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Implementation and Verification of Novel OFDM Modem for air-acoustic Channel

[1]Vaibhav Bhushan Tyagi

[1]Associate Professor
[1]Department of Electronics and Communication Engineering
[1]ISBAT University, Kampala, Uganda

Abstract: Effective communication through acoustic waves has abundant applications for researchers, marine commercial operators and defense organizations. The propagation of electromagnetic waves is very limited over long distances in seawater, acoustics provides the most apparent choice of channel to qualify acoustic communications. The purpose of this research to study and implement complete Orthogonal Frequency Division Multiplexing for acoustic channel and test it for different channel parameters. An OFDM modem for the acoustic channel developed for the real-time operation. The process of development includes study and simulation of signal processing algorithms in MATLAB. The algorithms result could be matched better to real time application of OFDM modem. The channel conditions (Ambient Noise, Transmission Loss, SNR at Rx etc.) and expected modem performance (BER etc) were observed by experiments.

Index Terms **- OFDM, MODEM simulation, FFT, IFFT, cyclic prefix, ambient noise, transmission loss, SNR.**

I. INTRODUCTION

Basic principles of OFDM OFDM consists of many orthogonal carriers each carrier is called a subcarrier or tone, depending on literature [1] and [2]. Usually some sort of QAM (Quadrature Amplitude Modulation) is used to modulate the symbols that are transmitted on the subcarriers. When a symbol is transmitted on a subcarrier its transmission time is extended N times. However, there is no reduction in symbol rate since there are N subcarriers transmitting N symbols during the time interval NT, where T is the original symbol rate. All symbols that are transmitted during the time interval NT forms an OFDM symbol. The advantage with OFDM systems is the ability to completely remove ISI (Inter Symbol Interference) between OFDM symbols.

The ISI is usually removed by adding a cyclic prefix to the OFDM symbol before transmitting it.A disadvantage with an OFDM system is that usually the subcarriers will not be orthogonal when received at the receiver due to Doppler shift and different frequencies in the local oscillators at the transmitter the receiver [4][10].

Hence, this frequency offset has to be estimated. Since the ISI can be removed; each subcarrier will experience only a flat fading channel. This statement would also hold for an FDM system (Frequency divisionmultiplexing), but in FDM there are guard bands between each carrier. Where as in OFDM there are no guard bands, it is even so that the different subcarriers share some of the spectra.

