ADAPTIVE MODULATION AND CODING

FOR

WIMAX SYSTEMS

By

WABO MAJAVU

FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
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CERTIFICATION OF APPROVAL

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Project Supervisor

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Wabo Majavu

ABSTRACT

This project is on design and implementation of adaptive modulation in Wimax systems for broadband wireless networks. The majority of the work done is on acquiring the cannel signal to noise ratio (SNR) and comparing two pilot aided SNR estimation techniques with a blind estimator. Reddy Noise power estimator and Subspace based estimator are pilot aided, both of which are a combination of channel estimation and noise estimation. The third is a blind autocorrelation based Linear Predictor Interpolator. Fixed transmission systems make use of average modulation and coding which has reasonable performance in both high and low SNR conditions in the communication channel. This results in channel bandwidth under-utilization in high SNR conditions. The use of adaptive modulation improves the spectral efficiency by making use of variable bit loading, depending on the prevailing SNR. A higher modulation and coding rate is used in high SNR conditions, while a lower and noise robust is used in low SNR conditions. The main task of the project is to do a performance analysis of SNR estimation algorithms by implementing each on the IEEE 802.16d standard for broadband wireless local and metropolitan area networks (WMAN) working model. The SNR estimation technique which results in optimal performance will later be used to in a feedback system which inputs the channel SNR into a control mechanism that makes the decision to switch modulation and coding rate based on a predetermined SNR threshold value for each rate that ensures acceptable bit error rate (BER). First the SNR estimation using the three algorithms is implemented in Wimax system, based on the transmission protocols specified in Wimax. The performance of the estimators is then compared by determining the mean square error and computation time for each as the performance criteria and to compare the performance of the unaided SNR estimator in comparison to the conventional pilot aided SNR estimators.

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LIST OF ABBREVIATIONS

ACF	Autocorrelation function
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BWA	Broadband Wireless Access
FFT	Fast Fourier Transform
LOS	Line of Sight
LPI	Linear Predictor Interpolator
MAN	Metropolitan Area Networks
MCM	Multicarrier Modulation
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnection
SNR	Signal to noise ratio
WIMAX	Wireless Interoperability Microwave Access
WLAN	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

1.1 Background Study

Wireless communication standards play a significant role in the development and advancement of wireless technology. There are a number of technologies for broadband wireless access (BWA) that are used for line of sight (LOS) coverage. However the increasing distances of data transmission require a technology that implements effective non-line-of-sight (NLOS) fixed broadband wireless access. This enables large data rates to be delivered to remote locations. Wireless Interoperability Microwave Access (WIMAX) provides this 'last mile' solution by providing coverage of up to 8 km in NLOS conditions and 50 km in LOS conditions.

The IEEE 802.16 air interface standards, referred to as Wimax by the Wimax forum, is a specification for the base concept of Metropolitan Area Network (MAN), which is fixed wireless because the distance between the subscriber and base station is fixed. This enables the transmission of video, voice while maintaining a reliable and fast link. The standard specifies operation of communication systems with frequencies between 10 GHz and 66 GHz. The first version of IEEE 802.16 adopts orthogonal frequency division (OFDM) to deal with multipath which is a result of NLOS and is specified for licensed service delivery. The IEEE 802.16-2004 standard is an extension of this standard and incorporates additions to the standard which are specified in the 802.16a and 802.16c updates. At very high frequencies NLOS communication is utilized therefore the sub-division of this spectrum (2-11GHz) incorporates NLOS capability. This technology is an improvement to the wired technologies for MANs such as Ethernet for connecting to the internet at high data rates, these improvements being wireless transmission at data rates of up to 70Mbps [1].The development of the IEEE 802 air interface standard is to facilitate conformity and interoperability amongst Wireless MANs by stipulating physical layer specifications. The physical layer is the first layer of the Open System Interconnection (OSI) model and is governed by protocols that stipulate the physical connection requirements between communication devices to facilitate data transmission [2]. The OFDM-PHY specification of the IEEE 802.16-2004 standard supports seven burst profiles of transmission which are defined by both the modulation scheme and the coding rate. The variable coding rates allow for multiplexing each of the seven profiles onto the physical layer [3].

Adaptive modulation is the transmission scheme used in digital communications, where the mode of transmission is adapted by the transmitter depending on the channel conditions. The system is a closed loop and the channel conditions are fed back to the transmitter in the form of the channel SNR which is determined by SNR estimation, after which the modulation and coding rate is chosen accordingly. The channel condition can vary from changing weather conditions to interference and noise present in the channel therefore decreasing the SNR. An adaptive modulation system can vary all or some of the following parameters to be adapted dynamically in order to optimize channel throughput: constellation size, symbol rate and power level. Throughput in the channel is defined as the number of bits correctly received and measures the quality of service in the data transmission system. The throughput decreases with channel instability therefore a flexible system that can adapt is required. The particular physical layer of the IEEE 802.16 for which adaptive modulation will be implemented, is the Wireless MAN-OFDM layer. This layer uses OFDM as the mode of modulation [4].

Effective adaptive modulation and coding for a transmission system requires the use of an effective SNR estimation scheme for accurate feedback of channel information. The signal to noise ratio is the ratio of the received signal power to the noise present in the channel. The received signal in wireless communication is usually a superposition of delayed versions of the transmitted signal, which is caused by multipath propagation. The transmitted signal undergoes both distortion and attenuation which are introduced by the channel as well as noise. The effect of the channel on the transmitted signal is modeled as the channel impulse response. The SNR of the channel is estimation because both the channel impulse response at any point is unknown due to the changing environment of transmission. The noise present in the channel is also unknown due to its random nature. The estimation of channel SNR indicates the reliability of the channel, therefore impacting the probability of error in the transmission. [5].

1.2 Problem Statement

Fixed modulation systems make use of an optimal modulating rate that is used when the channel conditions are good, with high SNR, and when the channel conditions degrade. This results in the need for retransmissions during poor channel conditions and repetitive error correction schemes. The bit error rate (BER) can be improved in poor channel conditions by stepping down the modulation and coding rate to a more robust level that can withstand noise within the channel. This reduces the number of retransmissions that would be required, had higher modulation rate been kept constant. These systems do not optimize good channel conditions with high SNR when the channel has the potential to transmit higher data rates without compromising the BER.

The varying modulation schemes and coding for the existing Wimax model are to be simulated and a fixed modulation scheme chosen that is robust at low SNR with reasonable throughput at good SNR conditions. The bit error rate (BER) can be improved in poor channel conditions by stepping down the modulation and coding rate to a more robust level that can withstand noise within the channel. This reduces the number of retransmissions that would be required, had higher modulation rate been kept constant. The use of adaptive modulation in wireless communicating systems has a significant contribution towards bandwidth optimization. The use of a robust modulation and coding in low SNR conditions eliminates the need for complex coding schemes in the attempt to compensate for degraded channel conditions. The channel throughput can be increased by higher data rate transmission when the channel improves. Variables that affect the channel conditions and hence the throughput are listed in [6] as the distance between the transmitter and the receiver, the channel fading characteristics and the noise and interference which continue to change with time.

The first step is to implement two different channel SNR estimation algorithms and carry out a performance analysis of the algorithms. The changing channel conditions require an SNR estimation technique whose performance is determined by the computation time and the accuracy of the acquired SNR. These two algorithms are compared to the third which is a novel algorithm and has previously been implemented only in single carrier systems. The time taken for the SNR acquisition is required to be a minimum due to the channel dynamic nature in order for the adaptive modulation implementation to be worthwhile. The three criteria used in the search for a good SNR estimator selection are accuracy, minimum computation time and minimum implementation complexity

The channel performance is evaluated by comparing the BER for each simulation. The different modulation schemes to be alternated amongst, are the seven burst profiles described in the standard which refer to the modulation rates and each of their coding rates according to the channel coding per modulation scheme. The task is to switch from the highest modulation rate (64 QAM) in good channel conditions to the lowest and most robust (BPSK) in bad channel conditions. The channel condition is determined at the receiver by monitoring the signal-to-noise-ratio (SNR) and each modulation scheme and coding is associated with an SNR, falling within a specific range, which is specified in SNR lookup table that should be constructed after the simulations have been performed.

The simulation of the existing IEEE 802-16 physical layer is significant in order to compare the effect on throughput that switching from between modulation and coding schemes has on the overall channel performance in order to quantify the improvements and justify the purpose of having implemented the system.

1.3 Objectives and Scope of the Project

These are the four main objectives of the project:

- Simulation of Wimax systems

A simulation model is studied in Matlab/ Simulink and the performance of the system, which is the measurement of BER for various SNR values, is studied. The channel information acquisition methods are to be investigated in order to add estimation blocks to the existing model which has been built previously. The project is to be implemented within a specified time frame and complete software simulations are possible to complete within this time limit.

- Addition of SNR Estimators which have been previously implemented

Two SNR estimation algorithms which have been previously implemented in OFDM systems are studied and implemented using MATLAB/Simulink. The SNR Estimator subsystem is developed and added to the Wimax system physical layer simulation model based on IEEE 802.16-2004 standard for each estimator. The measured SNR values are taken for the number of transmissions required to reach the required BER specified in the standard of 10^{-6} for each of the seven burst profiles of the AWGN channel. The following SNR estimation algorithms are to be implemented:

  - Reddy Algorithm

- Subspace-Based SNR Estimation

- Implementation of novel SNR estimation technique

The third SNR estimator which has been suggested previously for single carrier transmission, the Linear Predictor Interpolator is studied and modified accordingly in order to obtain optimum performance in OFDM system. This estimator is tested in three modulation and coding rates, namely: BPSK, QPSK ¾ and 64-QAM.

- Comparison of SNR Estimation Algorithms

The performance analysis is done by computing the time taken to acquire SNR in the channel and computing the minimum mean square error of the three estimators. The comparison results are used to identify the best SNR with minimum mean square error and computation time and minimum complexity for hardware implementation to be feasible at a later stage.

CHAPTER 2

LITERATURE REVIEW

2.1 Orthogonal Frequency Division Multiplexing (OFDM)

2.1.1 OFDM Transmission Theory

OFDM is multi-carrier transmission of a signal achieved by dividing the bandwidth into equally spaced sub-channels. Each sub-channel carrier frequency is therefore a multiple of the smallest sub-carrier used for, resulting in parallel transmission of the data. Each sub-carrier spacing is the inverse of the symbol duration.

OFDM is the preferred transmission scheme in wideband wireless communications because the transmitted signal is prone to simultaneous multipath propagation, therefore causing multiple delays in arrival of the direct path signal and the consecutive reflected path signals at the receiver. The reflected signals interfere on arrival with each other as well as with the direct signal and this results in Inter Symbol Interference. The received signal becomes distorted and this is known as fading. By dividing the channel bandwidth into sub-channels the effect of ISI can be minimized because the symbol period of each sub-channel is larger than the symbol period of the entire bandwidth. This is further increased by inserting a cyclic prefix to the transmitted symbol which is a cyclic extension of the symbol (with no additional data) to compensate for the time delay between each of the signals that are received and this results in the symbol time being larger than the channel delay spread. The insertion of a guard interval in each symbol is to ensure orthogonality [7].

OFDM modulation technique is used as the transmission mode in Wimax Systems which is a broadband technology characterized by high data rates in the range of mega bytes per second [7]. This method of modulation is resilient to frequency selective channel fading, where the signal bandwidth is larger than the channel coherence bandwidth [8]. The higher the data rates the more the resulting delay is greater than one symbol time which is the inverse of the data rate. OFDM, also referred to as a spread spectrum transmission, is a countermeasure to this problem. The division of the allocated channel bandwidth allows lower bit loading on each sub-carrier which increases the symbol transmission time while maintaining the overall desired bit rate for the entire bandwidth. This reduces complexity at the receiver by eliminating the need for complicated equalization to solve the multi-path fading problem. Figure 2.1 shows the optimum bandwidth usage in OFDM transmission in comparison to FDM [7] [9].

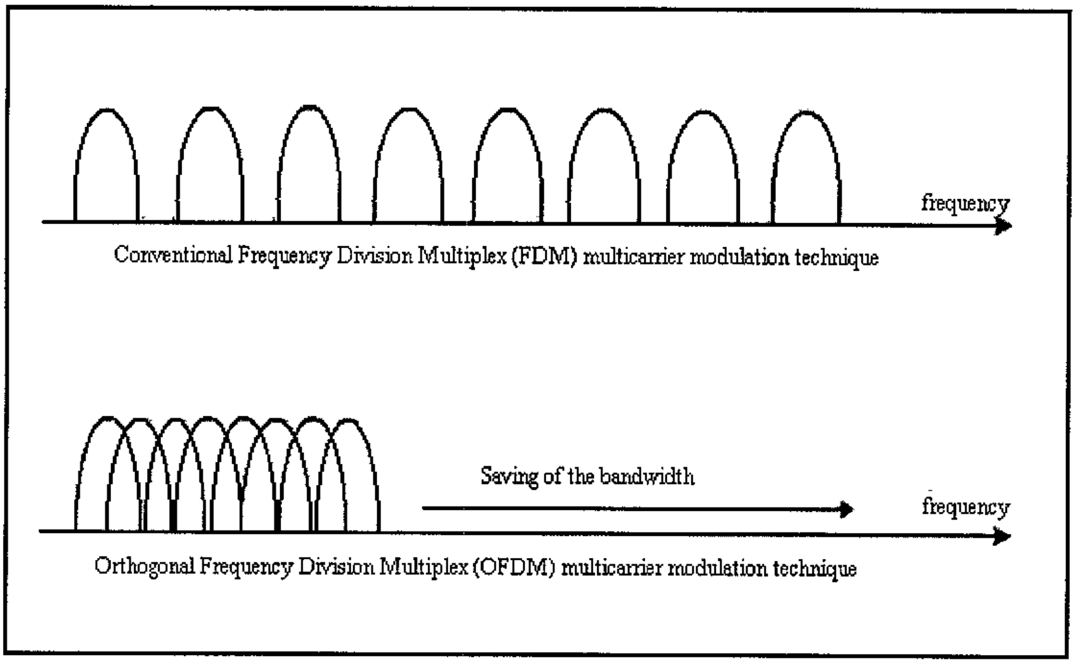

Figure 2.1 Comparison of the bandwidth utilization for FDM and OFDM[9]

The channel bandwidth is divided into equal and over-lapping sub channels (N). The sub-carriers are each an equal frequency gap from each other and separately modulated with the parallel data stream. OFDM uses the over-lapping of adjacent sub-channels by selecting frequency values of sub-carriers that allow all neighboring side-bands to overlap. The orthogonality of the carriers ensures that this is done without inter-channel interference and increasing spectral efficiency because of the overlapping of adjacent side bands. OFDM carrier is made up of a number of signals which are represented in terms of their complex exponentials [4].

2.1.2 Channel Model for OFDM Systems

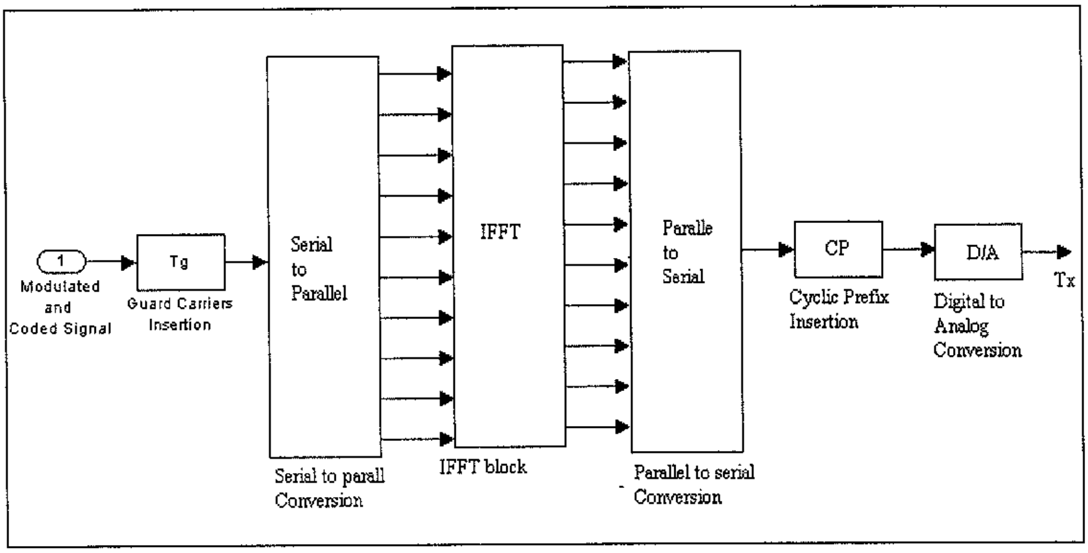

Figure 2.2 OFDM transmission system model

The OFDM system transmission block diagram is represented in figure 2.2. The input signal is coded and modulated according to one of the burst profile stipulated in the IEEE 802.16d standard after interleaving, zero padding and randomization has taken place. The insertion of the guard band is to increase the symbol time to be more than the delay spread in the channel. A cyclic prefix is later added in the time signal to minimize ISI distortion. The serial to parallel conversion is done together with the insertion of pilot symbols. For the IEEE 802.16d , each OFDM symbol is transmitted with the insertion of eight pilot sub-carriers. The binary sequence is then transformed into the time domain after symbol size has been allocated to the sub-band. Each carrier in each sub-band is allocated data to transmit. The transformation is done using an inverse fourier transform (IFFT) of size N=256, which is done by transforming the amplitude and phase difference of each frequency component into the time domain. This is the size of the OFDM symbol stipulated in the standard. The IFFT algorithm converts data points with complex co-ordinates of size (n) into time domain of (n) points. The mathematical representation of the OFDM signal is expressed in equation 2.1.

$$S_{RE,k}(t-kT)=\begin{cases}\mathrm{Re}\left\{w(t-kT)\sum_{i=-N/2}^{N/2-1} x_{i,k}e^{j2\pi(f+\frac{i}{T_{FFT}}_{c})(t-kT)}\right\} \\ kT-T_{win}-T_{guard}\leq t\leq kT+T_{FFT}+T_{win} otherwise 0\end{cases} \quad (2.1)$$

T= Period of symbol

T_{FFT} = Fast Fourier Transform (FFT) period

T_{guard} =Period of cyclic prefix

f_c =centre frequency of the spectrum

N = FFT size

2.2 Adaptive Modulation

Adaptive Modulation in a Wimax system adjusts the channel modulation scheme by using different order of modulation, depending on SNR. The higher the order of modulation, the higher the data rate and spectral efficiency which requires a high SNR present in the channel.

