PERFORMANCE COMPARISON OF OFDM AND DSSS ON AERONAUTICAL CHANNELS

Daniel Ehichioya, Arya Golriz
Advisors: Dr Arlene Cole-Rhodes, Dr Richard Dean
Morgan State University

ABSTRACT

This paper develops a performance framework for OFDM by contrasting its performance with Direct Sequence Spread Spectrum (DSSS) over aeronautical channels. Each of the OFDM and DSSS modulated simulations are put through the channel and compared on terms of signal to noise ratio (SNR) versus bit error rate. The simulation will show that DSSS will have better power efficiency on multipath channels because the rake receiver adds all multipath components to strengthen the receiver. By contrast OFDM with an equalizer will have better spectrum efficiency results where QAM modulation of multiple tones allows for high data rates in a limited bandwidth. This work develops a framework for contrasting the performance of the rake receiver and the equalizer for operation on multipath channels. By comparing these schemes on various channels the choice of OFDM for iNET can be clearly understood and evaluated.

INTRODUCTION

Multi-carrier modulation schemes, like Orthogonal Frequency Division Multiplexing (OFDM) have been successfully applied to a wide variety of communication systems for several years because of its superior performance over a time dispersive aeronautical channel. It is a spectrally efficient modulation scheme that can support very high data rates. It is no surprise that OFDM has been chosen for the physical layer for the iNET Telemetry Network System. This Telemetry network system uses state of the art network technologies to augment current telemetry standards based on IRIG 106 providing bi-directional shared communication links between Test Article and Ground Station, whilst maintaining Quality of Service and efficient spectrum utilization [2].

OFDM signals transmitted over a multipath fading channel experience random amplitude and phase variations due to reflection and diffraction by obstacles between the transmitter and the receiver. For coherent signal detection, an accurate estimation of the channel information for equalization is necessary.

Pilot symbols are inserted into the input data stream and are used at the receiver to estimate channel characteristics. The channel transfer function is computed at the pilots estimated for the entire schemes using interpolation and minimum mean square error (MMSE) filters [4].

Direct Sequence Spread Spectrum (DSSS) is a modulation scheme that is used in digital communication systems. Similar to OFDM, it has good immunity to multipath and fading. The DSSS rake receiver uses sub receivers to independently decode each multipath component and later combine them constructively resulting in a much higher SNR [7].

In this paper, we present the transmitter and receiver model for the OFDM scheme. We analyze the performance improvement attained from adding a cyclic prefix to the OFDM symbols. Pilot assisted channel estimation and equalization are also presented for the coherent detection of OFDM symbols. Three different pilot arrangement schemes are considered for the channel estimation each offering different levels of performance. Finally DSSS with a RAKE receiver is presented as a benchmark to which the performance of OFDM with equalization will be compared. The comparison will be on the basis of power and spectrum efficiency. By comparing these schemes over various channels, the choice of OFDM for INET can be clearly understood.

OFDM SYSTEM MODEL

Orthogonal Frequency Division Multiplexing is a multi-carrier digital modulation scheme that employs closely spaced orthogonal sub-carriers for data transmission. The input data stream is divided into several parallel lower rate sub streams; each sub stream is associated with a given sub-carriers to be transmitted simultaneously. Even though the sub carriers are spaced such that they overlap, the principle of orthogonality ensures that there is no cross talk or interference between the sub carriers. This eliminates the need for guard bands between the sub carriers allowing for higher data rates than other multi-tone schemes. OFDM is also less susceptible to narrowband interference, flat fading and other aeronautical channel attributes. The OFDM transmitter system model used in this paper is illustrated in figure 1 above.

