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Analysis and Performance Measurement of Adaptive Modulation and Coding

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***Abstract*—Wireless spectrum is considered a limited and valuable communications resource as it influences productivity, security and our daily lives. The usage of the wireless spectrum has been given much research focus due to its limited capacity. There is currently a large amount of white spaces and spectrum holes left unused. Therefore, researchers are motivated to invent methods to utilize the spectrum more efficiently and opportunistically. Adaptive modulation and coding (AMC) is a method which adapts its transmitting parameters according to the channel state and it is used in various modern wireless communications to maximize spectrum efficiency and minimize error rate. One of the driving strengths of AMC is the Signal-to-Noise Ratio (SNR) estimation and feedback channel for adaptation. Sudden time-varying channel degrading effects sometimes require the transmission link to react appropriately so it can minimize the Bit Error Rate (BER). Thus, the objective of this paper introduces an AMC scheme which utilizes a simple moments based SNR estimator and punctured convolutional coding for spectral and quality improvement for the wireless channel.**

***Index Terms*—adaptive modulation and coding, AWGN, flat fading, channel estimation**

I. INTRODUCTION

Adaptation and parameter estimation techniques are constantly improved in aspects of wireless communications to achieve cognitive communication systems. Over the past few decades, wireless communications have advanced leaps and bounds as the demand for ubiquitous computing and support for a variety of services are becoming more significant. The new technological age is a platform to realize its fullest potential. Compared to wired communication systems, wireless systems have different challenges that hinder the link performance. The medium that electromagnetic waves are travelling through is random and diverse. Unpredictable effects such as Additive White Gaussian Noise (AWGN) of such cause more than a type of interference. Systems in the traditional sense are designed to handle the worst channel conditions. The transmitted signal quality is meant to ensure the received quality is above par. If the received signal is of good quality which means the channel is quite favorable, the communication link does not exploit this. And if the link quality drops below a threshold, the link is dropped. These systems are rigid, inefficient and it uses the lowest modulation for lower bit error rate with suitable channel coding. Hence, there is still a margin of improvement that can be implemented into such fixed wireless communication systems. Inspired improvement is found in current technologies such as GSM, WLAN and (Code Division Multiple Access) CDMA systems [1].

Wireless spectrum is a limited resource as it directly influences our daily utilization in radio communication. Now that communication standards and services are starting to increase in numbers. It is now a priority to utilize the spectrum efficiently. Traditional systems allocate fixed resources to users, thus creates a situation where a user does not need as much resources as been allocated to. To avoid wastage in spectrum resources, adaptive design methodologies use the spectrum more efficiently and advantageously. Adaptive and artificial intelligence based cell assignment has been proven to achieve better results in [2].

Adaptive Modulation and Coding (AMC) is a method for communication links to gain efficiently in spectrum resources for noisy channels. It was pioneered in the late 1960s by Hayes [3]. Parameters such as modulation scheme, code rate, data rate and power can be modified to take advantage of favorable channel conditions. The adaptive modulation system needs to have an estimator to obtain Channel State Information (CSI), the CSI is then transferred through a reliable feedback channel for the transmitter to react accordingly. Fading channels are usually present in areas with little or heavy obstructions and mainly will be the cause for information outages and erroneous communication. The capacity and characteristics of fading channels is substantially studied upon in [4, 5]. Usually the performance of communications can be improved upon if a suitable transmission scheme can react to the channel variation or state as shown in [6]. Besides thriving in noisy path loss and fading channels, adaptive modulation and coding also maximizes spectral efficiency (SE) when channel conditions are good as shown in WiMAX networks [7], a cross-layer design of Adaptive modulation and coding hybrid Automatic

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ReQuest (ARQ) [8] and also microcellular network in urban areas [9]. Wireless vehicular communications also gain an edge from AMC as shown in [10].

This granularity of this field is extended to performance enhancing details such as the analysis and comparison of fast adaptive or slow adaptive modulation in [11]. The authors showed a different perspective that fast adaptation does not perform well compared to slow adapting modulation systems. Furthermore, the influence of estimator error and delay in the feedback link is researched upon in [12, 13].