The following sequence of events is followed for each cycle that the modulation rate is either stepped up or down:

- SNR Estimation

The signal to noise ratio is acquired at the receiver by using various channel estimation mechanisms. The channel condition can be determined by sending pilot signals to acquire bit error rate and this is used estimate the quality of channel and amount of noise present. The SNR is estimated according to the probability density function of the received signal which is used to estimate the noise in the channel. The SNR is estimated across all the sub-bands of the channel since blockwise adaptive modulation is implemented. The values of each of the SNR obtained in the sub-bands are averaged across the entire bandwidth and noise power is estimated. The channel is assumed to have white noise, which is the same level across all the sub-bands.

- Switching

The receiver sends a signal to the transmitter via a separate control channel in order for transmitter to select suitable transmission modes for the sub carriers. The channel SNR estimation result will give a signaling from the adaptive algorithm to the receiver to switch to a higher or lower modulation scheme according to the SNR of the channel.

2.3 SNR Estimation

The signal transmitted in the wireless channel arrives at the receiver with the addition of thermal noise and various other disturbances. This is modeled as Additive Gaussian random process in the channel. The purpose of modeling the channel is to predict the transformation of the transmitted signal in order for the receiver to determine the best hypothesis of the transmitted signal from the received signal and this information is used to adjust the modulation and coding rate accordingly. The SNR estimation in the channel involves two unknown variables: the signal power and the noise power. The signal power is unknown because the channel parameters are unknown.

SNR estimation algorithms can be classified into two groups: pilot aided and blind estimation. In blind estimation, the transmitted signal is not known and the transmitted signal is estimated from a number of hypotheses. Pilot aided estimators make use of pilot symbols in which the transmitted data is known and these provide a more accurate estimate of the SNR. One of the reasons for pilot symbols to be inserted into OFDM symbols is synchronization therefore no additional compromise of bandwidth for the sake of estimation is necessary. The pilot aided SNR estimation algorithms can further be subdivided into block-type pilot insertion and comb-type pilot insertion. This refers to the arrangement of the pilots in the 2-D time-frequency array, where in block-type the entire OFDM symbol consists of pilots and in comb-type data is inserted in the carriers between pilots. Figure 2.3 shows the arrangement of pilots, with figure 2.3(a) illustrating block-type pilot insertion and figure 2.3(b) illustrating comb-type. Channel estimation for OFDM systems makes use of statistical characteristics of the channel.

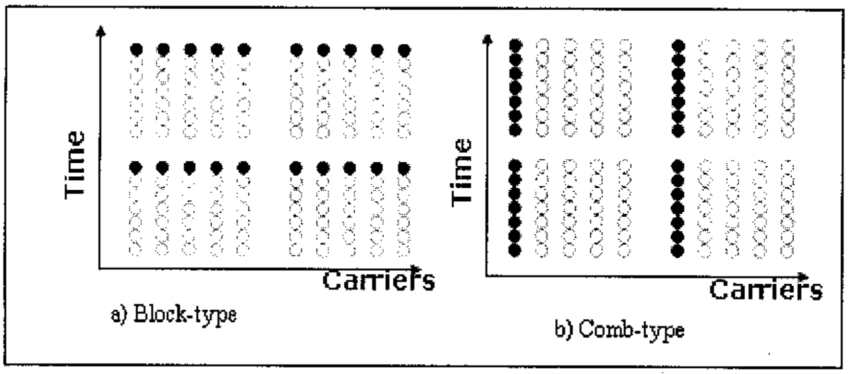

Figure 2.3 Pilot symbol arrangement

The search criteria for the algorithms to be implemented in the Wimax model was pilot aided estimators that have been previously implemented in OFDM systems. The two algorithms selected to be implemented are the Reddy algorithm [5] and Subspace based SNR estimation algorithm [10]. The performance of the two algorithms are then compared to each other and to a the LP-Interpolator algorithm. The LP-Interpolator is non-pilot aided and is a novel method whose performance has previously been evaluated for single carrier modulation and will be tested in the

OFDM system by treating each of the sub-carriers as a separate single carrier channel. Each of the three algorithms are described:

2.3.1 Reddy SNR estimation

In this method channel estimation is performed in the first realization of the channel, using pilot symbols and this estimate is used to estimate the signal noise power. The suggested method can be used for and Additive White Gaussian Noise (AWGN) channel and for colour dominated channel, in which the noise power varies across the frequency spectrum.

The system model is described in the frequency domain, where a signal is transmitted to obtain the estimated channel frequency response after which the instantaneous noise power mean square is determined. The transmitted signal includes white noise which is added by the channel of unknown amplitude. This is modeled in the frequency domain by the equation:

$$Y_{m(k)} = X_{m(k)} H_{m(k)} + N_{m(k)} \qquad (2.3.1.1)$$

$Y_{m(k)}$ = Transmitted signal

$Y_{m(k)}$ = Received signal

$N_{m(k)}$ = Channel white noise

The channel frequency response is estimated by transmitting preamble and performing division in the frequency domain of the received signal by the transmitted signal. When performing the division, the effect of noise is ignored. The pilot symbols are then used as the transmitted signal and the received signal in the pilot sub-carriers is used for the received signal and the estimated transfer function inserted in the equation to determine the noise power estimate. The noise power estimation is found by finding the difference between the noisy received signal and the noiseless signal.

$$E_{m(k)} = \left| Y_{m(k)} - \hat{X}_{m(k)} \hat{H}_{m(k)} \right|^2 \qquad (2.3.1.2)$$

The difference between the actual channel frequency response and the estimated is the channel estimation error.

2.3.2 Subspace based SNR estimation

The second algorithm uses statistical analysis and represents the channel model in terms of a subspace defined by the number of propagation multipaths, which is the dimension of the observation vector that satisfies the Minimum Descriptive Length (MDL) criteria described in [11] . Each of the paths (L) is modeled as a Gaussian process with varying time delays (τ) and path gains, expressed by the equation for channel impulse response:

$$h(t,\tau) = \sum_{l=1}^{L} h_l(t)\delta(t - \tau_l) \qquad (2.3.2.1)$$

The observations vector is defined as the signal received which is modeled as the maximum number of superimposed multipaths signals (k). The MDL criteria is used to search for estimate of the number of multipaths(L) by finding the value of k that minimizes the MDL, which is the partitioning of the observation vector into subspace [10]. The observation vector correlation matrix is decomposed into its eigenvalues and eigenvector, where the correlation matrix (**R**) is

$$\mathbf{R} = \mathbf{W}_p E(\mathbf{h}_l \cdot \mathbf{h}_l^H)\mathbf{W}_p^H \qquad (2.3.2.2)$$

$\mathbf{W}_p$ = FFT matrix of pilot symbols

$\mathbf{h}_l$ = channel impulse response for l-th multipath

$(\cdot)^H$ = Hermitian conjugate matrix transpose

p= pilot symbol index $\quad$ p $\in$ {1, 2,……, M)

M=number of pilot symbols

The eigenvalues of **R** when arranged in descending order of magnitude give an indication of the subspace. The smallest *M-L* eigenvalues are equal to the noise variance. The estimation of the correlation matrix is done using the channel frequency response by assuming a noiseless channel and averaging it across *K* OFDM symbols. The search for *L* is done by performing iterations of the MDL function:

$$MDL(k) = -K(M-k)\log\left[\frac{\prod_{i=k+1}^{M}\hat{\lambda}_i^{1/(M-k)}}{\frac{1}{M-K}\sum_{i=k+1}^{M}\hat{\lambda}_i}\right] + \frac{1}{2}k(2M-k)\log(K) \qquad (2.3.2.3)$$

The channel is characterized as a wide sense stationary uncorrelated process, which describes the random characteristics of the channel whose first and second moments do not change with time. The probability density functions of the noise in each of the multipaths are uncorrelated because each of the paths is independent.

The assumptions made are that the channel has a guard interval which is greater than the channel delay spread and that the channel is quasi- stationary. This refers to the assumption made that the noise does not change within each OFDM symbols. This can also be extended to a few consecutive OFDM symbols, therefore assuming a constant noise in a block of symbols.

The signal to noise ratio (SNR) during the i-th OFDM symbol is:

$$\rho = \frac{\sum_{i=1}^{N} | h_l(iT_s) |^2}{\sigma_N^2} \qquad (2.3.2.2)$$

σ_N^2 = noise variance

$$\sum_{i=1}^{N} | h_l(iT_s) |^2 = \text{Channel power} \qquad (2.3.2.3)$$

The transmitted channel power is assumed to be unity and this is scaled down by the channel the channel factor.

2.3.3 LP-based Interpolator

This method of noise estimation which is suggested by N.S Kamel and described in [12] makes use of a linear predictor to determine the coefficients of the autocorrelation sequence of the noisy received signal. The noise variance is found by finding the difference between the autocorrelation sequence of the noisy signal and the data signal which are said to be conjugate symmetric functions of the delay (m). The received signal is a combination of the data signal and the additive noise in the channel. The autocorrelation function of the received signal $r_x(m)$ has the following relationship to the autocorrelation of the data signal $r_s(m)$ and the noise $r_w(m)$:

$$r_x(m) = r_s(m) + r_w(m) \qquad (2.3.3.1)$$

The noise in the channel is modeled as Additive White Gaussian Noise and its autocorrelation function only has a value at a delay of m=0. The magnitude of which is the noise variance (σ^2), expressed as :

$$r_w(m) = \sigma^2\delta(m) \qquad (2.3.3.2)$$

This implies that the difference in amplitude at the origin of the autocorrelation functions of the noiseless data signal and the noisy received signal is the noise power. The value of this magnitude can be estimated by using linear prediction to estimate $r_w(0)$.

The linear predictor algorithm is performed using both forward and backward substitution to generate more error points and therefore provide a better estimate since the autocorrelation function sequence is symmetric. The error vector ($\mathbf{e}$) is expressed as:

$$\mathbf{e} = \mathbf{r} - \mathbf{R}\,\mathbf{a}_p^f \qquad (2.3.3.3)$$

where $\mathbf{r}$ is the vector of the first point (from the origin) in an N-point correlation sequence, $\mathbf{R}$ is the matrix of the remaining p autocorrelation points and $\mathbf{a}_p^f$ is the vector of forward linear prediction coefficients with p as the order of the predictor. The predictor coefficients can then be found for the least squared error which is presented by the equation:

$$\mathbf{a}_p^f = (\mathbf{R}^T \mathbf{R})^{-1} \mathbf{R}^T \mathbf{e} \qquad (2.3.3.4)$$

Finally the power of the signal can be computed by inserting the predictor coefficients in the following equation:

$$r_s(0) = \sum_{k=1}^{p} a_p^f(k) r(-k) \qquad (2.3.3.5)$$

CHATPER 3

METHODOLOGY

The project procedure is discussed in this chapter. The work done on the project is an addition to previous work done in the development of the IEEE 802.16-2004 physical layer model done by Lin Jin Guan for his final year project, which is in turn based on the Masters Research of Mr Michael Drieberg for the IEEE 802.162-2003 PHY Layers. The working model for the IEEE 802.16-2004 PHY was developed using Matlab/Simulink.

The major milestones of the project are literature review, identification of previous work done, Matlab/Simulink implementation and system performance and analysis. The project flow can be seen from figure 3.1 which is a flow chart of the steps leading to the fulfillment of the objective. The tools required for the project are Matlab version 7 and the subsystem that was developed to be added to the IEEE 802.16-2004 PHY model required the use of blocks from three libraries: Simulink, the Communications blockset and the Digital Signal Processing blockset. These are imperative in communication channel modeling.

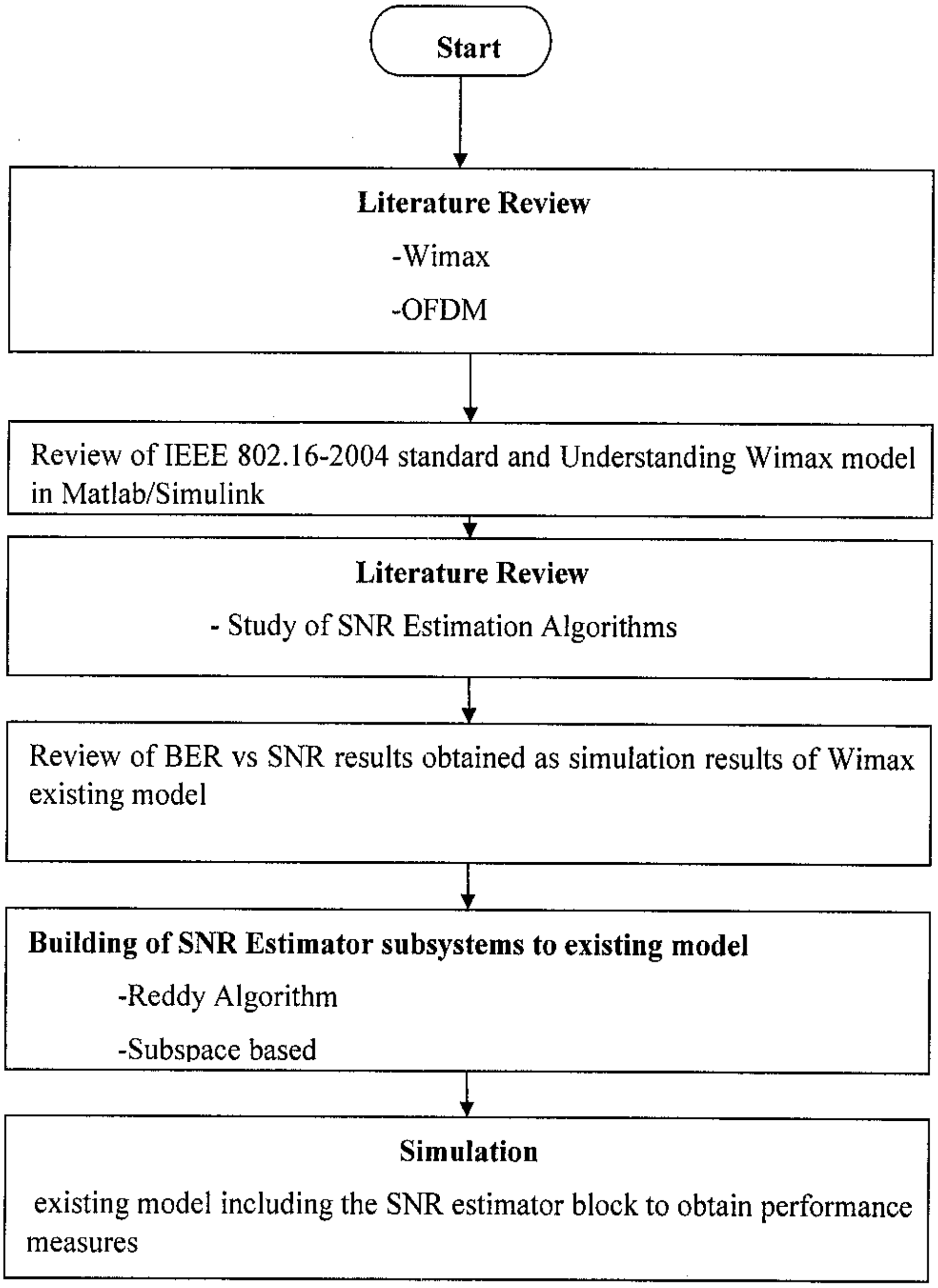

Figure 3.1 Project Flowchart

3.1 Project Procedure

The milestones of the project are summarized as follows:

- Literature Review
- Identification of previous work done
- Matlab/Simulink Implementations of modification to previously done work
- System performance analysis

Literature_Review

The three topics that were studied

1. Literature review on Adaptive Modulation
2. Literature review on Wimax and understanding the specifications of the IEEE 802.16 physical layer
3. SNR Estimation

Matlab/Simulink

1. Simulating and understanding the existing adaptive modulation model for IEEE 802.11a WLAN Physical layer
2. Model adaptive modulation model using Simulink Communication blockset
3. Determine performance measures of system, based on simulation results
4. Modify existing model and compare gain of improved system

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Analysis

The results for the SNR estimators are computed by Matlab/Simulink simulations. The Wimax model on which the estimators are inserted and simulated consists of an OFDM transmitter with 256 sub-carriers. Eight Pilot symbols are inserted in each OFDM block transmission and the two SNR estimators, Reddy and Subspace take advantage of this fact, while the LP estimator is a blind estimator placed at the front end of the receiver. The LP estimator is a novel approach to SNR estimation in OFDM systems as it has previously been implemented in single carrier systems. The channel is modeled as AWGN, where the frequency response is assumed to be an ideal unity , therefore the noise power added post channel is estimated. The sampling frequency of the model is 2.33 MHz.

Three SNR estimation subsystems are added to the IEEE 802.16-2004 PHY model, which is simulated and comparisons are done between the actual SNR and the estimated SNR. The SNR estimator is connected to the output of the OFDM receiver for the Reddy Estimator and the Subspace based estimator since they are both frequency based. The LP-based Interpolator subsystem is connected to the input of the OFDM Receiver as it is time based. The connection of the block to the existing model fro the three SNR estimation blocks can be seen in Appendix A.

4.1.1 Reddy SNR estimation

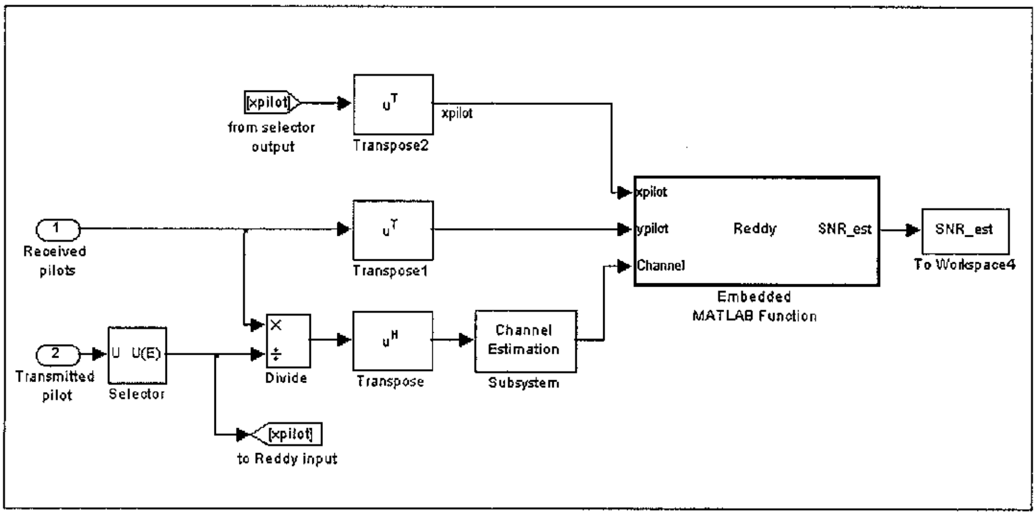

Figure 4.1.1.1 Reddy Estimator subsystem

The subsystem in Figure 4.1.1 has two input signals which are the input of the pilot symbols for the transmitted signal (xpilot) and the received signal (ypilot) from which the channel frequency response (Hls) is computed. Each of these input frames are vectors of size 8x1, which is the number of pilots inserted in the OFDM symbol. A memory block is used to delay real-time computation of the Hls received frame by one transmission because the channel frequency response estimate is first computed and then used to compute the instantaneous noise power. This computation is done in the Embedded Matlab Function with the program flow is illustrated in Figure 4.1.2.

