MIMO techniques with Channel Estimation Approaches for High Data Rate

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Abstract

In recent years, the demand for high data rate transmission has increased in wireless communications. High data rate transmission may require a very complex equalizer, which is not desirable in wireless communications. Orthogonal Frequency Division Multiplexing (OFDM) is a transmission scheme for which a receiver can be implemented easily without an equalizer. Therefore, the OFDM technique has attracted attention for many wireless applications. OFDM is a transmission technique that divides the data into several frequencies subchannels whose bandwidth is less than the total data rate. The uncoded performance of an OFDM system can be different in different frequency selective channels. Coded OFDM offers very robust communications with the frequency diversity that result from channel coding and interleaving. The proposed MIMO OFDM receiver uses channel estimation approach. The function of channel estimation is to form an estimate of the amplitude and phase shift caused by the wireless channel from the available pilot information. The objective of the project is to improve the system performance by reducing the BER or FER.

Keywords

Multi-input Multi-output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), Code division multiple access (CDMA)

***Nomenclature*:**

MIMO : Multiple Input Multiple Output
DMT : Diversity-Multiplexing Trade-off
CSI : Channel State Information
AF : Amplify-and-Forward
DF : Decode-and-Forward
ARQ : Automatic Repeat Request
CFAR : Constant False Alarm Rate (CFAR)
ADSL : Asymmetric Digital Subscriber Line

1. Introduction

The general multidimensional linear channel model adequately represents a plethora of communication system models which utilize multidimensional transmit-receive signals for attaining increased rates and reliability in the presence of fading. The logarithmic dependence of the spectral efficiency of the transmitted power makes it extremely expensive to increase the capacity solely by radiating more power. Also, increasing the transmitted power in a mobile terminal is not advisable due to possible violation of regulatory power masks and possible electromagnetic radiation effects. Alternately, MIMO schemes if properly exploited can exhibit a linearly increasing capacity, due to the presence of a rich scattering environment that provides independent transmission paths from each transmit to each receive antenna.

2. Problem statement and Proposed Solution

The communication system assumes perfect Channel State Information (CSI) and uses a linear transmitter to maximize the reliability of the wireless multi-antenna link. However, in actual practice the CSI is incomplete. As a result of this, there is a necessity to deal with argotic and compound capacity formulations and these factors are strongly dependent on the model utilized to characterize the channel. Practical system models include quasi-static multiple-input multiple-output (MIMO), MIMO-OFDM, ISI, amplify-and-forward (AF), decode-and-forward (DF), and MIMO automatic repeat request (ARQ) models. Each of the above models introduces its own structure, its own error performance limits, and its own requirements on coding and decoding schemes. Finding general-purpose transceiver structures with good performance in these scenarios, and with a reasonable computational complexity, is challenging.

Existing MIMO systems are able to provide either high spectral efficiency (spatial multiplexing) or low error rate (high diversity) via exploiting multiple degrees of freedom available in the channel, but not both simultaneously as there is a fundamental trade-off between the two. This Diversity-Multiplexing Trade-off (DMT) is best characterized using the concepts of multiplexing and diversity gains. Fundamentally, this is a trade-off between the Outage Probabilities, i.e. the probability that the fading channel is not able to support the transmission rate. In this context, this work identifies a general, explicit non-random MIMO encoder-decoder structures and also guarantee optimal diversity-multiplexing trade-off and is an effective alternative to the computationally expensive Maximum Likelihood (M-L) receiver. The results obtained lend them applicable to a plethora of pertinent communication scenarios such as quasi-static MIMO, MIMO-OFDM, ISI, cooperative-relaying and MIMO-ARQ channels.

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2.1 Objectives of the work

The main objectives of this paper work are as follows,

(i) To study the impact of imperfect Channel State Information (CSI) on multi-user scenario and perform the necessary changes required in transmission architecture so as to make it robust to the uncertainties of the side information available at both the Transmitter and Receiver.
(ii) To exploit the use of multiple antennas at both the transmitter and receiver and provide both an increase in reliability and also in information transmission rate.
(iii) To achieve high data rates by exploring the quality and quantity of the channel state information available at the communication ends.
(iv) To characterize the transmit covariance matrix that maximize the mutual information for the particular case of channel state uncertainty at the transmitter.
(v) To perform efficient power allocation strategies in a multi-user system with CSI uncertainty, so as to guarantee a certain quality of service per user.
(vi) To dynamically provide resource allocation so as to achieve better QoS and improve system capacity.

2.2 Advantages of MIMO system

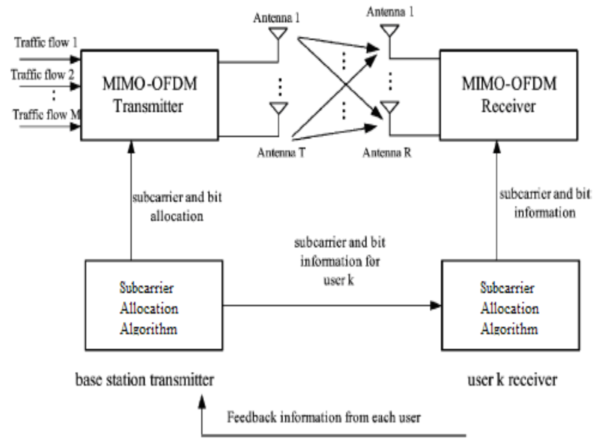

Fig. 1 Block diagram of multiple-antenna OFDM multicast system

An advantage of a MIMO system as shown in Figure 1 is that, it is said to achieve multiplexing gain r, and the achievable rates scale as [r log (SNR)]. The multiplexing gain (unique for MIMO systems) is defined as the increase of the rate that can be attained through the use of multiple antennas at both sides of communication links, with respect to the rate achievable with single antenna system, without utilizing additional power. Also, a MIMO communication system executes an average error probability that decays as 1/(SNR^d) where'd' is the diversity gain and is based on the assumption that at least one of the paths will not be in a deep fade state.