The subsequent sections of the paper are organized as follows. Section II provides a description of the system model. Section III introduces the BER performance of M-PSK which leads to the AMC derivation. Section IV covers the adaptive modulation scheme with convolutional coding and in section V contains the SNR estimator parameters. Next, section VI the results of AMC are displayed and discussed. Finally, section VII concludes the paper.

II. SYSTEM MODEL

This section introduces the system model and related representations. In this literature, complex signals are dealt with discrete sampling. Practical limitations for AMC system prior designing requires a feasible feedback path and a channel with slow varying conditions because the feedback must be able to keep up. The system model is illustrated in Fig. 1.

The system is a simple transmitter and receiver architecture with symbol rate of $R_s = 1/T_s$. The model uses the assumption of Nyquist pulses to discount the Intersymbol Interference (ISI) condition, pulses that are sinc(t/T_s), thus signal bandwidth is also $B = 1/T_s$. Next, the channels to be considered are AWGN and flat fading, they are applied to the transmitted signal. The channel also has ergodic and stationary time varying gain $\sqrt{g_x}$ that follows a certain statistical distribution with AWGN denoted by n_x with variance $2\sigma^2$, with power spectral density $N_0/2$ as mentioned in [5]. The signal on the receiving end will be finite number, N of samples:

$$y_x = \sqrt{g_x} s_x + n_x, \ x = 1, 2 \ldots N \tag{1}$$

Where s_x are the complex and discrete source signals from the transmitter and time x. Let the average transmit power be $\bar{S}$ and $\bar{g}$ as the average channel gain. Thus, the instantaneous received SNR is $\gamma_x = \bar{S} g_x / (N_0 B)$ which is the parameter needed for the feedback channel. For adaptive parameters, typically we change the data rate, R_x, transmit power, S_x and coding C_x. For M-ary psk modulation, the data rate is shown by $R_x = \log_2 M_x / T_s$ (bps/s) and the spectral efficiency is denoted as data rate over bandwidth, $R_x / B = \log_2 M_x$ (bps/Hz) The SNR estimate relies on $\hat{g}_x$, the estimated channel gain, which further brings us to estimated SNR, $\hat{\gamma}_x = \bar{S} \hat{g}_x / (N_0 B)$. So, with the CSI information $\hat{\gamma}_x$ we can compute the adaptation power at time x as $S(\hat{\gamma}_x) = S_x$ and received power will be $[S(\hat{\gamma}_x)/\bar{S}] \times \gamma_x$. The parameters of $C(\hat{\gamma}_x) = C_x$ relative and updated to the estimate $\hat{\gamma}_x$, and also data rate of modulation $R(\hat{\gamma}_x) = R_x$. The system model is illustrated in Fig. 2.

III. BER PERFORMANCE OF M-PSK

For a non-adaptive transmission method, the SE is the maximum limit of information bits a channel can allow per second per unit bandwidth. In addition, the Average Spectral Efficiency (ASE) is defined as the expected spectral efficiency over a finite range of adaptation schemes with $p(\gamma)$ as the probability distribution of received SNR among regions i:

$$\frac{R}{B} = \sum_{i=0}^{N-1} k_i \int_{\gamma_i}^{\gamma_i+1} p(\gamma) d\gamma \ \text{bit/s/Hz} \tag{2}$$

In this paper five M-psk modulation modes are selected for the AMC system. The approximated and simulated BER performance of each mode is shown in Fig. 2, both have quite similar characteristics. The maximum capacity of the AWGN channel is given by Shannon's theorem, stating that any wireless communication channel has a maximum rate of information C and a sufficiently advanced code with arbitrarily small error exists that can achieve the capacity.

