Al-Khwarizmi Engineering Journal, Vol. 8, No. 2, PP 84 - 96 (2012)

Al-Khwarizmi Engineering Journal

Channel Estimation and Prediction Based Adaptive Wireless Communication Systems

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(Received 8 March 2011; accepted 9 January 2012)

Abstract

Wireless channels are typically much more noisy than wired links and subjected to fading due to multipath propagation which result in ISI and hence high error rate. Adaptive modulation is a powerful technique to improve the tradeoff between spectral efficiency and Bit Error Rate (BER). In order to adjust the transmission rate, channel state information (CSI) is required at the transmitter side.

In this paper the performance enhancement of using linear prediction along with channel estimation to track the channel variations and adaptive modulation were examined. The simulation results shows that the channel estimation is sufficient for low Doppler frequency shifts (<30 Hz), while channel prediction is much more suited at high Doppler shifts with same SNR and target BER=10^{-4}. It was shown that the performance at higher Doppler frequency shifts (>30Hz) was improved by more than 2dB over channel estimation at target BER=10^{-4} and 32QAM constellation used.

Keywords: *channel estimation, adaptive communication.*

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1. Introduction

Wireless communications is an emerging field, which has seen enormous growth in the last several years [1]. The transmission performance and throughput of wireless communication systems is limited due to random variation of the channel. The exponential growth of the internet had resulted in an increased demand for new methods to obtain high capacity wireless networks. The wireless radio channel poses a severe challenge as a medium for reliable high-speed communication. It is not only susceptible to noise, interference, and other channel impediments, but these impediments change over time [2].

The basic idea behind adaptive transmission is to maintain a constant Signal to Noise Ratio (SNR). Thus, without sacrificing Bit Error Rate (BER), these schemes provide high average spectral efficiency by transmitting at high speeds under favorable channel conditions, and reducing throughput as the channel degrades [3]. Extensive research work was carried to improve the transmission rate over wireless link and efficient use of allowable bandwidth, using Adaptive transmission techniques, such as adaptive modulation, channel coding, power control, and antenna diversity [4,5,6]. The transmission scheme is selected relatively to the channel characteristics [7]. For very slowly fading channels, outdated CSI is sufficient for reliable adaptive communication while for faster fading, even small delay will cause significant degradation of performance since channel variation due to large Doppler shifts usually results in a different channel at the time of transmission than at the time of channel estimation. Due to unavoidable delays involved in signal estimation, feedback transmission, and modulation adjustment; the adaptation needs to be based on predicted channel rather than estimated one [7].

The rest of the paper is organized as follows. In the next section M-ary Quadrature amplitude modulation MQAM technique was presented. Wireless channel modeling, estimation, prediction are discussed in section 3، system architecture and simulation in section 4 and results and conclusions are discussed in section 5.

2. M-ary Quadrature Amplitude Modulation MQAM

Spectrum is the most precious commodity in wireless communications. Along with SNR, it determines the data rate at which the information can be transmitted.

In spectrally efficient M-ary QAM (MQAM), there are a total of (M) possible states for the signal with transition from any state to any other state at every symbol time. Since M=2^m, *m* bits per symbol can be sent. In Adaptive MQAM the transmission parameters are varied according to variation of the channel state.

For every modulation mode, its error probability is directly related to the received SNR. The symbol error rate (SER) of MQAM is given as [8]:

$$P_{s,MQAM}(\gamma) = \frac{2(\sqrt{M}-1)}{\sqrt{M}} Q\left(\sqrt{\frac{3}{M-1}\gamma}\right) \qquad \ldots(1)$$

Where (γ) is the received SNR. This approximation to the error probability is good for all values of *M*. When the Gray coding is used in the mapping of bits to constellation symbol, the equivalent bit error rate (BER) for MQAM is well approximated by [8]:

$$P_{b,MQAM}(\gamma) = \frac{1}{\log_2\sqrt{M}} P_{s,MQAM}(\gamma) \qquad \ldots(2)$$

In adaptive MQAM system, modulation is selected according to the channel state which is obtained in the form of Signal to Noise Ratio.

3. Channel Modeling

Unreliable wireless communication channel is resulted due to temporal and spatial variations of the received signal [8]. Besides the path loss, shadowing, and multipath fading the inherent noise from the receiver's electronics and interference from competing transmissions complicated the recovery of the original signal.

Multipath fading is the dramatic variation in signal power that occurs when the received signal is a sum of multipath components each with independent amplitude, phase, and frequency components. Fading is caused by a phenomenon known as the Doppler Effect [8].

$$f_d = f_c \frac{v}{c} \cdot \cos\theta = f_{dmax} \cos\theta \qquad \ldots(3)$$

Where f_c is the carrier frequency, θ is the angle of arrival of the received signal, v is the relative velocity, and f_{dmax} is the maximum Doppler frequency. The received signal was modeled as a sum of non-resolvable multipath components each with independent amplitude, phase and frequency components. The channel is thus modeled in a complex baseband as [9,10].

$$c(t) = \sum_{i=1}^{N} A_i \,.\, e^{j(2\pi f_{di} t + \theta_i)} \qquad \ldots(4)$$

Where N is the number of scatterers, A_i is the amplitude, and f_{di} is the Doppler frequency shift of the i^{th} complex sinusoid. Figure(1) shows a typical Rayleigh fading channel simulated over different Doppler frequency shifts. The multipath fading channel was modeled as a linear finite impulse response FIR filter using MATLAB7.6. The envelope of the channel was faded throughout the channel samples. The fading rate is highly dependent upon Doppler frequency shift.

