

# MGF Based Performance Analysis of Digital Wireless System in Urban Shadowing Environment

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**Abstract**—In this paper, a composite Rayleigh-Gamma distribution is proposed for the urban wireless channel environment which represents small-scale fading with no Line of sight (LoS) and shadowing. Moment Generation Function (MGF) and truncated MGF for the proposed model are derived. Using these MGFs, the performance of digital communication systems is investigated in terms of channel capacity and bit error rate probability. Results show that the performance is adversely affected by the urban channel environment. Thus, an adaptive  $M$ -QAM technique is proposed to enhance the system performance. With the aid of truncated MGF, the performance of adaptive  $M$ -QAM system is evaluated in terms of outage probability, system capacity (bit/s/Hz) and average bit error probability. The proposed adaptive technique shows high potential for achieving significant system capacity while maintaining acceptable bit error probability even under severe channel effects.

**Index Terms**—Urban channel, channel capacity, adaptive modulation, outage probability, bit error rate.

## I. INTRODUCTION

WIRELESS channel in an urban environment introduces serious impairments such as small and large scale fading which cause serious degradation in the signal to noise ratio (SNR) leading to poor system performance. Small-scale fading is mainly caused by multi-path fading due to reflection and diffraction [1]. The large-scale fading consists of two portions: path loss and shadowing. Path loss measures the average radio wave energy decay as a function of distance, frequency, and other location specific parameters. Shadowing is caused by the variability associated with large scale environmental obstacles. In [2], an urban wireless channel model based on path loss measurements for Cambridge, Massachusetts city is proposed. In [3], physical statistical characteristics of urban canyons are incorporated to estimate parameters of satellite urban channel model. Validation of large-scale fading channel for urban wireless channel has been carried out in [4]. Since urban wireless channel environment simultaneously subjects small scale and large scale fading, it is required to describe these effects using a composite model. Composite Rayleigh-Gamma (RG) distribution is considered in this paper in which the signal envelope is conditionally Rayleigh distributed and the signal power is modelled by Gamma distribution [5],[6]. Some works for evaluating the performance of communication system in shadowing multipath channel are available. Outage probability and channel capacity were investigated by using Nakagami-Inverse Gaussian channel model in [7]. Trigui et. al. have presented an analytical framework for performance evaluation of mobile radio systems operating in composite

fading/shadowing channels in the presence of co-channel interference in [8]. The MGF approach is proposed for the computation of the channel capacity only and outage probability by using numerical techniques [9]. A novel MGF based approach is developed for evaluation of channel capacity for various rate adaptations and transmit power in [10]. Several techniques have been proposed to enhance the performance of digital communication systems operating over fading channels. One of these techniques is adaptive modulation which can be effectively used to achieve significant capacity improvement over wireless channels subjected to fading and shadowing [11] [12].

In this work, performance of shadowing multipath with no LoS wireless channel is analyzed by using MGF based approach. Employing and analyzing adaptive modulation technique over shadowing urban wireless channel has not been addressed. In particular, a statistical distribution model approach including MGF is used to examine the performance of adaptive  $M$ -QAM modulation over RG channel.

The work is organized as follows: In Section II, shadowing multipath urban wireless channel model is presented; moreover, statistical characteristics of RG distribution are derived including MGF and truncated MGF. Section III addresses the channel capacity and bit error rate performance analysis for RG wireless channel using MGF based approach. In Section IV, an adaptive  $M$ -QAM technique is proposed for RG channel, using truncated MGF, to improve the performance. Finally, the work is concluded in Section V.