Figure 4.1.1.3 shows that Reddy SNR Estimator can be used for noise estimation in three of the burst profiles , namely BPSK, QPSK ¾ and 64 QAM ¾. These are the three lowest, intermediate and highest modulation and coding rates and the remaining of the burst profiles can be implemented similarly and the expected results are of a similar trend.

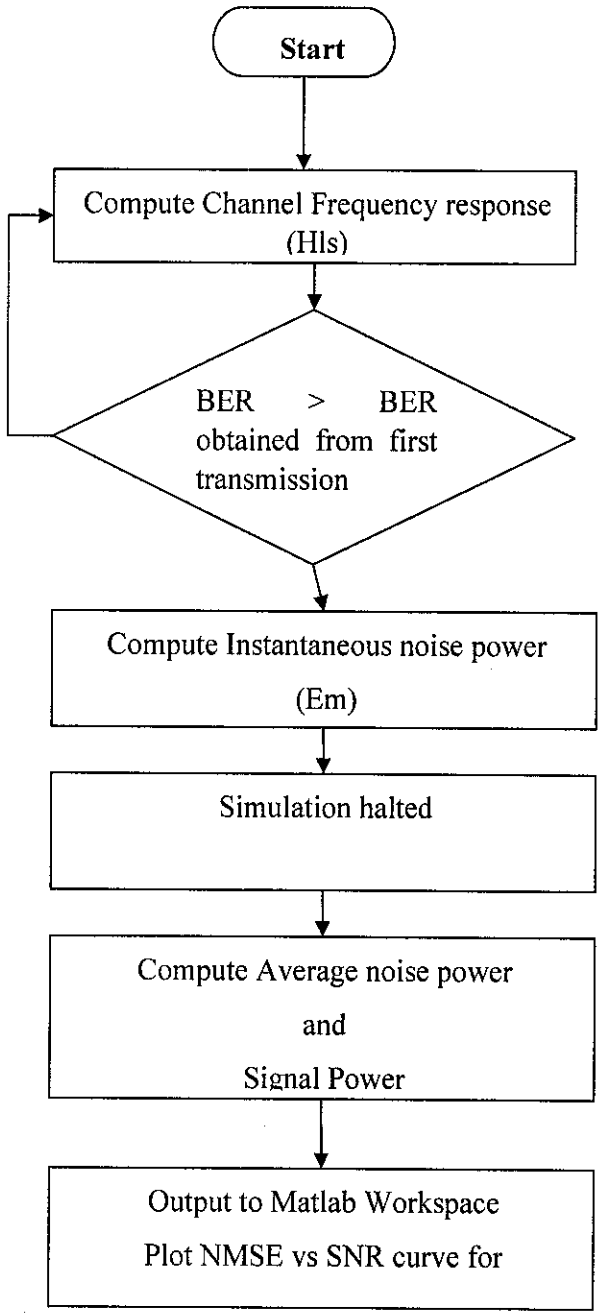

Figure 4.1.1.2 Reddy Estimator flow chart

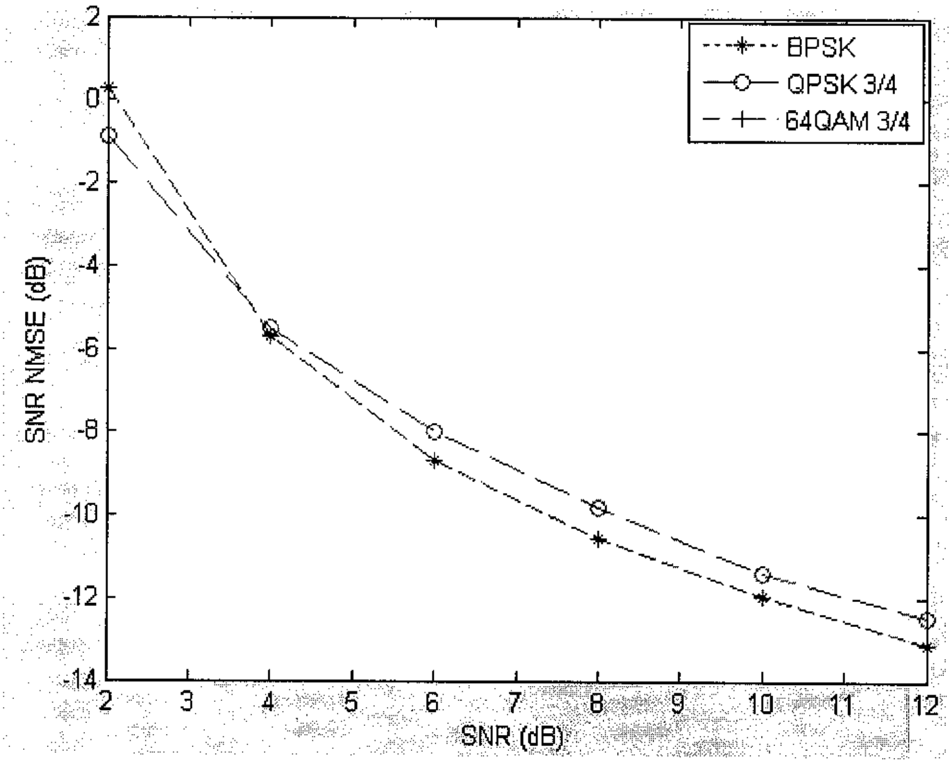

Figure 4.1.1.3 Comparison of Reddy SNR estimator performance in BPSK, QPSK and 64 QAM ¾

4.1.2 Subspace based SNR Estimation

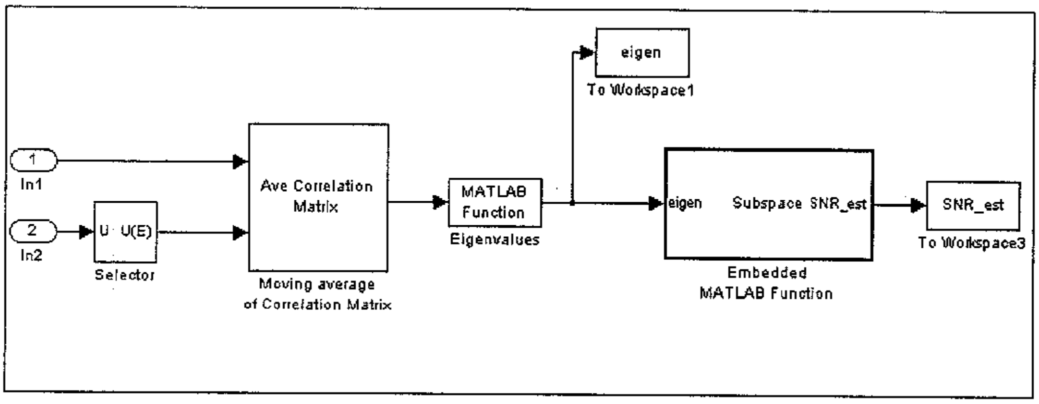

Figure 4.1.2.1 Subspace based subsystem

This subsystem shown in Figure 4.1.2.1 accepts the same two inputs as the previous block which is used to compute the moving average correlation matrix estimate. The window size of the moving average, which is specified by K in equation (2.3.2.3), is set to be equal to 10 in the results obtained as this is the suggested size in [10]. The subspace estimator then continues to compute the eigenvalues which are the input to the Matlab Embedded Function block that does the computation and outputs the estimated number of multipaths (L). This value of signal path which is calculated to be one for AWGN channel is used to compute the signal power using the eigenvalues. The remaining M-L eigenvalues are used to compute the noise power.

The subspace estimator shows gradual improvement as the size of the observation vector (K) is increased. This is a result of the accuracy in the correlation matrix, the values of which to which the eigenvalues are sensitive to.

4.1.3 LP Interpolator Estimator

The LP Interpolator Estimator is implemented for varying window sizes. Increasing the window size from 5 to 15 OFDM symbols before performing the autocorrelation function (ACF) reduces the noise leakage at the 1st delay and concentrates the noise on the zero offset. This decrease in noise leakage is shown in Figure 4.1.3 which shows the noise power obtained by subtracting the first ten samples of the ACF of the transmitted signal from the first 10 samples of the ACF of the received signal. This shows that the noise approaches the ideal delta response as the windowing effect is minimized. The more the number of samples used, the more the white noise characteristics of the autocorrelation function.

The performance of the LP Interpolator in OFDM system shows that the bias that is exhibited by the amplitude difference of the zero-th and first sample of the ACF results in inaccurate prediction of zero offset amplitude using the neighboring samples, regardless of the prediction order that may be used. This is due to the randomness that is introduced by the OFDM signal which is a combination of in the time domain of subcarrier harmonics. The autocorrelation is highly correlated only at zero offset. The combined autocorrelations at the first delay of the sinusoids at different frequencies results in the superposition of autocorrelation functions of the sinusoids which give a value uncorrelated to the origin where they all give normalized ACF amplitude of one. This challenge was compensated for by computing the bias for varying window sizes for three modulation and coding profiles: BPSK, QPSK ¾ and 64-QAM ¾ . These computations are shown in Appendix B and Appendix C The observations show a constant bias and this is added to the first delay amplitude of the received signal to compute the transmitted noise power. The noise is the difference between this value and the received signal ACF amplitude at zero offset. The results obtained show that for increasing window size the difference between the transmitted and the received signal exists at the zero offsets of the autocorrelation functions as shown in Figure 4.1.3.

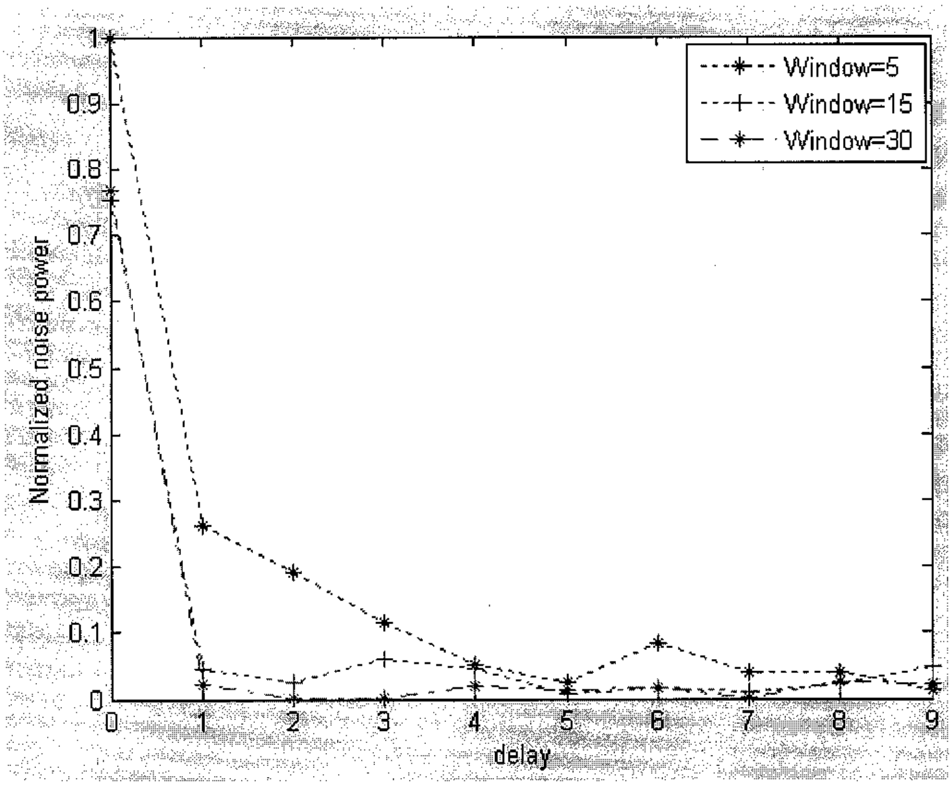

Figure 4.1.3 Decreasing noise leakage with increasing window size of 5-30 OFDM symbols

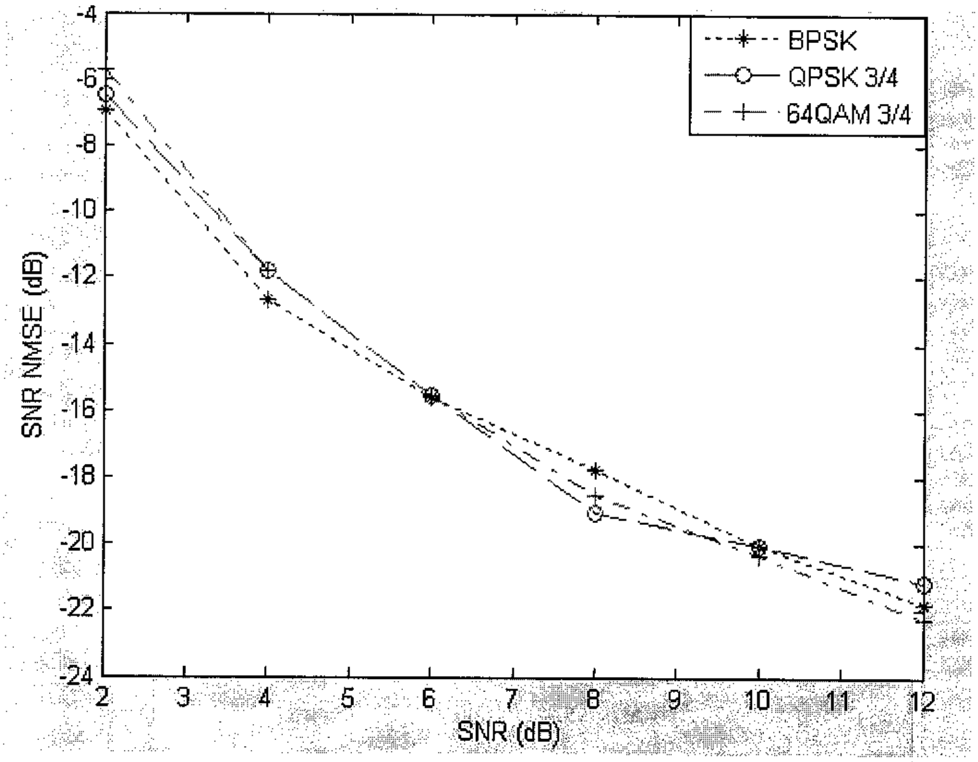

Figure 4.1.3.1 LP SNR Estimation NMSE variation for 3 Wimax burst profiles

4.2 Performance Comparison

4.2.1 Means Square Error

The performance comparison for each of the SNR estimators is done using the normalized mean square error (NMSE) of the estimated values, as suggested in [13]. Each OFDM symbol transmitted results in a variation of the estimated SNR value and these instantaneous values are used to compute the average SNR estimated. The NMSE is computed as follows:

$$NMSE = \frac{1}{M}\sum_{m=0}^{M-1}\left(\frac{\hat{\rho}-\rho}{\rho}\right)^2 \tag{4.2.1}$$

where M is the number of data for NMSE computation and $\hat{\rho}$ and ρ is the estimated SNR and true SNR respectively. The NMSE for each of the estimators is plotted and the algorithm which displays the least square error while maintaining ease of computation and implementation will be the preferred estimator. The SNR estimation computation for each SNR value is for M=10. This is to measure the accuracy with which each estimator estimates the signal to noise ratio by measuring the minimum square error of the bias, which is the difference between the actual SNR value and the estimated SNR values.

The performance of each of the estimators was further evaluated for increasing window size, varying from 320 samples per window to 9600 samples. Each of the results are shown in the following figures, for SNR NMSE vs SNR for increasing window sizes.