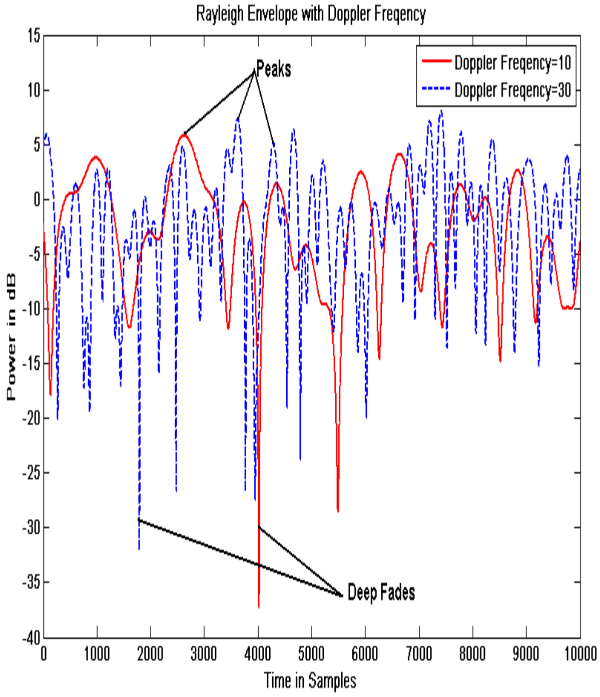


Fig. 1. Rayleigh Fading Envelope.

4. Proposed System Architecture

Figure (2) shows the proposed system block diagram. Where r(t), s(t), c(t) and n(t) is the received, transmitted, channel and noise signal respectively.

A pilot symbol which does not convey useful information is inserted every Lth channel symbol for real time channel monitoring, where each frame starts with a pilot symbol. The frame length (L) can be adjusted depending on the channel quality. The proposed system uses bandwidth efficient MQAM modulation technique with different levels. The randomly generated symbols are first mapped into M possible phases using Gray coding.

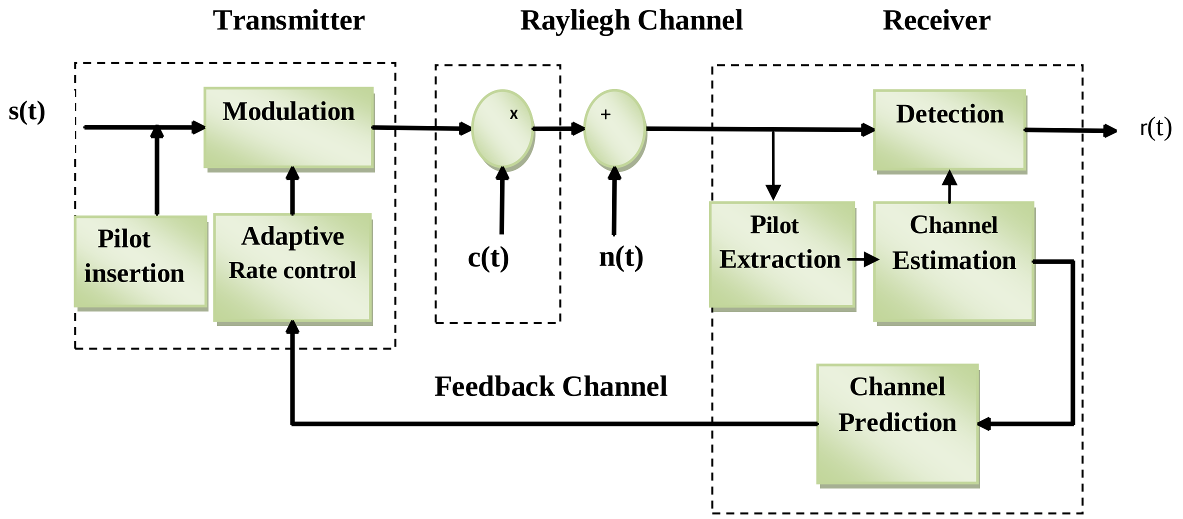


Fig. 2. System Architecture.

Received pilot symbols are extracted and used for channel estimation. The modulated symbols are then converted back to baseband bits with appropriate demodulation and Gray decoding. Coherent demodulation is used in order to achieve an undistorted bit stream. In order to cope with channel variations, the received data are fed through a baseband equalizer to reduce signal distortion. It is worthy to note that perfect clock and carrier recovery is assumed.

The estimated channel values are fed back to the transmitter to adjust the transmission mode suitable for the channel state at the transmission time.

4.1. Adaptive Modulation Boundaries

Switching between different modulation schemes was based on BER threshold which is directly related to the channel SNR, at the receiver.

Recall equation (2) SNR can be found as:

$$\gamma = 10 * log_{10} \frac{\left(Q^{-1}\left(\frac{P_{b,MQAM}\ (\gamma) * \sqrt{M} * log_{2}\sqrt{M}}{2(\sqrt{M}-1)}\right)\right)^{2}}{3/(M-1)} \quad \ldots(5)$$

Where Q^{-1} is the inverse of the Q-function. Proper switching boundaries are decided based on target BER selected specified depending on the type of information to be transmitted over the channel (voice, video, data,…etc). This means that the system will try to keep a BER lower than a target BER with the most spectrally efficient modulation scheme whenever possible. Figure (4) shows the BER performance for MQAM over AWGN channel with target BER=10^{-3}.