## II. URBAN SHADOWING CHANNEL ENVIRONMENT MODEL

Modeling urban wireless channel environment is essential when designing a digital communication system, particularly in congested areas such as city's downtown. Urban wireless channel introduces small-scale and large-scale fading which degrade performance of the system. Let the equivalent base-band received signal be:

$$r = X s + n \quad (1)$$

where  $s$  is the transmitted symbol, which can take values from different modulation constellation, e.g.,  $M$ -quadrature amplitude modulation (QAM),  $X$  is a random variable that describes the urban channel effect, and  $n$  is AWGN. For urban channel, it is fair to assume that there is no LoS signal path to the receiver. Thus, the small scale fading, which represents the fast fluctuations of the received signal envelope, can be modeled by Rayleigh distribution [1]. The large scale fading, which refers to the scattering of the transmitted signal by the large buildings and path loss, causes variations in the mean received power. These variations can be modeled using Gamma distribution [5]. Thus, to

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statistically model the shadowing multi-path urban wireless channel, composite Rayleigh-Gamma (RG) distribution is proposed that accounts for small and large fading effects. The composite model can be obtained by averaging the gamma PDF of SNR over the conditional Rayleigh PDF of average SNR. Hence, Rayleigh-Gamma distribution is given by [6]:

$$p_\gamma(\gamma) = \frac{2 \left(\frac{c}{\bar{\gamma}}\right)^{\frac{c+1}{2}}}{\Gamma(c)} \gamma^{\frac{c-1}{2}} K_{c-1} \left( \sqrt{4\frac{c\gamma}{\bar{\gamma}}} \right), \quad \gamma \geq 0 \quad (2)$$

Where  $K_{c-1}(\cdot)$  is the modified second order Bessel function,  $\gamma = \alpha^2 E_s/N_o$  is the SNR,  $\bar{\gamma} = \Omega c E_s/N_o$  is the average SNR,  $E_s = E[s^2]$  is the signal energy,  $\Omega = E[X^2]/c$  and  $N_o$  represents AWGN power spectral density. RG distribution is controlled by large scale fading parameter  $c$ . As  $c$  increases the shadowing becomes less severe and the channel approaches Rayleigh channel. The cumulative distribution function (CDF) of shadowing urban wireless channel is obtained using  $P(\gamma_1) = \int_0^{\gamma_1} p_\gamma(\gamma) d\gamma$  and is given by:

$$P(\gamma_1) = 1 - \frac{2}{\Gamma(c)} \left( \sqrt{\frac{c\gamma_1}{\bar{\gamma}}} \right)^c K_c \left( \sqrt{\frac{4c\gamma_1}{\bar{\gamma}}} \right), \quad \gamma_1 \geq 0 \quad (3)$$

The moment generation function (MGF) of the channel model in (2) can be derived by using the definition [1]:

$$M_\gamma(s) \triangleq \overline{e^{-s\gamma}} = \int_0^\infty \exp(-s\gamma) p_\gamma(\gamma) d\gamma \quad (4)$$

MGF is obtained By substituting the PDF of the channel distribution (2) into (4) and expressing the exponential term in (4) using Meijer G function as  $\exp(-s\gamma) = G_{0,1}^{1,0}(s\bar{\gamma} | 0)$ , and  $K_{c-1} \left( \sqrt{\frac{4\gamma}{\bar{\gamma}}} \right) = \frac{1}{2} G_{0,2}^{2,0} \left( \frac{\bar{\gamma}}{\gamma} \mid \frac{c-1}{2}, \frac{1-c}{2} \right)$  using [14, eq. (8.4.3/1),(8.4.23/1)]. The closed form MGF of  $\gamma$  is derived with the aid of [15, eq.(07.34.21.0011.01)] and can be expressed as:

$$M_\gamma(s) = \frac{1}{\Gamma(c)} G_{2,1}^{1,2} \left( \frac{s\bar{\gamma}}{c} \mid 1-c, 0 \right) \quad (5)$$

Several numerical techniques have been used to evaluate the truncated MGF [8] [9]; however, truncated MGF of shadowing urban fading channel distribution can be obtained in closed form. Truncated MGF is given by [10]:

$$\widehat{M}_\gamma(s, \gamma_k) \triangleq \int_0^{\gamma_k} \exp(-s\gamma) p(\gamma) d\gamma \quad (6)$$