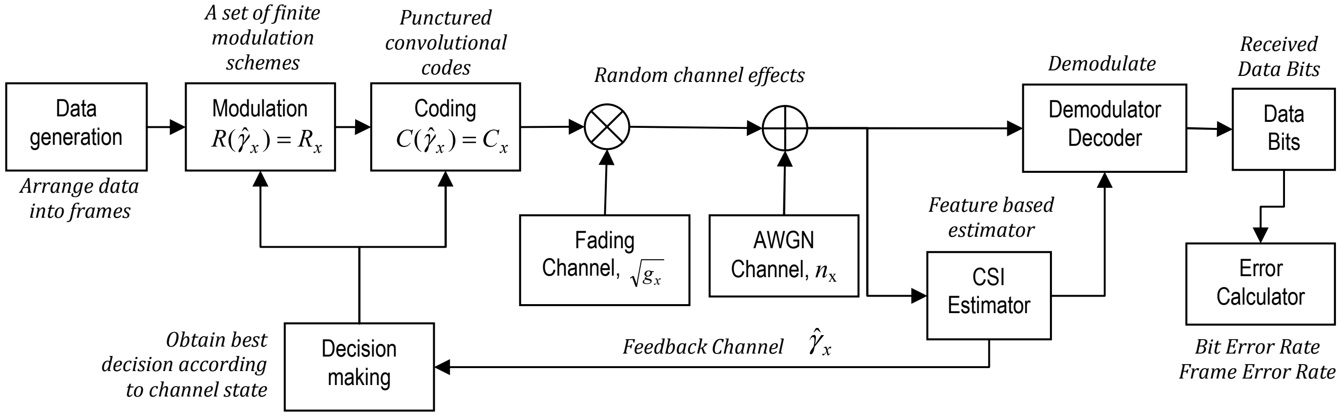

Fig. 1. AMC System model.

The Shannon-Hartley equation [14]:

$$C = B\log_2(1+\gamma)\ \text{, (bit/s/Hz)} \tag{3}$$

For probability of bit error, it is calculated as:

$$P_b = \frac{E[\text{number of error bits per transmission}]}{E[\text{number of bits per transmission}]} \tag{4}$$

The Symbol Error Rate (SER) expression for M-psk in AWGN channel with grey mapping is described in [14]:

$$\text{SER}_{\text{M-psk}}(\gamma) = 2Q(\sqrt{2\gamma}\sin(\frac{\pi}{M})) \tag{5}$$

Referring to Fig. 2 again, from the intersection of the simulation curves with the BER constraint line of value 0.001 we can derive the threshold for the AMC system. Note that $E_b/N_0 > 7.0\,\text{dB}$ gives $P_b < 10^{-3}$ for QPSK, hence the adaptive transmission will use QPSK scheme for $E_b/N_0 > 7.0\,\text{dB}$. Since $E_b/N_0 > 10.5\,\text{dB}$ yields $P_b < 10^{-3}$ for 8-PSK, then the AMC will utilize 8-PSK when $7.0\,\text{dB} \le E_b/N_0 < 10.5\,\text{dB}$. 16-PSK will occupy $10.5\,\text{dB} \le E_b/N_0 < 15.0\,\text{dB}$. For 32-PSK case, $15.0\,\text{dB} \le E_b/N_0$ and $E_b/N_0 < 19.8\,\text{dB}$ right at the intersection of the $BER = 10^{-3}$ line. Finally, the threshold at the last modulation will be used when $E_b/N_0 \ge 24.7\,\text{dB}$. Because of the slightly strict BER boundary imposed, the system will not transmit when E_b/N_0 is below $7.0\,\text{dB}$.

The methods of determining how often the Modulation Coding Schemes (MCS) are used are henceforth described, which will later obtain system ASE. With the thresholds listed in Table I, the ASE is obtained over a range of average SNR values which is affected by the average channel gain, $\bar{g}_x$ and also the average transmit power, $\bar{S}$. Described by, $\bar{\gamma}_x = \bar{S}\bar{g}_x/(N_0B)$. if the average SNR is $\bar{\gamma}_x = 20\,\text{dB}$, with conversion of value to decimal format $\bar{\gamma}_x = 10^{\frac{20}{10}} = 100$ then the spectral efficiency of MCS n = 1(QPSK) has probably transmitted a duration of time equal to:

$$P_{QPSK} = \int_{5}^{11.22} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.0574 \tag{6}$$