2.3 MIMO-OFDM Receiver

In this research work, the proposed MIMO-OFDM scheme has the following features:

(i) Coherent detection
(ii) Two-dimensional channel estimator: the ability to interpolate the channel estimates both in Time and frequency from the available information. The proposed receiver module is shown in Figure 2.

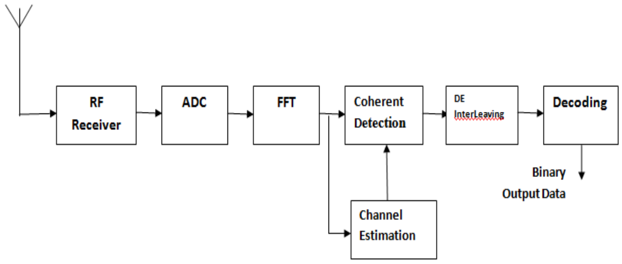

Fig. 2 Block diagram of MIMO-OFDM scheme with coherent detection and channel Estimation

3. Previous works

S. Buzzi and D. Saturnino [2011] presented in a large system analysis, a one-shot procedure for computing the user's transmit powers at the Nash equilibrium with no need for iteration among users. B. Smida et al., [2010] presented a white paper, where they develop a new closed-form expression for the conditional CF of the inter-carrier interference and provide a procedure for calculating the exact BER expressed in the form of a single numerical. S. Buzzi, et al., [2010] presented a novel blind estimation procedure which only requires knowledge of the spreading code of the user of interest, but, no prior information as to the transmitted data symbols and the structure of the multi-access interference for estimating the multipath signal delays in an asynchronous direct-sequence/code-division-multiple-access (DS/CDMA) system operating over a doubly-selective fading channel. L. Venturino, et al., [2010] presented a work to have a novel blind detection strategy that only requires knowledge of the spreading code of the user to be detected, but, no prior information as to the time-varying channel impulse response and the structure of the multi-access interference. The proposed detector has a bounded constant false alarm rate (CFAR) under the design assumptions while providing satisfactory detection performance even in the presence of strong co-channel interference and high user mobility. S. Buzzi and

D. Saturnino [2010] proposed that iterative SINR maximization converges in a finite number of steps and the equilibrium resulting from non-cooperative behavior is also Pareto-optimal. Mohammad G. Khoshkholgh, et al., [2010] proposed that it considers DS-CDMA/OFDM spectrum sharing systems and obtain the achievable capacity of the secondary service under different subchannel selection policies in the fading environment. B. M. Ghaffari, et al., [2009] presented a work on digital design and implementational details of a wireless optical CDMA (OCDMA) system based on generalized optical orthogonal codes (OOCs). Khairi A. Hamdi and P. Sedtheetorn [2008] proposed a new accurate mathematical analysis for the efficient computation of the spectral efficiency of CDMA downlink wireless communication systems in the presence of multipath Rayleigh fading and log-normal shadowing. A new explicit expression is derived for the spectral efficiency, which is based on an accurate interference model that accounts for both intra-cell and inter-cell interferences. P. Sedtheetorn and Khairi A Hamdi [2008] presented a new linear programming approach for throughput maximization on the uplink of a multiclass variable spreading gain code-division multiple-access (CDMA) multicellular system in Rayleigh fading for both binary phase-shift keying (BPSK) and quaternary phase-shift keying (QPSK) modulations. Lajos Hanzo [2003] proposed a work on Advances in Multi-user OFDM/MC-CDMA which deals with software radio for future advanced communication.

4. OFDM SYSTEM

4.1 OFDM system advantages

In OFDM, the total system bandwidth is divided into narrowband frequency strips (subcarriers). The information symbols are transmitted parallelly over the subcarriers. Each subcarrier has a bandwidth much smaller than the channel coherence bandwidth. In time domain, the symbol duration on each subcarrier is much larger than the multipath delay spread. Thus, to each subcarrier, the channel exhibits flat fading and the ISI effects due to the channel are negligible. However, ICI can exist and frequency domain equalization scheme is required to overcome ICI.

Orthogonal frequency-division multiplexing is a multicarrier digital modulation system that has been employed as a modulation system for terrestrial digital broadcasting. Compared with single-carrier digital modulation, OFDM can lengthen the symbol period while maintaining the same error-rate characteristics and band efficiency. It can also add a redundant signal period called a guard interval. For these reasons, OFDM features little deterioration of transmission characteristics with respect to multipath distortion, the main type of disturbance on a terrestrial transmission path. The OFDM signal multiplexes multiple digitally modulated waves that are mutually orthogonal in a certain signal interval.

OFDM can easily adapt to severe channel conditions without complex equalization. Robust against narrow-band co-channel interference. It is Robust against inter symbol interference (ISI) and fading caused by multipath propagation. It has High spectral efficiency, efficient implementation using Fast Fourier Transform (FFT) and Low sensitivity to time synchronization errors. Tuned sub-channel receiver filters are not required (unlike conventional FDM).

The advantages of using multicarrier modulation are thus reassured. Besides these enhancements, the proposed algorithm is simple and feasible in that it consists of only the traditional closed-loop power control algorithm and a target signal-to-interference ratio (SIR) reassignment at the receiver. Detailed channel information feedback from receiver to transmitter is not required. It has been recognized the performance of coded modulation over a Rayleigh fading channel can be improved by bit-wise interleaving at the encoder output, and by using an appropriate soft-decision metric as an input to decoder. The demultiplexed bits are mapped to a constellation point for the given modulation scheme. For bit-interleaved coded modulation, a Gray mapping is usually used. After mapping, the transmitter sends the modulated symbols to the channel. The channel is a time varying and frequency selective wireless channel.