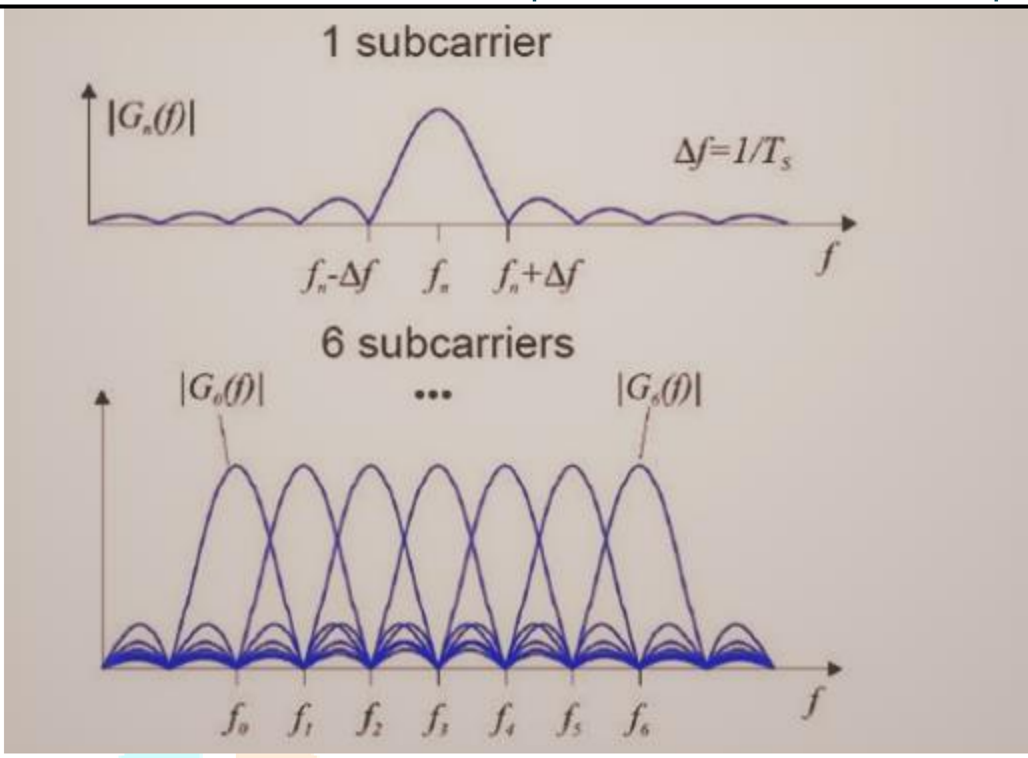


Fig1.1 Spectrum of OFDM Symbol

In Figure 1.1 there are six subcarriers, each subcarrier overlaps in some part all the other subcarriers. However, a receiver can still extract the symbols sent on each subcarrier since the subcarriers are orthogonal, i.e., at energy maximum of each subcarrier no other subcarrier contributes with any energy.

<u>Block Diagram:</u>

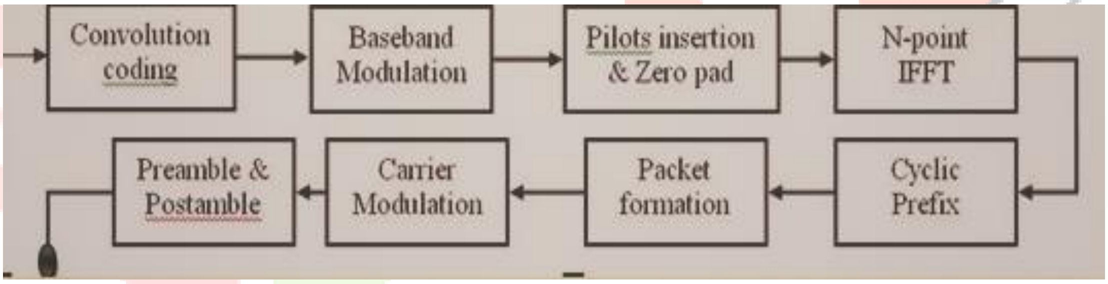


Fig.1.2 Basic block diagram of OFDM Transmitter

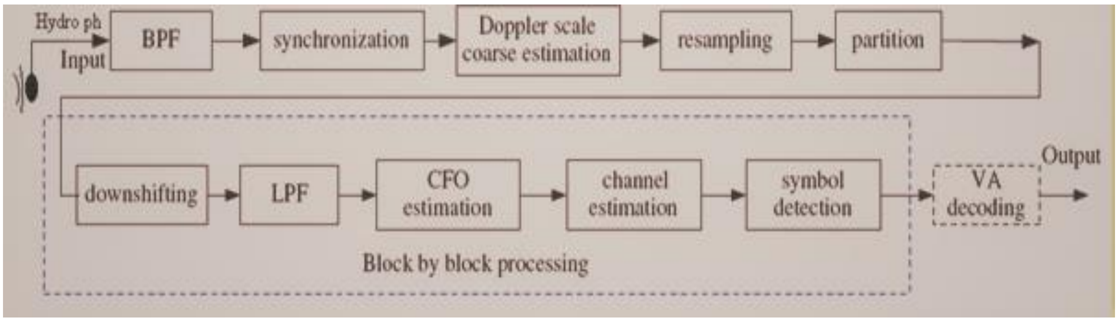


Fig.1.3 Basic block diagram of OFDM Receiver

For this study secondary data has been collected. From the website of KSE the monthly stock prices for the sample firms are obtained from Jan 2010 to Dec 2014. And from the website of SBP the data for the macroeconomic variables are collected for the period of five years. The time series monthly data is collected on stock prices for sample firmsand relative macroeconomic variables for the period of 5 years. The data collection period is ranging from January 2010 to Dec 2014. Monthly prices of KSE - 100 Index is taken from yahoo finance.