Transmitter Structure

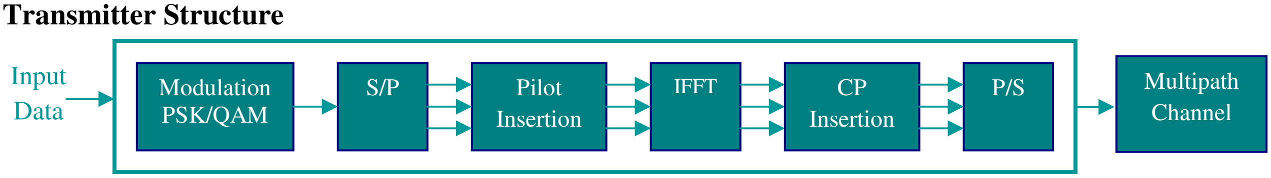


Figure 1: OFDM Transmitter Model

The input binary data sequence is first spilt into N parallel streams for N sub-carriers and then is phase and/or amplitude modulated using Quadrature phase shift keying (QPSK) or Quadrature amplitude modulation (QAM). Pilot symbols for channel estimation are then inserted the data symbol sequence. The OFDM symbol vector is modulated onto sub carriers using the Inverse Fast Fourier Transform

(IFFT) and the cyclic prefix (CP) is added. The parallel sub-streams (P/S) are concatenated back into a serial stream convolved with the multipath channel.

The cyclic prefix is used to mitigate the effect of Inter-symbol Interference (ISI) and Inter-carrier Interference (ICI) introduced from convolution with the multipath channel. The cyclic prefix is generated by copying samples from the end of the OFDM symbol and appending them to the front of the OFDM symbol. For the effect of ISI to be completely eliminated, the length of the cyclic prefix must be longer than the length of the channel impulse response. Doppler shift from the aeronautical channel destroys the orthogonality of sub-carriers. A loss of orthogonality introduces cross-talk between the sub-carriers causing the main premise behind OFDM to fail. The cyclic prefix maintains orthogonality, mitigating the effect of ICI.

Receiver Structure

The OFDM receiver structure is illustrated above in figure 2:

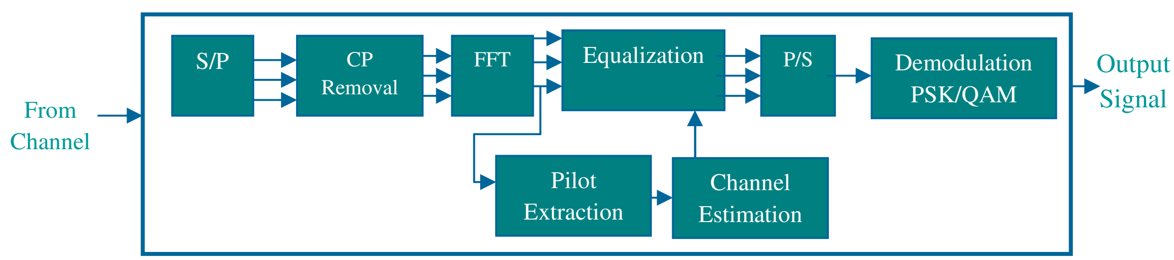
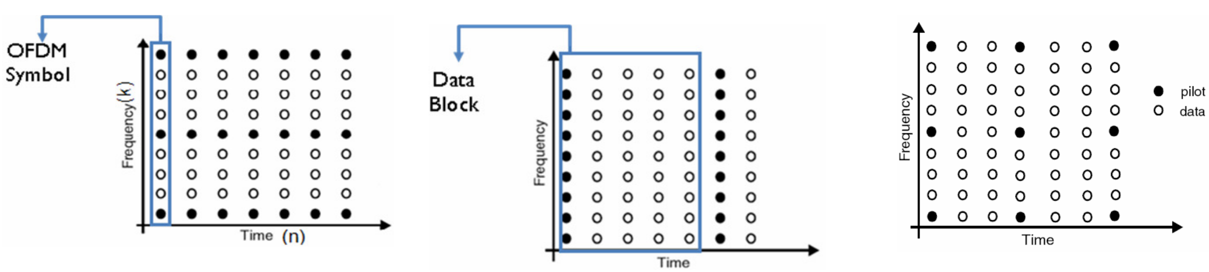


Figure 2: OFDM Transmitter Model

The received signal is split into parallel sub streams (S/P) and the cyclic prefix is discarded. The FFT transform is used retrieve the signal from the sub carriers. For coherent detection, channel estimation and equalization is necessary. The equalized data is then demodulated and the output signal is achieved. There are several pilot arrangement schemes each yielding different performance.