5. ADAPTIVE MODULATION

Adaptive modulation is a powerful technique for maximizing the data throughput of subcarriers allocated to a user. Adaptive modulation involves measuring the SNR of each subcarrier in the transmission, then selecting a modulation scheme that will maximise the spectral efficiency, while maintaining an acceptable BER. This technique has been used in Asymmetric Digital Subscriber Line (ADSL), to maximise the system throughput. ADSL uses OFDM transmission over copper telephone cables. The channel frequency response of copper cables is relatively constant and so reallocation of the modulation scheme does not need to be performed very often, as a result the benefit greatly out ways the overhead required for measuring of the channel response. Using adaptive modulation in a wireless environment is much more difficult as the channel response and SNR can change very rapidly, requiring frequent updates to track these changes.

Adaptive modulation has not been used extensively in wireless applications due to the difficulty in tracking the radio channel effectively. In the effectiveness of a multiuser OFDM system using an adaptive subcarrier, bit and power allocation was investigated. Optimization of the transmission was achieved by minimizing the power requirement for a given transmission channel and user data rate. It was found that the use of adaptive modulation, and adaptive user allocation reduced the required transmitter power, however investigate the effects of channel tracking errors on the BER performance. The simulated performance of an adaptive multiuser OFDM system investigates the effects of channel tracking errors on the BER performance. It demonstrates the effectiveness of using adaptive modulation in conjunction with different user allocation schemes. It also provides insight into the required tracking rate of the radio channel, the effectiveness of adaptive modulation using narrow bandwidth fading models.

Most OFDM systems use a fixed modulation scheme over all subcarriers for simplicity. However, each subcarrier in a multiuser OFDM system can potentially have a different modulation scheme depending on the channel conditions. Any coherent or differential, phase or amplitude modulation scheme can be used including BPSK, QPSK, 8-PSK, 16-QAM, 64-QAM, etc, each providing a tradeoff between spectral efficiency and the bit error rate. The spectral efficiency can be maximized by choosing the highest modulation scheme that will give an acceptable Bit Error Rate (BER). In a multipath radio channel, frequency selective fading can result in large variations in the received power of each subcarrier. For a channel with no direct signal path this variation can be as much as 30 dB in the received power resulting in a similar variation in the SNR. In addition to this, interference from neighboring cells can cause the SNR to vary significantly over the system bandwidth. To cope with this large variation in SNR over the system subcarriers, it is possible to adaptively allocate the subcarrier modulation scheme, so that the spectral efficiency is maximized while maintaining an acceptable BER. The adaptive modulation varies with time to an individual subcarrier as the channel SNR is shown in Figure 3.

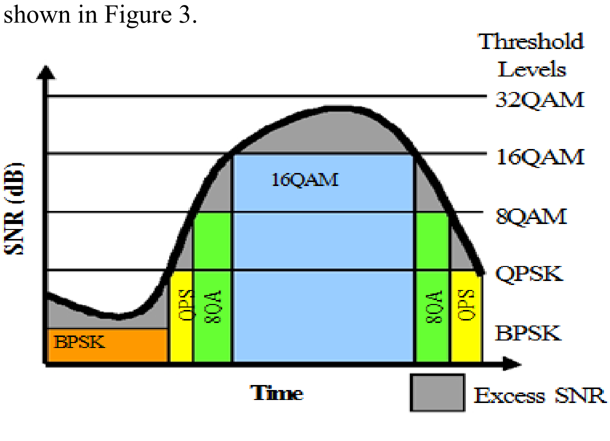

Fig. 3 Adaptive modulation to an individual subcarrier as the channel SNR varies with time

Figure 3 shows the SNR must be greater than the threshold to maintain a maximum BER. Excess SNR results in the BER being lower than the BER threshold. This diagram assumes that the modulation scheme is updated continuously and with no delay.

Using adaptive modulation has a number of key advantages over using static modulation. In systems that use a fixed modulation scheme the subcarrier modulation must be designed to provide an acceptable BER under the worst channel conditions. This results in most systems using BPSK or QPSK. However these modulation schemes give a poor spectral efficiency (1 - 2 b/s/Hz) and result in an excess link margin most of the time. Using adaptive modulation, the remote stations can use a much higher modulation scheme when the radio channel is good. Thus as a remote station approaches the base station the modulation can be increased from 1 b/s/Hz (BPSK) up to 4 - 8 b/s/Hz (16-QAM - 256-QAM), significantly increasing the spectral efficiency of the overall system. Using adaptive modulation can effectively control the BER of the transmission, as subcarriers that have a poor SNR can be allocated a low modulation scheme such as BPSK, or none at all, rather than causing large amounts of errors with a fixed modulation scheme. This significantly reduces the need for forward Error Correction.

5.1 Limitations of Adaptive Modulation

There are several limitations with adaptive modulation. Overhead information needs to be transferred, as both the transmitter and receiver must know what modulation is currently being used. Also, as the mobility of the remote station is increased, the adaptive modulation process requires regular updates, further increasing the overhead. There is a tradeoff between power control and adaptive modulation. If a remote station has a good channel path the transmitted power can be maintained and a high modulation scheme used (i.e. 64-QAM), or the power can be reduced and the modulation scheme reduced accordingly (i.e. QPSK). Distortion, frequency error and the maximum allowable power variation between users limit the maximum modulation scheme that can be used. The received power for neighbouring subcarriers must have no more than 20 - 30 dB variation at the base station, as large variations can result in strong signals swamping weaker subcarriers.