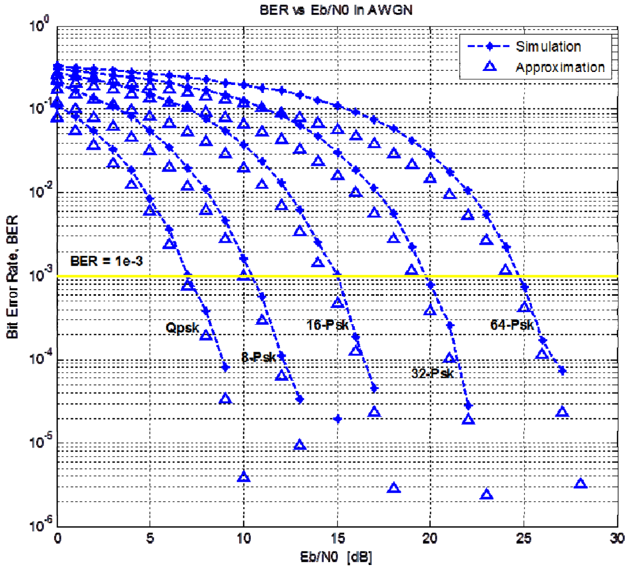

Fig. 2. AMC system model.

TABLE I. ADAPTATIONS OF M-ARY PSK MODULATION SCHEMES

MCS, n	Time duration distribution	With weight of SE
0	$P_0 = \int_{1}^{5} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.0388$	0.0388 x 0 = 0
1	$P_{QPSK} = \int_{5}^{11.22} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.0574$	0.0574 x 2 = 0.1148
2	$P_{8PSK} = \int_{11.2}^{31.6} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.1648$	0.1648 x 3 = 0.4944
3	$P_{16PSK} = \int_{31.6}^{95.5} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.3442$	0.3442 x 4 = 1.3768
4	$P_{32PSK} = \int_{95.5}^{295.1} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.3325$	0.3325 x 5 = 1.6125
5	$P_{64PSK} = \int_{295.1}^{\infty} \frac{1}{100} e^{-\gamma/100} d\gamma = 0.0523$	0.0523 x 6 = 0.3138
	Average Spectral Efficiency @ $\bar{\gamma}_x = 20\,\text{dB}$	3.9123 bps/Hz

Table I illustrates a derivation of average spectral efficiency from all the regions of adaptation with $\bar{\gamma}_x = 20\,\text{dB}$. The contribution for each scheme is the product of probability of time fraction under modulation scheme, P_M and Capacity, C. The sum of all will be the average spectral efficiency of the system under an average SNR value.

IV. PERFORMANCE OF M-ARY PSK WITH CODING ADAPTATION

An adaptive coding method possesses error correcting uniqueness to the transmitted information bits. Sometimes a certain code is particularly effective for a specific channel. The advantage provided by coding is noted as coding gain. Coding gain is measured using unit decibels and is defined as the amount of reducible SNR under that coding technique.

In Fig. 3, there shows a comparison of BER curves between coded and uncoded schemes. The curves with markers (with coding) trail off in the end without a continuous line means zero error at that SNR condition. The coding gain in Fig. 3 is labeled C_g for given P_b = 10^{-4} is approximately 2.5 dB. Some codes can also exhibit negative coding gain at lower SNR cases. This can be proven in Fig. 3's 64-PSK uncoded curve vs coded curve. At SNR > 26 dB, it performs without any errors. However, lower than that, it does not perform well at all. In short,

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TABLE II. ADAPTATIONS OF M-ARY PSK MODULATION SCHEMES

MCS, n	Specifications			
	Modulation	*Code Rate, R_c*	*SE, Bit/s/Hz*	*Threshold*
0	*hold*	-	0	$E_b/N_0 < 7.0\text{dB}$
1	QPSK	-	2	$7.0\,\text{dB} \le E_b/N_0 < 10.5\,\text{dB}.$
2	8-PSK	-	3	$10.5\,\text{dB} \le E_b/N_0 < 15.0\,\text{dB}$
3	16-PSK	-	4	$15.0\text{dB} \le E_b/N_0 < 19.8\text{dB}$
4	32-PSK	-	5	$19.8\text{dB} \le E_b/N_0 < 24.7\,\text{dB}$
5	64-PSK	-	6	$24.7\text{dB} \le E_b/N_0 < \infty$

*Result simulated under AWGN channel

various things such as random channel fluctuations can affect coding performance. Finally, error correcting coding methods comes with payoff. The increased complexity and extra overhead can affect the overall communication link.