The truncated MGF can be derived by expanding the exponential term using Taylor series and then performing integration. Thus,

$$\widehat{M}_\gamma(s, \gamma_k) = \int_0^{\gamma_k} \gamma^{\frac{c-1}{2}} \sum_{m=0}^{\infty} \frac{(-s\gamma)^m}{m!} K_{c-1} \left[ \sqrt{\frac{4c\gamma}{\bar{\gamma}}} \right] d\gamma \quad (7)$$

By expressing  $K_{c-1}(\cdot)$  using Meijer G-function and with the aid [15, eq.(03.04.21.0021.01)] , the truncated MGF in

closed form becomes:

$$\begin{aligned} \widehat{M}_\gamma(s, \gamma_k) &= \frac{\left(\frac{c\gamma_k}{\bar{\gamma}}\right)^{\frac{c+1}{2}}}{\Gamma(c)} \sum_{m=0}^{\infty} \frac{(-s\gamma_k)^m}{m!} \pi \csc \left( 2\pi \left( \frac{1-c}{2} \right) \right) \\ &\times \left\{ \Gamma(c+m) \left(\frac{c\gamma_k}{\bar{\gamma}}\right)^{\frac{c-1}{2}} {}_1F_2 \left( c+m, c; c+m+1; \frac{c\gamma_k}{\bar{\gamma}} \right) - \right. \\ &\left. \Gamma(m+1) \left(\frac{c\gamma_k}{\bar{\gamma}}\right)^{-\frac{c-1}{2}} {}_1F_2 \left( m+1, -c; m+2; \frac{c\gamma_k}{\bar{\gamma}} \right) \right\} \quad (8) \end{aligned}$$

where  ${}_1F_2(\cdot, \cdot, \cdot)$  is the generalized hypergeometric function [13]. Because the value of  ${}_1F_2$  decreases rapidly as  $m$  increases, it is sufficient to consider finite number of terms in the summation. The  $n^{th}$  order moment of  $\gamma$  is defined as  $m_n \triangleq E\langle \gamma^n \rangle$  and can be obtained using  $m_n = \int_0^\infty \gamma^n p_\gamma(\gamma) d\gamma$ .

By using (2), the  $n^{th}$  order moment becomes:

$$m_n = \frac{\bar{\gamma}^{-\frac{c+1}{2}}}{\Gamma(c)} \int_0^\infty \gamma^{\frac{c-1}{2}+n} G_{0,2}^{2,0} \left( \frac{\gamma}{c\bar{\gamma}} \mid \frac{c-1}{2}, \frac{1-c}{2} \right) d\gamma \quad (9)$$

The integral (6) can be solved using [14, eq.(2.24.1/1)]; thus  $m_n$  can be written as:

$$m_n = \left( \frac{\bar{\gamma}}{c} \right)^n \frac{\Gamma(c+n/2)\Gamma(1+n/2)}{\Gamma(c)} \quad (10)$$

The fading and shadowing effects can also be described by the amount of fading (AF), where  $AF = \frac{E(\gamma^2) - (E[\gamma])^2}{(E[\gamma])^2}$  [1]. Thus, AF can be obtained from the  $n^{th}$  order moment of  $\gamma$  as  $AF = 1 + \frac{2}{c}$ . From this formula, it can be shown that as  $c \rightarrow \infty$  there is no shadowing effect and RG approaches Rayleigh distribution.

### III. MGF BASED APPROACH PERFORMANCE ANALYSIS

The performance over shadowing urban fading channel can be evaluated in terms of channel capacity and bit error rate probability using MGF based approach for  $M$ -QAM modulation technique .