Inter-modulation distortion results from any non-linear components in the transmission, and causes a higher noise floor in the transmission band, limiting the maximum SNR to typically 30 - 60 dB. Frequency errors in the transmission due to synchronisation errors and Doppler shift result in a loss of orthogonality between the subcarriers. A frequency offset of only 1 - 2 % of the subcarrier spacing results in the effective SNR being limited to 20 dB. The limited SNR restricts the maximum spectral efficiency to approximately 5 - 10 b/s/Hz.

6. BER versus Eb/No for a CDMA system

The bit error rate (BER) that would occur for a CDMA system that does not use forward error correction. The energy per bit to noise ratio (Eb/No), is the energy in the demodulated data bit, to the noise energy in the same bit. It is similar to the signal to noise ratio, is shown in Table 1. The Eb/No is the effective signal to noise ratio of the demodulated, dispread CDMA signal. Any noise or interference in the radio channel is reduced by a factor equal to the process gain during dispreading. The minimum allowable Eb/No that can be used for a particular system depends on the forward error correction scheme used, and the type of data being sent. Voice communications typically requires a BER better then ~1/100 or 0.01. This is assuming some forward error correction is used.

Table 1 Shows the Expected BER Vs the energy per bit to noise ratio for a CDMA system

Eb/No (dB)	BER
0	0.158655
2	0.104029
4	0.056495
6	0.023007
8	0.006004
10	0.000783
12	3.43E-05
14	2.7E-07

6.1 Algorithm for complete CDMA System Environment simulation

In this work, the CDMA system environment simulation is shown as algorithm in the following steps,

(i) Initialize the CDMA system simulation by giving symbol rate, number of modulation levels, Bit rate, number of symbols and signal to noise ratio.
(ii) Give the filter specifications: Number of filter taps, number of over sample, roll off factor, T filter function and R filter function.
(iii) Initialize the spreading code by entering number of users, type of spreading code, number of stages, position for taps in the stages and initial value for register in the stages.
(iv) Generate the spread code for the selected type as per the above specifications.
(v) Initialize the fading conditions: Type of fading, delay time, attenuation level, number of waves to generate fading, initial phase of delayed wave, set fading counter, number of direct wave and delayed wave, time resolution, Doppler frequency, flat Rayleigh environment and number of fading counter to skip.
(vi) Start simulation for specified number of times to transmit the data.
(vii) Start transmitter simulation parameters: QPSK modulation, spreading, over sampling, filter and finally transmission.
(viii) Start fading environment simulation after transmission.
(ix) Start receiver simulation parameters: attenuation calculation, AWGN, filter, dispreading, QPSK demodulation.

Finally, calculate Bit error rate from the information available from transmitter and receiver simulation parameters.

7. Bit Error Rate (BER) Performance

(i) In a DS-CDMA system the average BER performance depends mainly on the correlation properties of the spreading sequences assigned to the users
(ii) In order to have low interference between users it is necessary to select sets of sequences having low cross-correlation values
(iii) Most DS-CDMA systems presented have used binary PN sequences including Gold sequences and Kasami sequences that has desirable cross correlation properties
(iv) Binary sequences generated using the proposed models can also be used as spreading sequences in DS-CDMA
(v) These sequences represent noise-like features that make them good for DS-CDMA systems

A simplified diagram of a CDMA system is presented in Figure 4.

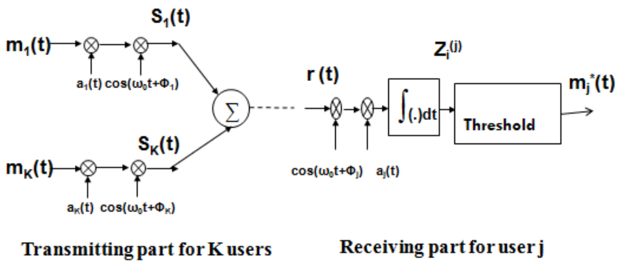

Fig. 4 A simplified diagram of a CDMA system

In the receiving part the received signal sk(t), originating from user 'k', is given by the expression

$$S_k(t) = (\sqrt{2}\, P_k)\, m_k(t)\, a_k(t) \cos(\omega_0 t + \Phi_k) \qquad \ldots (6)$$

where, P_k is the received power of user k, $a_k(t)$ is the spreading sequence, with the chip period Tc=T/N, and $m_k(t)$ is the data sequence for user 'k', both of them being binary sequences with values ±1.

(i) Signal r(t) at the input of a receiver is

$$r(t) = \sum_{k=1}^{K} S_k(t) + n(t) \quad \text{... (7)}$$

where, n(t) is additive white Gaussian noise with two-sided power spectral density $N_0/2$.

7.1 Bit Error Rate can be calculated using the equation,

$$P_e = Q\left(\sqrt{\frac{2E_b/N_0}{1+\frac{K-1}{N^2}C^2\, E_b/N_0}}\right) \quad \text{... (8)}$$

where, $E_B = P_K T$ is the signal energy per bit period, E_B/N_0 is the signal-to-noise ratio, K is number of users of, C^2 is the mean square cross-correlation value and N is the length and N of the spreading sequence.

(i) It can be seen that the average BER of a synchronous DS-CDMA system, the number of users K depends on the Multiple Access Interference (MAI) term
(ii) MAI contribution to BER grows with the number of simultaneous users 'K' in the system
(iii) In order to have lower BER values one has to choose sets of spreading sequences with low mean square cross-correlation values
(iv) Since, α is considered to be the peak CCR value, putting $C^2 = \alpha^2$ in the expression gives bit error rate under worst conditions. The equation (16) can be written as,

$$P_e \le Q\left(\sqrt{\frac{2E_b/N_0}{1+\frac{K-1}{N^2}\alpha^2\, E_b/N_0}}\right) \quad \text{... (9)}$$

Equality is considered here for comparison under worst case.

