Symbol Dispersion to Represent the Adaptive Modulation and Coding for Space-Time Block Coded OFDM System

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Abstract

It is important to estimate the instantaneous bit error rate (I-BER) as accurately as possible for effective utilization of the adaptive modulation and coding (AMC) for the system accurately. In this paper, a new method is developed to estimate the link performance for space time block code (STBC) systems with maximum likelihood detector (MLD). This can be achieved by using a dispersion of receiving symbols (DOS) in the constellation mapping to represent the current channel state information (CSI) in subsequent frame followed by the selection of an appropriate modulation coding scheme for the next frame. The transmission mode for each orthogonal frequency division multiplexing (OFDM) symbol is the updated frame-by-frame to match the conditions of the time-varying channel and to reduce the feedback information. Simulation results show that the spectral efficiency performance of the proposed AMC approximates both AMC of ideal and threshold. As the proposed AMC outperforms the fixed modulation coding schemes and there is no need for any predetermined parameters as in the threshold AMC.

Keywords: AMC, DOS, I-BER and STBC-OFDM.

1. INTRODUCTION

The requirements for the next generation of wireless communication systems can be achieved through high reliability, data rate, capacity and mobility with less cost and complexity. To meet these requirements in the frequency selective fading channels, it is recommended for a combination of Multi-input Multi-output (MIMO) (Jankiraman, 2004) and orthogonal frequency division multiplexing (OFDM) (Hanzo & Keller, 2007) that supports high data rates and efficient usage of the transmission bandwidth. It is known that MIMO systems which support multi independent transmission channels can increase the channel capacity and improve the reliability of the system with limited frequency resources. Also, the OFDM is an effective method used for the reduction of inter-symbol interference (ISI) and inter-carrier interference (ICI) that is made possible through the use of multi carrier modulation in frequency selective fading channel. Moreover, use of MIMO-OFDM can guarantee reliability and high data rates, by associating the bit-interleaved coded modulation (BICM) in wireless communication (Lee, Chan, & Sundberg, 2004). Furthermore, the adaptive modulation and coding (AMC) enhances the performance of data transmission system by adjusting the transmission data parameters such as power, coding rates and modulation levels. The parameters depend on channel state information (CSI) that is represented by the signal-to- noise ratio or signal-to-interference plus noise ratio as discussed in previous work. However, this research study presents a new metric called dispersion of symbols (DOS) (Hassib et al., 2013).

In order to utilize an AMC scheme effectively, it is required to provide an accurate estimation performance of the link such as bit error rate (BER) or packet error rate (PER) is required. In modern systems that use OFDM modulation through the mobile channel, the performances of BER dose not only depend on the received SNR, but it also depends on the frequency selective, delay spread and Doppler frequency of the channel. For example, for similar received SNR, the BER increases as a root mean square delay spread decrease. Whereas the BER increased as the Doppler frequency increased too (Song

& Mujtaba, 2003). Inaccurate estimation of CSI will worsen the performance of the system. So the use of a fixed link table which is supported only by SNR will not work well as (Goldsmith & Chua, 1998). Many research studies of AMC have proposed to either minimize the BER or maximize the throughput in multi-antenna broadband wireless communication. The adaptive modulation schemes in (Lin, Mahmoud, & Hussain, 2005) selected the best modulation scheme sizes provided BER is less than the target BER. In (Xia, Zhou, & Giannakis, 2004) posited that the adaptive modulation schemes determine the optimum modulation scheme for each subcarrier according to the targeted BER constraint in order to achieve the optimum allocation of data rate and power so that maximum spectral efficiency is achieved without the wastage of power or the sacrifices of BER. In (Zhang & Heng, 2009) proposed a cross-layer adaptive modulation and coding (AMC) design for space-time block coded in OFDM systems to maximize spectral efficiency. In both retransmission and traditional schemes, the transmission mode for each subcarrier is updated through frame-by-frame in order to match the time-varying channel conditions.

In practical systems, the full channel state information at the transmitter is impractical due to limitation in the feedback, errors in channel estimation and channel dynamics in the systems. Generally, the requirements for feedback increases with the number of subcarriers in OFDM symbol based on the threshold AM (Keller & Hanzo, 2000). The requirements for feedback are reduced gradually when the OFDM mode combines with the STBC based on the threshold of AM or when utilizing sub-bands BER in the estimation of AM. However, the adaptive modulation of symbol-by-symbol of fixed OFDM mode supported SE which be longs to the same as the subcarrier and sub-band grouping of AOFDM mode, when combine with the STBC based on threshold AM that reduces the requirements for feedback effectively (Liew & Hanzo, 2006). Moreover, is difficult to estimate the SNR for the representation of CSI in different environments and in dynamic channels. Thus, the use of the lookup table which minimizes feedback overhead is not a suitable method to overcome this problem. However, the partial CSI used to construct a particular channel scenario can lead to loose signal-to-noise ratio (SNR) approximation, making the adaptive modulation inaccurate and impractical for use theoretical method. Therefore, both reliable and limited feedback information as well as low complexity is necessary in practical systems (Love et al., 2008). As such, channel state information which is based on an instantaneous bit error rate (I-BER) is used to represent AMC effectively for a a practical system with previous assumption

The proposed scheme is compared to fixed modulation coding schemes, threshold AMC scheme and the ideal AMC scheme, in terms of BER and spectral efficiency, against SNR for STBC OFDM systems. The results of ideal AMC systems are obtained by setting all modulation coding schemes into the transmitter, and after which they are transmitted to the receiver. The selection of the modulation coding scheme undergoes an exhaustive search, whereby the receiver computes the spectral efficiency for all possible sets of AMC combinations. The selected modulation coding scheme is one that yields the highest spectral efficiency for each channel realization. When the size of the number of sets of AMC scheme increases, the processes of transmitting and receiving adds burden to the size of an exhaustive search size to the extent of the search becomes prohibitive. Practically, it is impossible to employ such a scheme due to the extremely high computational complexity (Kim, Lee, Sung, & Lee, 2009). Meanwhile, the threshold of AM scheme can be achieved by specific sets of SNR thresholds that are assigned to a specific modulation scheme level for a determined SNR range. Thus, for a given SNR range, the AMC scheme selects the modulation coding schemes with the best spectral efficiency.