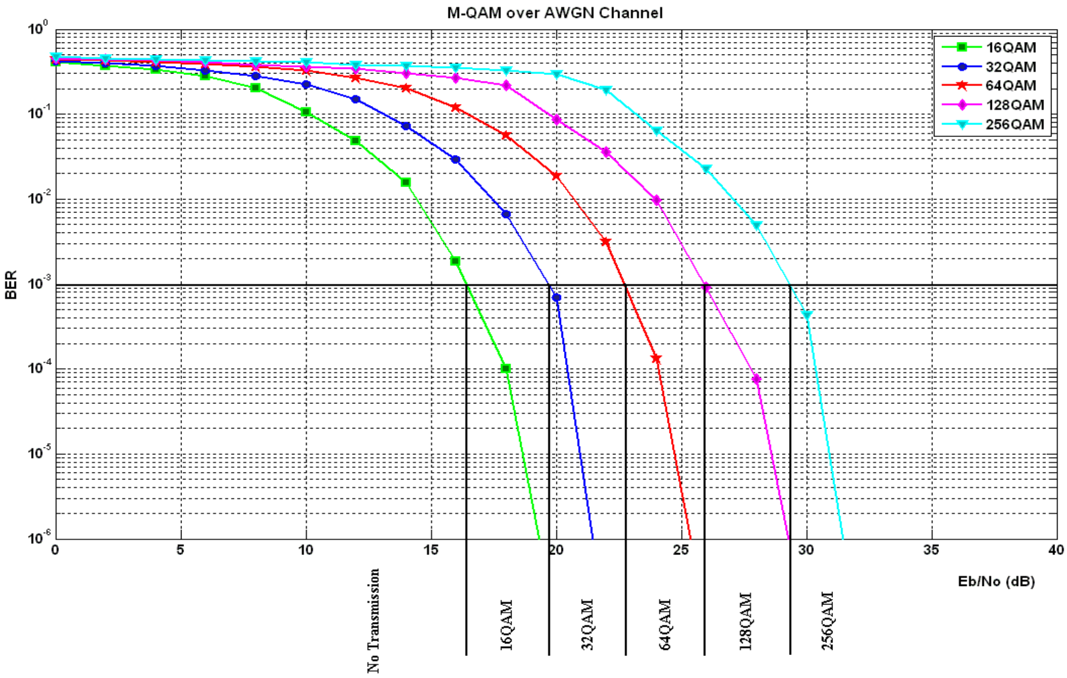


Fig. 4. BER Performance for MQAM in AWGN Channel with Threshold BER=10^{-3} .

Different modulation techniques were simulated over a Rayleigh fading channel with different Doppler frequency shifts. Fig. (5) and Fig. (6) show the BER performance for 64QAM and 256QAM over Rayleigh fading channel.

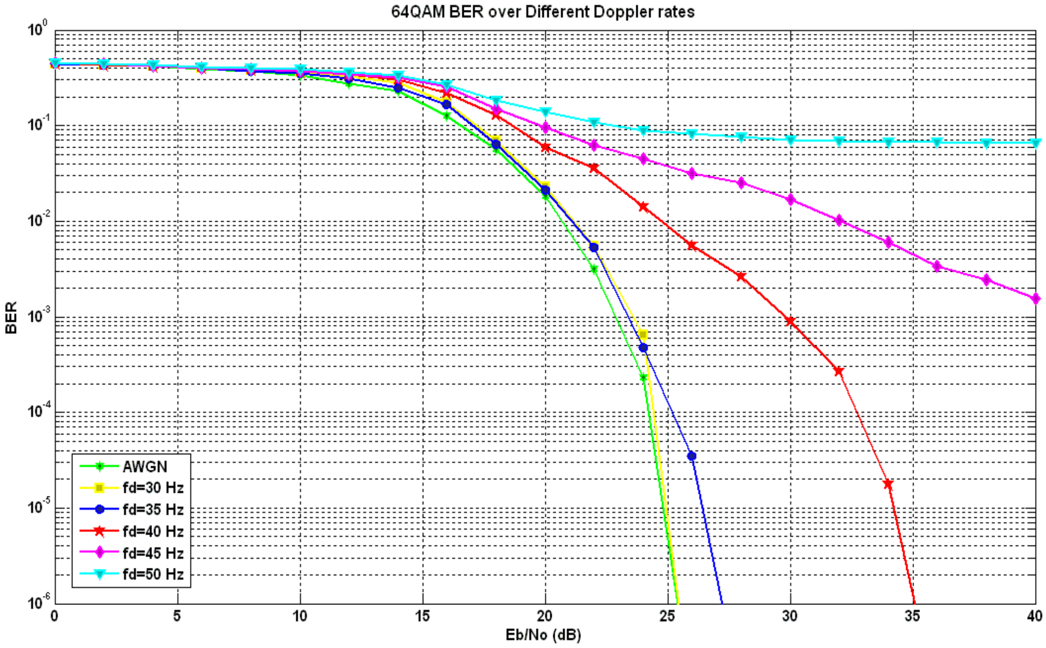


Fig. 5. 64QAM BER Performance Over Rayleigh Channel .

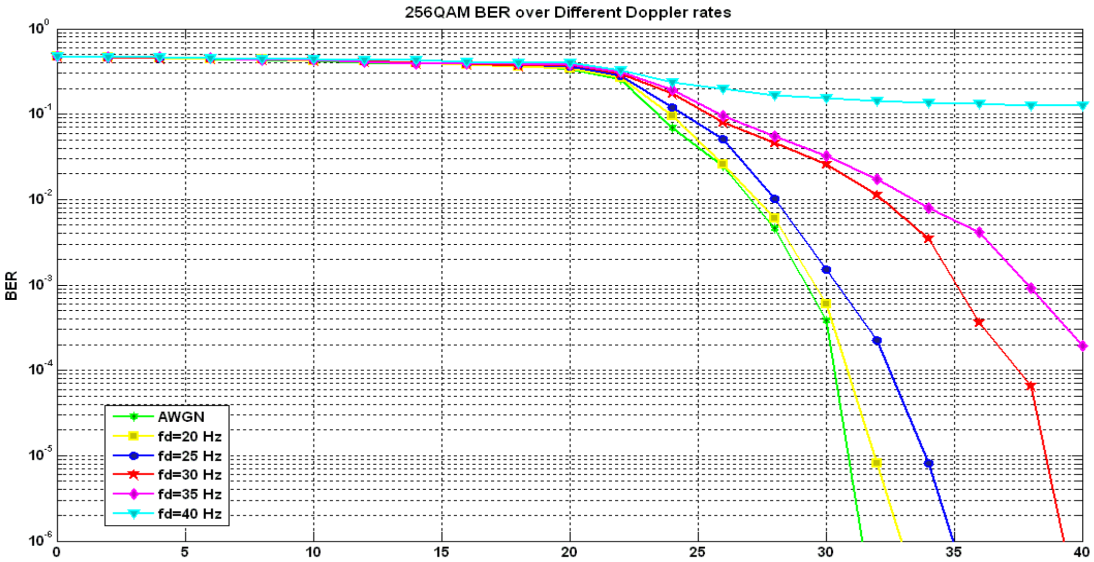


Fig. 6. 256QAM BER Performance over Rayleigh Channel .