The performance of any OFDM system using phase shift keying can be worked out using the Table 2 and Table 3 in (Appendix I).

7.2 Spreading codes in MIMO System

(i) Using Binary Conversion
(ii) Chaotic functions can be considered with a real valued sequence $\{y_k\}$ generated by choosing initial value x_0 and bifurcation parameter 'r'
(iii) This real valued sequence $\{y_k\}$ is converted to binary using the proposed model by choosing values of multiplication factor 'n' and reducing to modulo 4.

7.3.1 Properties of Gold sequences

There are $((2^N-1)+2)$ Gold sequences of length (2^N-1) bits that can be generated using two N stage Linear Feedback Shift Register (LFSR) and hence, the linear complexity is 2N. To use this proposed model to generate following possibilities:

(i) Few sequences of different lengths with pairwise CCR value less than that of Gold sequences and Kasami sequences of same length
(ii) More number of sequences than that of Gold sequences of same length having peak CCR value same as that of Gold sequences
(iii) Sequences with Linear Complexity more than 2N
(iv) To study the properties of the generated binary sequence, non-overlapping segments of different lengths (15 bits, 31 bits, 63 bits, 127 bits and 255 bits) are considered
(v) Number of sequences having pairwise cross correlation values denoted by α, are determined for different α values based on the segment lengths
(vi) Values of multiplication factor n chosen is from 5 to 10 insteps of 1 and reduced to modulo 4.

8. Results and Discussion

8.1 CDMA Results

The link of the CDMA system model uses orthogonal codes to separate the users. Each user is randomly allocated a code to spread the data to be transmitted. The transmitted signals from all the users are combined together, then passed through a radio channel model. This allows for clipping of the signal, adding multipath interference, and adding white Gaussian noise to the signal. The receiver uses the same code is used by the transmitter to demodulate the signal and recover the data. After the received signal has been dispread using the code, it is sub-sampled back down to the original data rate. This is done by using an integrate-and-dump filter, followed by a comparator to decide whether the data was a 1 or a 0.

The received data is then compared with the original data transmitted to calculate the bit error rate (BER). The RMS amplitude error is also worked out. The signal level after it has been demodulated and filtered is compared with the expected amplitude of the signal based on the transmitted data. The RMS amplitude error directly relates to the bit error rate, so is a useful measurement to make.

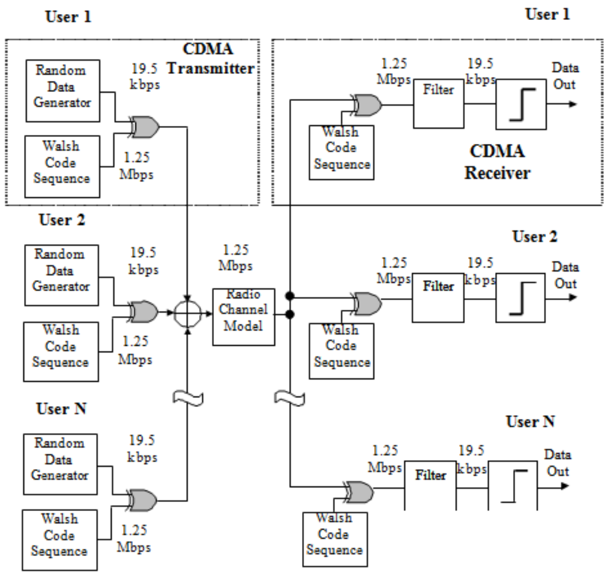

Fig. 5 shows the model used for the simulations of the CDMA forward link

8.2 Gold codes for spreading

The eye diagram plot for the I and Q channel after spreading with Gold Codes for variable number of users (N=3,5) is shown in Figure 6 to Figure 9.