However, the expected spectral efficiency for each AMC set can be easily obtained from the proposed AMC scheme. Furthermore, this research study focuses on discrete rate adaptation because it is more practical than continuous rate adaptation. Also, it pays no attention to power adaptation because there is little gain when combines with rate adaptation (Chung & Goldsmith, 2001). As such, paper proposes a new method with the earlier considerations mentioned without the need for any predetermined parameters. This method uses a dispersion of symbol (DoS) in the receiver for two purposes. The first purpose is to estimate the channel, while the second one is to select a better modulation coding scheme. The simulation results show that the proposed AMC method has outperformed the fixed modulation coding scheme (FMC) and it approximates the ideal and threshold AMC scheme.

2. Proposed Adaptive Modulation and Coding Scheme

2.1 System Model

This Section explains the STBC-OFDM system with adaptive modulation. Figure 1 illustrates the proposed scheme. The system considered in the ideal state, in the absence of delay and noise in the feedback path from receiver to transmitter.

The proposed AMC scheme uses different levels of modulation coding schemes. The level of modulation coding schemes is defined by the use of dispersion of symbol to estimate the condition of the channel after the computation of the BER for each block, followed by comparison with the assumed target BER of the system.

Figure 1 illustrates the structure of STBC-OFDM systems with two transmitter and two receiver antennas. At the transmitter, the source generates random data as information bits to be fed to the CRC encoder. These data bits are then encoded by convolution codes (CC), after which they are passed to the channel interleaver. Later, the coded bits are modulated by the M-QAM modulator. Subsequently, the output of the M-QAM modulator is forwarded to the STBC encoder. After that, the two output of the space-time encoder are modulated by OFDM for transmission after the addition of a cyclic prefix (CP) by the corresponding antenna. At the receiver, the signal of each receiver antenna is demodulated by OFDM after the removal of a CP. The demodulated signals of the receiver antennas are fed to the STBC decoder. The output of space-time decoders applies the M-QAM demodulator before the CC decoder with it is de-interleaver and then to the CRC decoder before the sink. The sink is used for the calculation of bit error rate (BER).

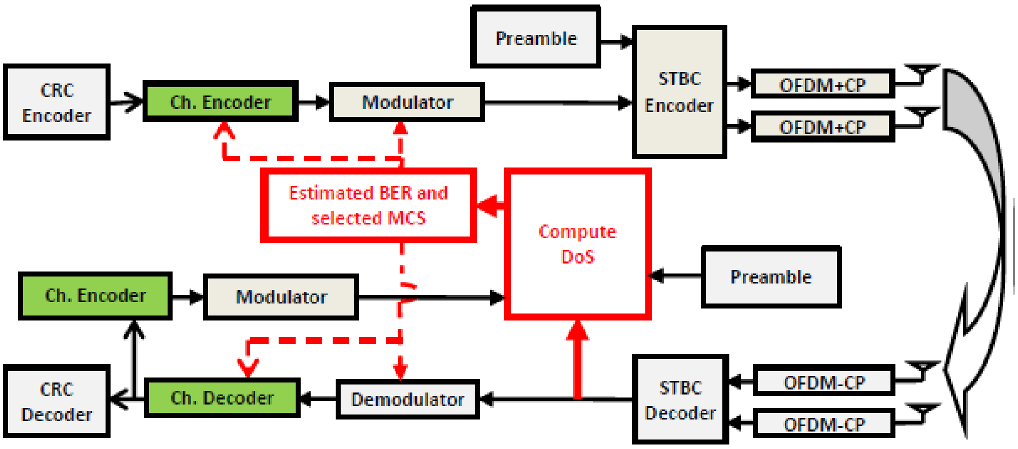


Figure 1. Block diagram for 2x2 STBC-OFDM system models.

The level of the modulation coding scheme in feedback information is identified and adjusted according to the effects in the conditions of the channel on the data frame, if Mj is a considered as the level of the modulation coding scheme for *jth* data transmission mode. Meanwhile, the AMC scheme at the receiver determines Mj for each transmission mode independently according to the current CSI, and the receiver reports the indices of AMC that correspond to Mj for each transmission mode to the transmission side through the feedback channel.

The CRC decoder (checker) in the receiver is used for the selection of data that is considered as data aided to compute the CSI or to estimate the current channel. Currently, there are two states to the CRC checker. The first state occurs when the CRC checker equals zero. This means there are no errors in the received data and the data can be considered as aided to the receiver corresponding to the received symbols after demodulation in the receiver. Thus, this data can be considered for the computation of the current CSI. The second state takes place, when the CRC checker fails to equal zero. This means that there are some errors in the received data so the data cannot be assumed the aided data to the receiver

corresponding to the received symbols after demodulation. In this case the preamble signal which is an aid to the receiver, is considered for the estimation of the current channel condition. It is to be noted that the CRC in this method is not used to retransmit the data when the CRC checker fails, as in the previous work. However, it is used to select data for the estimation of the BER.

2.2. DOS Calculations

Figure 2 shows the dispersion, d_i of receiving symbols is computed in the receiver instead of the estimation of the SNR. The magnitude and phase of dispersion for a received symbol position r_i is calculated with respect to each ideal transmitted symbol position, s_i as in (1), (2) and (3).

$$\ell_i = \sqrt{(r_i(Re) - s_i(Re))^2 - (r_i(Im) - s_i(Im))^2} \quad (1)$$

$$\varphi_i = \frac{(r_i(Im)-s_i(Im))}{(r_i(Re)-s_i(Re))} \quad (2)$$

$$d_i = \ell_i e^{j\varphi_i} = r_i - s_i \quad (3)$$

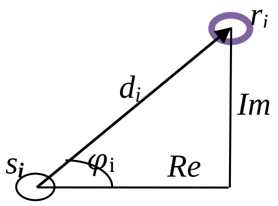


Figure 2. Dispersion of receiving symbol.

