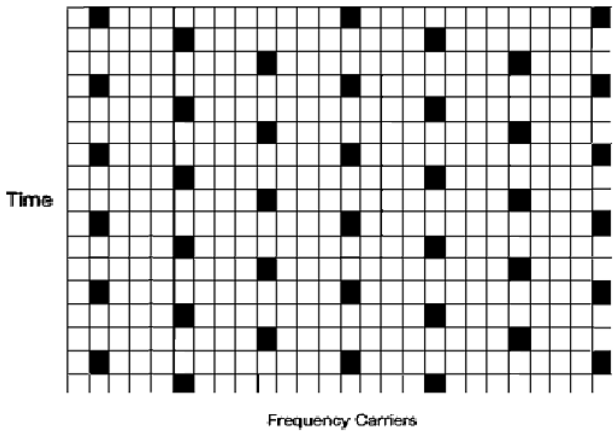

Fig. 4. Scattered Pilot Distribution, with pilots (darkened boxes) following a pattern scattered in both time and frequency dimensions.

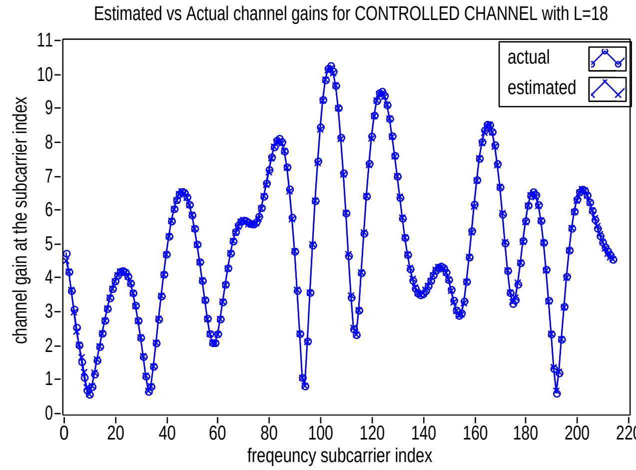

Fig. 6. Performance of LS channel estimation with scattered pilots for a controlled channel with multipath L=18.

at the pilot subcarriers and then interpolation techniques are employed to obtain channel response over data subcarriers [7].

IV. Simulations and Analysis

OFDM based transmission system has been simulated for both controlled channel with multipath and actual channel. Simulations pertaining to controlled channel environment are performed exclusively in LabVIEW by creating virtual an ISI channel with specified multipath. However, simulations pertaining to the actual channel are performed using USRP.

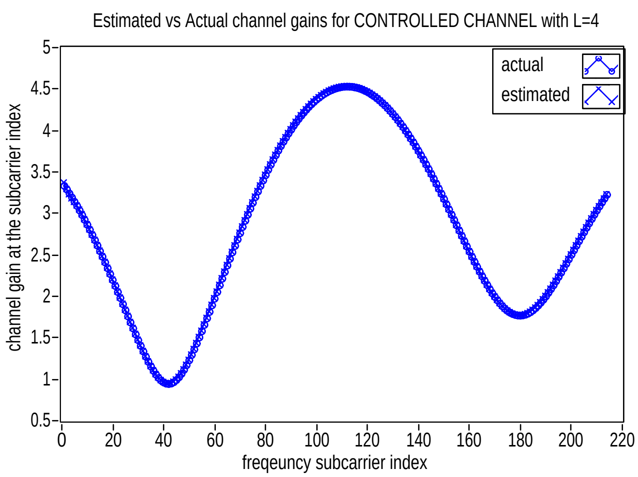

Fig. 5. Performance of LS channel estimation with scattered pilots for a controlled channel with multipath L=4.

Fig. 5 and 6 show performance results of LS based channel estimation for two simulations with multipath $L = 4$ and 18 respectively by comparing the estimated channel gains across subcarriers to the actual channel gains. All the simulations are performed using a 256 length IFFT with 180 data subcarriers, 18 pilot subcarriers and the others being null subcarriers. The pilot distribution is as in Fig. 4 and other OFDM PHY parameters are as in [5]. The precision in channel estimation ensures that the process of demodulation is accurate and thus improves the reliability of the transmission system. Also, the erratic variations in the channel gains of adjacent subcarriers in Fig. 6 manifest the fact that channel becomes highly frequency selective as multipath increases. Fig. 7 shows a plot of Bit Error Rate (BER) as function of Signal to Noise Ratio (SNR) for a controlled channel with $L = 4$. Predictably, BER decreases with increase in SNR at the receiver.

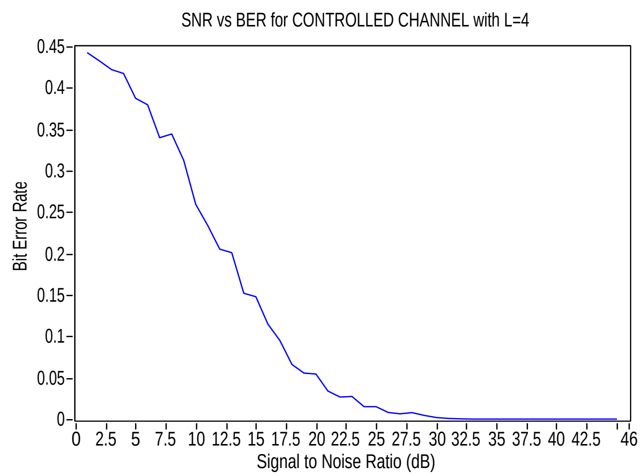

Fig. 7. Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) for a controlled channel with multipath L=4.

