Analysis of Energy and Spectral Efficiency 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. The spectral efficiency (SE) and the energy efficiency (EE) for a digital communication system are defined and introduced as efficiency metrics. The SE and EE are derived and evaluated in shadowing urban environment using MGF approach. Both efficiency metrics are also simulated for a particular M-QAM modulation technique. The obtained results show that the efficiency metrics are adversely affected by the urban channel environment. Thus, an energy efficient transmission technique which is based on employing a modulation level of M-QAM to provide a maximum EE in a specific region of the signal to noise ratio (SNR). With the aid of truncated MGF, the performance of adaptive M-QAM system is evaluated in terms of efficiency metrics, outage probability and average bit error probability. The proposed adaptive technique shows high potential for achieving significant improvement in SE and EE while maintaining acceptable bit error probability even under severe channel effects.**

***Index Terms*—Urban Channel, Spectral Efficiency, Energy Efficiency, M-QAM, 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 modeled 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-located interference in [8]. Spectral efficiency (SE) is a critical performance metric of digital wireless communication systems and energy efficiency (EE) is a required measure to deal with the energy consumption that is escalated by increasing of data traffic. These metrics are expected to play a substantial role for the new digital wireless communication standards [9]. The bound of SE for a communication channel was established by Shannon's theorem as the maximum attained data rate over a certain channel band while maintaining an arbitrarily low probability of error for SISO [10]. This definition does not provide an insight of how the energy resources are efficiently utilized. Hence, EE metric is introduced as bit/J to consider the energy consumption which is defined as the maximum amount of bits that can be reliably delivered by a digital wireless communication system per unit of consumed energy in the system [11]. The relationship between SE and EE for additive white Gaussian noise (AWGN) channel has been introduced and discussed in [12]. Indeed, these two important metrics are in conflict and a careful study of their trade-off is mandatory for designing future wireless communication systems. For a particular modulation technique M-QAM, the SE and EE have been evaluated and discussed for an AWGN channel in [13].

The MGF approach is proposed for the computation of the SE only and outage probability by using numerical techniques [14]. A novel MGF based approach is developed for evaluation of SE for various rate adaptations and transmit power in [15]. 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 improve the SE over wireless channels subjected to fading and shadowing [16]. The adaptive technique has been investigated in severe channel conditions and has shown superior performance [17]. However, the idea of adapting modulation scheme to maximize the EE is a new concept. In this work, the adapting constellation size approach of M-QAM modulation technique to improve the EE is applied where the wireless channel effects are considered. SE and EE boundaries of shadowing multipath with no LoS wireless channel are derived and analyzed by using MGF based approach. Also, SE and EE of M-QAM are investigated and evaluated in a shadowed urban environment using a statistical distribution model approach including MGF is used

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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 definitions and analysis of SE and EE and their relationship for digital communication systems aver AWGN and Rayleigh-Gamma channels. Moreover, evaluation of SE and EE for particular modulation M-QAM technique are carried out using Monte Carlo simulation for different channel conditions in Section IV. In Section V, an adaptive M-QAM technique is proposed for RG channel to enhance the SE and EE, and the performance analysis of the proposed technique is done using MGF approach. Finally, the work is concluded in Section VI. In this work, bold lower case letter is used to denote a complex variable, e.g., $\boldsymbol{x}$ while x is designated to indicate a scalar variable and the bold math case will be used to denote vectors, $\mathbf{x}$.