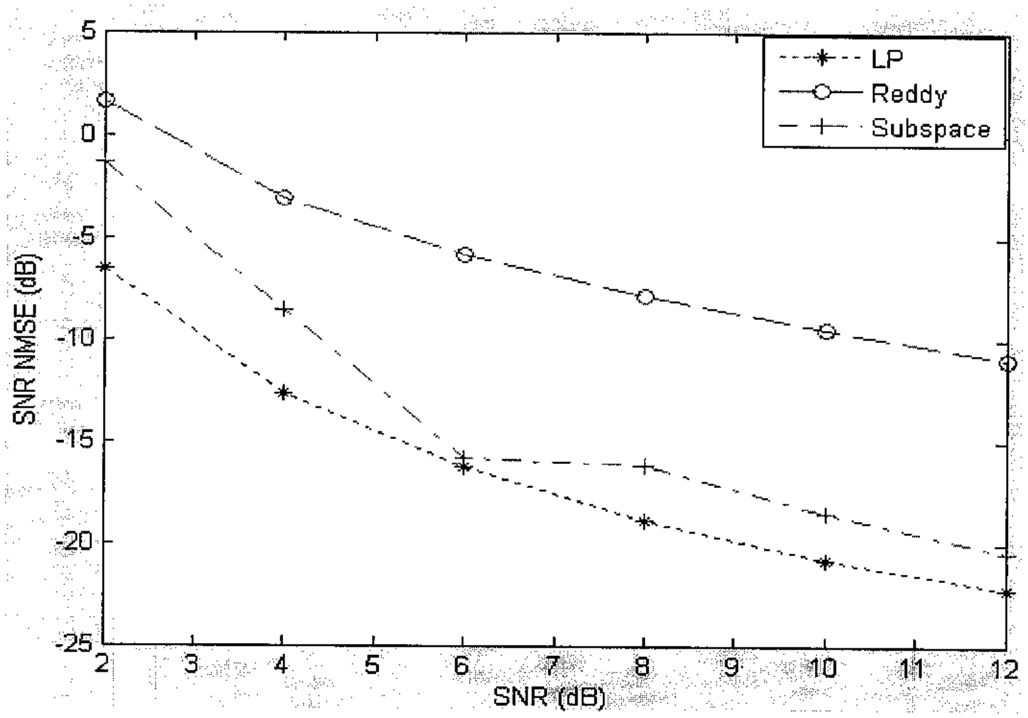

Figure 4.2.1.1 Comparison of Reddy and Subspace estimators vs NMSE for window size= 5 OFDM symbols

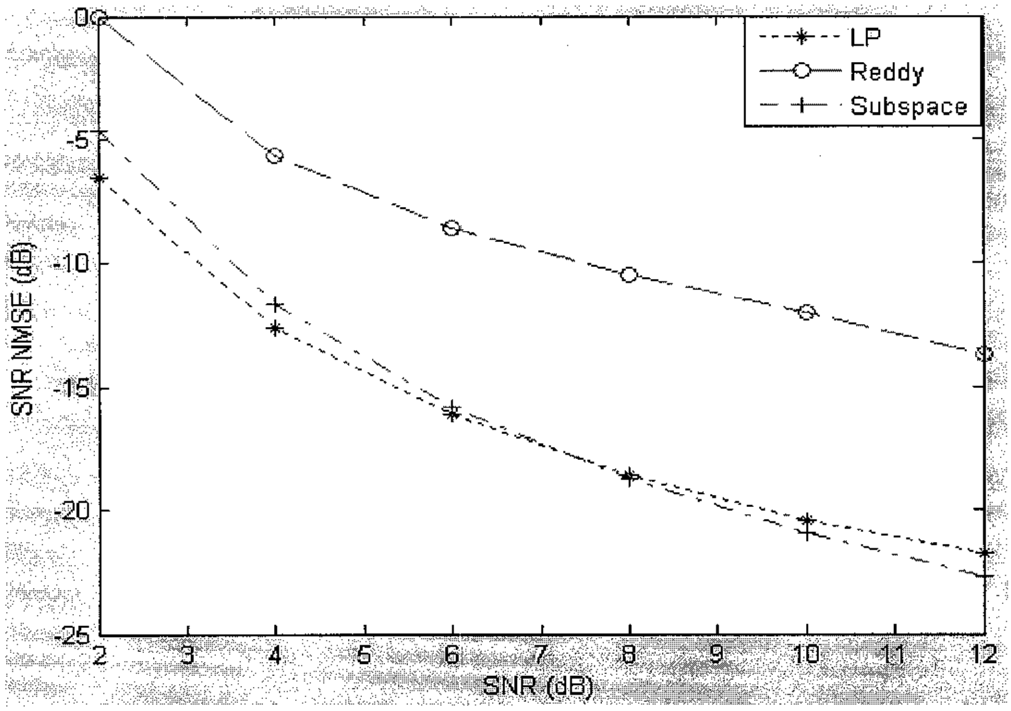

Figure4.2.1.2 Comparison of Reddy and Subspace estimators vs NMSE for window size= 10 OFDM symbols

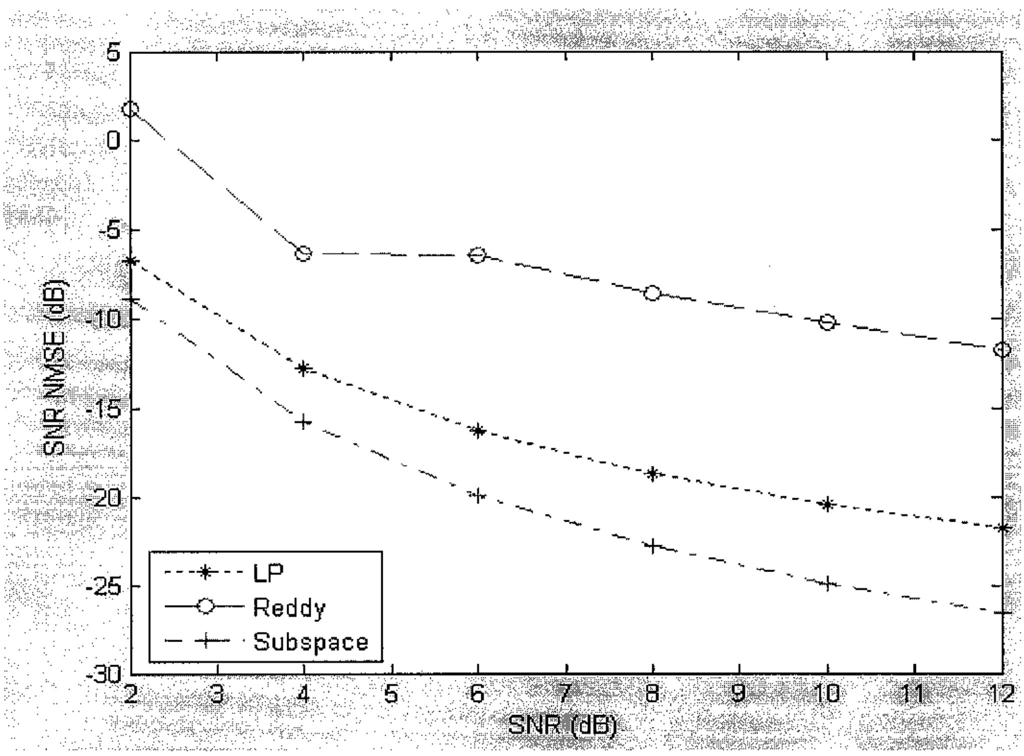

Figure 4.2.1.3 Comparison of Reddy and Subspace estimators vs NMSE for window size= 15 OFDM symbols

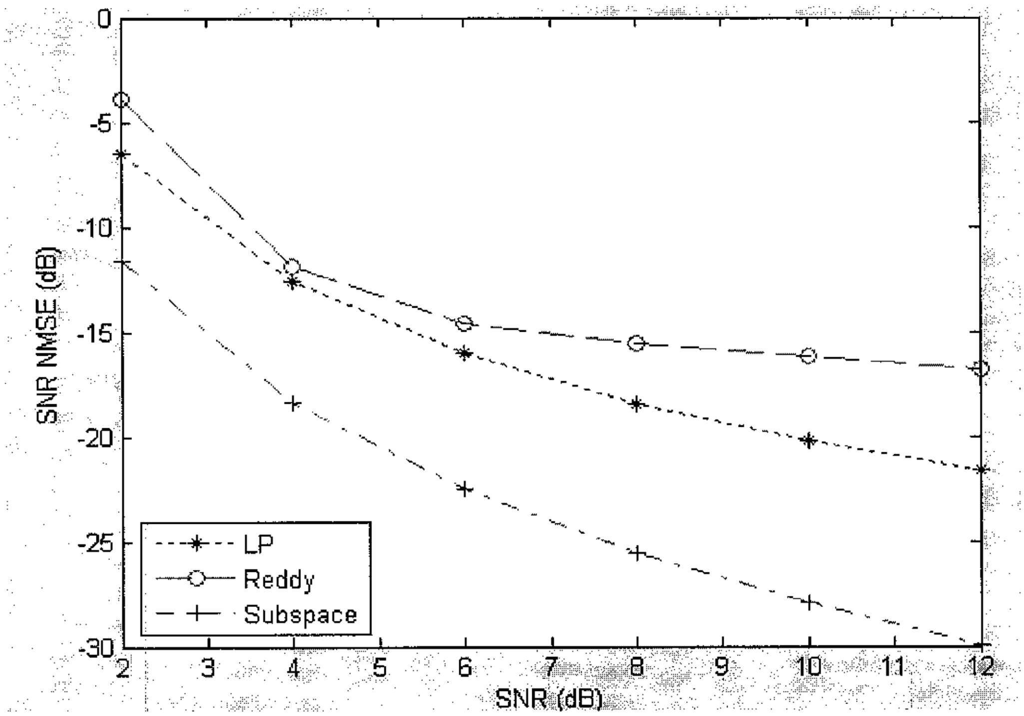

Figure 4.2.1.4 Comparison of Reddy and Subspace estimators vs NMSE for window size= 20 OFDM symbols

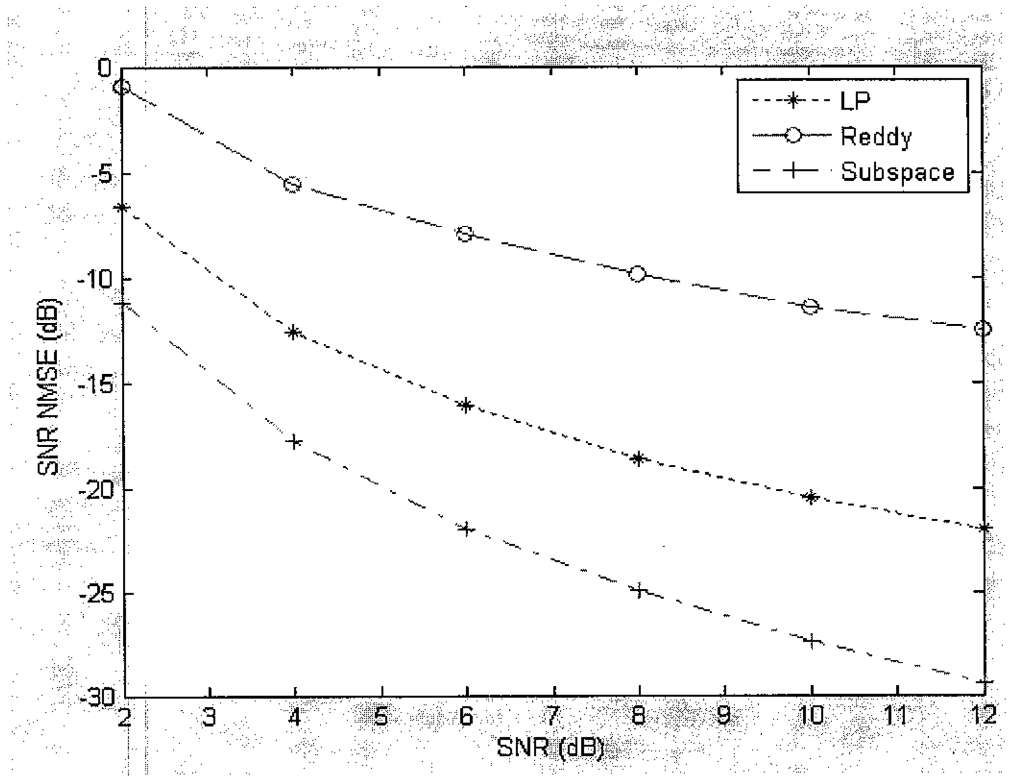

Figure 4.2.1.5 Comparison of Reddy and Subspace estimators vs NMSE for window size= 25 OFDM symbols

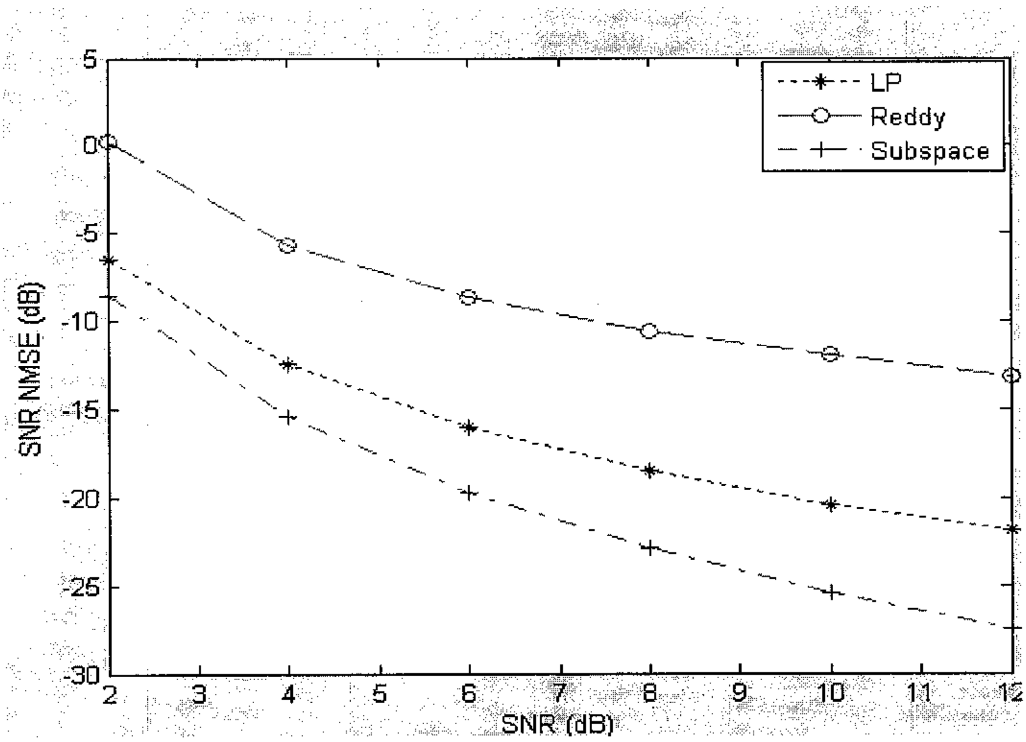

Figure 4.2.1.6 Comparison of Reddy and Subspace estimators vs NMSE for window size= 30 OFDM symbols

4.2.2 Computation Time

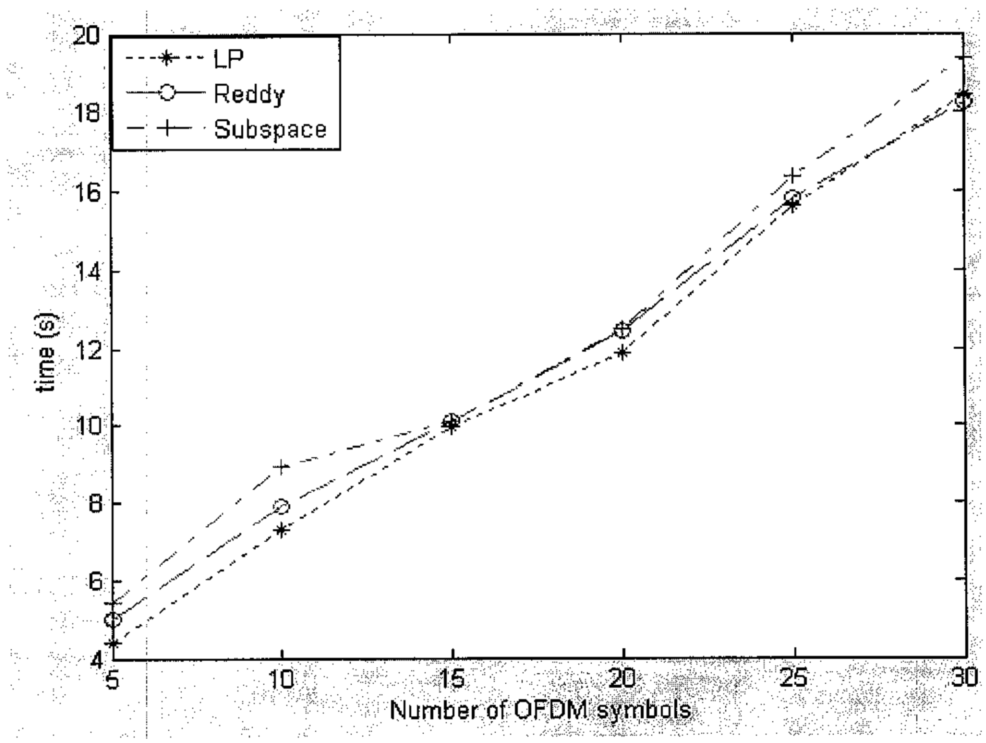

Figure 4.2.2 Average Computation time for SNR=2dB for increasing window size

The computation time of the LP Estimator is reduced considerably by computing only the first 10 samples of the received signal ACF therefore reducing it to less than that of the Subspace and the Reddy algorithm. The computation time is calculated using Matlab clock and the average time is used for the plot in Figure4.2.2 because the measurements are not exact for each time measurement. The time increases as expected for all three algorithms as the window size increases because of the larger number of samples used in the computation.

4.2.3 Implementation Complexity

The complexity of the LP interpolator is reduced by computing 10 samples of the ACF therefore decreasing the data array to be processed. The bias addition can be implemented by providing a table with the bias value for each modulation type or an average bias can be fixed and added as the values do not differ significantly for different modulation types. The LP and Reddy estimator present the least implementation complexity.

The Subspace based estimator introduces complexity in the computation of eigenvalues. Hardware implementation of eigenvalue decomposition may cause deterioration in the system performance in terms of speed and accuracy. Data storage capabilities also need to be taken into consideration.

4.3 Discussion

The noise power estimates for all three estimators depend on the noise power. The MSE decreases as the SNR increases. When the SNR is low the deviation between the actual and the estimated is high because at high noise power errors occur in the received signal which will result in the likelihood of incorrect decisions. It is suggested in [5] that this can be improved by incorporating decoded decisions. The overall MSE of each of the algorithms decreases with increased window size because as the number of samples over which the estimates are averaged, the more accurate the results tend to be.

The results show that the LP estimator performs better that the pilot aided estimators for window size of 5 and 10 OFDM symbols. The Subspace estimator performs better, by displaying minimum square error for window sizes 15 to 30. The comparison between the conventional SNR estimators (pilot aided) and the proposed LP estimator shows that shows that the LP works well in measuring both the noise power and the signal power. The noise power measurement of the LP on its own is most accurate for window size of 30 OFDM symbols as at this is when the autocorrelation function of the noise approaches the desired shape of being concentrated at zero-th delay.

The LP estimator shows superior performance in terms of computation time and is can be implemented with relative ease. The computing to be done by hardware is in determining the autocorrelation sequence of the first 10 delays of the received signal. This estimator shows that it performs equally as well as pilot aided estimators, therefore eliminating the need to extract pilot symbols in the received and transmitted signals in order to estimate channel response. This method can be implemented in changing channel conditions because the performance for window size of 5 symbols is superior to that of the conventional pilot aided estimators.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Three SNR estimation algorithms have been described and implemented in AWGN channel. The performance of the LP estimator which relatively matches that of pilot aided estimators shows that it can be implemented without prior knowledge of the transmitted signal, which is the case for real systems. This can be useful for adaptive modulation where the modulation type can be adjusted accordingly.