Hence, in the receiver, there are three methods to compute the dispersion of symbol. The first method is based on data symbol, in the case when the CRC checker equals to zero, while the condition of the channel is represented by a dispersion vector, **D** that contains, N_d with dispersion symbols for vector $d_i$as in (4) where N_d represents the number of data in OFDM symbol. the second method is based on preamble symbols in the case when the CRC checker fails to equal zero, while, the condition of the channel is represented by a dispersion vector, **D** that contains, N_d dispersion symbols for vector $d_i$as in (4) where N_d represents the number of preamble symbols that is clipping to the number of data in OFDM symbol.

$$D = \{d_1, d_2, \dots \dots, d_{N_d}\} \quad (4)$$

2.3 Simple BER Estimation Scheme Based on DOS

Figure 3 shows the block diagram of the proposed method. This proposed method depends on the fact that the dispersion due to channel fading is independent of the type of modulation scheme in the fading channel for the aided data (Choi, Shoji, & Ogawa, 2011) and (Sen, Santhapuri, Choudhury, & Nelakuditi, 2010). The channel condition is represented by a vector, **D** of dispersion due to the N_d symbol of aided data that is generated at the rate R (for example, QAM) over a channel. The implementation of the proposed method begins with the generation of N_d Symbol for different modulations coding scheme

randomly. Secondly, these vectors of symbol are added to the dispersion vector, **D** separately in a parallel form after modulation.

Then, the demodulated signal at the j-th transmission mode of aided data after demodulation can be expressed as in (5).

$$ds_j = ms_j + D_j \tag{5}$$

Where ds_j represents the demodulated signal vector of length N_d, while ms_j indicates the modulated signal vector of length N_d that was generated randomly, D_j is a dispersion vector of symbols and lastly N_d is the number of symbols of aided data. Finally, it is very easy for the calculation the bit error rate (P_e) for all types of MCS after demodulating by (6) from (5).

$$P_e = \frac{Number\ of\ bits\ error\ per\ transmission}{Number\ of\ bits\ per\ transmission} \tag{6}$$

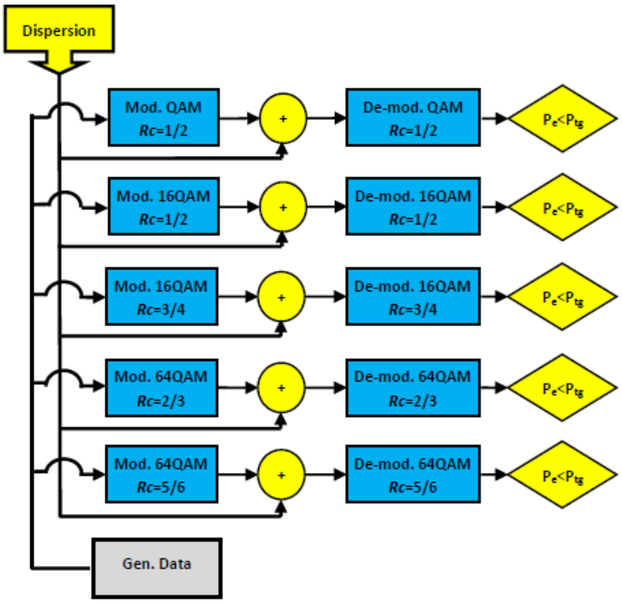


Figure 3. Block diagram for the proposed method with coding.

2.4. Modulation Scheme (MS) Selection and Spectral Efficiency

Hence, the P_e calculated by (6) is compared with a target bit error rate (P_{tg}) which is assumed for all the branches of modulator and demodulator. However, to maximize the spectral efficiency of a system by assuming ideal Nyquist data pulses ($sinc\ [t/T_s]$) in order to avoid the reducing of spectral efficiency (Goldsmith & Chua, 1997). The selection of the modulation scheme targets the highest MCS rate for each transmission mode with $P_e \leq P_{tg}$ as in (7).

$$SE = R_i\ R_c \tag{7}$$

where SE is the spectral efficiency of the adaptive modulation scheme, $R_i = log_2(M_i)$ represents the rate of the highest MS that has been selected with a constellation size of M_i in transmission mode when $P_e \leq P_{tg}$, $R_i \in$ MS Set (QAM, 16QAM and 64QAM) and R_c is the rate of code used with the modulation scheme. The overall process of the adaptation scheme is represented in Algorithm 1.

Algorithm 1 adaptive modulation and coding scheme

1: Initialize the MCS for transmission mode M_j
where *j* represents transmission mode
2: Receive transmission mode
3: Compute P_e and SE for current MCS set by (6) and (7) respectively
4: Compute CRC
5: Select DA to receiver to compute dispersion as;
if CRC=0
compute dispersion of data symbol by using (4)
eles
compute dispersion of preamble by using (4)
end
6: Construct virtual channel as in (4) depend on CRC value
7: Generate all sets of MCS
8: Reflect virtual channel to all MCS set as in (5)
9: Calculate the BER (P_e) to all MCS set as in (10)
10: Select MS for the next transmission mode as;
if $P_{e(QAM)-Rc1/2} \leq P_{target}$
elesif $P_{e(16\_QAM)-Rc1/2} \leq P_{target}$
elesif $P_{e(16\_QAM)-Rc3/4} \leq P_{target}$
elesif $P_{e(64\_QAM)-Rc2/3} \leq P_{target}$
eles $P_{e(64\_QAM)-Rc5/6} \leq P_{target}$
end
11: Feedback select MCS in 10 to 1 for the next transmission mode

3. Results and Discussion

This section, presents the simulation results for the proposed scheme. The consideration for the simulation is an OFDM system with 512 subcarriers, 432 data and pilot subcarriers, 48 sub-bands, 1/8 cyclic prefix, 5MHz channel bandwidth and 2.4GHz carrier frequency that corresponds to the OFDM WiMax parameter (Ahmadi, 2010). The 3GPP pedestrian without LOS and vehicle channel model were also given consideration (Salo et al., 2005). The CRC is determined by the polynomial ($x^{16} + x^{15} + x^2 + 1$). The AMC set is adopted in the simulations of this study with five modulation coding schemes, by puncturing the half-rate convolutional code with a constraint length that equals 7 with an octal polynomial $[133, 171]_8$ like the QAM with a code rate of 1/2 one bit per symbol, 16-QAM with a code rate of 1/2 two bits per symbol, 16-QAM with a code rate of 3/4 three bits per symbol, 64-QAM with a code rate of 2/3 four bits per symbol and 64-QAM with a code rate of 5/6 five bits per symbol, the different rates are obtained by the puncturing method.