Pilot Symbol Channel Estimation

The channel can be viewed as a 2-D lattice on a time-frequency plane sampled at pilot positions and the channel characteristics between pilots are estimated by interpolation. The different pilot arrangement schemes are shown in figure 3 below:



(a) Comb Type *(b) Block Type* *(c) Combined*

Figure 3: Pilot Arrangement Schemes

The comb type channel estimation scheme is illustrated in figure 5a. In this scheme, pilots are inserted uniformly within each OFDM symbol and constantly transmitted at all times. The channel conditions from the pilot locations can be generated in the using least square estimates as

$$H_{n,k}^{p} = \frac{Y_{n,k}^{p}}{X_{n,k}^{p}} + \frac{N_{n,k}^{p}}{X_{n,k}^{p}} \qquad (1)$$

where $H_p(n,k)$ is the channel estimate, $Y_p(n,k)$ is the received pilot symbol, $X_p(n,k)$ is the transmitted pilot symbol and $N_p(n,k)$ is the additive white Gaussian noise at the n^{th} time on the k^{th} sub carrier. The estimated channel conditions on all sub carriers can be obtained using 1-D interpolation schemes. Low pass interpolation has been shown in [4] to have the best performance. Low Pass Interpolation is performed by inserting zeros into the original sequence of least squared (LS) estimates from the pilots and then applying a low pass finite impulse response (FIR) filter that allows the original data to pass through unchanged. This FIR filter interpolates such that the mean square error between the interpolated points is minimized.

Block type channel estimation is illustrated in Figure 3b above. In this scheme, pilot symbols are inserted on all sub carriers and transmitted at different time intervals. The channel characteristics are estimated from the pilot locations using LS estimates. The estimated channel characteristics from the pilots is put through an MMSE filter and applied to the data sub carriers within a data block until the arrival of the next set of pilot symbols. According to [6], The MMSE estimator is modeled as:

$$H_{MMSE} = U\tilde{\Delta}U^{H}H_{LS} \qquad (2)$$

where $\tilde{\Delta}$ is a rank reduced matrix of singular values ,U is a unitary matrix of singular vectors from the SVD of the channel correlation matrix and H_{LS} is the LS estimate of the channel vector computed as $\boldsymbol{X_p^{-1}Y}$ at the pilot positions, $\mathbf{X}_p$.

The combined scheme illustrated in figure 3c above combines the block and comb type pilot schemes. Pilot symbols are inserted uniformly within select OFDM symbols and transmitted at select times. The channel conditions at the pilot sub carriers are computed by LS estimates and the channel conditions at the data sub carriers are generated by interpolation similar to the comb type estimation scheme. The combined scheme is expected to perform slightly worse than the other two scheme because it uses less pilot symbols.