The work done so far has been for the AWGN channel and performance results have been compared for three burst profiles. From the performance results the estimator with the least mean square error while maintaining ease of computation and implementation will be used in the implementation of adaptive modulation. SNR estimation plays a prominent role in adaptive modulation algorithms and also has wide application in telecommunications as a wireless communication channel monitoring tool.

The problem of obtaining accurate estimates in real time is faced in the project because for each of the SNR estimators more than one OFDM symbol is estimated in order to obtain the SNR estimated value. The subspace SNR estimator is proposed to only provide accurate results after 20 OFDM symbols have been transmitted. The SNR estimation algorithms have shown an increase in the accuracy of the results after 30 OFDM symbols while minimizing computation time. The LP estimator performance has proved to work well in OFDM systems by fulfilling the criteria of computation time and accuracy while minimizing complexity.

5.2 Recommendations

The performance of the SNR Estimators has been evaluated for AWGN channel, this should later be expanded by adding a multipath channel to the model in the form of a filter. The multipath estimation capability of the Subspace method by using the minimum descriptive length can then be utilized. Further all three estimators should be implemented and tested for different wireless channel models which are characteristic of multipath, for example Rician fading and Rayleigh fading channels. The LP estimator bias should be measured in these environments and compensation made for the varying amplitude of the first delay amplitude of the received signal ACF as the channel filter coefficients change. The estimators can further be used in sending the SNR value to the receiver in order for the modulation and coding rate to be adapted accordingly.

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APPENDICES

APPENDIX A
SYSTEM MODEL

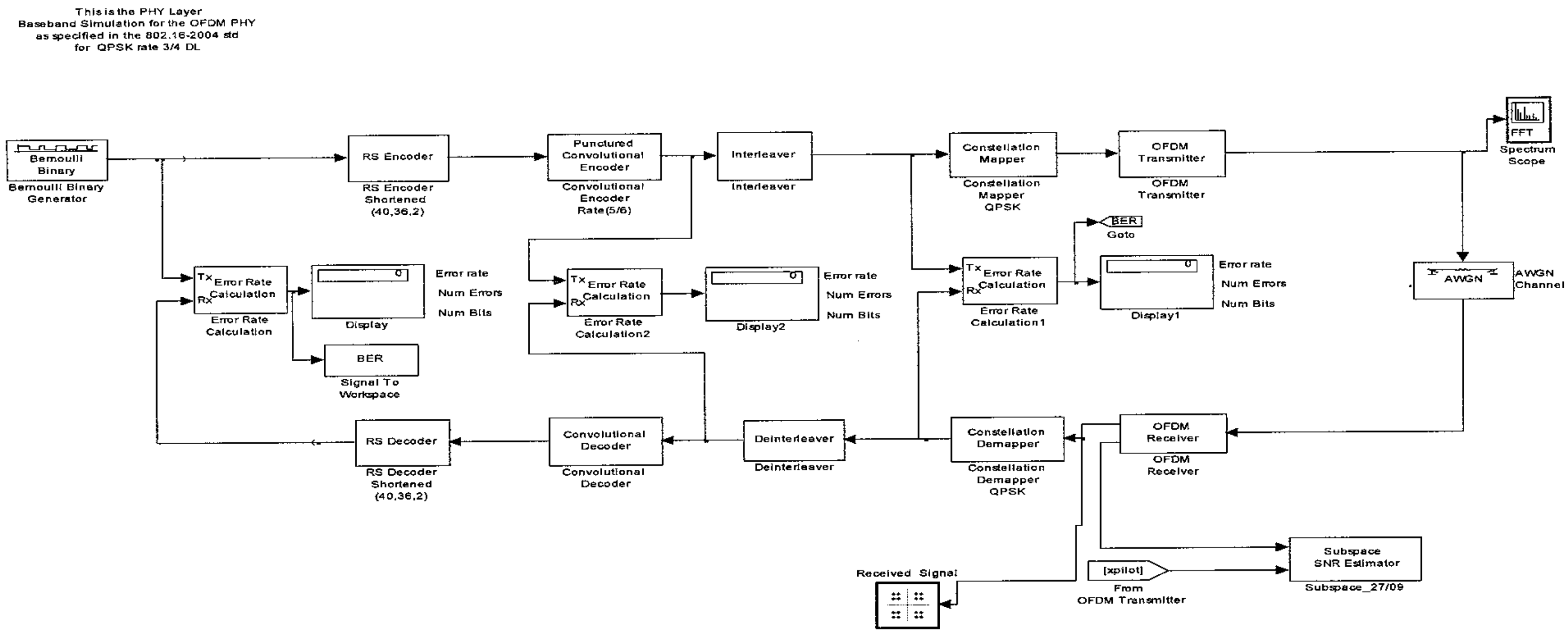

Figure 1A: IEEE 802.16-2004 PHY model with addition of Subspace based SNR Estimator block

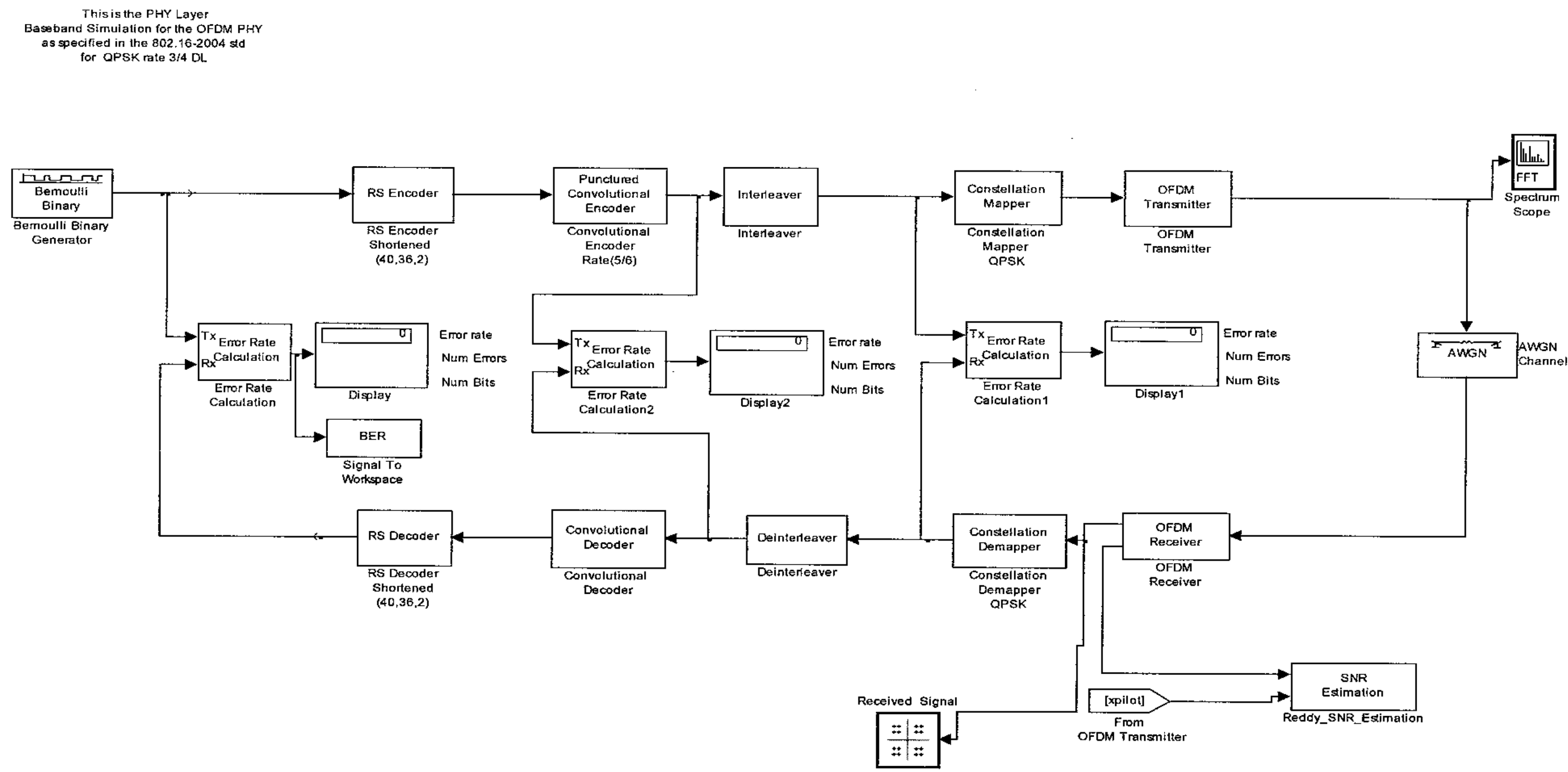

Figure 2A: IEEE 802.16-2004 PHY model with addition of Reddy SNR Estimator block

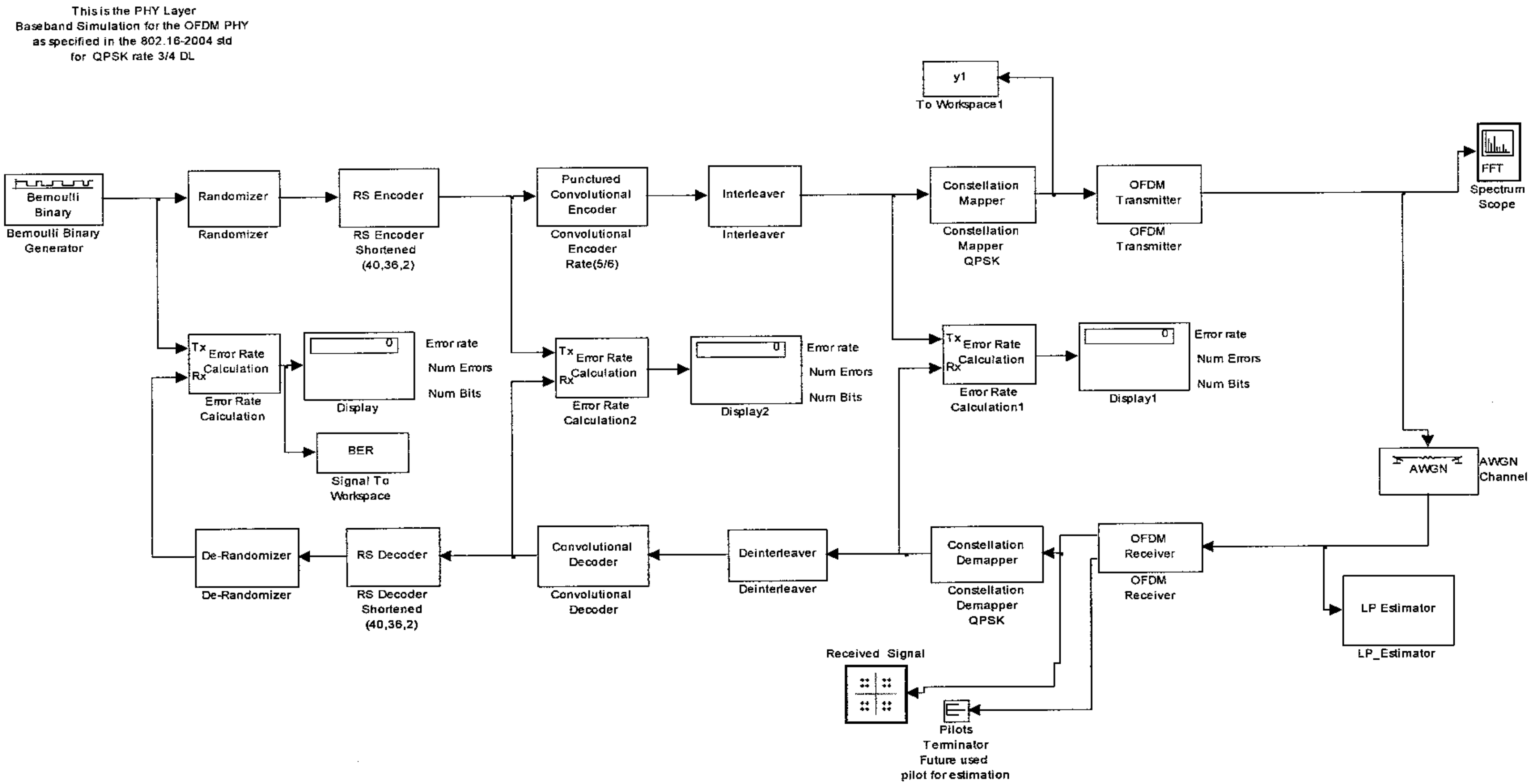

Figure 3A: IEEE 802.16-2004 PHY model with addition of Reddy SNR Estimator block

APPENDIX B

LP- BIAS COMPUTATION

Table B1: LP Bias computation between zeroth and first delay for increasing window size

Transmitted

	W= 320									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.26185	0.25725	0.21889	0.23726	0.23748	0.24726	0.27538	0.24224	0.24319	0.22130
Rxx(2)	0.19232	0.22096	0.24160	0.21996	0.21329	0.19294	0.17392	0.22909	0.20305	0.22646
Rxx(3)	0.11458	0.10012	0.10224	0.12538	0.11481	0.12706	0.11418	0.12334	0.12268	0.12687
Rxx(4)	0.05018	0.03237	0.06714	0.04972	0.07506	0.05413	0.05693	0.02047	0.04434	0.04256
Rxx(5)	0.02620	0.02699	0.02121	0.05241	0.03591	0.03071	0.03114	0.03750	0.01419	0.01267
Rxx(6)	0.08401	0.05039	0.08088	0.06957	0.08329	0.05297	0.07768	0.03173	0.04947	0.04525
Rxx(7)	0.03984	0.03188	0.08117	0.05842	0.05901	0.08147	0.04168	0.03608	0.07588	0.07881
Rxx(8)	0.04028	0.03684	0.03899	0.03600	0.03383	0.00966	0.04040	0.04783	0.03221	0.04147
Rxx(9)	0.01277	0.03175	0.02413	0.02031	0.01666	0.02872	0.02781	0.02926	0.00944	0.03263

Received

	W= 320									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.86960	1.93540	1.63850	1.76030	1.86050	1.77890	1.68690	1.82450	1.90350	1.69120
Rxx(1)	0.31760	0.31078	0.26660	0.22547	0.18982	0.21698	0.24421	0.25635	0.25621	0.27520
Rxx(2)	0.19467	0.24072	0.19568	0.29725	0.29569	0.24100	0.22679	0.17221	0.13811	0.15392
Rxx(3)	0.09685	0.16353	0.10847	0.16261	0.19339	0.12615	0.02114	0.14278	0.22364	0.07395
Rxx(4)	0.06836	0.02770	0.13252	0.12050	0.15297	0.14008	0.01294	0.06570	0.00966	0.01354
Rxx(5)	0.14280	0.04764	0.06683	0.14500	0.02934	0.10779	0.05781	0.08428	0.10775	0.01959
Rxx(6)	0.22127	0.03019	0.12785	0.18436	0.13273	0.11695	0.01672	0.08102	0.09471	0.08616
Rxx(7)	0.12689	0.02944	0.07262	0.15608	0.06327	0.15258	0.07334	0.04148	0.10075	0.05381
Rxx(8)	0.06446	0.10295	0.10952	0.12166	0.09796	0.12147	0.06330	0.04397	0.09002	0.10874
Rxx(9)	0.09089	0.05190	0.03302	0.03791	0.05415	0.00843	0.06964	0.05142	0.02923	0.08294

Noise

	W= 320									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.86961	0.93536	0.63847	0.76035	0.86050	0.77885	0.68692	0.82449	0.90345	0.69121
Rxx(1)	0.05575	0.05353	0.04771	0.01180	0.04766	0.03028	0.03117	0.01412	0.01303	0.05390
Rxx(2)	0.00235	0.01976	0.04592	0.07729	0.08241	0.04806	0.05287	0.05688	0.06495	0.07254
Rxx(3)	0.01774	0.06341	0.00623	0.03723	0.07858	0.00092	0.09304	0.01943	0.10096	0.05292
Rxx(4)	0.01818	0.00467	0.06538	0.07078	0.07791	0.08595	0.04399	0.04523	0.03468	0.02902
Rxx(5)	0.11661	0.02065	0.04562	0.09260	0.00658	0.07708	0.02667	0.04678	0.09356	0.00692
Rxx(6)	0.13726	0.02020	0.04697	0.11479	0.04944	0.06398	0.06096	0.04930	0.04524	0.04091
Rxx(7)	0.08705	0.00244	0.00855	0.09767	0.00426	0.07112	0.03166	0.00540	0.02487	0.02500
Rxx(8)	0.02418	0.06611	0.07053	0.08566	0.06412	0.11181	0.02290	0.00386	0.05781	0.06726
Rxx(9)	0.07812	0.02015	0.00889	0.01759	0.03750	0.02030	0.04182	0.02216	0.01978	0.05031

Transmitted

	W= 1600									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.25399	0.24616	0.24637	0.24094	0.24315	0.24768	0.24490	0.26107	0.25196	0.24545
Rxx(2)	0.19657	0.20202	0.20762	0.20266	0.19770	0.21882	0.19515	0.18605	0.20805	0.20026
Rxx(3)	0.11461	0.12780	0.11428	0.12234	0.12765	0.10020	0.12737	0.11588	0.10853	0.13275
Rxx(4)	0.05474	0.04277	0.04505	0.04777	0.05881	0.04071	0.05127	0.05651	0.05150	0.04222
Rxx(5)	0.02939	0.01871	0.01709	0.02453	0.03781	0.01504	0.01784	0.02401	0.03575	0.03407
Rxx(6)	0.04602	0.05695	0.04576	0.04146	0.04804	0.04877	0.04486	0.05839	0.04262	0.05171
Rxx(7)	0.05862	0.07476	0.07125	0.05683	0.06144	0.05869	0.07934	0.04237	0.06214	0.06111
Rxx(8)	0.03372	0.02122	0.03178	0.04604	0.03952	0.03703	0.04116	0.04861	0.04156	0.02011
Rxx(9)	0.01834	0.00688	0.02298	0.01941	0.01267	0.01374	0.01479	0.01048	0.00481	0.00838