4.2. Channel Estimation

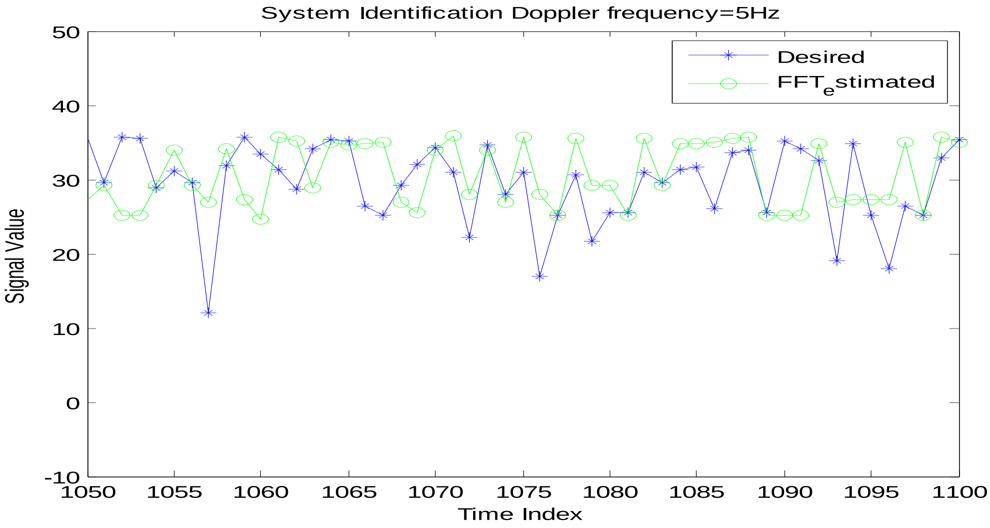
The ultimate goal at the receiver is to recover the transmitted signal that was subjected to both time varying attenuation and phase distortion. Using pilot symbols accurate channel values can be obtained at the pilot times. In order to obtain the channel impulse response, the channel values can be interpolated. FFT-based interpolation approach was used to interpolate in between channel values.

The input data to the channel estimator is the ratio of the received pilot symbols to the known pilot symbols g(n) [7]. This factor gives a measure of the distortion that the pilot symbol has undergone due to the channel fading.

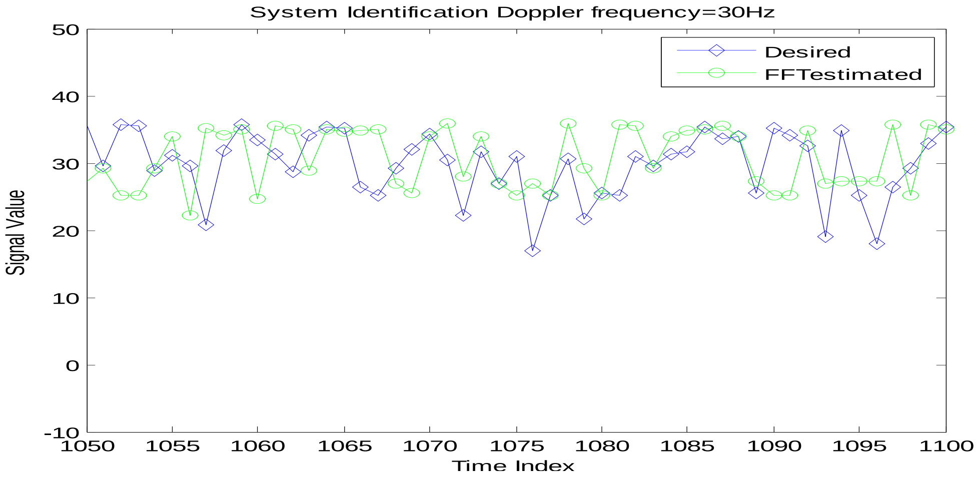
$$G(K) = \sum_{n=0}^{N_p-1} g(n)\exp(-\frac{j2\pi nk}{N_p}) \qquad \ldots(6)$$

Where N_p is the number of pilot symbols used to create channel estimate.

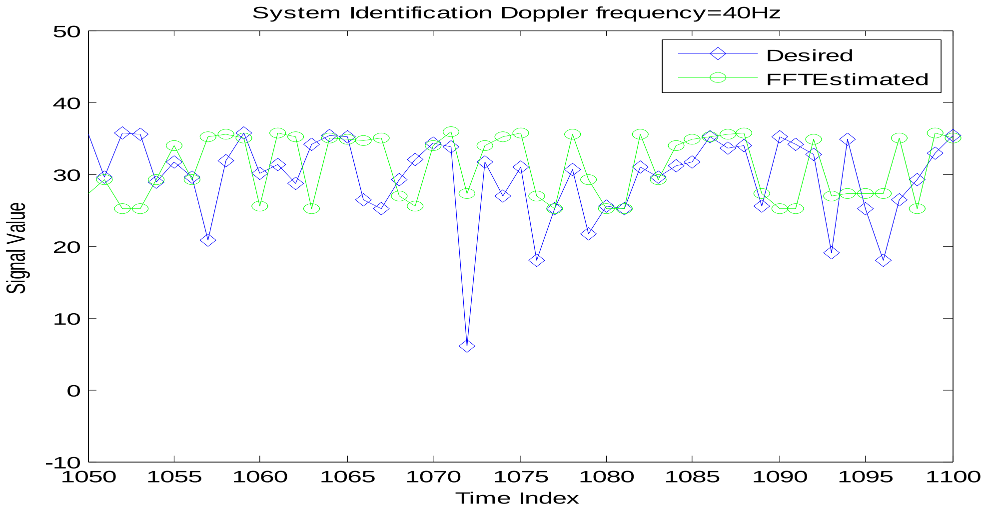
Both SNR and the Doppler frequency shift have a strong impact on the performance of channel estimation and hence rate adaptation. The effect of different values of Doppler frequency shift on channel estimation was simulated as shown in Figure (7).



a. Doppler Frequency= 5 Hz.



b. Doppler Frequency=30 Hz.



c. Doppler Frequency=40 Hz

Fig. 7. FFT Estimation of Signal Transmitted over Rayleigh Fading Channel.

4.3. Channel Prediction

In channel prediction, the future power level of the channel can be estimated using past and present channel samples [11].