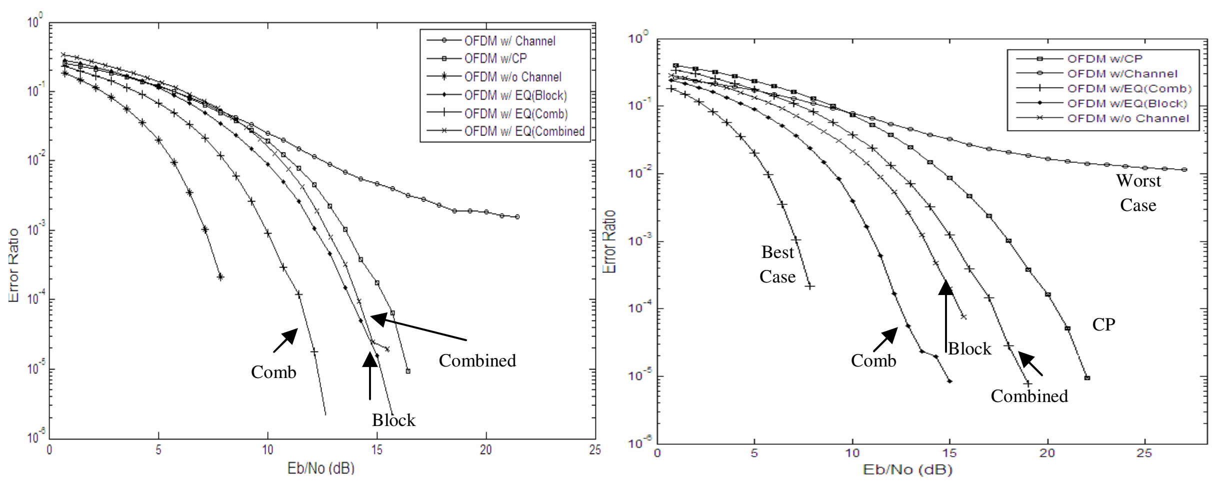
Using the estimated channel vector from data interpolation from the pilot symbols, the equalizer can be modeled as a zero forcing equalizer [3]. The zero-forcing equalizer applies the inverse of the estimated channel to the received signal to restore the signal. The equalizer is inserted on a per sub carrier basis. This means that each sub-carrier is equalized independently from the others. For N sub carriers, N equalizers will be required.

OFDM SIMULATION RESULTS

In the simulations, we consider two channel models, a constant non varying channel model and a time varying model. The constant channel model is a multipath channel with three non zero taps. The channel tap amplitudes remain constant over time. The second channel model is a time varying channel also with three non-zero taps however the channel model is designed such that channel tap amplitudes can be varied with time with different levels of severity. The channel model also incorporates the effect of Doppler shift and additive white Gaussian noise. The simulation was done using Matlab using the following parameters:

Channel Taps	[1, 0, 0.5, 0,0.2]
Number of sub carriers	64
FFT Length	64
Modulation scheme	QPSK
Cyclic Prefix length	8
Pilot Spacing	8

The resulting plots are displayed in figure 4 below



(b) Constant Channel Scenario *(a) Time Varying Channel Scenario*

Figure 4: Performance of OFDM with Cyclic Prefix and Equalization

Figure 4 above shows the bit error ratio versus SNR plots for the OFDM simulation with cyclic prefix and equalization over two channel models. The worst case simulation was done without the cyclic prefix, channel estimation or equalization. In both scenarios, the error ratio reaches an irreducible error floor. The best case simulation was done without multipath. The OFDM scheme was implemented over an additive white Gaussian Noise (AWGN) channel. This scenario represents the ideal operating conditions for OFDM. The best and worst case simulations provide an upper and lower performance threshold for the OFDM scheme.

Introducing the cyclic prefix significantly improves the performance of the OFDM scheme in both scenarios. Looking at both plots in figure 4, the error floor is eliminated. Implementing the OFDM scheme over a time varying channel model is expected to have worse performance that the constant channel model as evident in figure 4 above. In the constant channel model scenario, an error ratio of 10^{-6} is achieved at an SNR of about 17dB after the introduction of the cyclic prefix. In the time varying channel model scenario which incorporate fading and Doppler shift into the channel characteristics, an error ratio of 10^{-6} is achieved at about 23dB.