Figure 4 and 5, show the results of the BER estimation method proposed in section 2 for three methods based on the preamble, data and CRC for all fixed modulation coding schemes (FMCS). These figures reveal that the estimated BER based on the CRC is better than the estimated BER based on the preamble and data. The reduction of the estimated BER based on data method occurs in low SNR of the modulation schemes, whereas, the reduction of the estimated BER based on preamble method occurs in the high SNR of modulation schemes. Generally, the performance of the BER estimation deteriorates when the fading channel and the Doppler frequency increases, especially in the low modulation coding scheme. However, the proposed BER estimation based on CRC is less than 0.1 dB, from the actual simulation in the worst case scenario. The accuracy in estimation of the system is the result of the accuracy in the estimation of BER based on the data method that occurs in high SNR and the accuracy in the estimation of BER based on the preamble method that occurs in the low SNR of modulation schemes, in addition to the ability of FECC to correct the received symbols over uncoded system.

The results of the spectral efficiency (SE) corresponds to the actual BER simulation and proposed method of the BER estimation based on CRC for all fixed modulation and coding schemes (FMCS) presented in

Figure 6 and 7 for the target BER of 10^{-2} and 10^{-4} respectively. The findings in these Figures show that SE has the same value due to accuracy in the estimation of BER.

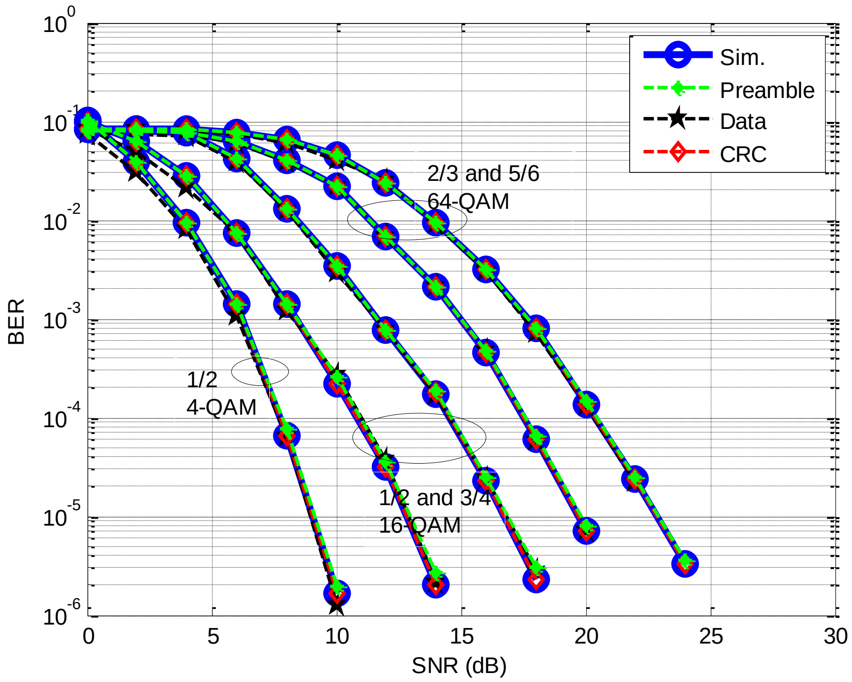


Figure 4. The performance of estimation BER in pedestrian 3GPP channel model

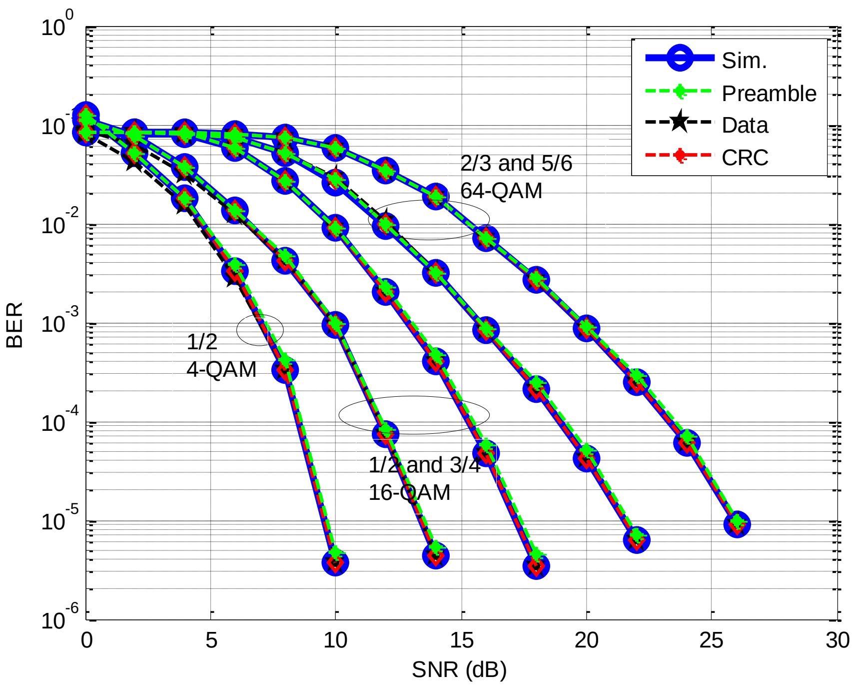
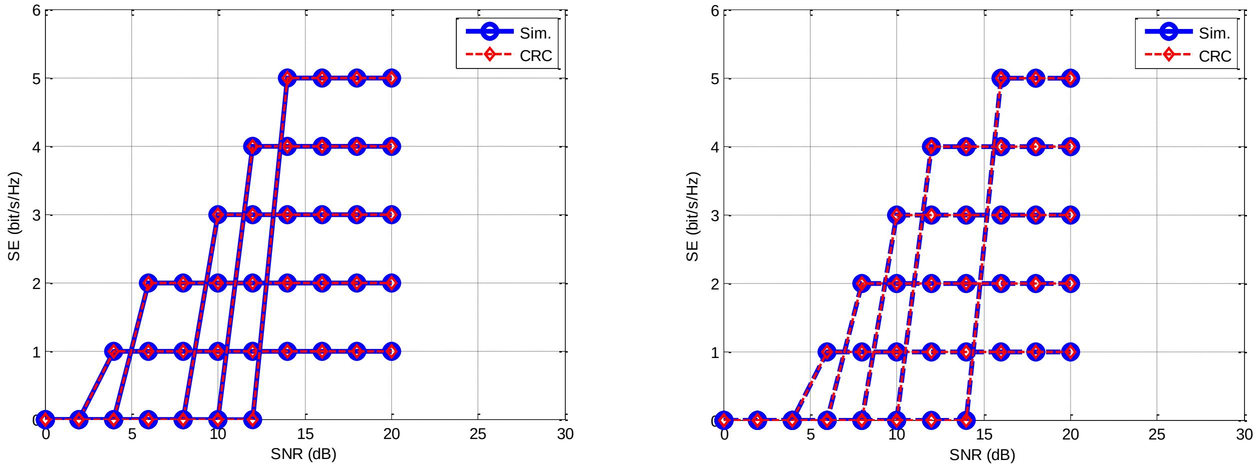