II. FLOW OF BASIC OFDM SYSTEM

The main reason that the OFDM technique has taken a long time to become a prominence has been practical [1]. 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 flow of OFDM transmitter and receiver is given in the block diagrams Figure2.1. 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.

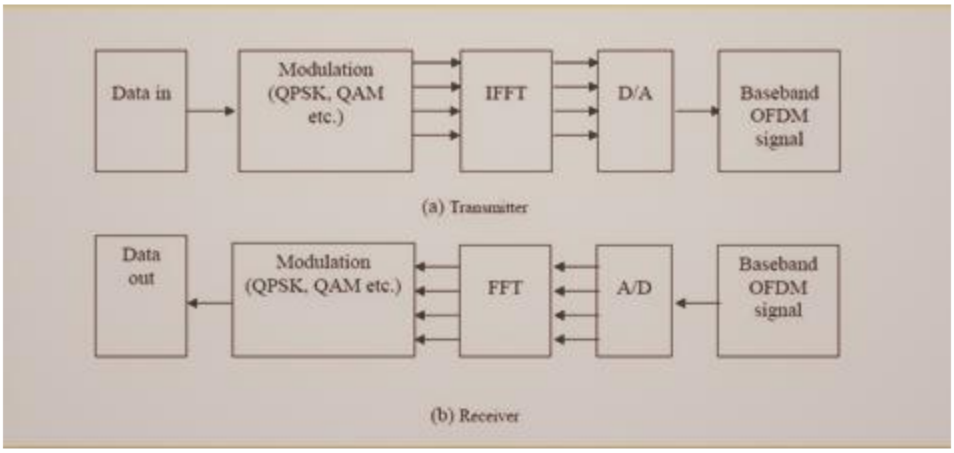


Fig.2.1 Block Diagram of OFDM modulation and demodulation

Figure.2.1 illustrates the process of a typical FFT-based OFDM system. The incoming serial data is first converted form serial to parallel and grouped into *x* bits each to form a complex number. The number *x* determines the signal constellation of the corresponding sub-carrier, such as BPSK or QPSK or any higher modulated symbol [4]. The complex numbers are modulated in the base band by the inverse FFT (IFFT) and converted back toserial data for transmission. A guard interval is inserted between symbols to avoid inter symbol interference (ISI) caused by multi-path 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 the channel information. By carefully selecting the carrier spacing, the OFDM signal spectrum can be made flat and the orthogonality among the sub-channels can be guaranteed.

OFDM system has the ability to completely remove ISI between two OFDM symbols[7]. A simple solution, which would remove the ISI, is to simply insert a guard interval between the OFDM symbols, i.e., simply wait for all the multipaths reflections of the transmitted OFDM symbol to fade out before transmitting another OFDM symbol

Fig.2.2 Remove ISI through guard interval

There is however a problem using guard intervals to remove the ISI, which has do with the property of the DFT. The DFT is cyclic, so if the received OFDM symbol is not cyclic, it will cause ICI (Inter Carrier Interference) between the subcarriers. The solution is to add a cyclic extension to the OFDM symbol before transmitting it [3]. The cyclic extension that is added before the transmission is simply the end part of the OFDM symbol that has been copied and transmitted before the OFDM symbol as in Figure 2.3. The cyclic extension is referred to as CP (Cyclic Prefix).