The different pilot arrangement schemes perform differently as seen in figure 4 above. The comb scheme where pilot symbols are inserted on sub carriers and transmitted at different time intervals outperformed the other two schemes. An error ratio of 10^{-6} is achieved at about 16dB. In the block scheme where pilots are inserted uniformly in the OFDM symbol and then interpolated achieves an error ratio of 19dB at about 10^{-6}. With channel estimation and equalization, the OFDM scheme achieves an error ratio of 10-6 at an SNR of about 16-21dB depending on the pilot arrangement scheme used.

DIRECT SEQUENCE SPREAD SPECTRUM (DSSS)

Direct Sequence Spread Spectrum is another modulation scheme used for radio signal transmission. DSSS with a rake receiver will serve as a performance benchmark to which the performance of OFDM with equalization. Both OFDM and DSSS are tolerable to poor channel conditions handling the effects of multipath in different ways. DSSS uses a rake receiver uses sub receivers to isolate each multipath component and constructively combines them resulting in an overall better channel. OFDM with equalization on the other hand eliminates the multipath components using pilot symbols to estimate the channel.

DSSS System Model

DSSS uses a pseudo-noise (PN) code, independent of the information data carrier signal used to modulate the information data. The PN code is ‘spread’ over a bandwidth much larger than that of the information signal. The DSSS signal is modulated by both the PN sequence and BPSK, which is used to vary the phase of the signal. In order to produce the DSSS signal, the BPSK and PN sequence are multiplied to produce the following: $s(t) = Ad(t)c(t)\cos(2\pi f_c t)$, where c(t) is the PN sequence. Figure 5 illustrates the DSSS transmitter and receiver model. The input data is phase modulated binary data with symbols rate R_s. The data is directly multiplied by a PN code with chip rate R_c which is independent of the data to produce the DSSS symbols. The multiplication of the phase modulated binary data and PN code spreads the bandwidth, R_s of the input data over the bandwidth R_c of the PN code. The spread occurs and then the baseband data pulses are multiplied with the PN sequence. Spread system signals are demodulated at the receiver by performing a cross-correlation with a copy of the PN code, which is produced at the transmitter. Cross-correlation with the same PN code de-spreads the signal and restores the modulated message in the same narrow-band as the original data. Synchronization of the PN code generators at the receiver and transmitter is vital because otherwise the signal may not be recovered.

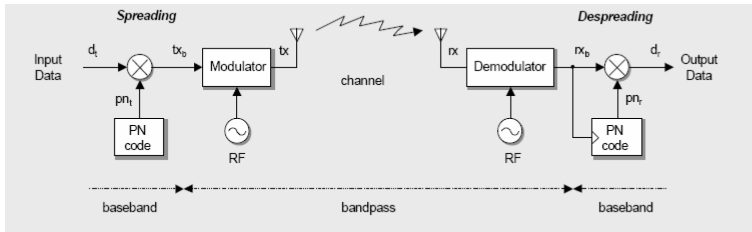


Figure 5: DSSS Transmitter and Receiver Model

Rake Receiver

A rake receiver is a radio receiver designed to counter the effects of multipath fading. Each component of multipath, such as line of sight, reflected, and scattered paths are picked up by sub-receivers and delayed slightly in order to tune them. Each component is decoded independently and at a later stage combined constructively in order to make the most use of the different transmission characteristics of each transmission path [7]. The end result of the rake receiver is that all these multipath components are then added in order to restore the signal to its original state. This is the main advantage of DSSS as opposed to OFDM because being able to use multipath to recreate the original signal, the probability of error in the received signal will be much less than that of OFDM.

In a fading environment such as an aeronautical channel, propagation delay in an aeronautical channel produces multiple versions of the transmitted signal at the receiver. A direct sequence system in combination with a rake receiver can almost completely mitigate multipath, making it a near optimal aeronautical channel by coherently combining resolvable multipath components. For this reason DSSS provides a good performance baseline for evaluation of OFDM performance in multipath.