#### A. Channel Capacity

Channel capacity is investigated accordingly as the channel side information (CSI) that is available at either the transmitter or at the receiver. Two cases of CSI availability are considered in this paper. First, when the CSI is available at the receiver under a constant optimal power rate adaptation to channel fading. Second, when the transmitter adapts its power to keep the received SNR constant. For the first case, the channel capacity in bits/s/Hz can be obtained using [10]:

$$C_{ora} = \frac{1}{\log 2} \int_0^\infty E_i(-s) M_\gamma^{(1)}(s) ds \quad (11)$$

where  $E_i(\cdot)$  denotes the exponential integral function. The quantity  $M_\gamma^{(1)}(s)$  is the first derivative of the MGF and can be derived using [15, eq.(07.34.20.0001.01)]. For the shadowing urban channel, the first derivative of MGF is obtained as:

$$M_\gamma^{(1)}(s) = \frac{s}{\Gamma(c+1)} G_{3,2}^{1,3} \left( \frac{s\bar{\gamma}}{c} \mid -1, -c, -1 \right) \quad (12)$$

By expressing  $E_i(-s) = -G_{1,2}^{2,0} \left( s \mid \begin{matrix} 1 \\ 0,0 \end{matrix} \right)$  [14, eq.(8.4.11/1)] in (11), a closed form expression for channel capacity can be obtained as [15, eq.(07.34.21.0011.01)]:

$$C_{ora} = \frac{1}{\log 2\Gamma(c)} G_{4,2}^{1,4} \left( \frac{\bar{\gamma}}{c} \mid \begin{matrix} 1, 1, 1-c, 0 \\ 1, 0 \end{matrix} \right) \quad (13)$$

The optimal power rate adaptation channel capacity,  $C_{ora}$  in bit/s/Hz for shadowing urban channel is plotted as a function of SNR for several values of  $c$  in Fig. 1. As expected,  $C_{ora}$  is always less than the capacity provided by Rayleigh and AWGN channels, and it improves as  $c$  increases.

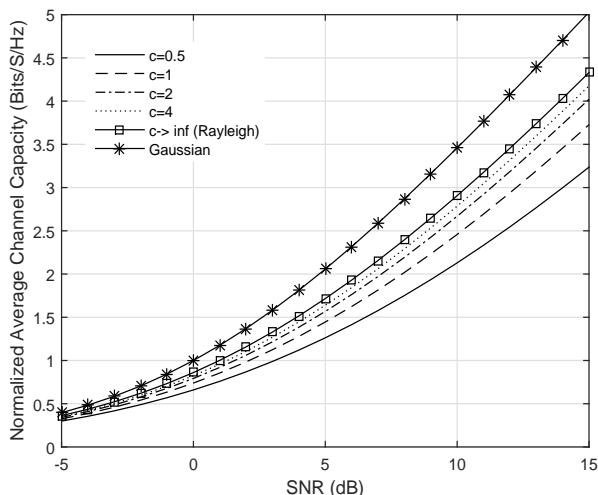


Fig. 1: Channel capacity with side information at the receiver as a function of SNR for different values of  $c$

For the second case, the fading channel is inverted; hence the capacity becomes channel capacity with channel inversion ( $C_{cifr}$ ). In this case,  $C_{cifr}$  can be obtained using [10] and is given by:

$$C_{cifr} = \log_2 \left( 1 + \frac{1}{\int_0^\infty M_\gamma(s) ds} \right) \quad (14)$$

The quantity  $C_{cifr}$  is derived by substituting MGF from (5) in (14) and evaluating the integral using [15, eq.(07.34.21.0009.01)]. The channel capacity is thus given by:

$$C_{cifr} = \log_2 \left( 1 + \frac{\Gamma(c)\bar{\gamma}}{c\Gamma(c-1)} \right) \quad (15)$$

The channel capacity  $C_{cifr}$ , for shadowing urban channel is plotted as a function of SNR for different values of channel parameter  $c$  in Fig. 2. It is noted that the capacity is impacted by channel impairments for small values of  $c$ .