Unlike AWGN the channel is correlated from sample to sample. Therefore, advantage of the deterministic properties can be taken and what the value of the channel will be at a later time can be predicted. In the linear prediction (LP) model, the current sample is approximated by a linear combination of past samples of the input signal [10,12,13]:

$$\grave{c}_n = \sum_{j=1}^{p} d_j\, c_{n-j} \qquad \text{...(7)}$$

Where $\grave{c}_n$ is the predicted value based on the linear combination of (p) previous values (c_{n-j}) multiplied by the prediction coefficients(d_j). And the error generated by this estimate is [14]:

$$e_n = c_n - \grave{c}_n \qquad \text{...(8)}$$

Where c_n is the true channel value.
In order to predict multiple samples in the future, the latest predicted sample is just treated as an actual sample. In linear prediction the state of the channel will be up to date at the time the transmitter receives the control information from the receiver hence propagation delay of the feedback channel will be less of a problem.

In order to predict the Rayleigh fading channel, channel estimation followed by linear prediction will be employed. A linear predictor is used to predict the channel status based on the outdated estimates.

Figures from (8) to (10) show the prediction of future channel values. The prediction efficiency is depending on the number of symbols that could be predicted ahead. As the number of symbols increases, the accuracy of the prediction would be decrease.

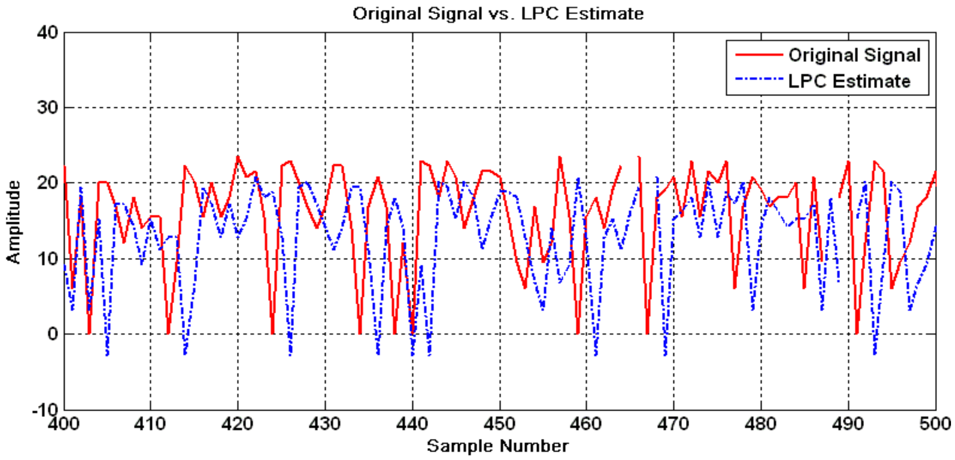


Fig. 8. Linear Prediction for 1 Symbols Ahead.

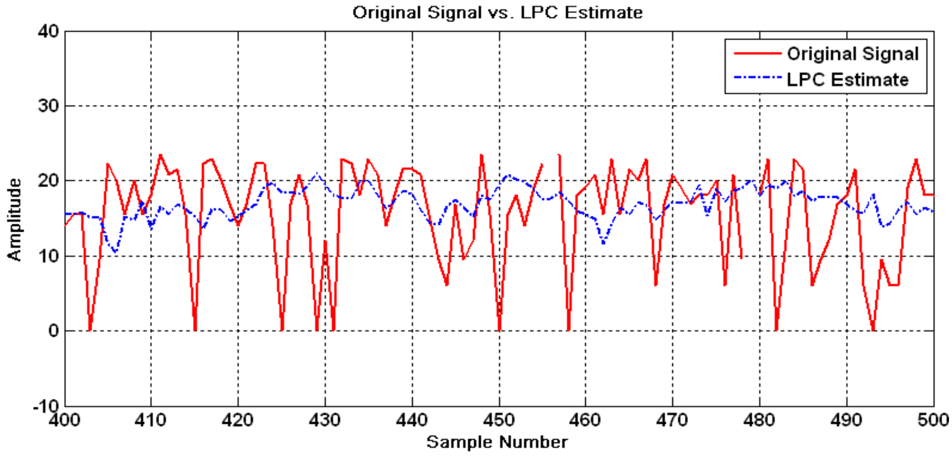


Fig. 9. Linear Prediction for 10 Symbols Ahead.

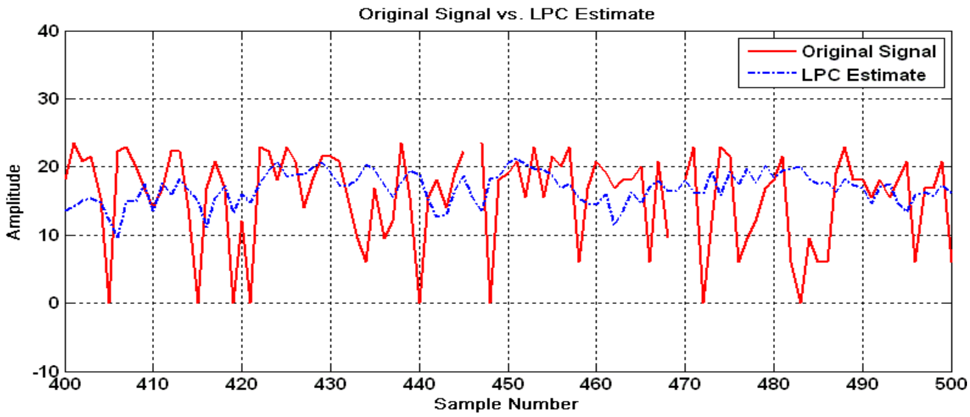


Fig. 10. Linear Prediction for 20 Symbols Ahead.

BER performance of 64QAM and 256QAM simulated over predicted channel with different prediction depth (10 and 20 samples ahead) is shown in Fig. (11) and Fig. (12).