For N=3; N-number of users

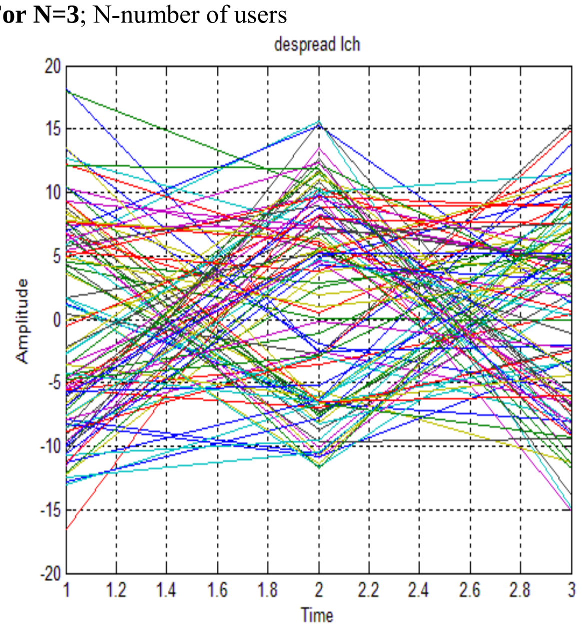

Fig.6 Eye Diagram of De-spread I-Channel using Gold code for 3 users

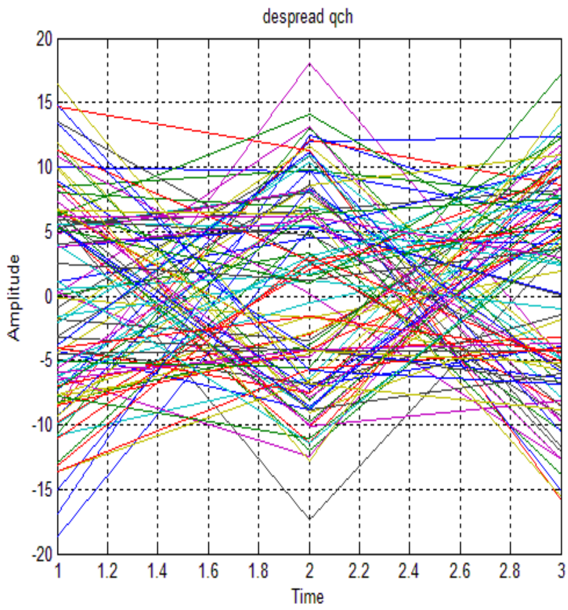

Fig. 7 Eye Diagram of De-spread Q-Channel Using Gold code for 3 users

For N=5

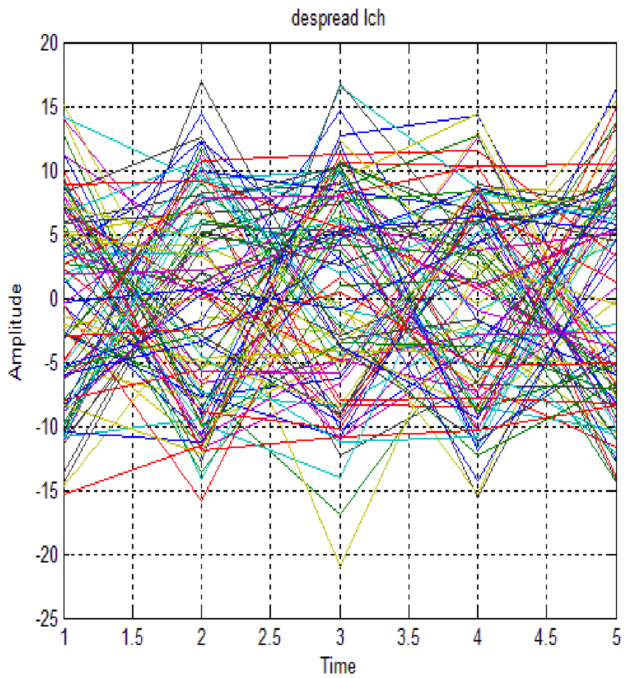

Fig.8 Eye Diagram of De-spread I-Channel using Gold code for 5 users

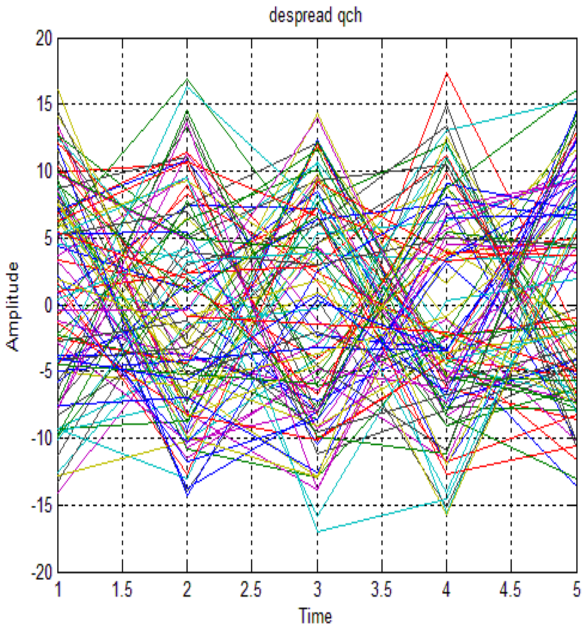

Fig. 9 Eye Diagram of De-spread Q-Channel Using Gold code for 5 users

8.3 Spreading with m-sequence codes

The eye diagram plot using m-sequence codes for spreading in the CDMA system for variable number of users (N=3,5) is shown in Figure 10 to Figure 13.