### B. Bit Error Rate Performance

Bit error rate probability of digital communication system in a shadowing urban environment is investigated by using MGF approach. The analysis presented is valid for any arbitrary modulation technique; however, the investigation is presented for  $M$ -QAM modulation technique as an example. The BER of  $M$ -QAM for AWGN channel can be tightly

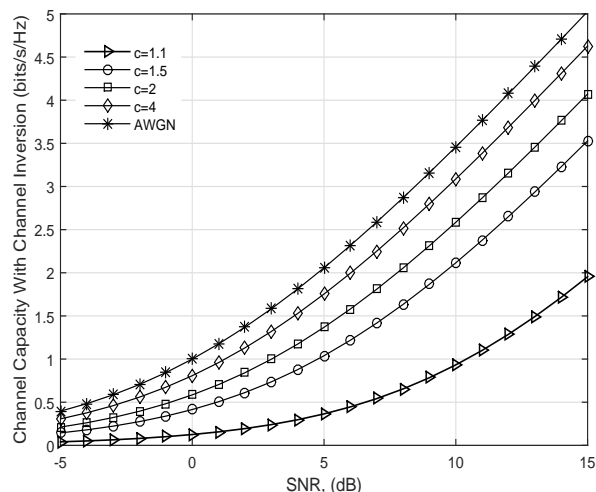


Fig. 2: Channel capacity With channel Inversion as a function of SNR for different values of  $c$

bounded using the approximation given in [11] and thus the average BER using MGF approach can be shown to be given by:

$$p_e(\gamma, M) \leq 0.2 \exp \left( -\frac{1.5\gamma}{M-1} \right), \quad \gamma \geq 0, \quad M \geq 4 \quad (16)$$

The average bit error probability ( $\bar{p}_e$ ) for a given modulation over a fading channel can be determined by averaging the error probability for a given  $\gamma$  over the Probability Density Function (PDF) of  $\gamma$  as:

$$\bar{p}_e = \int_0^\infty p_e(\gamma, M) p_\gamma(\gamma) d\gamma \quad (17)$$

The performance of  $M$ -QAM system operating in shadowing urban fading channel can be obtained by substituting (16) in (17) which yields:

$$\bar{p}_e = 0.2 \int_0^\infty \exp \left( -\frac{1.5}{M-1} \gamma \right) p_\gamma(\gamma) d\gamma \quad (18)$$

Using the MGF approach and comparing (18) with (4),  $\bar{p}_e$  can be easily derived and expressed as:

$$\begin{aligned} \bar{p}_e &= 0.2 M_\gamma(s) \Big|_{s=\frac{1.5}{M-1}} \\ &= \frac{0.2}{\Gamma(c)} G_{2,1}^{1,2} \left( \frac{1.5 \bar{\gamma}}{c(M-1)} \mid \begin{matrix} (1-c), 0 \\ 0 \end{matrix} \right) \end{aligned} \quad (19)$$

As an illustration example,  $\bar{p}_e$  of 16-QAM system for shadowing urban channel is plotted as a function of SNR and channel parameter in Fig.3. The performances of AWGN and Rayleigh channel are also plotted for comparison. It is observed that as  $c$  increases the performance is improved and for a large values of  $c$ , the  $\bar{p}_e$  approaches the performance of Rayleigh channel.

### IV. PERFORMANCE IMPROVEMENT USING ADAPTIVE $M$ -QAM TECHNIQUE

As shown in Figs. 1, 2 and 3, the performance of digital communication system is very sensitive to the channel

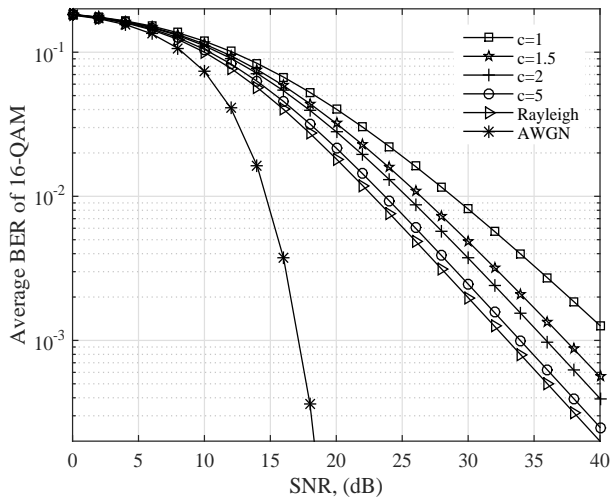


Fig. 3: Average BER of 16-QAM system as a function of SNR for different shadowing factor  $c$