Received

	W= 1600									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.75310	1.73720	1.89680	1.79500	1.85080	1.82250	1.75040	1.81550	1.77630	1.80290
Rxx(1)	0.30056	0.20402	0.23091	0.21714	0.25559	0.24642	0.27044	0.22535	0.20928	0.26740
Rxx(2)	0.17170	0.19044	0.20120	0.22939	0.20731	0.22925	0.19557	0.23978	0.19007	0.23349
Rxx(3)	0.05368	0.13457	0.13064	0.12249	0.11832	0.10633	0.10696	0.11983	0.10156	0.15805
Rxx(4)	0.10046	0.04419	0.11840	0.06890	0.11614	0.06813	0.04030	0.04509	0.02974	0.04834
Rxx(5)	0.02142	0.01702	0.05479	0.04762	0.06848	0.02289	0.03636	0.02321	0.03054	0.06403
Rxx(6)	0.02932	0.06413	0.06898	0.08225	0.07543	0.08256	0.01569	0.10714	0.04764	0.10278
Rxx(7)	0.06966	0.09704	0.07734	0.04271	0.03327	0.07735	0.07649	0.05246	0.06630	0.04141
Rxx(8)	0.01051	0.05034	0.05156	0.02641	0.06359	0.04578	0.05274	0.05370	0.05209	0.05930
Rxx(9)	0.06740	0.01689	0.04643	0.04596	0.02799	0.02131	0.02465	0.01630	0.03976	0.03821

Noise

	W= 1600									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.75308	0.73716	0.89675	0.79497	0.85082	0.82251	0.75039	0.81546	0.77625	0.80291
Rxx(1)	0.04656	0.04214	0.01546	0.02380	0.01243	0.00126	0.02554	0.03572	0.04268	0.02195
Rxx(2)	0.02487	0.01158	0.00642	0.02673	0.00961	0.01043	0.00042	0.05373	0.01799	0.03322
Rxx(3)	0.06094	0.00677	0.01637	0.00015	0.00933	0.00613	0.02041	0.00395	0.00697	0.02530
Rxx(4)	0.04572	0.00142	0.07336	0.02112	0.05733	0.02741	0.01097	0.01142	0.02177	0.00612
Rxx(5)	0.00797	0.00169	0.03771	0.02309	0.03068	0.00785	0.01853	0.00080	0.00521	0.02996
Rxx(6)	0.01670	0.00718	0.02322	0.04079	0.02739	0.03379	0.02917	0.04875	0.00502	0.05107
Rxx(7)	0.01104	0.02228	0.00609	0.01412	0.02817	0.01866	0.00285	0.01009	0.00416	0.01971
Rxx(8)	0.02321	0.02912	0.01978	0.01963	0.02407	0.00875	0.01158	0.00509	0.01053	0.03919
Rxx(9)	0.04906	0.01001	0.02345	0.02655	0.01532	0.00757	0.00986	0.00582	0.03495	0.02983

Transmitted

	W= 3200									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.25308	0.24522	0.25361	0.24322	0.24673	0.24702	0.24983	0.24980	0.25479	0.25079
Rxx(2)	0.19851	0.20102	0.19801	0.20686	0.19481	0.19705	0.20779	0.20319	0.19886	0.20027
Rxx(3)	0.11746	0.11309	0.11113	0.11537	0.12595	0.11666	0.10854	0.11653	0.11336	0.11426
Rxx(4)	0.04652	0.06576	0.05076	0.05338	0.05414	0.06602	0.04664	0.04554	0.04814	0.05205
Rxx(5)	0.02368	0.03424	0.02118	0.02494	0.01855	0.03079	0.01990	0.02194	0.02569	0.01927
Rxx(6)	0.05078	0.04653	0.04955	0.04814	0.05442	0.05601	0.04238	0.05082	0.04909	0.06140
Rxx(7)	0.06039	0.06332	0.06534	0.06533	0.07304	0.06375	0.06411	0.06490	0.05913	0.06362
Rxx(8)	0.02354	0.03711	0.02849	0.03823	0.02668	0.03021	0.03222	0.02881	0.03000	0.02850
Rxx(9)	0.02684	0.01104	0.01184	0.01613	0.01598	0.01145	0.02859	0.01774	0.01771	0.01049

Received

	W= 3200									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.76250	1.83710	1.83110	1.77850	1.81580	1.79190	1.81540	1.77330	1.75560	1.79490
Rxx(1)	0.23904	0.24666	0.25951	0.22823	0.26375	0.23777	0.22923	0.23068	0.22615	0.24718
Rxx(2)	0.17472	0.21703	0.19870	0.20665	0.18048	0.21924	0.23316	0.22307	0.20327	0.20084
Rxx(3)	0.13561	0.09421	0.11110	0.14173	0.14191	0.10604	0.09617	0.11782	0.14026	0.14110
Rxx(4)	0.05520	0.10626	0.06416	0.04094	0.03177	0.08044	0.04183	0.02717	0.04419	0.07748
Rxx(5)	0.01138	0.04480	0.02897	0.03535	0.02246	0.06990	0.02474	0.01396	0.05445	0.01116
Rxx(6)	0.07404	0.04996	0.10213	0.07375	0.06623	0.04639	0.03202	0.07327	0.05530	0.09647
Rxx(7)	0.07718	0.05129	0.04647	0.06712	0.03947	0.07957	0.07417	0.06126	0.07029	0.05915
Rxx(8)	0.03144	0.03975	0.03876	0.03632	0.05901	0.01539	0.01843	0.05555	0.02642	0.02269
Rxx(9)	0.03695	0.02793	0.02692	0.00597	0.03018	0.00414	0.02630	0.02697	0.03105	0.01726

Noise

	W= 3200									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.75308	0.73716	0.89675	0.79497	0.85082	0.82251	0.75039	0.81546	0.77625	0.80291
Rxx(1)	0.04656	0.04214	0.01546	0.02380	0.01243	0.00126	0.02554	0.03572	0.04268	0.02195
Rxx(2)	0.02487	0.01158	0.00642	0.02673	0.00961	0.01043	0.00042	0.05373	0.01799	0.03322
Rxx(3)	0.06094	0.00677	0.01637	0.00015	0.00933	0.00613	0.02041	0.00395	0.00697	0.02530
Rxx(4)	0.04572	0.00142	0.07336	0.02112	0.05733	0.02741	0.01097	0.01142	0.02177	0.00612
Rxx(5)	0.00797	0.00169	0.03771	0.02309	0.03068	0.00785	0.01853	0.00080	0.00521	0.02996
Rxx(6)	0.01670	0.00718	0.02322	0.04079	0.02739	0.03379	0.02917	0.04875	0.00502	0.05107
Rxx(7)	0.01104	0.02228	0.00609	0.01412	0.02817	0.01866	0.00285	0.01009	0.00416	0.01971
Rxx(8)	0.02321	0.02912	0.01978	0.01963	0.02407	0.00875	0.01158	0.00509	0.01053	0.03919
Rxx(9)	0.04906	0.01001	0.02345	0.02655	0.01532	0.00757	0.00986	0.00582	0.03495	0.02983

Transmitted

	W= 4800									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.25243	0.24826	0.25384	0.25236	0.24795	0.25146	0.24813	0.24536	0.24795	0.24882
Rxx(2)	0.19624	0.20102	0.19881	0.19422	0.20416	0.19977	0.19864	0.19745	0.20205	0.20636
Rxx(3)	0.11609	0.11345	0.11076	0.11564	0.11906	0.11666	0.12450	0.12417	0.11985	0.10995
Rxx(4)	0.05105	0.04990	0.04832	0.05323	0.04507	0.04792	0.04511	0.05139	0.04762	0.05317
Rxx(5)	0.02199	0.01868	0.02404	0.01813	0.02751	0.02532	0.02279	0.01936	0.02464	0.02829
Rxx(6)	0.05305	0.04224	0.04130	0.04895	0.04132	0.04676	0.04847	0.05330	0.04520	0.04192
Rxx(7)	0.06216	0.06758	0.06313	0.06499	0.06522	0.06271	0.06292	0.06287	0.06701	0.06268
Rxx(8)	0.03082	0.03686	0.03282	0.03573	0.03489	0.03273	0.04099	0.03597	0.03586	0.03981
Rxx(9)	0.01286	0.02053	0.02017	0.01449	0.01870	0.01551	0.01005	0.01368	0.01080	0.00774

Received

	W= 4800									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.79090	1.77920	1.75350	1.77920	1.80170	1.80920	1.75350	1.78710	1.83180	1.83080
Rxx(1)	0.24573	0.25061	0.23729	0.28386	0.24108	0.24971	0.25620	0.26309	0.24699	0.29421
Rxx(2)	0.17808	0.19473	0.18570	0.18533	0.19255	0.21183	0.18696	0.19467	0.20338	0.22497
Rxx(3)	0.11805	0.10051	0.10531	0.10364	0.12275	0.13847	0.11624	0.13221	0.13725	0.10116
Rxx(4)	0.06950	0.07064	0.02025	0.03370	0.06440	0.03867	0.05372	0.06464	0.07800	0.05766
Rxx(5)	0.00849	0.02577	0.02941	0.04257	0.05675	0.02441	0.00562	0.01920	0.04908	0.01914
Rxx(6)	0.05434	0.06205	0.03370	0.02834	0.05269	0.03904	0.06527	0.06410	0.06370	0.06739
Rxx(7)	0.09651	0.06071	0.04981	0.07004	0.04881	0.07452	0.07878	0.08080	0.07066	0.06783
Rxx(8)	0.03992	0.05646	0.03147	0.01454	0.03501	0.06441	0.03475	0.03350	0.02653	0.07213
Rxx(9)	0.01333	0.00483	0.01900	0.02470	0.02323	0.00921	0.00836	0.01385	0.03806	0.02635

Noise

	W= 4800									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.79090	0.77919	0.75348	0.77922	0.80166	0.80925	0.75347	0.78712	0.83184	0.83077
Rxx(1)	0.00669	0.00235	0.01655	0.03150	0.00686	0.00175	0.00806	0.01773	0.00096	0.04539
Rxx(2)	0.01815	0.00629	0.01311	0.00889	0.01161	0.01206	0.01168	0.00278	0.00133	0.01861
Rxx(3)	0.00196	0.01294	0.00545	0.01199	0.00369	0.02182	0.00826	0.00804	0.01740	0.00879
Rxx(4)	0.01846	0.02074	0.02807	0.01953	0.01933	0.00925	0.00861	0.01324	0.03039	0.00449
Rxx(5)	0.01350	0.00709	0.00537	0.02443	0.02924	0.00091	0.01717	0.00016	0.02444	0.00914
Rxx(6)	0.00129	0.01982	0.00760	0.02062	0.01137	0.00772	0.01680	0.01080	0.01850	0.02547
Rxx(7)	0.03436	0.00686	0.01332	0.00505	0.01642	0.01181	0.01587	0.01794	0.00365	0.00514
Rxx(8)	0.00909	0.01961	0.00135	0.02118	0.00012	0.03168	0.00624	0.00248	0.00933	0.03232
Rxx(9)	0.00047	0.01569	0.00117	0.01021	0.00453	0.00630	0.00169	0.00017	0.02727	0.01861

Transmitted

	W= 6400									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.24443	0.24642	0.25157	0.24397	0.25473	0.24781	0.24816	0.25156	0.24211	0.24825
Rxx(2)	0.20381	0.20302	0.20420	0.20324	0.19644	0.20364	0.20377	0.20513	0.20767	0.19756
Rxx(3)	0.12114	0.11933	0.10934	0.11907	0.11413	0.12261	0.11182	0.10965	0.12024	0.12299
Rxx(4)	0.04666	0.04845	0.05049	0.04963	0.05012	0.04005	0.04954	0.04600	0.04909	0.05114
Rxx(5)	0.02023	0.02605	0.02478	0.02108	0.02107	0.02290	0.02150	0.02113	0.02740	0.03039
Rxx(6)	0.04954	0.04803	0.04680	0.05232	0.04726	0.05130	0.04753	0.05200	0.04473	0.04310
Rxx(7)	0.06301	0.06560	0.05988	0.06681	0.06763	0.05649	0.06387	0.05262	0.06306	0.06429
Rxx(8)	0.03355	0.02443	0.03891	0.02805	0.03244	0.03429	0.03702	0.04034	0.03897	0.03701
Rxx(9)	0.02023	0.02273	0.01236	0.01372	0.00909	0.01302	0.01004	0.01506	0.01173	0.01358

Received

	W= 6400									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.77720	1.78440	1.77420	1.81630	1.75620	1.77920	1.81970	1.79320	1.80320	1.79150
Rxx(1)	0.22905	0.24889	0.25391	0.24502	0.25427	0.26618	0.25639	0.25314	0.24196	0.25019
Rxx(2)	0.18638	0.21269	0.19371	0.20537	0.18491	0.19681	0.21018	0.21177	0.21777	0.20276
Rxx(3)	0.12208	0.09556	0.11319	0.11844	0.12784	0.13660	0.11193	0.14261	0.10634	0.11696
Rxx(4)	0.09109	0.04229	0.04193	0.03704	0.03765	0.03090	0.06482	0.02857	0.03085	0.03880
Rxx(5)	0.01404	0.02086	0.02312	0.01841	0.02274	0.02734	0.03424	0.01165	0.02504	0.01955
Rxx(6)	0.06137	0.05941	0.03704	0.05442	0.03605	0.05411	0.07618	0.06700	0.04740	0.05075
Rxx(7)	0.07608	0.06136	0.06614	0.07538	0.06625	0.05778	0.05673	0.04280	0.06362	0.08299
Rxx(8)	0.04494	0.02662	0.05402	0.00300	0.03483	0.03031	0.04871	0.04761	0.03666	0.04818
Rxx(9)	0.01407	0.04704	0.00510	0.02355	0.01065	0.02206	0.00679	0.02990	0.01855	0.02651

Noise

	W= 6400									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.77720	0.78443	0.77425	0.81626	0.75623	0.77916	0.81971	0.79325	0.80323	0.79154
Rxx(1)	0.01538	0.00247	0.00234	0.00105	0.00047	0.01837	0.00823	0.00158	0.00015	0.00194
Rxx(2)	0.01743	0.00967	0.01050	0.00213	0.01153	0.00683	0.00640	0.00664	0.01010	0.00520
Rxx(3)	0.00094	0.02377	0.00385	0.00063	0.01371	0.01399	0.00011	0.03296	0.01390	0.00603
Rxx(4)	0.04444	0.00616	0.00856	0.01259	0.01247	0.00916	0.01528	0.01743	0.01825	0.01234
Rxx(5)	0.00619	0.00519	0.00166	0.00267	0.00166	0.00444	0.01275	0.00948	0.00236	0.01084
Rxx(6)	0.01184	0.01138	0.00976	0.00210	0.01121	0.00280	0.02864	0.01500	0.00267	0.00765
Rxx(7)	0.01307	0.00424	0.00626	0.00857	0.00138	0.00129	0.00714	0.00982	0.00056	0.01870
Rxx(8)	0.01138	0.00220	0.01511	0.02505	0.00238	0.00399	0.01169	0.00727	0.00231	0.01117
Rxx(9)	0.00616	0.02431	0.00725	0.00983	0.00157	0.00904	0.00325	0.01484	0.00682	0.01293

Transmitted

	W= 8000									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.25055	0.25060	0.24546	0.25021	0.24618	0.24682	0.24427	0.25239	0.24927	0.25189
Rxx(2)	0.20154	0.19977	0.20530	0.20073	0.20509	0.20264	0.20917	0.20010	0.20345	0.19938
Rxx(3)	0.11558	0.11732	0.12062	0.11348	0.11731	0.12054	0.11610	0.11541	0.11857	0.11840
Rxx(4)	0.04746	0.04966	0.04589	0.05439	0.04710	0.04551	0.04874	0.04717	0.04349	0.04457
Rxx(5)	0.02315	0.02680	0.02775	0.02927	0.02211	0.02736	0.02578	0.02075	0.02897	0.02521
Rxx(6)	0.04668	0.04848	0.04571	0.04240	0.05031	0.04689	0.04938	0.04802	0.04127	0.04253
Rxx(7)	0.06034	0.06135	0.06133	0.06475	0.05894	0.05750	0.06687	0.06667	0.06151	0.06156
Rxx(8)	0.03280	0.03346	0.03592	0.03480	0.03963	0.03283	0.02470	0.03383	0.03191	0.03749
Rxx(9)	0.02172	0.01440	0.01130	0.00991	0.00887	0.01541	0.01453	0.00950	0.02086	0.01874

Received

	W= 8000									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.79210	1.77210	1.81090	1.77290	1.79460	1.79460	1.77580	1.77200	1.80710	1.77750
Rxx(1)	0.25594	0.23870	0.24455	0.23774	0.25704	0.25245	0.23913	0.22985	0.23849	0.25599
Rxx(2)	0.18612	0.20506	0.19649	0.20840	0.20492	0.20845	0.19517	0.20547	0.22681	0.20726
Rxx(3)	0.11227	0.11195	0.13602	0.11457	0.13060	0.15035	0.12799	0.12064	0.12832	0.11260
Rxx(4)	0.06454	0.03937	0.03430	0.06778	0.05348	0.03489	0.03546	0.04915	0.04861	0.04671
Rxx(5)	0.01359	0.02481	0.02949	0.02018	0.02908	0.03876	0.02632	0.03590	0.02622	0.01519
Rxx(6)	0.04275	0.05894	0.01910	0.04314	0.06386	0.05986	0.03927	0.05212	0.05771	0.04953
Rxx(7)	0.07314	0.05905	0.07102	0.08519	0.03839	0.04397	0.07393	0.05777	0.04853	0.05197
Rxx(8)	0.02414	0.03326	0.04995	0.04672	0.05749	0.02931	0.03123	0.03851	0.03189	0.04328
Rxx(9)	0.03210	0.02882	0.01873	0.01855	0.02347	0.03475	0.01824	0.02367	0.02273	0.03507

Noise

	W= 8000									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.79212	0.77210	0.81092	0.77290	0.79459	0.79461	0.77582	0.77196	0.80709	0.77751
Rxx(1)	0.00538	0.01190	0.00091	0.01246	0.01086	0.00564	0.00514	0.02254	0.01077	0.00410
Rxx(2)	0.01542	0.00528	0.00881	0.00767	0.00017	0.00580	0.01401	0.00536	0.02336	0.00788
Rxx(3)	0.00331	0.00537	0.01540	0.00109	0.01329	0.02981	0.01188	0.00522	0.00976	0.00580
Rxx(4)	0.01708	0.01028	0.01158	0.01339	0.00638	0.01062	0.01328	0.00199	0.00513	0.00214
Rxx(5)	0.00956	0.00199	0.00174	0.00909	0.00696	0.01140	0.00053	0.01515	0.00275	0.01003
Rxx(6)	0.00393	0.01046	0.02661	0.00073	0.01355	0.01297	0.01011	0.00410	0.01645	0.00699
Rxx(7)	0.01280	0.00230	0.00969	0.02044	0.02055	0.01353	0.00706	0.00890	0.01298	0.00959
Rxx(8)	0.00866	0.00020	0.01404	0.01192	0.01786	0.00352	0.00653	0.00468	0.00002	0.00579
Rxx(9)	0.01039	0.01442	0.00743	0.00864	0.01460	0.01934	0.00371	0.01416	0.00186	0.01633