There are two main categories of coding: Linear block codes and convolutional codes. The former are basically simple codes that extend a single bit parity bit for a block. The former type generates coded symbols through a linear finite-state shift register. This paper introduces punctured convolutional coding to the AMC system. A mixture of ½, ⅔ ¾, ⅘ and ⅚ code rates are used in the system. The performance gain by the codes can be seen in Fig. 3. This results in another new set of threshold regions as what was mentioned in section III.

From Fig. 3, again the regions are segmented according to the BER constraint, $P_b < 10^{-3}$. First obvious thing noticeable is the cutoff SNR is lower compared to non-coded modulations, $4.7\text{dB} > E_b/N_0$. Since $E_b/N_0 > 10.0\,\text{dB}$ yields $P_b < 10^{-3}$ for QPSK, then the AMC will utilize 8-PSK when $10.0\text{dB} \le E_b/N_0 < 15.7\text{dB}$ whereas 16-PSK will occupy $10.0\text{dB} \le E_b/N_0 < 15.7\text{dB}$. For 32-PSK case, $15.7\,\text{dB} \le E_b/N_0$ and $E_b/N_0 < 21.0\ \text{dB}$ right at the intersection of the $\text{BER} = 10^{-3}$ line. Finally, the threshold at the last modulation will be used when $E_b/N_0 \ge 26.4\,\text{dB}$. The following data in Table III contain details for the AMC parameters.

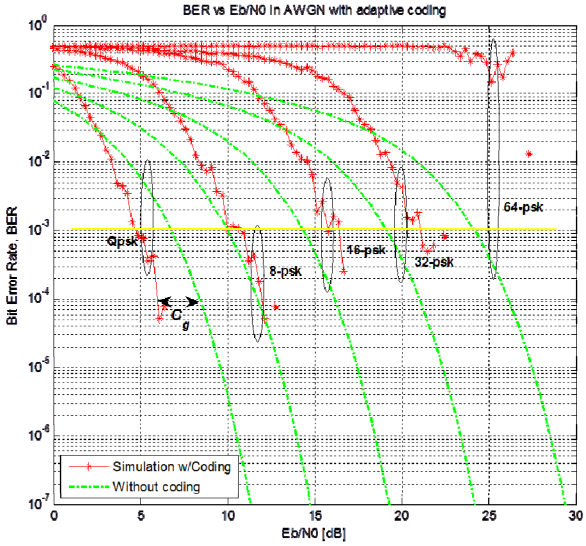

Fig. 3. Coding performance for different coding and modulation schemes.

TABLE III. ADAPTATION REGIONS FOR ADAPTIVE MODULATION WITH CODING.

MCS, n	Specifications			
	Modulation	*Code Rate, R_c*	*SE Bit/s/ Hz*	*Threshold*
0	*hold*	-	0	$E_b/N_0 < 4.7\text{dB}$
1	QPSK	1/2	1	$4.7\,\text{dB} \le E_b/N_0 < 10.0\,\text{dB}$
2	8-PSK	2/3	2	$10.0\text{dB} \le E_b/N_0 < 15.7\text{dB}$
3	16-PSK	3/4	3	$15.7\,\text{dB} \le E_b/N_0 < 21.0\,\text{dB}$
4	32-PSK	4/5	4	$21.0\,\text{dB} \le E_b/N_0 < 26.4\,\text{dB}$
5	64-PSK	5/6	5	$26.4\ \text{dB} \le E_b/N_0$

Next, the new adaptive transmission scheme with and without coding has Average spectral efficiencies as shown in Fig. 4. The spectral efficiency of the coded scheme is less efficient than that of non-coded because of the additional puncture codes that are present. These may cause a sacrifice in information data capacity, but its forward error correction mechanism can reduce error rates.

V. CHANNEL ESTIMATION

In wireless communication system, the channel estimate such as the SNR can provide invaluable information for consequent communication processes. It can pair with adaptive modulation and coding schemes to overcome the uncertainties in time-varying conditions. Other applications of SNR information include: information in tactical applications, jamming analysis, and electronic surveillance system [15].