impairments. Thus, maintaining an acceptable system performance is an essential objective for any digital communication system. Thus, in this paper, an adaptive  $M$ -QAM modulation technique for shadowing fading channel is proposed to improve the channel capacity while maintaining certain level of bit error rate performance.

#### A. Adaptive $M$ -QAM System Model

The basic concept of adaptive modulation technique is based on the fact that the modulator and demodulator are configured simultaneously with the same constellation size,  $M$ , and according to SNR  $\gamma$  estimation that is required to achieve targeted BER as shown in Fig. 4. Therefore, mapping  $\gamma$  to the modulation level is the fundamental point to switch constellation size,  $M$ ; thus, the range of  $\gamma$  is divided into  $N$  regions in order to decide which  $M$ -QAM is used when the estimated  $\gamma$  falls in the  $n^{th}$  region. Each region is specified with boundaries,  $\gamma_n, \gamma_{n+1}$ , which are determined to obtain the target BER ( $10^{-3}$ ) and are indicated in Table I. It is assumed that when  $\gamma$  is estimated below  $\gamma_1$ , the transmission is suspended.

TABLE I:  $\gamma_n$  BOUNDARIES

Mode $n$	$M$	$\gamma_n - \gamma_{n+1}$ [dB]
1	4	10.2-13.9
2	8	13.9-17.2
3	16	17.2-20.4
4	32	20.4-23.5
5	64	23.5 - $\infty$

#### B. Performance Analysis of Adaptive $M$ -QAM technique

In this section, the performance of adaptive  $M$ -QAM modulation over shadowing multi-path urban channel that is modeled by (2), is evaluated in terms of outage probability  $P_o$ , average system capacity  $\bar{C}$ , and average bit error rate probability,  $\bar{p}$ .

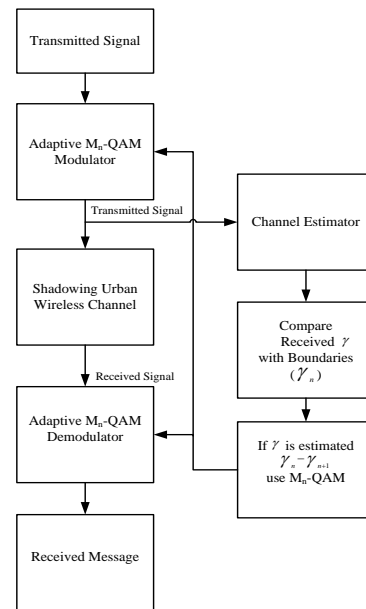


Fig. 4: Block diagram of  $M$ -QAM adaptive modulation technique

1) *Outage probability*: Since the transmission is suspended when the received  $\gamma$  falls below  $\gamma_1$ , the  $M$ -QAM adaptive modulation suffers an outage probability, which can be obtained using  $P_o = \int_0^{\gamma_1} p_\gamma(\gamma) d\gamma$ . Thus,  $P_o$  can be obtained directly from (3) where  $\gamma_1 = 10.2$  dB is calculated using (16) for  $p_e = 10^{-3}$ .  $P_o$  is plotted in Fig. 5 as a function of SNR for several values of channel parameter. It is noted that the outage probability  $P_o$  improves as  $c$  increases, which implies that the shadowing effects become less severe.