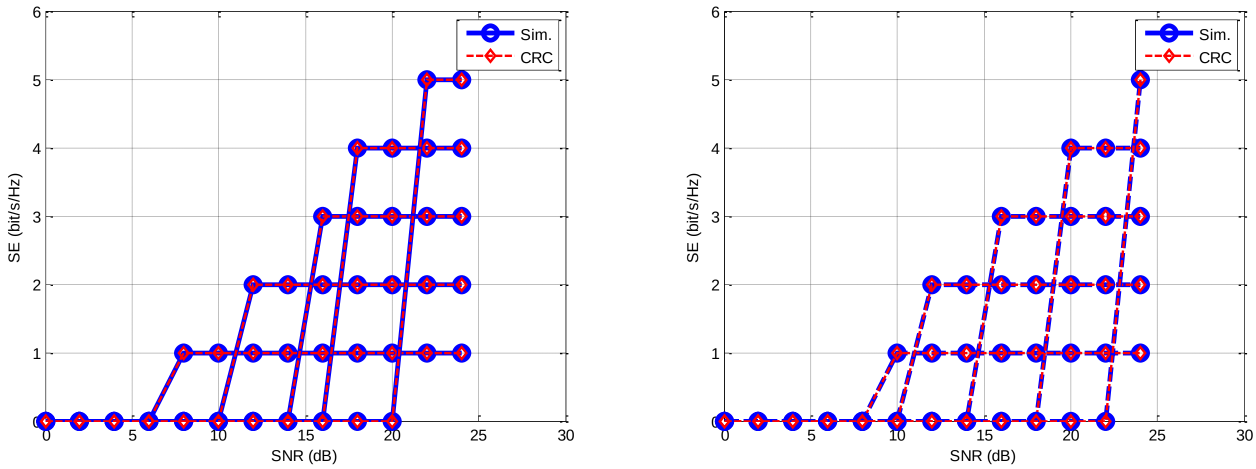
Figure 5. The performance of estimation BER in vehicle 3GPP channel model



a. Pedestrian 3GPP channel model

b. Vehicle 3GPP channel model

Figure 6. The SE performance with convolution code when targets BER 10^{-2}



a. Pedestrian 3GPP channel model

b. Vehicle 3GPP channel model

Figure 7. The SE performance with convolution code when targets BER 10^{-4}

The SNR thresholds of each modulation scheme obtained from simulation in Figures 4 and 5 is used to achieve BER performance for target BER 10^{-2} and 10^{-4} in different channel model. These boundaries are listed in Table 1 should be used as a reference in the comparison of performance between the proposed adaptive modulation coding scheme and threshold adaptive modulation coding scheme.

Table 1. Threshold switching for threshold adaptive modulation and coding scheme

MS		QAM	16-QAM	16-QAM	64-QAM	64-QAM
R_c		1/2	1/2	3/4	2/3	3/4
Pedestrian with LOS	Speech	3.9	5.55	8.35	11.15	13.85
	data	7.75	10.8	14.55	17.5	20.35
Vehicle	Speech	4.7	6.55	9.8	11.9	15.25
	data	8.5	11.75	15.3	18.1	23.25

The proposed adaptive modulation coding scheme with convolution code is based on a fixed OFDM modem. The proposed scheme is compared with the individual fixed modulation coding schemes, threshold AMC scheme (AMT) and the ideal AMC scheme (AMI) in terms of BER and SE against SNR for STBC OFDM systems. The results of the ideal AMC systems are obtained as explained in the introduction. The result of the fixed MS is obtained by the calculation of the BER and spectral efficiency (SE) for each modulation scheme individually. Finally, the threshold AMC scheme can be achieved by assigning specific sets of SNR thresholds to a specific level of modulation scheme as tabulated in Table 1. The results of the BER performance of the proposed AMC scheme (Prop. AM CRC) and that of the comparison schemes are compared with findings that show they approximate each other and they outperform the individual fixed modulation coding schemes, Figure 8 and 9 illustrate the BER performance of the AMC scheme when the targets of BER is lower than 10^{-2}. The findings in these Figures show that the gain in dB is 9.9 and 10.9 away from the BER performance of the 64-QAM with 5/6 code rate. Figure 10 and 11 presented the BER performance of the proposed AMC scheme (Prop. AM CRC) and of the comparison schemes when the target BER equals 10^{-4}. The findings in these Figures show that the gain in dB are 12.6 and 15.15 away from the BER performance of the 64-QAM with 5/6 code rate. Another, findings is the BER gain performance of AMC schemes increases when there is an increase in fading channel and speed, at the same time when the target BER of the system shows a decrease.