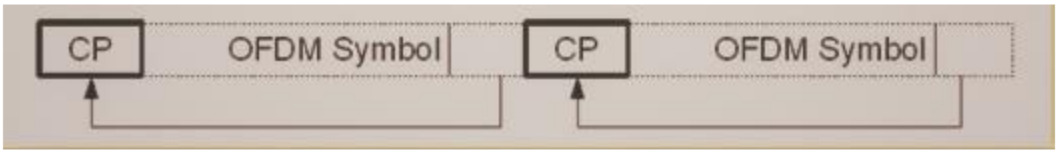


Fig.2.3 Cyclic Prefix

The length of the CP is set to at least to the maximum length of multipath delay of the radio channel, i.e. to at least the same number of taps as the channel.

III. OFDM System Design Basics

System design always needs sound and comprehensive understanding and consideration of crucial parameters. Basic OFDM philosophy is to decrease data rate at the sub-carriers, so that the symbol duration increases, thus the multi-path effects are removed. This poses a challenging problem, as higher value for CP interval will give better result, but it will increase the loss of energy due to insertion of CP. Thus, a trade-off between these two must be made for a reasonable design.

OFDM systems depend on four system design requirements:

- **Bandwidth:** Bandwidth is always the scarce resource. The amount of bandwidth will play a significant role in determining number of sub-carriers, because with a large bandwidth, we can easily fit in large number of sub-carriers with reasonable guard space.
- **Bit Rate:** The overall system should be able to meet the data rate required by the users.
- **Delay Spread:** Delay spread will depend on the user environment. For indoor environment maximum delay spread is around few hundreds of n sec at most, whereas for acoustic environment it is up to 10ms. So the length of CP should be determined according to the tolerable delay spread.
- **Doppler values:** The Doppler value increases with the increase in velocity of the user. So velocity of expected users must be considered carefully.

OFDM system design parameters:

- **Useful symbol duration**: The useful symbol duration *T* affects the carrier spacing and coding latency. To maintain the data throughput, 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 [10]. Generally, the useful symbol duration should be chosen so that the channel is stable for the duration of a symbol.
- **Sub Carrier spacing:** The sub-carrier spacing Δf is inversely related to the Useful symbol duration. Larger the symbol duration, smaller will be the sub carrier spacing. Thus, the lower limit of sub-carrier spacing is decided by the coherence time of the channel i.e. the time for which the channel is stable. The upper limit of Δf is decided by the coherence bandwidth of the channel. The spacing should be much below the coherence bandwidth so as to alleviate frequency selective fading. Further, Larger the sub carrier spacing the better the phase noise immunity becomes. Hence, it is preferable to keepa sufficiently larger sub carrier spacing and try to maintain it across most of the channel bandwidths by assigning ranges for each FFT size.
- **Number of carriers**: The number of sub-carriers can be determined based on the channel bandwidth, data throughput and useful symbol duration. 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.
- **Guard time (CP interval) and symbol duration:** A good ratio between the CP interval and symbol duration should be found, so that all multi-paths are resolved and not significant amount of energy is lost due to CP. As a rule of thumb, the CP interval must be two to four times larger than the *Root-Mean-Square* (RMS) delay spread.
- **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 dn = an+jbn. The symbols an and bn can be selected to (±1, ±3) for 16QAM and ±1 for QPSK. In general, the selection of the modulation scheme applying to each sub-channel 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 sub-channels for layered services.

OFDM performance expectations

It should be noted that for the additive white Gaussian channel, OFDM and single carrier modulation have comparable performance. However, the acoustic channel consists of various other impairments: random noise, impulse noise, multi-path distortion, fading and interference [6].