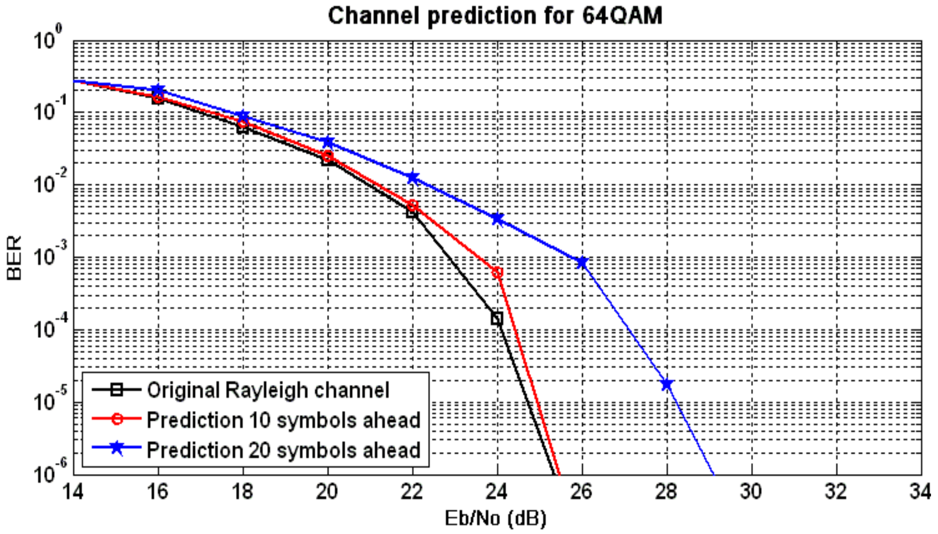


Fig. 11. 64QAM BER Performance for Predicted Rayleigh Fading Channel .

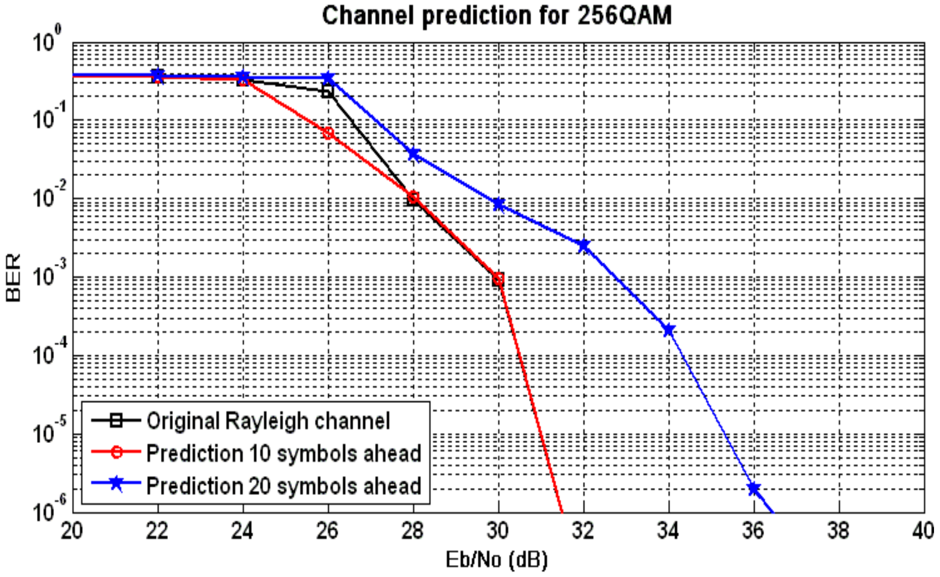


Fig. 12. 256QAM BER Performance for Predicted Rayleigh Fading Channel .

5. Results and Conclusions

It is worthy to note that the channel estimation and prediction at the receiver side differ from the original Rayleigh channel because of the error due to estimation and prediction process. As Doppler frequency increases, the BER also increases because of the deep fades that occur on Rayleigh channel during data transmission.

From previous results it can be concluded that the BER performance over predicted channel with 10 symbols ahead is better than the BER performance over predicted channel with 20 symbols ahead since as farther as many samples predicted, the less accuracy of the channel will be observed because of accumulated error.

Figures (13-14-15) show the BER performance for 32QAM, 64QAM and 256QAM constellations with different values of Doppler frequency shift for each case simulated over original, estimated, and predicted Rayleigh fading channels.

The results clearly reveal that the channel estimation was sufficient for low Doppler frequency shifts (<30 Hz). At higher Doppler shifts the channel estimator fails to track the channel variations due to high fading rate, while channel prediction is much more suitable at high Doppler shifts and same SNR.

Channel prediction based on the estimated channel samples was simulated and tested for target BER=10^{-4}. It was shown that the performance at higher Doppler frequency shifts was improved by more than 2dB over channel estimation and 32QAM modulation used. Higher constellation size is more sensitive to increased Doppler shift.

Fig. (16) shows that the BER performance of adaptive system is much better than static system because it provides efficient spectral efficiency at any given SNR. The reason for such improvement is that when a channel encounters a deep fade, it is better to use a modulation with lower constellation size in order to get low error probability, while in good channel state it is better to transmit as many bits as possible. As a result, in order to overcome the outdated CSI ,when channel estimation is used, past and present channel symbols can be used to predict future channel symbols.