This section introduces an envelope moments based NDA estimator from [16] that will be used with AMC. This estimator applies to constant modulus (CM) modulations and non-constant modulus cases.

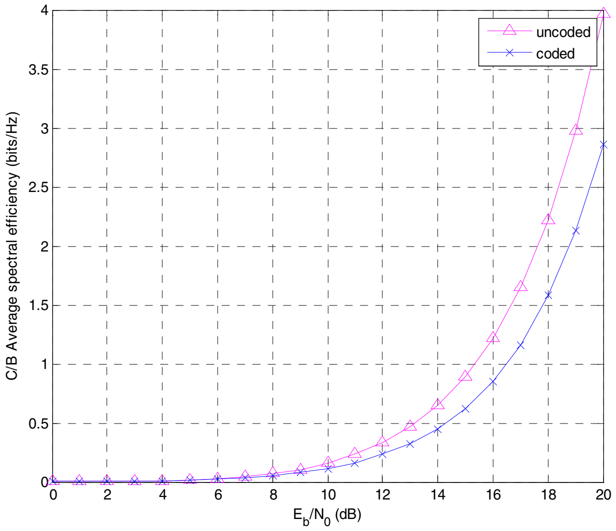

Fig. 4. Spectral efficiency of coded versus non-coded adaptive transmission.

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In this paper, only CM modulation schemes are considered. More specifically, the estimator uses only the Second- and Fourth-Order Moments (M_2M_4) to estimate the channel SNR. This algorithm deals with complex form signals. The simple estimation algorithm is as follows.

The received symbols are from a constellation set which is known to the receiver and has I different amplitudes, having i^{th} amplitude A_i and probability P_i ($I = 1, ..., I$). The constellation p^{th} moment is denoted by

$$M_p = E\{|x_k|^p\} = \sum_{i=1}^{I} P_i A_i^p \tag{7}$$

Let second moment M_2 be written as:

$$\begin{aligned} M_2 &= E\{y_x y_x^*\} = E\{\left|y_x\right|^2\} \\ &= E\{y_{Ix}^2 + y_{Qx}^2\} \\ &= 2a^2 + 2\sigma^2 = P + N \end{aligned} \tag{8}$$

And M_4 is the fourth moment of the received signal, denoted as,

$$\begin{aligned} M_2 &= E\{(y_x y_x^*)^2\} = E\{\left|y_x\right|4\} \\ &= E\{(y_{Ix}^2 + y_{Qx}^2)^2\} \\ &= 4a^2 + 16a^2\sigma^2 + 8\sigma^2 \\ &= P + 4PN + 2N^2 \end{aligned} \tag{9}$$

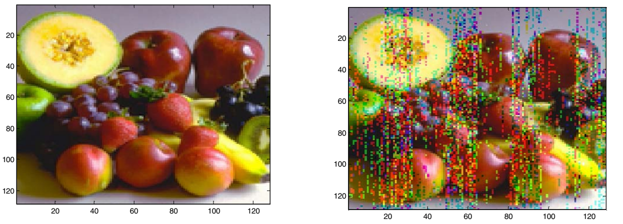
y_x is the complex received signal, and a and σ is amplitude and standard deviation. P is the received power, $2a^2$ and N is noise in the received signal equals to $2\sigma^2$. To find out P and N,

$$\begin{aligned} \hat{P} &= \sqrt{2M_2^2 - M_4} \\ \hat{N} &= M_2 - \sqrt{2M_2^2 - M_4} \end{aligned} \tag{10}$$

Therefore,

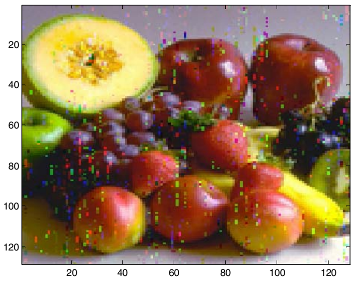
$$\text{SNR, } \hat{\rho} = \frac{\hat{P}}{\hat{N}} = \frac{\sqrt{2M_2^2 - M_4}}{M_2 - \sqrt{2M_2^2 - M_4}} \tag{11}$$

The performance of M_2M_4 is satisfactory, with the worst Mean Square Error (MSE) value of approximately 0.035 and increasing estimation accuracy with increasing SNR for all M-PSK modulation. This proves it to be a suitable and well performing multi-level PSK estimator. The normalised MSE is shown in Fig. 5.