- **Multi-path/fading:** It is believed that with properly designed guard interval, interleaving and channel coding, OFDM is capable of handling very strong echoes. In addition to channel fading, time-variant signals caused by transmitter swaying, AUV fluttering and even wave swaying generate dynamic ghosts and consequently produce errors in digital transmission. With its parallel transmission structure as well as the use of coding, OFDM systems might present advantages in fading and time-invariant environments.
- **Phase noise and jitter:**An OFDM system is much more affected by carrier frequency errors. A small frequency offset at the receiver compromises the “orthogonality” between the sub-channels, giving degradation in a system performance that increases rapidly with frequency offset and with the number of sub-carriers. Phase noise and jitter can be influenced by the transmitter up-converter and tuner. A possible solution is the use of pilots which can be used to track phase noise in the demodulation. However, this is done under the penalty of reducing the payload data throughput.
- **Carrier recovery / Equalization:** In the severe channel conditions, such as low C/N, strong interference and fading, OFDM signal must be designed to provide robust carrier recovery. Carrier frequency detection could be one of the biggest limitations in OFDM design. The use of pilots and reference symbols are efficient methods for carrier recovery and sub-channel equalization. A pilot can be a sine wave or a known binary sequence. A reference symbol can be a chirp or a pseudo-random sequence.The two-dimensional (time/frequency) signal feature in OFDM makes pilot and reference symbol insertion very flexible [3]. Pilots can be inserted in frequency-domain (fixed carriers) and reference symbols in the time domain (fixed data packets). Because they are transmitted at the predeterminedpositions in the signal frame structure, it can be captured in the receiver whenever the frame synchronization is recovered. In a frequency-selective channel, high correlation between the complex fading envelopes of the pilots and data must be ensured. The appropriate complex correction can be obtained by interpolating among the pilots. Interpolation in real and imaginary parts of the complex fading envelopes outperformed the interpolation in amplitude and phase.For an OFDM system, assuming multi-path delay is less than the guard interval, a frequency domain one-tap equalizer could be used for each sub-channel to correct the amplitude and phase distortions [8]. This corresponds to 4 real multiplication-accumulations per data symbol. Additionally, the FFT operations requires a computational complexity that is proportional to C* 2 log (M), where M is the size of the FFT and C is the constant between 1.5 to 4 depending on the FFT implementation. The number of pilots and

reference symbols used in an OFDM system determines the trade-off between payload capacity and transmission robustness.

- **Impulse interference:**OFDM is more immune to impulse noise than single carrier system, because an OFDM signal is integrated over a long symbol period and the impact of impulse noise is much less than that for single carrier systems. As a matter of fact, the immunity of impulse noise was one of the original motivations for MCM. It has been shown that the threshold level for the impulse noise, at which errors occur, can be as much as 11 dB higher for MCM than for a single carrier system. Meanwhile, studies indicated that the best approach of impulse noise reduction for OFDM involves a combination of soft and hard error protection.
- **Peak-to-average ratio:** The peak-to-average ratio for a single carrier system depends on the signal constellation and the roll-off factor of the pulse shaping filter (Gibbs' phenomenon). For the Grand Alliance 8-VSB system (single carrier rival for the HDTV broadcast), roll-off factor=11.5 %. The corresponding peak-to-average power ratio is about 7 dB for 99.99 % of the time.
- **Nonlinear distortion:**Since a transmitter is a nonlinear device, clipping will always happen for OFDM signal. However, clipping of an OFDM signal is similar to the impulse interference on which OFDM systems have strong immunity. Tests show that when clipping occurs at 0.1% of the time, the BER degradation is only 0.1-0.2 dB. Even at 1% of clipping, the degradation is 0.5-0.6 dB. However, the BER performance of OFDM system under nonlinear distortion might not be the decisive factor. When clipping occurs, energy would spill into the adjacent channels. More studies are required in this area. It has been reported that, for an OFDM system, a 9 dB output back-off causes negligible BER degradation and adjacent channel interference. Another study indicated that, for modern solid-state transmitters, a prudent back-off level would be around 6 dB.

IV. OFDM TRANSMITTER AND RECEIVER DESIGN

The structures chosen for implementation of OFDM based modem is derived from basic operations carried out for OFDM symbol generation. Apart, general digital communication modules have been included. The various signal processing modules of the Transmitter and Receiver have been implemented with specific attention to the characteristics of the UW Channel. This chapter describes the final structures that were selected for implementation of the OFDM-based data modem for the UW channel. This is followed by channel parameter determination and setting of OFDM design parameters.