PERFORMANCE OF OFDM VERSUS DSSS

In [3], Proakis analyses the performance characteristics of a linear equalizer over a discrete channel model with two normalized taps of equal amplitude. A channel model with taps of equal amplitude would introduce very high levels of ISI and can be considered as a worst case channel. Assuming the equalizer has infinite taps (best case), and adjusted on the basis of the MSE criterion, the corresponding output SNR can be shown to be

$$\gamma_\infty \approx \sqrt{\frac{2}{N_0}} \qquad N_0 < 1 \qquad (3)$$

The rake receiver on the other hand, operating under ideal conditions would combine both channel taps in the model creating an overall better channel. Theoretically, for a channel with two equal taps, the rake receiver would combine the multipath components, doubling the output SNR. Therefore assuming and input signal with amplitude, ε, and additive noise N_0, the input SNR would be $\frac{\varepsilon}{N_0}$and the output SNR would be twice the input. i.e. $\frac{2\varepsilon}{N_0}$ Assuming ε = 1, the following results are generated

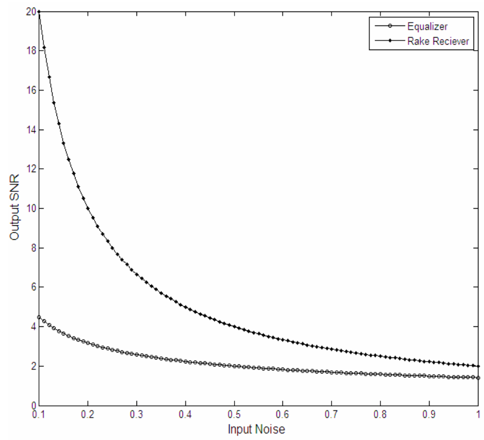


Figure 6: Performance of Theoretically ideal Equalizer and Rake Receiver

The figure 6 above illustrates the performance of an ideal equalizer of infinite tap length and an ideal rake receiver operating in a channel with normalized taps of equal amplitude. The channel is considered very poor condition and expected to introduce very high ISI. Comparing both plots, it is seen that the output SNR of the rake receiver significantly outperforms the equalizer. This is expected as the rake receiver combines the multipath components resulting in an overall better channel while the equalizer tries to eliminate the multipath components by inverting the channel response.

OFDM VERSUS DSSS SIMULATION RESULTS

The DSSS scheme with a rake receiver was simulated over the time varying channel model described in the previous section. The results are compared to that of OFDM with cyclic prefix and Equalization implemented over the same channel.

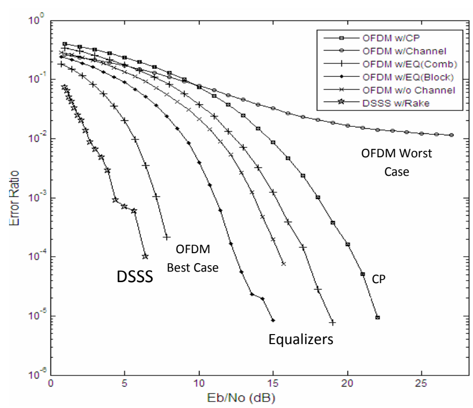


Figure 7: Performance comparison of OFDM and DSSS over an aeronautical channel

From the figure 7, it is seen that DSSS with a rake receiver grossly outperforms the best case OFDM. This means that even over fading aeronautical channel with Doppler shift, the DSSS scheme with a rake receiver out performs the best case OFDM scheme implemented over an impairment free channel From these results, it can be immediately inferred that DSSS with Rake receiver is the superior scheme However, for proper comparison, both schemes will be compared using power efficiency and spectral efficiency.

Power efficiency is the ability of a modulation scheme to preserve signal fidelity at low received SNR. It is measured as the required energy per bit Eb for a reference noise power spectrum. For this analysis, the error ratio threshold was set to 10^{-6} and the required Eb/No to achieve this threshold error ratio will be observed. From figure 7 above, it is observed that the DSSS achieves an error ratio of 10^{-6} at an SNR of about 8-9dB. OFDM with cyclic Prefix and equalization achieves the same error ratio at about 16-20dB depending on the channel estimation method.