Transmitted

	W= 9600									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Rxx(1)	0.24833	0.24923	0.25062	0.24509	0.25002	0.24728	0.24925	0.24762	0.25116	0.25221
Rxx(2)	0.20396	0.19873	0.20265	0.20619	0.20003	0.20147	0.20235	0.20087	0.20218	0.20063
Rxx(3)	0.11499	0.11613	0.11307	0.11868	0.11564	0.11772	0.11603	0.11674	0.11339	0.11513
Rxx(4)	0.04632	0.05224	0.04939	0.04721	0.05118	0.05210	0.04450	0.04849	0.04580	0.04970
Rxx(5)	0.02004	0.02267	0.02489	0.02762	0.02424	0.02180	0.02040	0.02102	0.02115	0.03254
Rxx(6)	0.05048	0.05008	0.04825	0.04805	0.04989	0.05161	0.04471	0.04853	0.04640	0.04374
Rxx(7)	0.06114	0.06552	0.05966	0.06194	0.05724	0.06514	0.06195	0.06156	0.05879	0.05802
Rxx(8)	0.03537	0.03050	0.03180	0.02904	0.03998	0.03330	0.03363	0.03031	0.03968	0.03670
Rxx(9)	0.01200	0.01221	0.01613	0.01684	0.01305	0.01279	0.01964	0.01806	0.01708	0.01075

Received

	W= 9600									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	1.76800	1.77380	1.80380	1.78910	1.77680	1.78170	1.78700	1.79170	1.75600	1.78810
Rxx(1)	0.22620	0.24840	0.24702	0.23982	0.24196	0.24601	0.25899	0.23801	0.26386	0.24972
Rxx(2)	0.20256	0.19035	0.20749	0.21622	0.21018	0.19625	0.20652	0.23295	0.18689	0.19557
Rxx(3)	0.11439	0.11462	0.12267	0.13452	0.12961	0.11780	0.11012	0.10589	0.11831	0.10894
Rxx(4)	0.06482	0.04220	0.04480	0.05157	0.03854	0.03164	0.04037	0.04535	0.02112	0.05507
Rxx(5)	0.00774	0.02577	0.03234	0.02563	0.02035	0.01246	0.02321	0.02578	0.01199	0.02448
Rxx(6)	0.03308	0.04379	0.04439	0.05374	0.05367	0.05297	0.04293	0.06059	0.04589	0.03700
Rxx(7)	0.06194	0.07755	0.07606	0.07789	0.06848	0.07721	0.06660	0.04038	0.06897	0.06485
Rxx(8)	0.05996	0.03336	0.01962	0.03170	0.05902	0.02919	0.02458	0.03535	0.02373	0.04980
Rxx(9)	0.03336	0.01681	0.01423	0.01981	0.01461	0.00964	0.03006	0.00521	0.01315	0.01103

Noise

	W= 9600									
	Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5	Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
Rxx(0)	0.76798	0.77382	0.80376	0.78913	0.77676	0.78172	0.78700	0.79169	0.75597	0.78811
Rxx(1)	0.02212	0.00083	0.00360	0.00528	0.00806	0.00128	0.00974	0.00961	0.01270	0.00249
Rxx(2)	0.00140	0.00837	0.00484	0.01003	0.01015	0.00522	0.00417	0.03208	0.01529	0.00507
Rxx(3)	0.00060	0.00152	0.00959	0.01584	0.01397	0.00008	0.00591	0.01085	0.00492	0.00619
Rxx(4)	0.01850	0.01003	0.00459	0.00436	0.01264	0.02046	0.00413	0.00314	0.02468	0.00537
Rxx(5)	0.01230	0.00310	0.00745	0.00199	0.00389	0.00934	0.00281	0.00476	0.00917	0.00806
Rxx(6)	0.01740	0.00629	0.00386	0.00569	0.00379	0.00136	0.00178	0.01206	0.00051	0.00674
Rxx(7)	0.00081	0.01203	0.01640	0.01594	0.01124	0.01207	0.00465	0.02118	0.01017	0.00683
Rxx(8)	0.02459	0.00287	0.01218	0.00265	0.01904	0.00411	0.00905	0.00504	0.01596	0.01311
Rxx(9)	0.02136	0.00460	0.00189	0.00297	0.00156	0.00315	0.01042	0.01284	0.00393	0.00029

APPENDIX C

LP BIAS COMPUTATION FOR THREE MODULATION TYPES

Table C1: LP Bias and SNR Estimation results for three modulation and coding types averaged over to transmissions

		BPSK				QPSK 3/4				64 QAM 3/4			
		Initial Seed=61				Initial Seed=61				Initial Seed=61			
	transmission	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)
2 dB	1	1.0000	0.2477	0.7523	0.9987	1.0000	0.2476	0.7524	0.9811	1.0000	0.2495	0.7505	1.1317
	2	1.0000	0.2504	0.7496	1.1546	1.0000	0.2511	0.7490	1.2246	1.0000	0.2487	0.7513	0.9819
	3	1.0000	0.2484	0.7516	1.0764	1.0000	0.2463	0.7537	1.0267	1.0000	0.2531	0.7469	0.8013
	4	1.0000	0.2473	0.7527	1.1384	1.0000	0.2461	0.7539	1.0665	1.0000	0.2494	0.7506	1.0219
	5	1.0000	0.2462	0.7538	1.1954	1.0000	0.2467	0.7533	1.1530	1.0000	0.2591	0.7409	1.1020
	6	1.0000	0.2456	0.7544	1.0441	1.0000	0.2503	0.7497	1.0907	1.0000	0.2495	0.7505	1.0424
	7	1.0000	0.2471	0.7529	1.0318	1.0000	0.2519	0.7481	0.8155	1.0000	0.2510	0.7490	0.8542
	8	1.0000	0.2508	0.7492	1.1278	1.0000	0.2484	0.7516	1.1830	1.0000	0.2393	0.7607	0.8209
	9	1.0000	0.2493	0.7507	1.1605	1.0000	0.2490	0.7510	0.9413	1.0000	0.2549	0.7451	1.0161
	10	1.0000	0.2485	0.7515	1.0983	1.0000	0.2515	0.7485	1.0975	1.0000	0.2482	0.7518	0.9560
	Average			0.7519	1.1026			0.7511	1.0580			0.7498	0.9728
	NMSE				0.2022				0.2252				0.2667

		Initial Seed=51				Initial Seed=51				Initial Seed=51			
	transmission	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)
4 dB	1	1.0000	0.2527	0.7473	3.0267	1.0000	0.2463	0.7537	2.8063	1.0000	0.2524	0.7476	3.0508
	2	1.0000	0.2505	0.7495	3.2632	1.0000	0.2476	0.7524	2.8886	1.0000	0.2506	0.7494	3.2077
	3	1.0000	0.2470	0.7530	2.9549	1.0000	0.2494	0.7506	2.9707	1.0000	0.2487	0.7513	2.9410
	4	1.0000	0.2516	0.7484	3.2485	1.0000	0.2488	0.7512	3.0074	1.0000	0.2462	0.7538	3.0089
	5	1.0000	0.2473	0.7527	2.9720	1.0000	0.2473	0.7527	2.9334	1.0000	0.2480	0.7520	2.8599
	6	1.0000	0.2537	0.7463	3.0615	1.0000	0.2517	0.7483	3.0611	1.0000	0.2521	0.7479	3.0062
	7	1.0000	0.2492	0.7508	2.9780	1.0000	0.2490	0.7510	3.0520	1.0000	0.2490	0.7510	2.9505
	8	1.0000	0.2497	0.7503	2.9715	1.0000	0.2506	0.7494	2.9026	1.0000	0.2478	0.7522	2.8365
	9	1.0000	0.2501	0.7499	3.2414	1.0000	0.2470	0.7530	3.1473	1.0000	0.2465	0.7535	3.0206
	10	1.0000	0.2495	0.7505	3.0800	1.0000	0.2474	0.7526	3.0193	1.0000	0.2482	0.7518	2.8861
	Average			0.7499	3.0798			0.7515	2.9789			0.7510	2.9768
	NMSE				0.2022				0.2252				0.2667

		Initial Seed=40				Initial Seed=40				Initial Seed=40			
	transmission	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)
6 dB	1	1.0000	0.2509	0.7491	4.9903	1.0000	0.2505	0.7495	4.9102	1.0000	0.2524	0.7476	4.9455
	2	1.0000	0.2494	0.7506	4.8607	1.0000	0.2457	0.7543	4.8587	1.0000	0.2506	0.7494	4.9081
	3	1.0000	0.2495	0.7505	5.0469	1.0000	0.2515	0.7485	4.8813	1.0000	0.2487	0.7513	4.9329
	4	1.0000	0.2465	0.7535	5.0469	1.0000	0.2510	0.7490	5.2160	1.0000	0.2462	0.7538	5.1808
	5	1.0000	0.2466	0.7534	5.1842	1.0000	0.2513	0.7487	5.0487	1.0000	0.2480	0.7520	5.3667
	6	1.0000	0.2447	0.7553	4.9868	1.0000	0.2481	0.7519	5.1834	1.0000	0.2521	0.7479	5.5714
	7	1.0000	0.2535	0.7466	4.9536	1.0000	0.2462	0.7538	5.0289	1.0000	0.2490	0.7510	4.7415
	8	1.0000	0.2510	0.7490	5.0653	1.0000	0.2487	0.7514	4.9517	1.0000	0.2478	0.7522	5.0146
	9	1.0000	0.2440	0.7560	5.1014	1.0000	0.2478	0.7522	5.1559	1.0000	0.2465	0.7535	5.0067
	10	1.0000	0.2470	0.7530	4.8767	1.0000	0.2474	0.7526	4.8313	1.0000	0.2482	0.7518	4.6618
	Average			0.7517	5.0113			0.7512	5.0066			0.7510	5.0330
	NMSE				0.2022				0.2252				0.2667

		Initial Seed=5				Initial Seed=5				Initial Seed=5			
	transmission	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)
8 dB	1	1.0000	0.2480	0.7520	6.7388	1.0000	0.2503	0.7497	7.1743	1.0000	0.2497	0.7503	6.9259
	2	1.0000	0.2484	0.7516	6.8705	1.0000	0.2530	0.7470	7.4804	1.0000	0.2484	0.7516	7.2301
	3	1.0000	0.2500	0.7500	7.0247	1.0000	0.2496	0.7504	6.8178	1.0000	0.2464	0.7536	6.8403
	4	1.0000	0.2537	0.7463	7.3818	1.0000	0.2467	0.7533	7.2457	1.0000	0.2586	0.7414	7.1246
	5	1.0000	0.2525	0.7476	7.1596	1.0000	0.2484	0.7517	6.8138	1.0000	0.2525	0.7475	7.0388
	6	1.0000	0.2541	0.7459	7.1343	1.0000	0.2506	0.7494	7.1750	1.0000	0.2580	0.7420	7.2682
	7	1.0000	0.2474	0.7526	7.0714	1.0000	0.2469	0.7531	7.1142	1.0000	0.2581	0.7419	7.2050
	8	1.0000	0.2449	0.7551	6.7951	1.0000	0.2457	0.7543	7.1615	1.0000	0.2504	0.7496	6.9795
	9	1.0000	0.2452	0.7548	6.8180	1.0000	0.2533	0.7467	7.2310	1.0000	0.2446	0.7554	6.8282
	10	1.0000	0.2488	0.7512	6.8735	1.0000	0.2466	0.7534	7.0677	1.0000	0.2599	0.7401	7.2404
	Average			0.7507	6.9868			0.7509	7.1281			0.7473	7.0681
	NMSE				0.2022				0.2252				0.2667

		Initial Seed=10				Initial Seed=10				Initial Seed=10			
	transmission	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)
10 dB	1	1.0000	0.2496	0.7504	9.2919	1.0000	0.2454	0.7546	9.0467	1.0000	0.2529	0.7471	9.1522
	2	1.0000	0.2511	0.7489	9.2215	1.0000	0.2495	0.7505	9.0925	1.0000	0.2534	0.7466	9.1411
	3	1.0000	0.2502	0.7498	9.1195	1.0000	0.2480	0.7520	8.8994	1.0000	0.2432	0.7568	8.7276
	4	1.0000	0.2491	0.7510	9.1164	1.0000	0.2500	0.7500	9.4902	1.0000	0.2496	0.7504	9.0234
	5	1.0000	0.2510	0.7490	9.0271	1.0000	0.2498	0.7502	8.7167	1.0000	0.2512	0.7488	9.0760
	6	1.0000	0.2486	0.7514	8.8513	1.0000	0.2448	0.7552	8.8240	1.0000	0.2583	0.7417	9.0332
	7	1.0000	0.2482	0.7518	8.9775	1.0000	0.2480	0.7520	8.9220	1.0000	0.2491	0.7510	9.2485
	8	1.0000	0.2466	0.7534	9.0303	1.0000	0.2481	0.7519	9.0058	1.0000	0.2452	0.7548	8.6212
	9	1.0000	0.2434	0.7567	8.8262	1.0000	0.2483	0.7517	9.4210	1.0000	0.2576	0.7424	9.6590
	10	1.0000	0.2479	0.7521	8.7329	1.0000	0.2478	0.7522	8.8974	1.0000	0.2470	0.7530	9.0863
	Average			0.7514	9.0195			0.7520	9.0316			0.7493	9.0769
	NMSE				0.2022				0.2252				0.2667

		Initial Seed=12				Initial Seed=12				Initial Seed=61			
	transmission	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)	Rss(0)	Rss(1)	Bias	SNR (dB)
12 dB	1	1.0000	0.2508	0.7492	10.9080	1.0000	0.2517	0.7483	11.3135	1.0000	0.2529	0.7471	11.2198
	2	1.0000	0.2522	0.7478	11.7850	1.0000	0.2465	0.7536	10.6946	1.0000	0.2534	0.7466	11.0128
	3	1.0000	0.2467	0.7533	10.9338	1.0000	0.2498	0.7502	11.0681	1.0000	0.2432	0.7568	11.2422
	4	1.0000	0.2495	0.7505	11.2452	1.0000	0.2481	0.7519	10.9798	1.0000	0.2496	0.7504	11.1317
	5	1.0000	0.2501	0.7499	10.8238	1.0000	0.2456	0.7544	10.6340	1.0000	0.2512	0.7488	10.9018
	6	1.0000	0.2475	0.7525	10.9575	1.0000	0.2454	0.7546	10.8546	1.0000	0.2583	0.7417	11.9206
	7	1.0000	0.2462	0.7538	10.9154	1.0000	0.2504	0.7496	10.7970	1.0000	0.2491	0.7510	11.2580
	8	1.0000	0.2487	0.7514	11.4290	1.0000	0.2517	0.7483	11.3530	1.0000	0.2452	0.7548	11.0231
	9	1.0000	0.2486	0.7514	10.6894	1.0000	0.2512	0.7488	11.1461	1.0000	0.2576	0.7424	10.6333
	10	1.0000	0.2521	0.7479	11.0675	1.0000	0.2476	0.7524	10.9168	1.0000	0.2470	0.7530	10.9984
	Average			0.7508	11.0755			0.7512	10.9758			0.7493	11.1342
	NMSE				0.2022				0.2252				0.2667

Average bias	0.75105	0.75132	0.74961

APPENDIX D

AVERAGE SNR COMPUTATION

Table A1 : Average SNR Computation Results for LP, Reddy and Subspace Estimators averaged over 10 transmissions

Window size= 5 OFDM Symbol

		LP Estimator	**Reddy Estimator**	**Subspace Estimator**
	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
2 dB	1	0.94135	0.90515	2.66960
	2	1.04570	3.74610	3.49750
	3	0.92989	-0.62761	3.54230
	4	0.95621	0.31050	3.14740
	5	1.03370	-1.15190	3.67210
	6	1.03600	-3.31840	3.91290
	7	1.14700	-0.28249	3.43030
	8	1.05100	2.99440	4.00550
	9	0.97823	2.01850	4.08770
	10	1.66890	2.34730	4.41440
	MeanSNRdB (dB)	1.07880	0.69416	3.63797
	NMSE	0.22277	1.46360	0.72742

	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
4 dB	1	2.87410	2.16400	4.51720
	2	3.06570	5.05630	5.27600
	3	2.96550	0.92827	5.35860
	4	2.92720	1.69020	4.92930
	5	3.05020	-0.08757	5.38300
	6	3.13620	-1.58370	5.59400
	7	3.15180	0.76025	5.19010
	8	3.09540	4.30970	5.73990
	9	3.00170	3.56700	5.83150
	10	3.67530	3.84400	6.30110
	MeanSNRdB	3.09431	2.06485	5.41207
	NMSE	0.05406	0.48717	0.13845
	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
6 dB	1	4.79090	3.60040	5.93800
	2	5.07860	6.54560	6.58040
	3	4.99880	2.70110	6.79670
	4	4.88850	3.28720	6.55920
	5	5.07110	1.33080	7.20790
	6	5.25510	0.27813	7.15230
	7	5.17850	2.13630	7.01330
	8	5.14600	5.76550	7.11590
	9	5.01160	5.24350	7.42330
	10	5.72530	5.53200	7.00150
	MeanSNRdB	5.11444	3.64205	6.87885
	NMSE	0.02340	0.26282	0.02604

	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
8 dB	1	6.68220	5.18430	8.37470
	2	7.08360	8.17950	8.99270
	3	7.03350	4.61490	9.13950
	4	6.83870	5.04520	8.67990
	5	7.09750	3.03200	9.03430
	6	7.40750	2.21920	9.21520
	7	7.23430	3.78590	8.92730
	8	7.20680	7.34050	9.42590
	9	7.01140	7.01600	9.54770
	10	7.82140	7.35480	10.19800
	MeanSNRdB	7.14169	5.37723	9.15352
	NMSE	0.01289	0.16535	0.02430
10 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
	1	8.53510	6.88390	10.34600
	2	9.07690	9.92330	10.90300
	3	9.07220	6.60990	11.07500
	4	8.77520	6.91240	10.61200
	5	9.13140	4.92380	10.93100
	6	9.61520	4.20590	11.10600
	7	9.33340	5.62740	10.85800
	8	9.28370	9.01240	11.33700
	9	9.00220	8.85750	11.47000
	10	9.97300	9.26490	12.17700
	MeanSNRdB	9.17983	7.22214	11.08150
	NMSE	0.00822	0.11202	0.01400