The main features of a practical OFDM system are as follows:

- Some processing is done on the source data, such as coding for correcting errors, interleaving and mapping of bits onto symbols. An example of mapping used is QPSK.
- The symbols are modulated onto orthogonal sub-carriers. This is done by using IFFT
- Orthogonality is maintained during channel transmission. This is achieved by adding a cyclic prefix to the OFDM frame to be sent. The cyclic prefix consists of the L last samples of the frame, which are copied and placed in the beginning of the frame. It must longer than the channel impulse response.
- Synchronization: the introduced cyclic prefix can be used to detect the start of each frame. This is done by using the fact that the L first and last samples are the same and therefore correlated. This works underthe assumption that one OFDM frame can be considered to be stationary.
- Demodulation of the received signal by using FFT
- Channel equalization: the channel can be estimated either by using atraining sequence or sending known so-called pilot symbols at predefined sub-carriers.

Transmitter Structure: The transmitter section of the data modem comprises of the data source, Convolutional encoder, symbol mapping device, serial-to-parallel conversion block, differential encoder, IFFT block. The block diagram of the Transmitter is shown in *Figure 6.2* Since the modem was initially designed for the purpose of data transfer only, the message to be transmitted is assumed to have no redundancy. Hence, no Source Coding module has been included in the Transmitter. However, the UW Modem may also be used for digital transmission of audio/speech. In such an application the inclusion of a suitable Vocoder will be required.

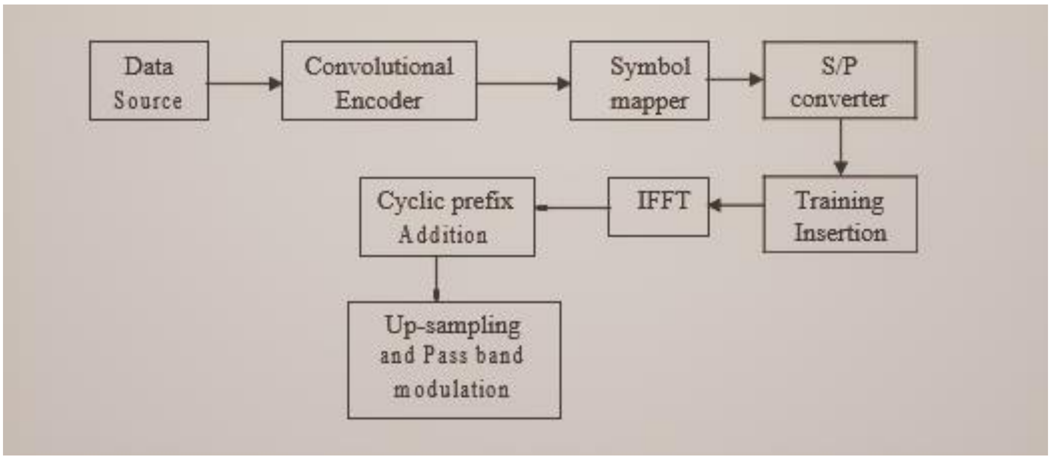


Fig. 4.1 OFDM transmitter block diagram

Receiver Structures: The receiver structure of the modem comprises of the Packet Synchronization/Recognition module, demodulation and down sampling module, Cyclic prefix removing module, FFT block, Differential decoder, Symbol de-mapper and Viterbi Decoder. The block diagram of the receiver is shown in *Figure 6.4*. All the above-mentioned modules have beenimplemented in software so that after sampling the received signal the entire processing is performed digitally.