For N=3

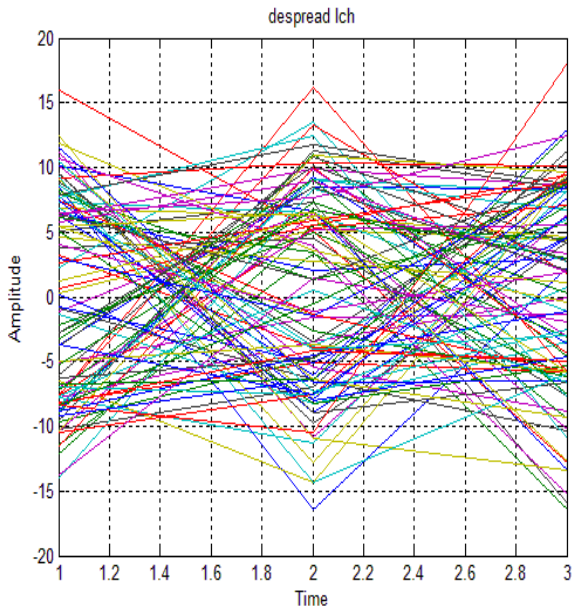

Fig. 10 Eye Diagram of De-spread I-Channel

Using m-sequence for 3 users

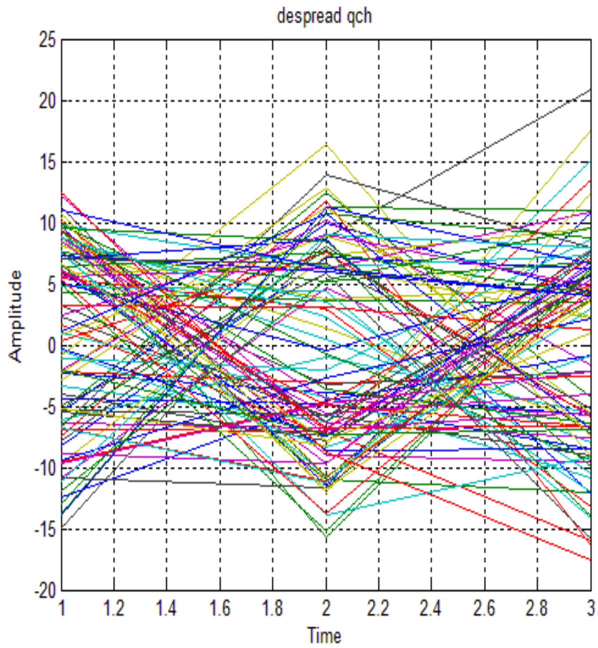

Fig. 11 Eye Diagram of De-spread Q-Channel Using m-sequence for 3 users

For N=5

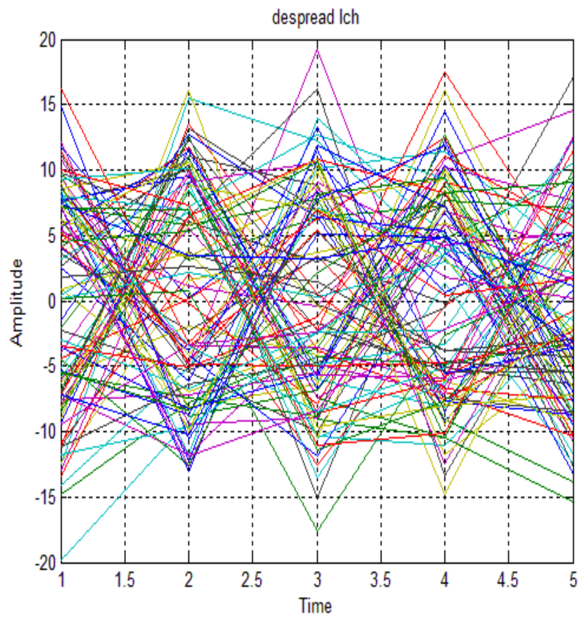

Fig. 12 Eye Diagram of De-spread I-Channel Using m-sequence for 5 users

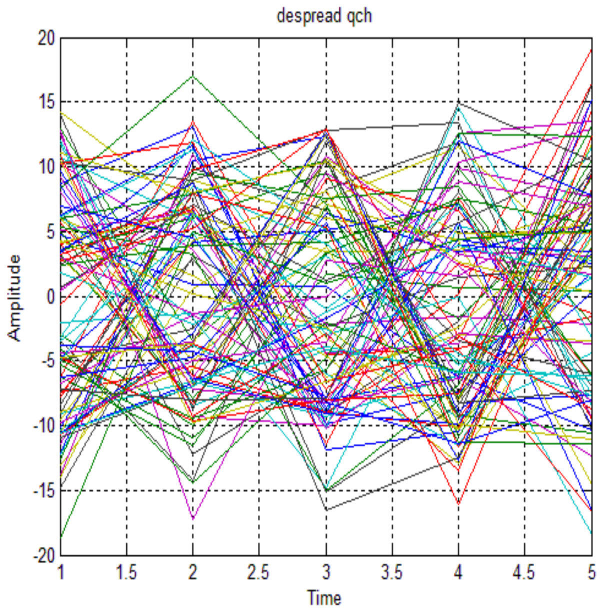

Fig. 13 Eye Diagram of De-spread Q-Channel Using m-sequence for 3 users

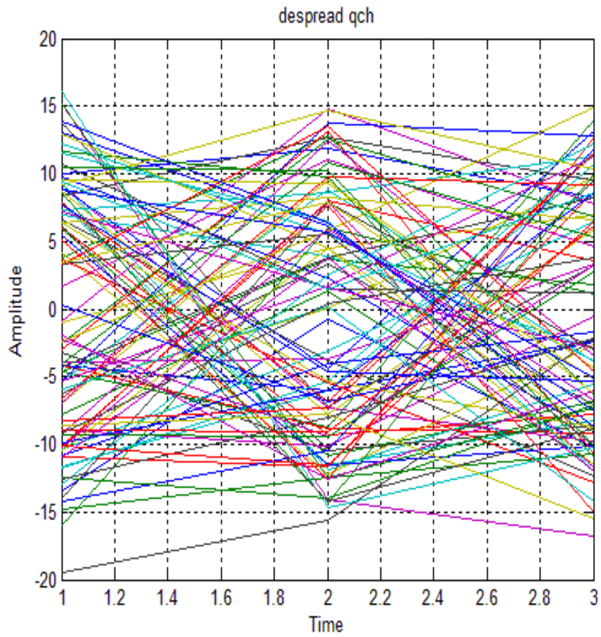

Fig. 15 Eye Diagram of De-spread Q-Channel Using Orthogonal sequence for 3 users

7.3 Results with orthogonal sequence for spread

The eye diagram for the I and Q channel when using orthogonal sequence codes for spreading in the CDMA system is shown in Figures 14 to figure 17.