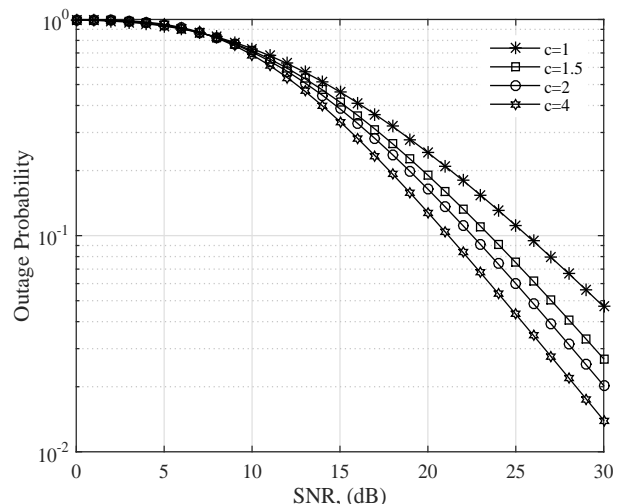


Fig. 5: Outage probability as a function of SNR for different values of  $c$

2) *Average System Capacity (bits/s/Hz)*: Average system capacity  $\bar{C}$  is the sum of data rates ( $\log_2 M$ ) corresponding to  $N$  regions each weighted by the probability that  $\gamma$  falls in the  $n^{th}$  region,  $P_r(n)$  and is given by [11] :

$$\bar{C} = \sum_{n=1}^N (\log_2 M_n) P_r(n) \quad (20)$$

where  $P_r(n) = \int_{\gamma_n}^{\gamma_{n+1}} p_\gamma(\gamma) d\gamma$  and can be directly calculated from (3) as:

$$P_r(n) = \frac{2}{\Gamma(c)} \left\{ \left( \sqrt{\frac{c\gamma_{n+1}}{\bar{\gamma}}} \right)^c K_c \left( \sqrt{\frac{4c\gamma_{n+1}}{\bar{\gamma}}} \right) - \left( \sqrt{\frac{c\gamma_n}{\bar{\gamma}}} \right)^c K_c \left( \sqrt{\frac{4c\gamma_n}{\bar{\gamma}}} \right) \right\} \quad (21)$$

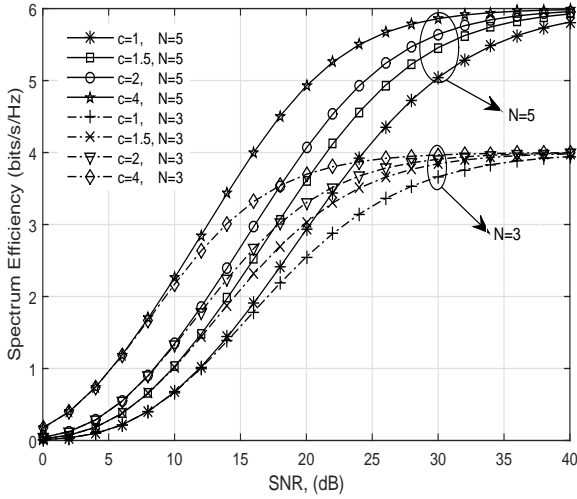


Fig. 6: Average capacity of adaptive modulation technique versus SNR for different values of  $c$

Fig. 6 shows the average capacity ( $bits/s/Hz$ ) of adaptive  $M$ -QAM for three ( $N = 3$ ) and five ( $N = 5$ ) regions as a function of SNR for various channel parameters  $c$ . It is observed that the overall system capacity is improved as the adaptive system utilizes high constellation size. Also, the adaptive modulation shows a good adaptation with channel conditions.