The results of the spectral efficiency (SE) of the ideal, threshold and proposed of adaptive modulation coding schemes (AMCS) presented in Figure 12 and 13 for the target BER of 10^{-2}.and 10^{-4} respectively. The findings in these figures show that SE has the same value due to accuracy in the estimation of BER.

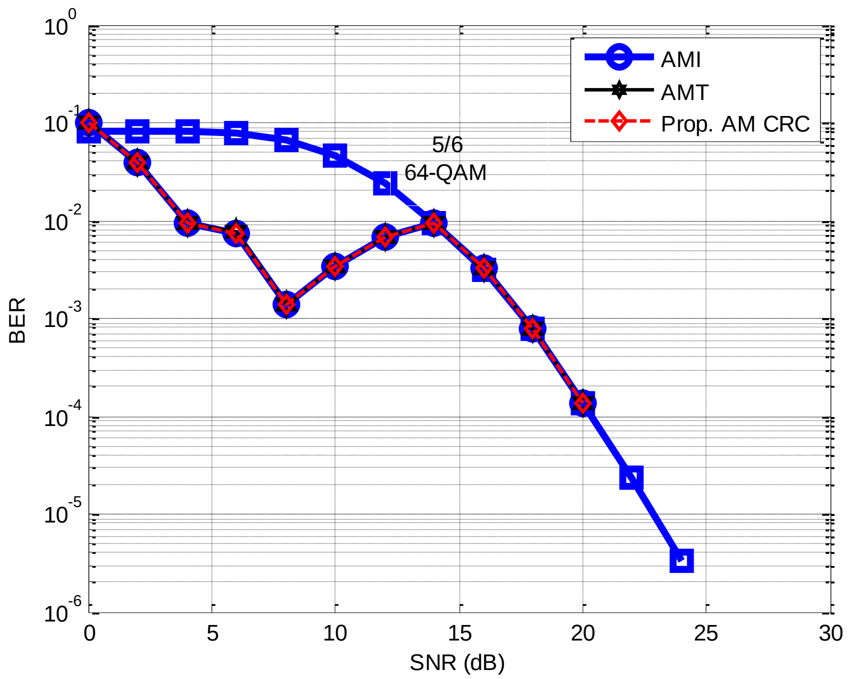


Figure 8. The BER performance of AM in pedestrian 3GPP channel model when target BER 10^{-2}

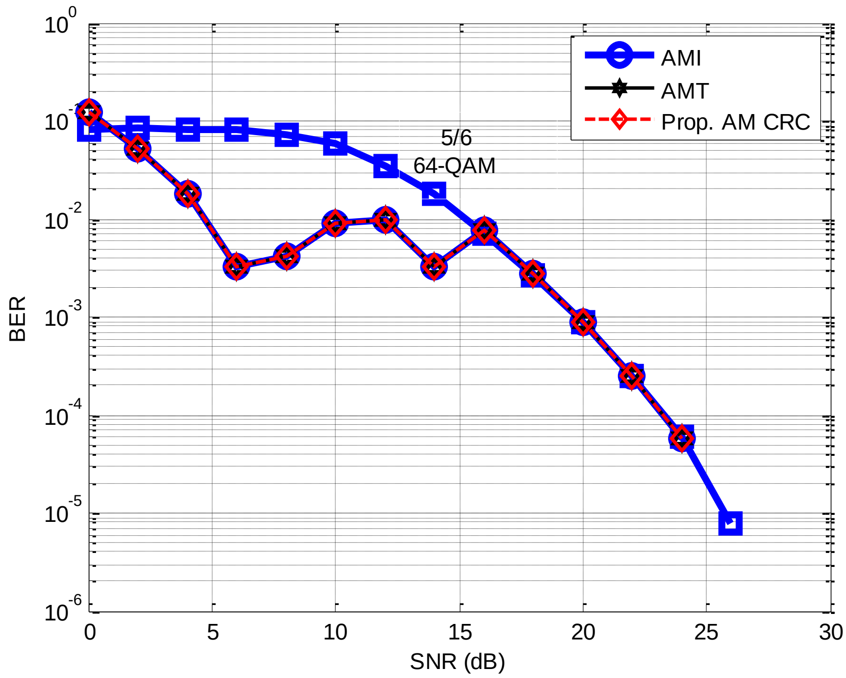


Figure 9. The BER performance of AM in vehicle 3GPP channel model when target BER 10^{-2}

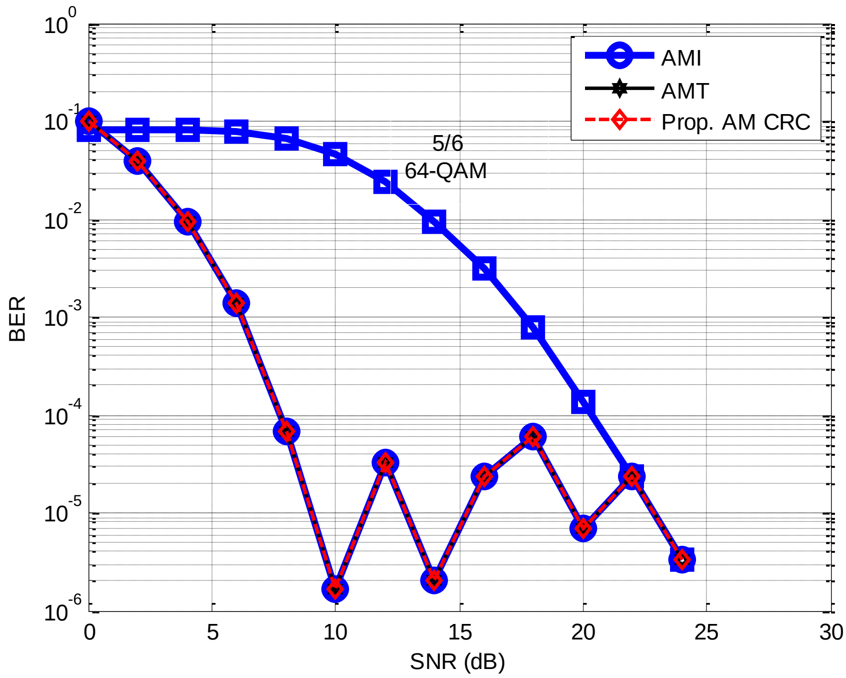


Figure 10. The BER performance of AM in pedestrian 3GPP channel model when target BER 10^{-4}