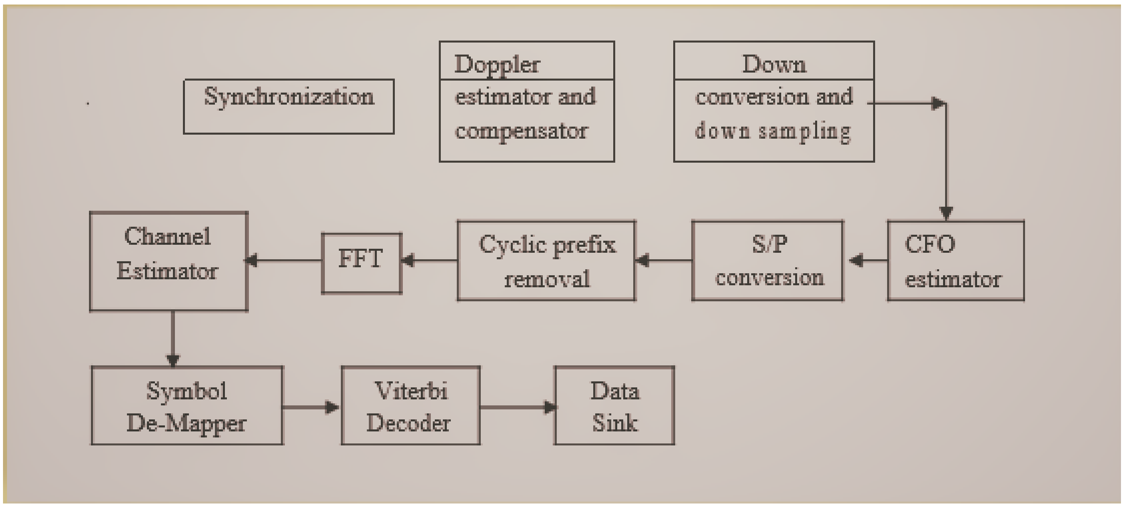


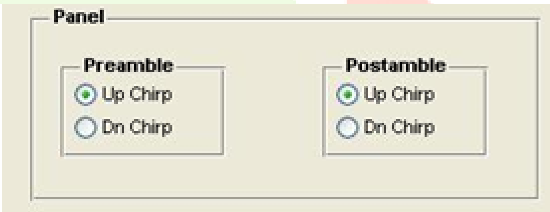
Fig. 4.2 OFDM Receiver block diagram

V. MODEM SIMULATION

A user-friendly graphic user interface is developed to test modem in different parameters. Which will have access on baseband modulation, packet formation, sampling frequency, carrier frequency, code rate etc at any time we can check any variable and plot it.

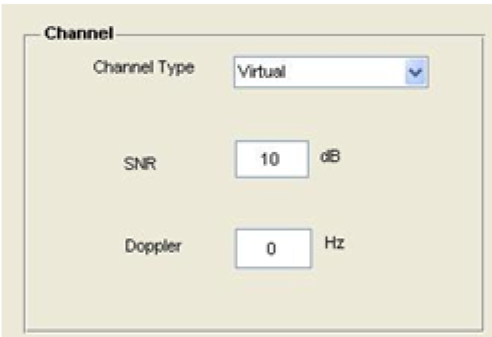
- **Preamble and Postamble selection**

Facility of selecting preamble and posamble is also provided so that it would help to find optimized preamble and postamble. Two radio button are given in GUI to select one of up or down chip as preamble and same for postamble.



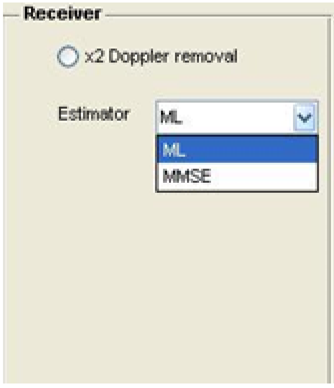
- **SNR input**

In virtual mode of modem, we have to provide SNR for the receiving signal after passing through AWGN channel. Default value of SNR is taken as 10dB.



- **Estimator Selection**

One can toggle between Least Squares or MMSE estimator using this popup menu and compare between two estimator at different SNR



VI. SIMULATION RESULT ON VIRTUAL AND REAL CHANNEL

Modem was tested on the real channel using speakers as transmitter and mike as receiver. The better results can be achieved using specially designed hardware. The following figure shows the results.