### C. Average Bit Error Rate

The proposed adaptive modulation technique is designed based on disjoint SNR regions for targeted BER. Thus, average BER ( $\bar{p}$ ) is calculated by averaging the BER for all SNR regions. This can be computed exactly as the ratio of the average number of bits in error over the total average number of transmitted bits and is given by [11]:

$$\bar{p} = \frac{1}{C} \sum_{n=1}^N (\log_2 M) \bar{p}_n \quad (22)$$

Where  $\bar{p}_n$  is average AWGN bit error rate for  $n^{th}$  region and can be obtained using:

$$\bar{p}_n = \int_{\gamma_n}^{\gamma_{n+1}} p_e(\gamma, M) p_\gamma(\gamma) d\gamma \quad (23)$$

By substituting (16) into (23),  $\bar{p}_n$  can be written as:

$$\bar{p}_n = 0.2 \int_0^{\gamma_{n+1}} \exp\left(-\frac{1.5\gamma}{M-1}\right) p_\gamma(\gamma) d\gamma - 0.2 \int_0^{\gamma_n} \exp\left(-\frac{1.5\gamma}{M-1}\right) p_\gamma(\gamma) d\gamma \quad (24)$$

By comparing (24) with (6) which is the definition of truncated MGF,  $\bar{p}_n$  can be obtained directly as:

$$\bar{p}_n = 0.2 \widehat{M}_\gamma(s, \gamma_{n+1})|_{s=\frac{1.5}{M-1}} - 0.2 \widehat{M}_\gamma(s, \gamma_n)|_{s=\frac{1.5}{M-1}} \quad (25)$$

Average bit error rate of the proposed adaptive  $M$ -QAM for  $n$  regions is derived by using truncated MGF. Fig. 7 shows  $\bar{p}_n$  for ( $N = 3$ ) and ( $N = 5$ ) as a function of SNR and for different values of  $c$ . It is clear that the adaptive modulation technique maintains the target BER ( $10^{-3}$ ) for all values of  $c$ . Also, for high values of SNR, the performance is dominated by the highly utilized  $M$ -QAM modulation level.

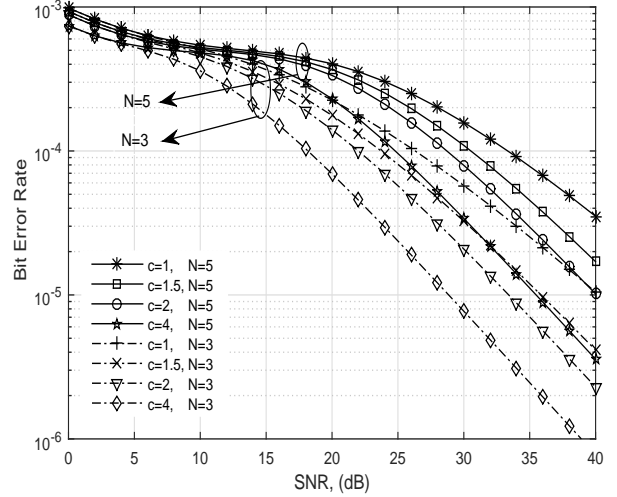


Fig. 7: Average bit error rate of adaptive modulation technique as function of  $\bar{\gamma}$  for different values of  $c$

## V. CONCLUSION

The performance of  $M$ -QAM digital modulation has been evaluated over multi-path superimposed on shadowing urban channel environment in terms of two important system parameters: average BER and channel capacity. For the channel capacity analysis, two different CSI availability cases were assumed, one is when the CSI is available at the receiver under a constant power rate adaptation and another is when the transmitter adapts its power to keep the received SNR constant. It is observed that the capacity decreases due to the shadowing effect and is slightly better in the second case. To cope with the deterioration in the BER performance and channel capacity due to shadowing effect, an adaptive modulation technique based on target BER has been suggested and explained. The performance of the proposed technique has been analyzed in terms of outage probability, average system capacity and average bit error rate probability. It is found that as the number of disjoint of SNR regions increases, the capacity significantly improves but at the cost of BER performance degradation. The proposed system not only improves system capacity but also provides the trade-off between capacity and BER performance; hence, offers flexibility in the design of digital communication system.

### ACKNOWLEDGMENT

The second author would like to gratefully thank Taif University and the ministry of higher education in Saudi Arabia for their support and scholarship.

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