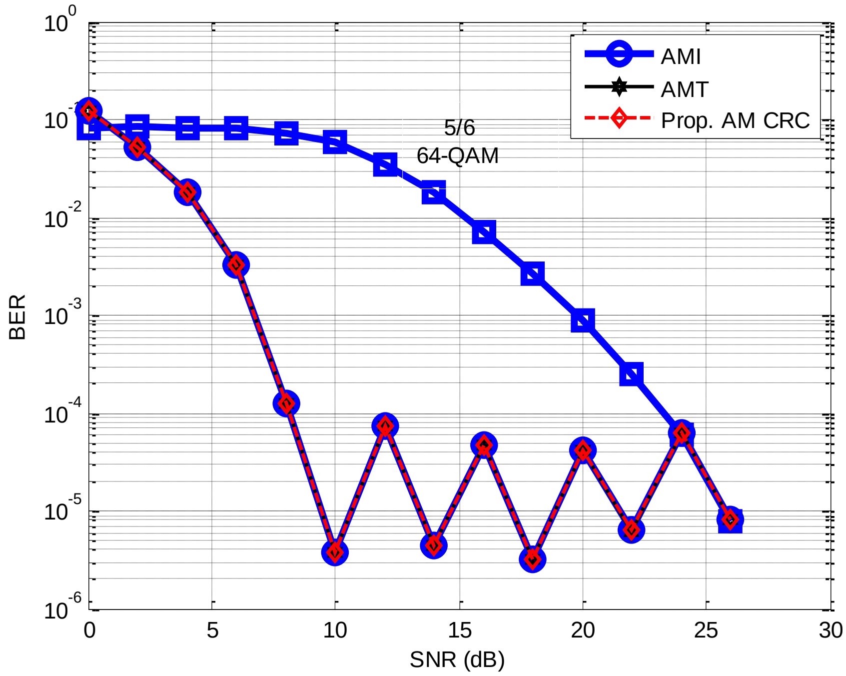
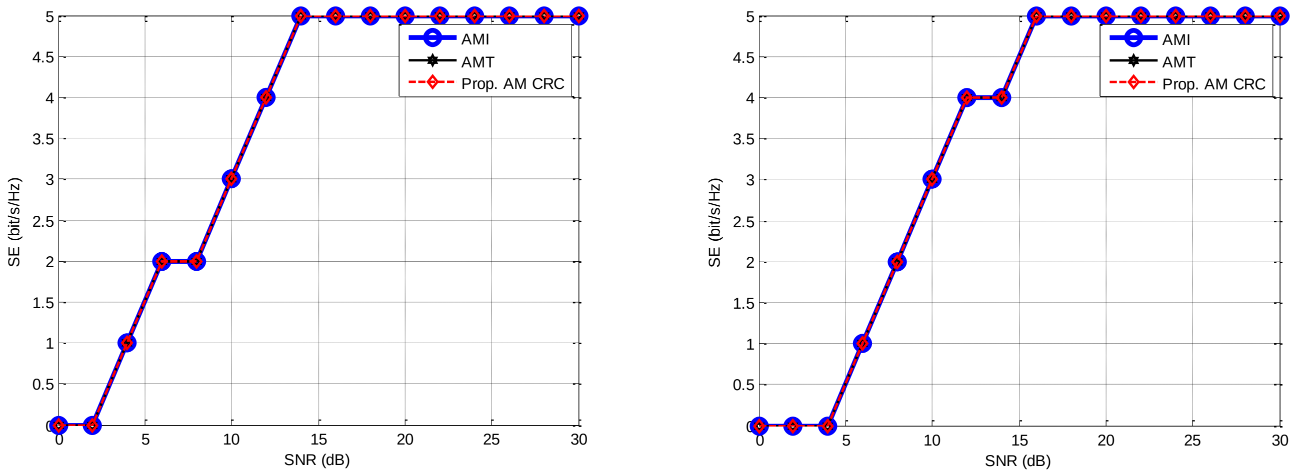


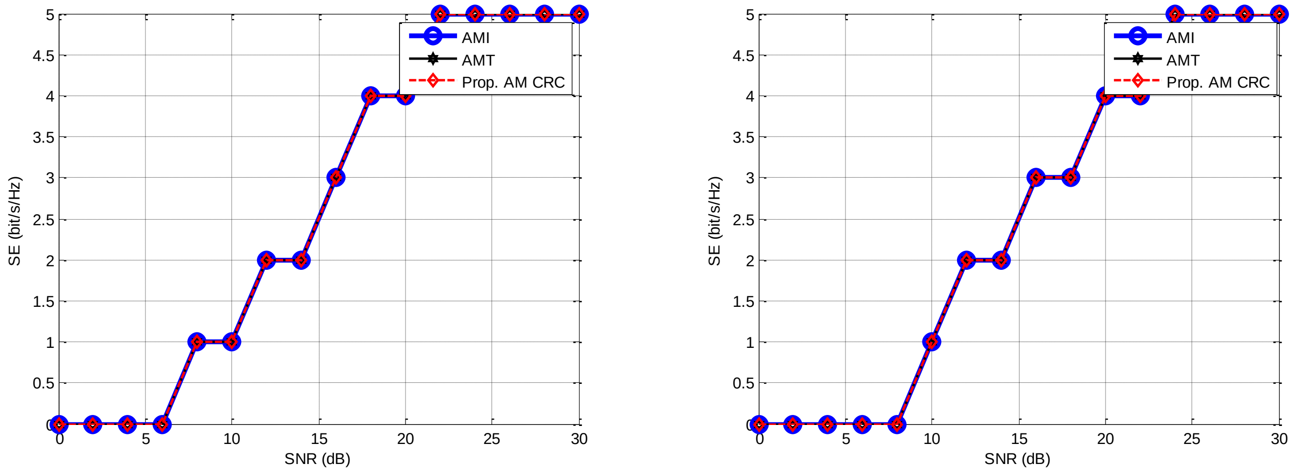
Figure 11. The BER performance of AM in vehicle 3GPP channel model when target BER 10^{-4}