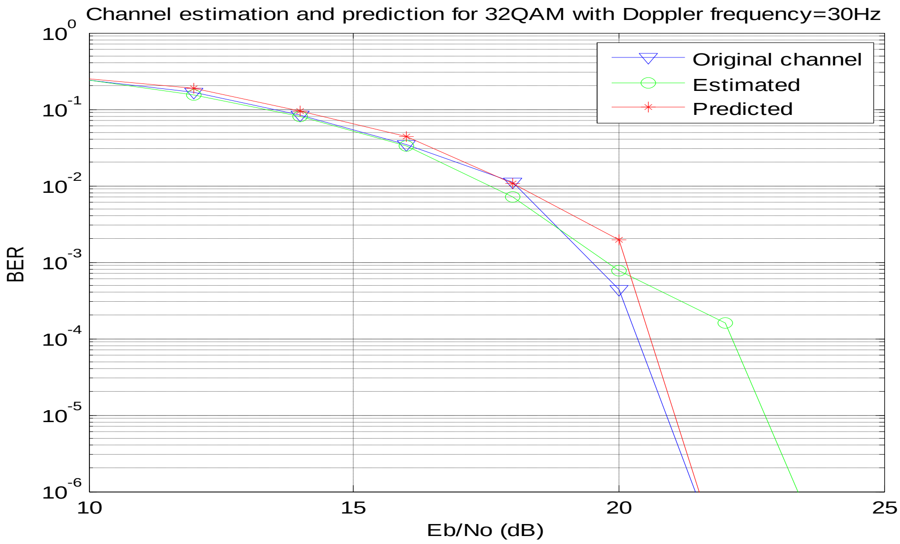
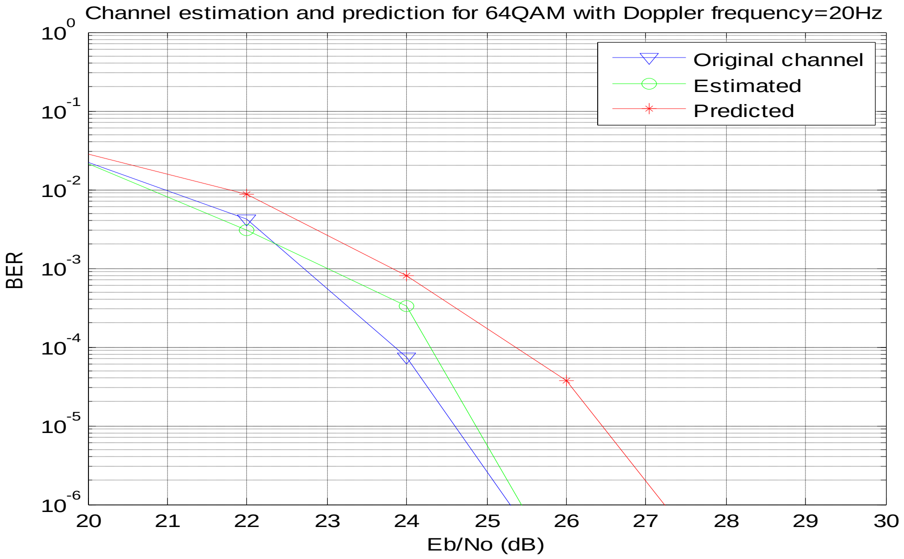
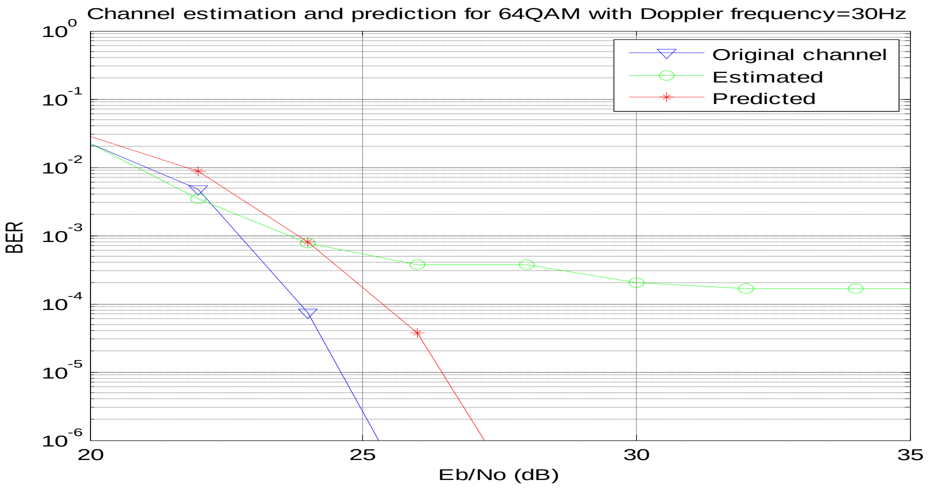


Fig. 13. Channel Estimation and Prediction 32QAM.

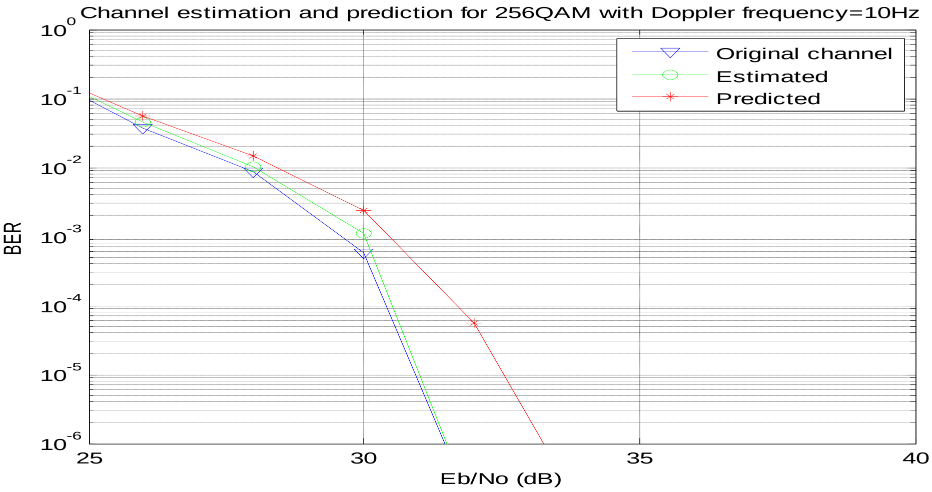


a. Doppler Frequency=20 Hz.

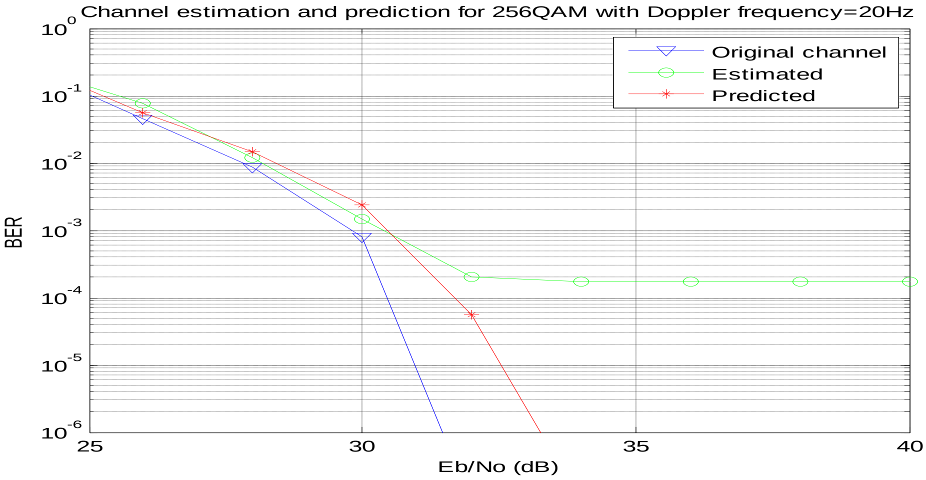


b. Doppler Frequency=30 Hz.