For simulations concerning actual channel, the transmission system has been implemented using a single USRP device which is used for both transmission and reception. Two antennas connected to the same USRP device are used for transmission and reception. For analysing the performance of this system, a grayscale image as shown in Fig. 8 is being transmitted over the two antennas. The implementation of this system starts with first converting the grayscale image to corresponding binary values and then performing the operations involved in OFDM transmission. A Barker Code preamble is added before transmission to facilitate synchronization of the transmit and the receive antenna. Synchronization at the receiver is achieved using cross-correlation. Fig. 9 shows

Fig. 8. 291 x 240 sized grayscale image transmitted using USRP.

the cross-correlation output of the preamble sequence with the received signal. First peak in the figure below indicates the beginning of the transmitted signal and the second peak ensures that the received signal contains the whole transmitted signal as a single block.

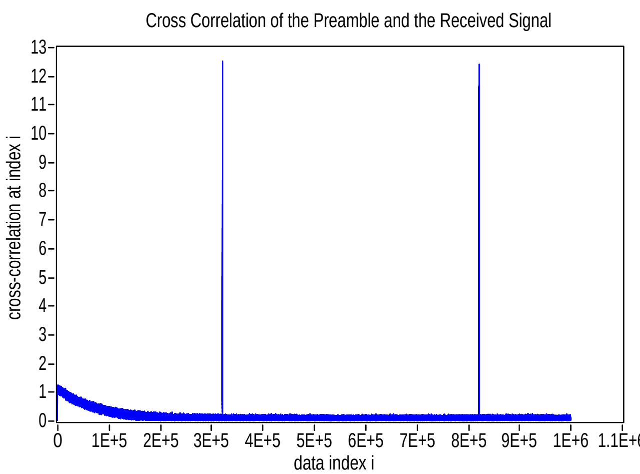

Fig. 9. Cross-correlation of the received signal with preamble, clearly depicting peaks in the correlation output.

Operations involved in OFDM reception are then performed on the received signal. The estimated channel gains across subcarriers for actual channel are used to map the complex symbols back to bits. These bits are reshaped according the dimensions of the transmitted image and then converted back to the grayscale image. Fig. 11 shows the image received via the actual channel. This image has a BER of the order 10^{-4}.

V. Conclusion

OFDM is a a multi-carrier modulation technique that pursues transmission over complex exponential functions at different frequencies. These complex exponentials are orthogonal and generated using IDFT. In this report, the principles of working of a basic OFDM are discussed. Advantages of an

Fig. 10. Grayscale image received across actual channel using USRP.

OFDM system in contrast with conventional modulation techniques are illustrated. Fundamentals of OFDM transmission and reception are represented, along with the behaviour of multipath channel. Inter Symbol Interference (ISI) is explained along with the techniques to eliminate it. Advantages of guard interval are mentioned. Need for channel estimation and pilot distributions are introduced. Pilot-based channel estimation is presented. Finally, Least Squares based Channel Estimation has been simulated in LabVIEW for 256 subcarriers (180 data, 18 pilot and others null) for different number of multipath in case of controlled channel environment and also for actual channel using USRP by transmitting a grayscale image. Simulation results are analysed accordingly for both the cases.

Appendix A
Orthogonality in OFDM

OFDM, similar to FDM, divides the available bandwidth into narrowband subcarriers to carry the information. To prevent Inter Carrier Interference (ICI), conventional FDM systems have small guard bands between any two carriers, where no information is transmitted [3]. However, this results in wastage of spectrum. To avoid this, OFDM uses subcarriers which are orthogonal to each other. As the subcarriers are completely unrelated, even their overlap causes no interference and makes OFDM very efficient. This orthogonality is achieved using IDFT. In using IDFT for modulation, the subcarrier spacing is chosen such that at central frequency of a subchannel, all other signals are zero as shown in Fig. 11.

Appendix B
Barker Code as Preamble

Barker sequence of length 13 (+1 +1 +1 +1 +1 -1 -1 +1 +1 -1 +1 -1 +1) is used as preamble for the simulations in this report. +1 and -1 are mapped to $(1 + j)/\sqrt{2}$ and $-(1 + j)/\sqrt{2}$ corresponding to QPSK modulation used for these simulations. The reason behind choosing Barker code as preamble is it's not far from ideal autocorrelation property and low cross correlation with other sequences [8]. Side lobes of

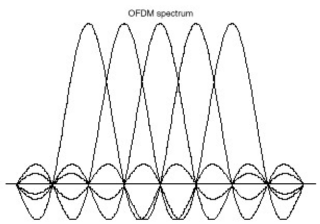

Fig. 11. OFDM spectrum with five subcarriers. It can be observed that at central frequency of each subcarrier, there is no interference from other subcarriers.

the autocorrelation function of a Barker Code are very small as compared to the peak value as shown in Fig. 12. This mostly makes it insusceptible to distortion caused by other sequences that are likely to interfere with the Barker code. Consequently, synchronization at the receiver is effectively achieved, thus leading to better performance in transmission.