Spectral Efficiency is the amount of data that can be transmitted over a given bandwidth based on the modulation scheme used. The simulations in this project do not compute the spectral efficiency of DSSS or OFDM. The data rates used for the comparison were derived from the 802.11 protocol standard. From the IEEE standard, with 64-QAM modulation and a coder of rate ½, OFDM can attain a maximum data rate of 54Mbps. DSSS on the other hand can only achieve up to maximum data rate of 11Mbps under similar conditions.

Trade-Off	Modulation Scheme	Power Efficiency*	Spectral Efficiency**
	OFDM	16-20dB	54Mbps
	DSSS	8-9dB	11Mbps

*Eb/No required for Error Ratio of 10^{-6} **Derived from 802.11 Standard

OFDM makes very efficient use of the available spectrum but requires a high SNR of 16-20dB to attain an error ratio of 10^{-6}. DSSS on the other hand, is not as spectrally efficient as OFDM only able to support a data rate of 11 Mbps compared to 54Mbps supported by OFDM however DSSS with the Rake Receiver is able to attain an error ratio of 10^{-6}.From the trade off analysis, it is seen that OFDM with equalization requires much higher SNR to achieve similar error ratios with DSSS with a rake receiver. However from the INET needs discernment, the proposed telemetry network system will support Quality of Service application requiring very high data rates. Even though OFDM requires higher SNRs, it makes very efficient use of limited spectrum resources, achieving much higher data rates than DSSS with a rake receiver and more suitable to the INET project.

CONCLUSION

In this paper, the OFDM model has been described and analyzed. The insertion of a cyclic prefix was shown to improve the performance of the OFDM scheme mitigating the effects of ICI and ISI. Three different pilot arrangement schemes were presented for channel estimation and equalization. Each pilot arrangement scheme provided different levels of performance with the comb type pilot scheme having the best performance of the three under the channel conditions used. The combined type pilot scheme was shown to perform very similar to the block scheme but it uses much less pilot symbols for estimation making more bandwidth available for actual data transmission. DSSS with a rake receiver was presented as a performance benchmark to which OFDM with equalization was compared. There is trade-off between power and spectral efficiency with OFDM with equalization less power efficient than DSSS with a rake receiver requiring higher SNRs to achieve similar errors but is more spectral efficient, able to support much higher data rates than DSSS. OFDM satisfies the QOS requirement with its high data rate making it ideal for the INET Telemetry Network system.

ACKNOWLEDGEMENT

The authors acknowledge the support of the DOD CTEIP and INET program offices for this effort.

REFERENCES

[1] Rappaport T, Wireless Communications - Principles and Practices, IEEE Press, Prentice Hall 1996

[2] US Navy,T & E Community, CTEIP Development. *iNET Needs Discernment Report*. May 2004

[3] Proakis John G., Digital Communication s. New York: McGraw-Hill, 2001.

[4] Shen Y., Martinez Ed., "*Channel Estimation in OFDM Systems*" Freescale Semiconductor, AN3059

[5] W. Henkel, G. Taubock, P.O. Bjoresson, and A. Johansson, "*The Cyclic Prefix of OFDM/DMT - an* analysis," in *Proc. IEEE International h Seminar on Broadband Communications Access-Transmission* 2002, pp. 22.1–22.3.

[6] Edfors Ove, Sandell, M, Van De Beek J.J. Wilson S., Borjesson Per O, "*OFDM Channel Estimation by Singular Value Decomposition*" IEEE Transactions on Communications Vol 26. pp 931-939 July 1996

[7] Dixon Robert, Spread Spectrum Systems 2nd Edition, John Wiley & Sons, Inc., NY. 1984.