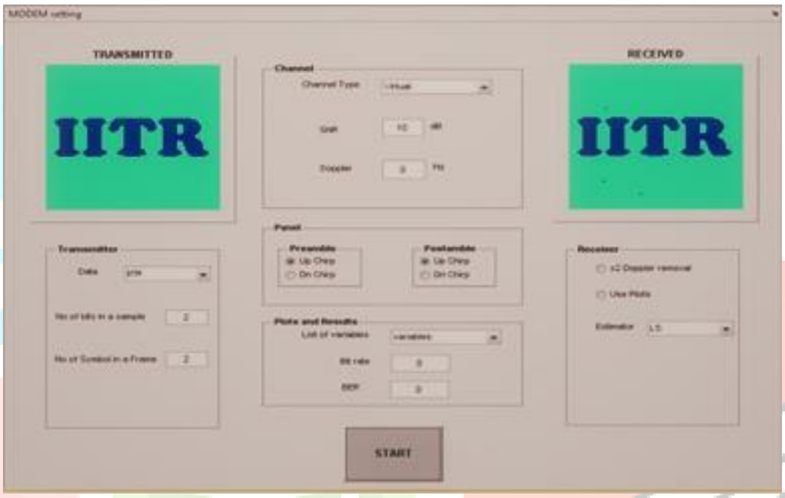


Fig.6.1 Simulation results for Virtual Channel

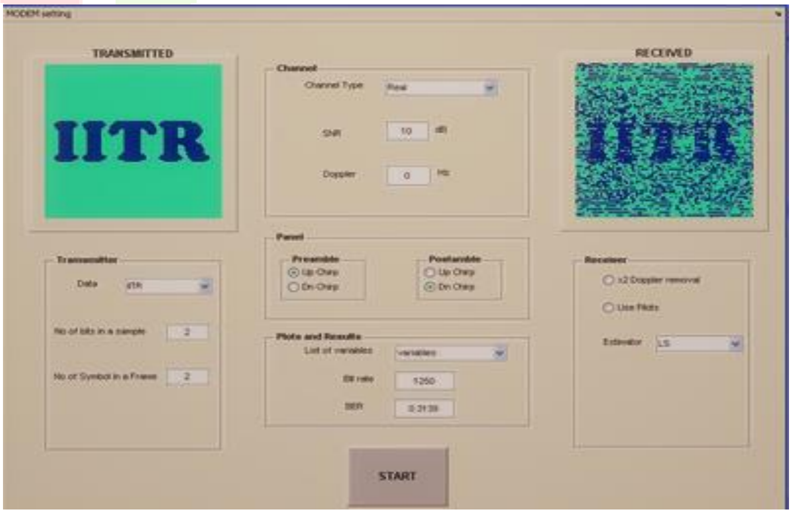


Fig.6.2 Simulation results for Real Channel

VII. COCLUUSION AND FUTURE SCOPE

Modem is completed and tested in different channel conditions for virtual as well as real channel in air. Modem tested for different SNR, Doppler, baseband modulation etc. modem had shown encouraging results. An OFDM modem for the acoustic channel was developed for real-time operation. The development process included studies and simulations of signal processing algorithms in MATLAB. Thus, results of the algorithms could be matched better to real time application of OFDM modem. User friendly GUI has been developed so one can test modem in different channel conditions. The modem's parameters were chosen in accordance with the end application and the expected conditions in the acoustic channel. The channel conditions (Ambient Noise, Transmission Loss, SNR at Rx etc.) and expected modem performance (BER etc) were observed by experiments. A MATLAB based modem for the acoustic channel was realized for operation in Real-Time. Preliminary trials of the modem in offline mode and through channel have yielded encouraging results. Although some aspects of the modem have been identified for improvement, only thorough lab and field trials will bring out the shortfalls of the modem, leading to further improvements in design.

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