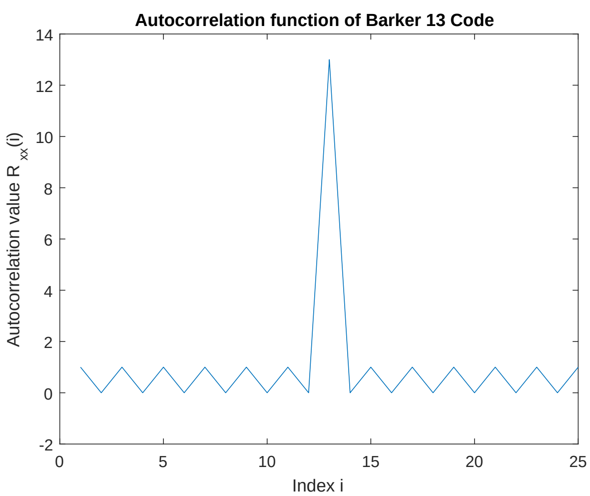

Fig. 12. Autocorrelation function of Barker 13 Code depicting the ideal autocorrelation property of the Barker 13 sequence.

Appendix C
Least Squares Channel Estimation

Least Squares based channel estimation is usually suited for an overdetermined system where the number of equations is more than the number of unknowns. As in any typical channel estimation technique, the channel is first estimated at the pilot locations based on the known pilot tones and the outputs at these locations [7]. Least Squares channel estimation works by minimizing the norm of the vector containing the errors in estimation at each pilot location. Let $\mathbf{Y}$ be a column vector containing data in the received signal corresponding to the pilot locations and say $\mathbf{H}$ is a column vector containing actual channel gains at all the pilot locations. The pilot tones are arranged in a diagonal matrix $\mathbf{X}$. Assuming the subcarriers are perfectly orthogonal and that there are say M pilot locations, the vector $\mathbf{Y} = [Y[0]\ Y[1]\ ..\ Y[M-1]]^T$ can be represented ($\mathbf{N}$ represents the noise due to the receiver) as -

$$\mathbf{Y} = \mathbf{XH} + \mathbf{N}$$

Let $\hat{\mathbf{H}}$ denote the channel response to be estimated i.e. estimate of $\mathbf{H}$. Let $f(\hat{\mathbf{H}})$ represent the norm of the error vector i.e.

$$f(\hat{\mathbf{H}}) = \left\|\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}}\right\|^2 = (\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}})^H(\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}})$$

On simplifying this expression further, we have -

$$\begin{aligned} f(\hat{\mathbf{H}}) &= (\mathbf{Y}^H - \hat{\mathbf{H}}^H\mathbf{X}^H)(\mathbf{Y} - \mathbf{X}\hat{\mathbf{H}}) \\ &= \mathbf{Y}^H\mathbf{Y} - \mathbf{Y}^H\mathbf{X}\hat{\mathbf{H}} - \hat{\mathbf{H}}^H\mathbf{X}^H\mathbf{Y} + \hat{\mathbf{H}}^H\mathbf{X}^H\mathbf{X}\hat{\mathbf{H}} \end{aligned}$$

To minimize $f(\hat{\mathbf{H}})$, it is differentiated with respect to $\hat{\mathbf{H}}$ and equalled to zero. On differentiation [9], the first term equals zero. The second term is a linear form of $\hat{\mathbf{H}}$ whose derivative can be found out by dropping $\hat{\mathbf{H}}$ term and taking hermitian of the leftover expression. Similarly, the differentiation is performed for the third term, there is no need to take hermitian as the term is already function of $\hat{\mathbf{H}}^H$. The fourth term is quadratic form of $\hat{\mathbf{H}}$, whose derivative is found by dropping $\hat{\mathbf{H}}^H$ term and multiplying by 2. So,

$$\frac{\partial f(\hat{\mathbf{H}})}{\partial \hat{\mathbf{H}}} = -2\mathbf{X}^H\mathbf{Y} + 2\mathbf{X}^H\mathbf{X}\hat{\mathbf{H}} = 0$$

$$i.e.\ \boxed{\hat{\mathbf{H}}_{LS} = (\mathbf{X}^H\mathbf{X})^{-1}\mathbf{X}^H\mathbf{Y}}$$

The operator on X in the above equation is known as *pseudo-inverse* of $\mathbf{X}$. However, if $\mathbf{X}$ is a square matrix, this pseudo inverse reduces to simple matrix inversion. Thus, the vector $\hat{\mathbf{H}}_{LS}$ consists the estimated channel gains at each of the pilot locations. Interpolation techniques are employed to estimate the channel gains at data subcarriers.

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