Fig. 14.Channel Estimation and Prediction for 64QAM.



a. Doppler Frequency=15 Hz.



b. Doppler Frequency=20 Hz.

Fig. 15.Channel Estimation and Prediction 256Q AM.

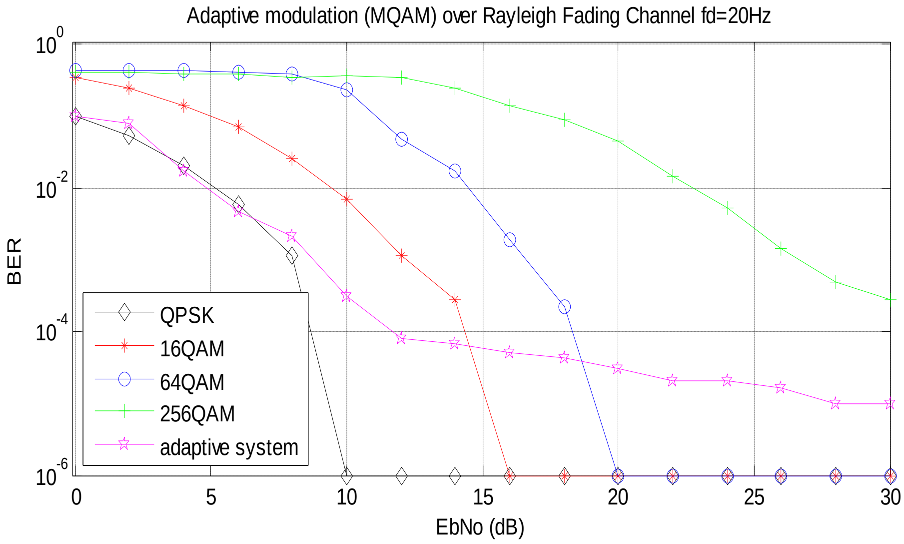


Fig. 16. BER Performance of Adaptive System.

Fig. (17) shows the spectral efficiency throughput for estimated and predicted Rayleigh fading channel taken over BER threshold 10^{-4} and Doppler frequency shift f_d =20 Hz and 40 Hz**.** It is clear that when the Doppler frequency increases the channel estimation alone fails to track the channel variations, and hence low spectral efficiency, while channel prediction is much more efficient with high spectral efficiency.

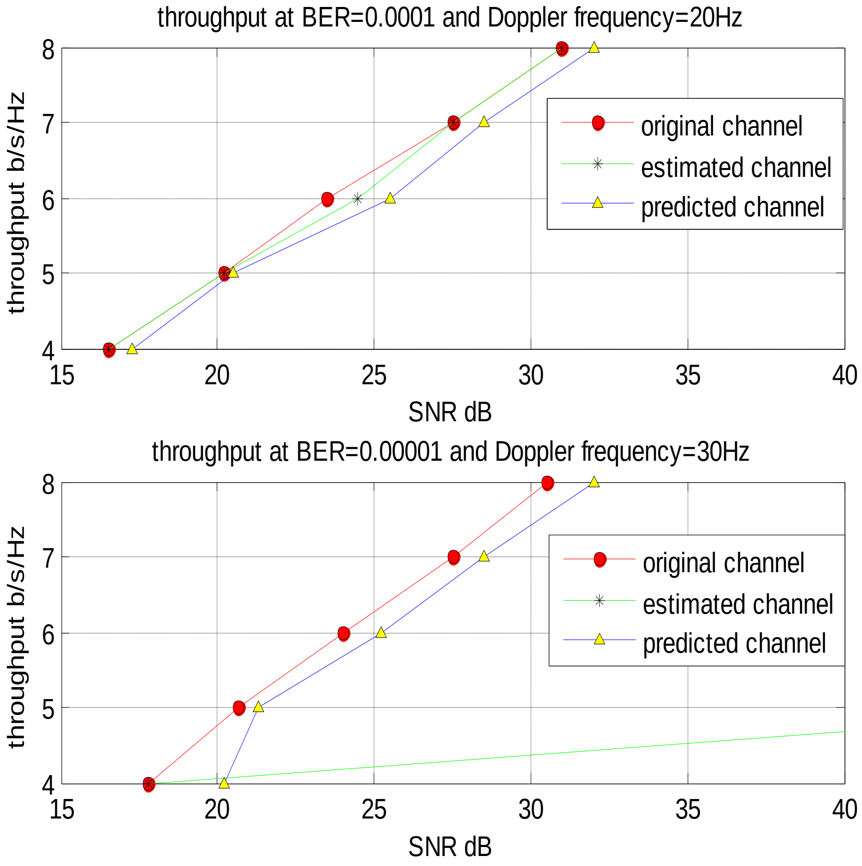


Fig. 17. Throughput of Predicted and Estimated Channel f_d=20Hz, and 30Hz BER=10^{-4}.

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تخمين ألقناة لأغراض ألأتصالات أللاسلكية ألمتكيفة

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الخلاصة

يعتبر التضمين المتكيف احد التقنيات الكفوءة لتحقيق التوازن بين سعة القناة ومقدار نسبة الخطأ الحاصلة في ارسال البيانات. لغرض تغيير سرعة ارسال البيانات فأنه يتطلب معرفة حالة القناة عند جهة الارسال. ان المنظومة المقترحة تتضمن ارسال رموز معروفة لتخمين حالة القناة من خلالها. وجد ان اداء المنظومة يكون جيدا في الحالات التي يكون فيها تردد دوبلر قليل، ولكن عند زيادة تردد دوبلر(< 30Hz) فان تخمين القناة لا يعطي نتائج جيدة بسبب ان التخمين لا يستطيع ملاحقة التغييرات المتسارعة للقناة والتي تحدث بسبب معاملات الاضمحلال. لذلك تم اللجوء الى التنبؤ بحالة القناة لفترة قادمة من خلال التنبؤ الخطي ووجد بأنه يعطي تحسين مقداره اكبر من2 ديسيبل مقارنة بحالة التخمين ونسبة الخطأ المستهدفة= 10^{-4} عند استخدام 32QAM.