For N=3

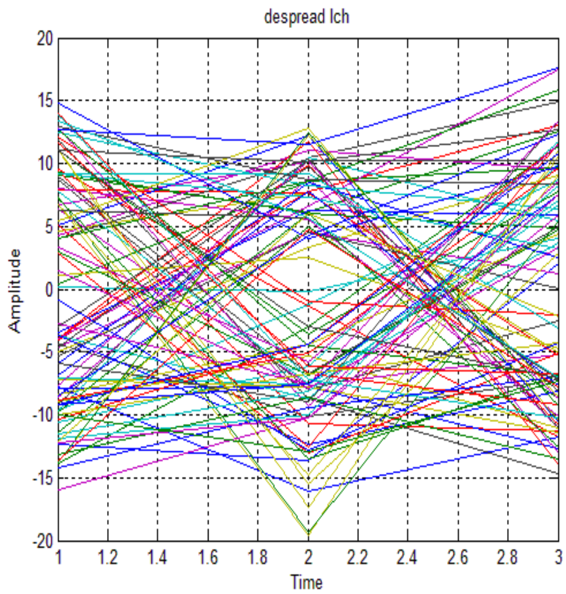

Fig. 14 Eye Diagram of De-spread I-Channel Using Orthogonal sequence for 3 users

For N=5

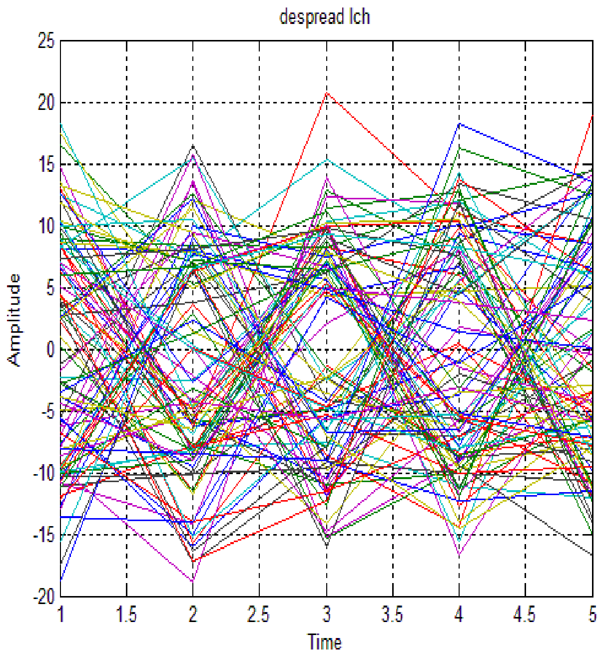

Fig. 16 Eye Diagram of De-spread I-Channel Using Orthogonal sequence for 5 users

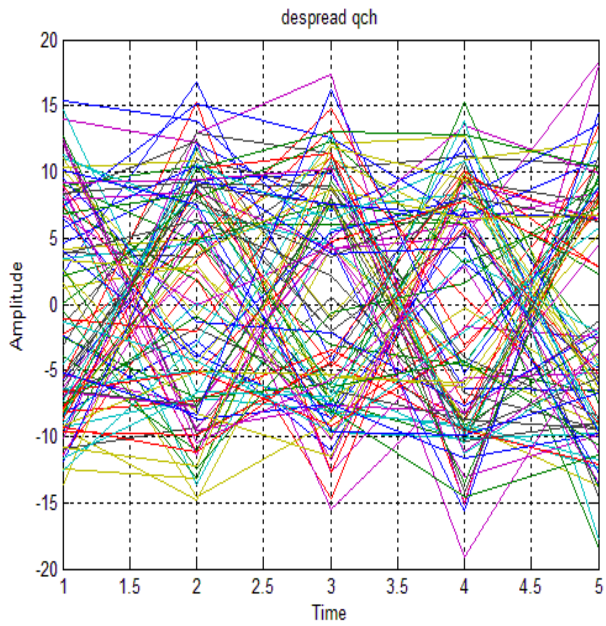

Fig. 17 Eye Diagram of De-spread Q-Channel Using Orthogonal sequence for 5 users

8. CONCLUSION

In this work, an investigation of adaptive communication techniques is presented and studied for different critical performance measures. An adaptive MIMO-OFDM scheme with two-dimensional channel state estimator is designed and implemented in this work. The critical performance measures of practical interest are evaluated for study. The modulation schemes applied to each subcarrier is independently optimized in this work, and as a result the spectral efficiency is maximized, without any tradeoff in the target Bit Error Rate (BER). The results are demonstrated for a fading channel and improve in the Signal to Noise Ratio (SNR) required maintaining a BER, as compared with other fixed modulation schemes. Adaptive user allocation exploits the difference in frequency selective fading between users, to optimize user subcarrier allocation. In a multipath environment the fading experienced on each subcarrier varies from user to user, thus by utilizing user/subcarrier combinations that suffer the least fading, the overall performance is maximized.

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APPENDIX I

OFDM Guassian Noise Performance Prediction

Table 2 Expected Phase Error on an OFDM carrier at difference SNR levels

SNR (dB)	RMS Phase Error (degrees) q error(rms)
0	63.63
2	44.85
4	34.25
6	26.65
8	20.92
10	16.5
12	13.05
14	10.34
16	8.198
18	6.505
20	5.164
22	4.1
24	3.256
26	2.586
28	2.054
30	1.631
32	1.296
34	1.029
36	0.8175
38	0.6494
40	0.5158
42	0.4097
44	0.3254
46	0.2585
48	0.2053
50	0.1631

Table 3 Expected Bit Error Rate for various noise levels. Z is the ratio of the maximum allowable phase angle / RMS phase error

Z (number of standard deviations)	BER
0	1
0.2	0.841481
0.4	0.689157
0.6	0.548506
0.8	0.423711
1	0.317311
1.2	0.230139
1.4	0.161513
1.6	0.109599
1.8	0.071861
2	0.0455
2.2	0.027807
2.4	0.016395
2.6	0.009322
2.8	0.00511
3	0.0027
3.2	0.001374
3.4	0.000674
3.6	0.000318
3.8	0.000145
4	6.34E-05
4.2	2.67E-05
4.4	1.08E-05
4.6	4.23E-06
4.8	1.59E-06
5	5.74E-07