a. Pedestrian 3GPP channel model

b. Vehicle 3GPP channel model

Figure 12. The SE performance of AM when targets BER 10^{-2}



a. Pedestrian 3GPP channel model b. Vehicle 3GPP channel model

Figure 13. The SE performance of AM when targets BER 10^{-4}

4. Conclusion

This paper has investigated the performance of the proposed AMC scheme by combining STBC with a fixed OFDM modem. The proposed scheme has exploited the dispersion of symbols for two purposes; to estimate the BER and to select best MCS. The proposed scheme dose not requires any predetermined parameters (SNR) as in threshold AMC in different environments. Also, it is more practical and less complex scheme than the ideal AMC scheme. The simulations prove that the performance of the proposed scheme has outperformed in terms of BER and spectral efficiency (SE) of the individual fixed modulation coding schemes. Also, the performance of the proposed scheme approximates the conventional ideal and threshold adaptive modulation coding schemes. The feature works can be conducted by proposing AMC scheme for adaptive OFDM modem based on pilot signal as aided data to the receiver.

References

Ahmadi, S. (2010). *Mobile WiMAX: A systems approach to understanding IEEE 802.16 m radio access technology*: Academic Press.

Choi, C.-S., Shoji, Y., & Ogawa, H. (2011). Implementation of an OFDM baseband with adaptive modulations to grouped subcarriers for millimeter-wave wireless indoor networks. *Consumer Electronics, IEEE Transactions on, 57*(4), 1541-1549.

Chung, S. T., & Goldsmith, A. J. (2001). Degrees of freedom in adaptive modulation: a unified view. *Communications, IEEE Transactions on, 49*(9), 1561-1571.

Goldsmith, A. J., & Chua, S.-G. (1997). Variable-rate variable-power MQAM for fading channels. *Communications, IEEE Transactions on, 45*(10), 1218-1230.

Goldsmith, A. J., & Chua, S.-G. (1998). Adaptive coded modulation for fading channels. *Communications, IEEE Transactions on, 46*(5), 595-602.

Hanzo, L. L., & Keller, T. (2007). *OFDM and MC-CDMA: a primer*: John Wiley & Sons.

Hassib, M. D., Mandeep, J., Nordin, R., Ismail, M., Abdullah, M., & Islam, M. (2013). *Adaptive modulation for space-time block code OFDM systems based on the dispersion of symbol.* Paper presented at the Space Science and Communication (IconSpace), 2013 IEEE International Conference on.

Jankiraman, M. (2004). *Space-time codes and MIMO systems*: Artech House.

Keller, T., & Hanzo, L. (2000). Adaptive multicarrier modulation: A convenient framework for time-frequency processing in wireless communications. *Proceedings of the IEEE, 88*(5), 611-640.

Kim, J., Lee, K.-J., Sung, C. K., & Lee, I. (2009). A simple SNR representation method for AMC schemes of MIMO systems with ML detector. *Communications, IEEE Transactions on, 57*(10), 2971-2976.

Lee, I., Chan, A. M., & Sundberg, C.-E. (2004). Space-time bit-interleaved coded modulation for OFDM systems. *Signal Processing, IEEE Transactions on, 52*(3), 820-825.

Liew, T.-H., & Hanzo, L. (2006). Space-time trellis and space-time block coding versus adaptive modulation and coding aided OFDM for wideband channels. *Vehicular Technology, IEEE Transactions on, 55*(1), 173-187.

Lin, K. H., Mahmoud, S. S., & Hussain, Z. M. (2005). *Adaptive modulation with space-time block coding for MIMO-OFDM systems.* Paper presented at the Information Technology and Applications, 2005. ICITA 2005. Third International Conference on.

Love, D. J., Heath, R. W., Lau, V. K., Gesbert, D., Rao, B. D., & Andrews, M. (2008). An overview of limited feedback in wireless communication systems. *Selected Areas in Communications, IEEE Journal on, 26*(8), 1341-1365.

Salo, J., Del Galdo, G., Salmi, J., Kyösti, P., Milojevic, M., Laselva, D., & Schneider, C. (2005). MATLAB implementation of the 3GPP spatial channel model (3GPP TR 25.996). *on-line, Jan*.

Sen, S., Santhapuri, N., Choudhury, R. R., & Nelakuditi, S. (2010). *AccuRate: Constellation Based Rate Estimation in Wireless Networks.* Paper presented at the NSDI.

Song, K.-B., & Mujtaba, S. A. (2003). *On the code-diversity performance of bit-interleaved coded OFDM in frequency-selective fading channels.* Paper presented at the Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th.

Torabi, M., & Soleymani, M. R. (2003). *Adaptive bit allocation for space-time block coded OFDM system.* Paper presented at the Acoustics, Speech, and Signal Processing, 2003. Proceedings.(ICASSP'03). 2003 IEEE International Conference on.

Xia, P., Zhou, S., & Giannakis, G. B. (2004). Adaptive MIMO-OFDM based on partial channel state information. *Signal Processing, IEEE Transactions on, 52*(1), 202-213.

Zhang, L., & Heng, W. (2009). Cross-layer adaptive modulation and coding design for space-time block coded MIMO–OFDM systems. *Computer Communications, 32*(3), 540-545.