(a)
Image transmitted over a fixed favorable AWGN, SNR = 10 dB (same as original).

(b)
Image transmitted over a range of random SNR values.



(c) Image received using AMC technique.

Fig. 5. Comparison of both received images over different channel scenarios.

VI. RESULTS AND DISCUSSIONS

The performance of the AMC transmission system is tested with different conditions and then the results are analyzed. In the simulations, a 120 x 120 bitmap image is sent over the channel. The received copy of the image is compared to the original one. As displayed in Fig. 6, there is noticeable difference between the images transferred over with AWGN channel 10 dB. However, for a situation where there is presence of random noise from flat fading (b) there will be distortions in the image information.

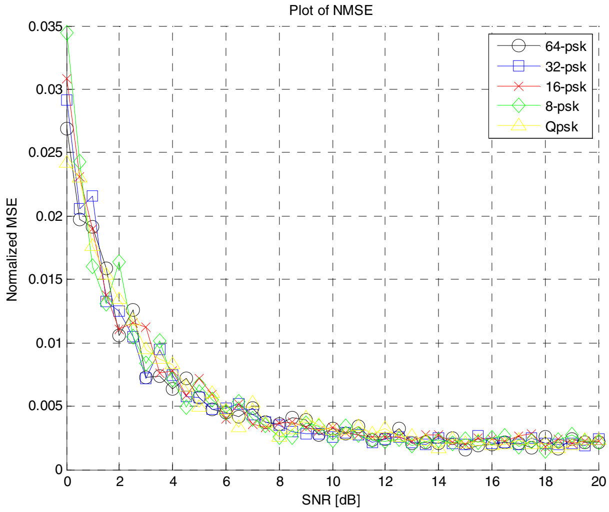


Fig. 6. Normalized MSE of the estimator for all five M-PSK modulation schemes.

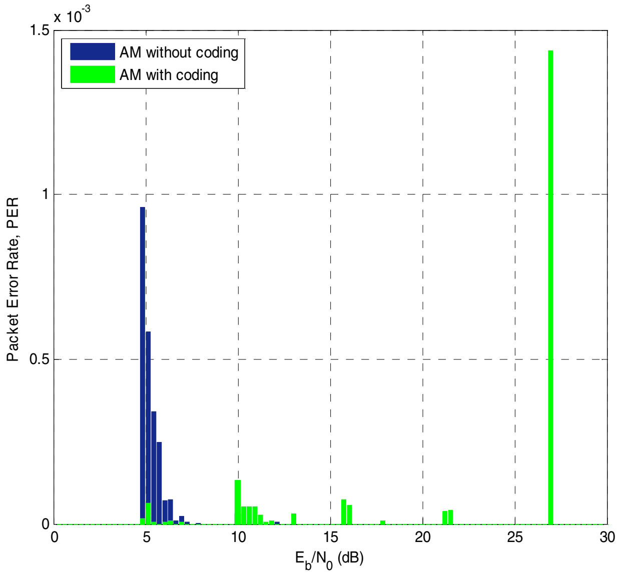


Fig. 7. Packet error rate for both types of adaptive transmission over range of SNR.

The packet error rate (PER) of both coded and non-coded AMC is illustrated in Fig. 7. At different regions the characteristics of the AMC scheme shows a spike in PER value. This maximum PER is relatively small, so overall the system performs well in packet transmissions. A change in the region thresholds can yield different results.

VII. CONCLUSION

In this paper, two models of AMC over AWGN channel are presented. Both models are analyzed and discussed in terms of overall BER and spectral efficiency. The extra advantage offered by coding will give a robust transmission system if designed properly. The gains over fading channels are proven using image transmission. For future work, more wireless channel models will be tested on different configurations of variable rate and coding AMC. Furthermore, predictive channel estimation can be incorporated as a feasible solution to the delay impact on AMC systems.

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