	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
12 dB	1	10.33300	8.66980	12.33000
	2	11.05100	11.74700	12.83600
	3	11.11600	8.64640	13.02800
	4	10.69400	8.84830	12.56500
	5	11.17600	6.92670	12.85700
	6	11.91300	6.21680	13.02800
	7	11.50300	7.58690	12.81200
	8	11.38500	10.76100	13.27400
	9	10.98300	10.74800	13.41600
	10	12.19900	11.22800	14.16600
	MeanSNRdB	11.23530	9.13789	13.03120
	NMSE	0.00594	0.07965	0.00900

Window size= 10 OFDM Symbol

		LP Estimator	Reddy Estimator	Subspace Estimator
	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
2 dB	1	0.98560	3.74610	2.48490
	2	0.94238	0.31050	2.84370
	3	1.03780	-3.31840	3.04550
	4	1.07800	2.99440	2.76520
	5	1.30770	2.34730	3.45290
	6	1.29930	2.83890	3.31060
	7	0.87065	1.39010	3.08670
	8	0.96729	1.73280	3.37070
	9	1.25580	0.64341	3.71680
	10	0.98139	3.03150	3.09240
	MeanSNRdB	1.07259	1.57166	3.11694
	NMSE	0.22070	0.98300	0.34140

	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
4 dB	1	2.96490	5.05630	4.35970
	2	2.94510	1.69020	4.69080
	3	3.09610	-1.58370	4.90080
	4	3.10740	4.30970	4.64240
	5	3.32130	3.84400	5.30690
	6	3.38150	4.13140	5.21010
	7	2.85920	2.71850	5.03060
	8	2.91570	3.08370	5.21650
	9	3.28640	2.23310	5.53790
	10	2.93420	4.16540	5.02760
	MeanSNRdB	3.08118	2.96486	4.99233
	NMSE	0.05480	0.27120	0.06850
6 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	4.93060	6.54560	6.27650
	2	4.94140	3.28720	6.58040
	3	5.16530	0.27813	6.79670
	4	5.14840	5.76550	6.55920
	5	5.34900	5.53200	7.20790
	6	5.47900	5.56300	7.15230
	7	4.85120	4.31200	7.01330
	8	4.85050	4.55710	7.11590
	9	5.31880	3.96140	7.42330
	10	4.88170	5.46820	7.00150
	MeanSNRdB	5.09159	4.52701	10.55500
	NMSE	0.02430	0.13950	0.02620

8 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	6.87800	8.17950	8.22060
	2	6.93230	5.04520	8.49970
	3	7.25330	2.21920	8.72140
	4	7.20760	7.34050	8.50180
	5	7.39290	7.35480	9.13990
	6	7.60080	7.11390	9.11930
	7	6.84680	6.09930	9.01510
	8	6.76520	6.13540	9.04950
	9	7.35280	5.78790	9.35000
	10	6.81460	6.92130	8.99640
	MeanSNRdB	7.10443	6.21970	8.86137
	NMSE	0.01370	0.08900	0.01340
10 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
	1	8.79850	9.92330	10.18300
	2	8.91740	6.91240	10.44000
	3	9.37110	4.20590	10.66600
	4	9.29570	9.01240	10.46200
	5	9.45680	9.26490	11.09200
	6	9.75930	8.76340	11.10100
	7	8.84700	8.01200	11.02500
	8	8.65060	7.80090	11.00500
	9	9.38600	7.68050	11.30300
	10	8.72200	8.50090	11.00200
	MeanSNRdB	9.12044	8.00766	10.82790
	NMSE	0.00900	0.06260	0.00810

	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
12 dB	1	10.67900	11.74700	12.15700
	2	10.89500	10.03800	12.39600
	3	11.53500	8.88640	12.62500
	4	11.43000	9.40840	12.43300
	5	11.54700	10.77300	13.05900
	6	11.97200	8.17400	13.09100
	7	10.85400	7.88650	13.03900
	8	10.49400	10.46000	12.97500
	9	11.41300	9.97230	13.27300
	10	10.59000	10.67300	13.01200
	MeanSNRdB	11.14090	9.80186	12.80600
	NMSE	0.00670	0.04280	0.00540

Window size= 15 OFDM Symbol

		LP Estimator	Reddy Estimator	Subspace Estimator
	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
2 dB	1	0.96445	-0.62761	2.63060
	2	1.00380	-3.31840	2.87420
	3	1.03510	2.01850	2.97020
	4	1.42310	2.83890	2.90880
	5	0.96105	2.29610	2.83000
	6	1.10550	0.64341	2.72540
	7	0.96584	-1.78810	2.52300
	8	1.22250	4.68360	2.57050
	9	0.89698	1.46840	2.64410
	10	1.42540	1.18970	2.29550
	MeanSNRdB	1.10037	0.94045	2.69723
	NMSE	0.21070	1.50780	0.13110
	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
4 dB	1	2.96260	0.92827	4.57930
	2	3.03280	3.22560	4.81080
	3	3.06480	2.56720	4.86200
	4	3.47870	2.90260	4.78070
	5	2.95790	4.18850	4.73080
	6	3.08500	-0.22114	4.65150
	7	2.93000	1.53800	4.49000
	8	3.20410	4.24390	4.51430
	9	2.86720	3.28210	4.59010
	10	3.40660	3.71100	4.29370
	MeanSNRdB	3.09897	2.63660	4.63032
	NMSE	0.05310	0.23670	0.02650

	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
6 dB	1	4.95060	2.70110	6.55200
	2	5.06470	0.27813	6.77310
	3	5.09670	5.24350	6.78760
	4	5.55940	5.56300	6.69670
	5	4.96220	4.87330	6.67150
	6	5.05160	3.96140	6.61360
	7	4.88250	1.09730	6.48090
	8	5.19790	7.28580	6.48070
	9	4.83540	3.84210	6.56000
	10	5.40210	4.35120	6.30040
	MeanSNRdB	5.10031	3.91968	6.59165
	NMSE	0.02380	0.23020	0.01030
	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
8 dB	1	6.92640	4.61490	8.53840
	2	7.10400	2.21920	8.75080
	3	7.13660	7.01600	8.73540
	4	7.67180	7.11390	8.64100
	5	6.97560	6.51280	8.63630
	6	6.99900	5.78790	8.59600
	7	6.81550	2.96630	8.48360
	8	7.20120	8.77780	8.46070
	9	6.79860	5.32310	8.54350
	10	7.40590	6.16700	8.31020
	MeanSNRdB	7.10346	5.64989	8.56959
	NMSE	0.01360	0.14090	0.00530

	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
10 dB	1	8.88490	6.60990	10.53200
	2	9.15630	4.20590	10.73800
	3	9.19200	8.85750	10.69800
	4	9.82680	8.76340	10.60300
	5	9.00170	8.30870	10.61600
	6	8.91690	7.68050	10.58900
	7	8.71860	4.98200	10.49200
	8	9.21340	10.37300	10.44900
	9	8.75310	6.95540	10.53500
	10	9.41240	8.07250	10.32100
	MeanSNRdB	9.10761	7.48088	10.55730
	NMSE	0.00900	0.09440	0.00320
	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
12 dB	1	10.81700	8.64640	12.53100
	2	11.22900	6.21680	12.73000
	3	11.27300	10.74800	12.67100
	4	12.04200	10.49200	12.57800
	5	11.04600	10.20700	12.60300
	6	10.79000	9.61610	12.58900
	7	10.57700	7.06990	12.50200
	8	11.23600	12.05400	12.44300
	9	10.69400	8.70210	12.53100
	10	11.41400	10.03300	12.33000
	MeanSNRdB	11.11180	9.37853	12.55080
	NMSE	0.00660	0.06700	0.00220

Window size= 20 OFDM Symbol

		LP Estimator	Reddy Estimator	Subspace Estimator
2 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
	1	0.96256	0.31050	2.33020
	2	1.05260	2.99440	2.51200
	3	1.30320	2.83890	2.52080
	4	0.91997	1.73280	2.41970
	5	1.09350	3.03150	2.40140
	6	1.15600	4.68360	1.96890
	7	1.00160	2.58180	1.26540
	8	1.33120	2.92210	1.36200
	9	1.04890	2.70110	1.62370
	10	0.85615	3.24670	1.17520
	MeanSNRdB	1.07257	2.70434	1.95793
	NMSE	0.22040	0.40300	0.06870
4 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	2.95390	1.69020	4.29220
	2	3.09720	4.30970	4.45930
	3	3.35060	4.13140	4.46080
	4	2.88880	3.08370	4.35970
	5	3.08800	4.16540	4.34740
	6	3.14040	5.91570	3.95040
	7	2.98480	4.06370	3.31930
	8	3.32810	4.12790	3.37610
	9	3.05280	3.95710	3.60140
	10	2.82550	4.56090	3.24250
	MeanSNRdB	3.07101	4.00057	3.94091
	NMSE	0.05560	0.06450	0.01470

	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
6 dB	1	4.93520	3.28720	6.27590
	2	5.15260	5.76550	6.42820
	3	5.41250	5.56300	6.42110
	4	4.85260	4.55710	6.32290
	5	5.07870	5.46820	6.31460
	6	5.12770	7.28580	5.95040
	7	4.96680	5.70450	5.37770
	8	5.33820	5.49020	5.40410
	9	5.05640	5.36350	5.60270
	10	4.78500	6.06180	5.30520
	MeanSNRdB	5.07057	5.45468	5.94028
	NMSE	0.02500	0.03440	0.00560
	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
8 dB	1	6.90450	5.04520	8.27130
	2	7.22590	7.34050	8.40980
	3	7.49420	7.11390	8.39410
	4	6.80830	6.13540	8.29970
	5	7.06100	6.92130	8.29430
	6	7.11490	8.77780	7.95760
	7	6.94400	7.46390	7.43130
	8	7.36070	6.98920	7.43420
	9	7.06050	6.89930	7.61310
	10	6.73340	7.71180	7.35860
	MeanSNRdB	7.07074	7.03983	7.94640
	NMSE	0.01430	0.02780	0.00280

	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
10 dB	1	8.85740	6.91240	10.27300
	2	9.32770	9.01240	10.39900
	3	9.60330	8.76340	10.37500
	4	8.75140	7.80090	10.28500
	5	9.02800	8.50090	10.28100
	6	9.09910	10.37300	9.96710
	7	8.91250	9.30680	9.47720
	8	9.39680	8.60190	9.46180
	9	9.06620	8.54140	9.62610
	10	8.66890	9.47330	9.40260
	MeanSNRdB	9.07113	8.72864	9.95478
	NMSE	0.00940	0.02410	0.00160
12 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
	1	10.78600	8.84830	12.27600
	2	11.47500	10.76100	12.39300
	3	11.75100	10.49200	12.36200
	4	10.67600	9.53720	12.27500
	5	10.97000	10.18200	12.27300
	6	11.07700	12.05400	11.97700
	7	10.86600	11.20600	11.51500
	8	11.45000	10.30600	11.48600
	9	11.07600	10.26800	11.63900
	10	10.58900	11.31400	11.43800
	MeanSNRdB	11.07160	10.49685	11.96340
	NMSE	0.00690	0.02090	0.00100

Window size= 25 OFDM Symbol

		LP Estimator	Reddy Estimator	Subspace Estimator
2 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
	1	0.97403	-1.15190	1.84820
	2	1.15740	2.34730	1.56940
	3	1.08860	2.29610	1.60290
	4	1.04070	3.03150	1.62360
	5	1.12860	3.31270	1.46720
	6	1.18040	1.18970	1.43350
	7	1.10210	-1.88070	1.28500
	8	0.89338	3.24670	1.41650
	9	0.94801	1.21740	1.34970
	10	1.15770	0.64786	1.20210
	MeanSNRdB	1.06709	1.42567	1.47981
	NMSE	0.21980	0.81600	0.07560
4 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	2.96990	-0.08757	3.84680
	2	3.19560	3.84400	3.57840
	3	3.11800	3.45070	3.59990
	4	3.01270	4.16540	3.60140
	5	3.10680	4.42300	3.47640
	6	3.15850	2.67320	3.47110
	7	3.09940	-0.36924	3.35810
	8	2.88790	4.56090	3.45390
	9	2.95610	2.51250	3.39250
	10	3.16010	1.96180	3.29390
	MeanSNRdB	3.06650	2.71347	3.50724
	NMSE	0.05510	0.27980	0.01660

6 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	4.95850	1.33080	5.85500
	2	5.24710	5.53200	5.59740
	3	5.15700	4.87330	5.60960
	4	4.97380	5.46820	5.59760
	5	5.08670	5.73990	5.49580
	6	5.14410	4.35120	5.51140
	7	5.10000	1.44280	5.42240
	8	4.87240	6.06180	5.48730
	9	4.96440	3.97600	5.43310
	10	5.17310	3.52230	5.36820
	MeanSNRdB	5.06771	4.22983	5.53778
	NMSE	0.02450	0.15940	0.00640
8 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	6.93850	3.03200	7.86630
	2	7.31850	7.35480	7.61830
	3	7.20980	6.51280	7.62310
	4	6.91680	6.92130	7.60140
	5	7.06600	7.23660	7.51680
	6	7.13130	6.16700	7.54770
	7	7.10610	3.43950	7.47570
	8	6.84650	7.71180	7.51500
	9	6.97390	5.57860	7.46790
	10	7.19870	5.26800	7.42710
	MeanSNRdB	7.07061	5.92224	7.56593
	NMSE	0.01380	0.10410	0.00320

	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
10 dB	1	8.90640	4.92380	9.87780
	2	9.41970	9.26490	9.63780
	3	9.28260	8.30870	9.63670
	4	8.83180	8.50090	9.60790
	5	9.04260	8.87800	9.53610
	6	9.11410	8.07250	9.57860
	7	9.12210	5.53040	9.51870
	8	8.80780	9.47330	9.53720
	9	8.98640	7.28970	9.49660
	10	9.24150	7.13860	9.47340
	MeanSNRdB	9.07550	7.73808	9.59008
	NMSE	0.00890	0.07220	0.00180
	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
12 dB	1	10.85600	8.10660	11.88800
	2	11.56600	6.92670	11.65500
	3	11.38400	11.22800	11.64900
	4	10.70400	10.20700	11.61500
	5	11.01400	10.18200	11.55300
	6	11.08500	10.62900	11.60400
	7	11.15600	10.03300	11.55300
	8	10.75300	7.65810	11.55500
	9	11.00400	11.31400	11.52000
	10	11.30900	9.08180	11.51000
	MeanSNRdB	11.08310	9.08620	11.61020
	NMSE	0.00630	0.05670	0.00110

Window size= 30 OFDM Symbol

		LP Estimator	**Reddy Estimator**	**Subspace Estimator**
2 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
	1	0.98302	-3.31840	1.42390
	2	1.22660	2.83890	1.52080
	3	1.02870	0.64341	1.60330
	4	1.06850	4.68360	1.39380
	5	1.15490	1.18970	1.39520
	6	1.09270	2.70110	1.14490
	7	0.81746	3.74670	1.02380
	8	1.18500	2.54220	1.07530
	9	0.94328	1.66790	1.17900
	10	1.09950	1.80490	1.04170
	MeanSNRdB	1.05997	1.85000	1.28017
	NMSE	0.22430	1.06680	0.13960
4 dB	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
	1	2.99650	-1.58370	3.46330
	2	3.26820	4.13140	3.55430
	3	3.01700	2.23310	3.62260
	4	3.04720	5.91570	3.42420
	5	3.12890	2.67320	3.44220
	6	3.10760	3.95710	3.22440
	7	2.79400	4.89700	3.12290
	8	3.20700	3.92520	3.15890
	9	2.91000	2.71620	3.25780
	10	3.12510	3.08730	3.16850
	MeanSNRdB	3.06015	3.19525	3.34391
	NMSE	0.05630	0.26900	0.02870

	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
6 dB	1	5.00620	0.27813	5.50180
	2	5.32310	5.56300	5.58590
	3	5.00210	3.96140	5.64050
	4	5.02360	7.28580	5.45350
	5	5.10850	4.35120	5.48380
	6	5.12390	5.36350	5.29150
	7	4.76580	6.22630	5.20380
	8	5.23750	5.46110	5.22660
	9	4.87190	3.92750	5.32260
	10	5.15820	4.52070	5.26710
	MeanSNRdB	5.06208	4.69386	5.39771
	NMSE	0.02510	0.13520	0.01070
	transmission	Estimated SNR (dB)	Estimated SNR (dB)p	Estimated SNR (dB)p
8 dB	1	7.01320	2.21920	7.53550
	2	7.39730	7.11390	7.61310
	3	6.98170	5.78790	7.65540
	4	6.99330	8.77780	7.47880
	5	7.08900	6.16700	7.51810
	6	7.14390	6.89930	7.34590
	7	6.73380	7.71220	7.26830
	8	7.27800	7.11970	7.27990
	9	6.82640	5.28950	7.37430
	10	7.20360	6.08220	7.34340
	MeanSNRdB	7.06602	6.31687	7.44127
	NMSE	0.01420	0.08770	0.00510

	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
10 dB	1	9.01730	4.20590	9.56360
	2	9.49950	8.76340	9.63530
	3	8.95190	7.68050	9.66750
	4	8.95080	10.37300	9.49960
	5	9.06540	8.07250	9.54580
	6	9.17120	8.54140	9.38920
	7	8.70030	9.32690	9.31910
	8	9.33060	8.87210	9.32170
	9	8.77110	6.78370	9.41490
	10	9.26840	7.74760	9.40260
	MeanSNRdB	9.07265	8.03670	9.47593
	NMSE	0.00920	0.06360	0.00290
	transmission	Estimated SNR (dB)	Estimated SNR (dB)	Estimated SNR (dB)
12 dB	1	11.01700	6.21680	11.58700
	2	11.64300	10.49200	11.65300
	3	10.90700	9.61610	11.67700
	4	10.88800	12.05400	11.51600
	5	11.03100	10.03300	11.56800
	6	11.21100	10.26800	11.42400
	7	10.67000	11.04300	11.35900
	8	11.39800	10.69400	11.35400
	9	10.70400	8.38870	11.44700
	10	11.36400	9.49440	11.44900
	MeanSNRdB	11.08330	9.83000	11.50340
	NMSE	0.00650	0.04880	0.00180