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 the performance of the system. Let the equivalent baseband received signal be:

$$r = X\ s\ +\ n \tag{1}$$

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 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]:

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

Where $K_{c-1}(.)$ is the modified second order Bessel function, $\gamma = \alpha^2 E_s/N_o$ is the SNR, $\overline{\gamma} = \Omega c E_s/N_o$ 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:

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

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

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

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 $\exp(-s\gamma) = G_{0,1}^{1,0}\left(s\overline{\gamma}\ \middle|\ {}_{0}\right)$, and $K_{c-1}\left(\sqrt{\frac{4\gamma}{\overline{\gamma}}}\right) = \frac{1}{2}G_{0,2}^{2,0}\left(\frac{\overline{\gamma}}{\gamma}\ \middle|\ {}_{\frac{c-1}{2},\frac{1-c}{2}}\right)$ using [19, eq. (8.4.3/1),(8.4.23/1)]. The closed form MGF of γ is derived with the aid of [20, eq.(07.34.21.0011.01)] and can be expressed as:

$$M_\gamma(s) = \frac{1}{\Gamma(c)} G_{2,1}^{1,2}\left(\frac{s\overline{\gamma}}{c}\ \middle|\ \begin{matrix}1-c,\ 0\\ 0\end{matrix}\right) \tag{5}$$

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]:

$$\widehat{M_\gamma}(s,\gamma_k) \triangleq \int_0^{\gamma_k} \exp(-s\gamma)\ p_\gamma(\gamma)\ d\gamma \tag{6}$$

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

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

By expressing $K_{c-1}(.)$ using Meijier G-function and with the aid [20, eq.(03.04.21.0021.01)] , the truncated MGF in closed form becomes:

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

where ${}_1F_2(.,.;.)$ is the generalized hypergeometric function [18]. 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 γ 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:

$$m_n = \frac{\overline{\gamma}^{-\frac{c+1}{2}}}{\Gamma(c)} \int_0^\infty \gamma^{\frac{c-1}{2}+n}\ G_{0,2}^{2,0}\left(\frac{\gamma}{c\overline{\gamma}}\ \middle|\ {}_{\frac{c-1}{2},\frac{1-c}{2}}\right) d\gamma \tag{9}$$

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

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

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 γ as $AF = 1 + \frac{2}{c}$. From this formula, it can be shown that as $c \to \infty$ there is no shadowing effect and RG approaches Rayleigh distribution.

III. Spectral and Energy Efficiency over Wireless Channel

Spectrum and energy are the main resources of wireless communication systems, and their efficiencies are considered as the crucial performance design metrics for an efficient wireless communication system. In this section, the upper bounds of SE and EE for a digital communication channel are introduced and How to measure these metrics for a specific modulation technique is also presented.

A. Spectral Efficiency

The upper bound of SE quantifies the amount of bit rate that can be reliably conveyed over a band-limited wireless channel and hence it represents how the channel band is efficiently utilized. For AWGN, the SE bound is specified as

$$\eta_{S_G} = \log_2(1+\gamma), \quad (bit/s/Hz). \tag{11}$$

However, for a certain modulation scheme, the constrained spectral efficiency is determined according to the average mutual information of the modulation scheme and how much channel bandwidth is required. Thus, SE is defined as the number of bits per channel use that can be conveyed over unit Hz of normalized channel bandwidth and it is given by [11]

$$\eta_{S_M} = \frac{I(X;Y)}{BT_s}, \qquad \left[\frac{bit}{s.Hz}\right] \tag{12}$$

where BT_s in (Hz/baud) is the product of occupied bandwidth by the symbol duration with assuming no channel interference. For realistic wireless communication system, it is assumed that a practical Nyquist filter with nonzero excess bandwidth (ρ) is constructed at the modulator and demodulator. The excess bandwidth is also called roll-off factor which controls the occupied bandwidth. Thus, the BT_s can be related to roll-off factor as $(1+\rho)$. The $I(X;Y)$ in (bits/ch use) is the achievable average information rate of the modulation scheme which can be statistically estimated.

B. Energy Efficiency

Energy efficiency, η_E, is generally defined as the maximum amount of information rate, R, in (bit/sec) that can be reliably delivered by the wireless communication system per unit of its transmission power, P, [21].

$$\eta_E = \frac{R}{P}, \quad (bit/s/Watt) \tag{13}$$

Other definitions of energy efficiency have also been introduced which involves the wireless channel effects. Since the SNR is directly linked to the transmitted power, $\gamma = P/BN_o$, energy efficiency can be related with SNR as introduced in [22]

$$\eta_E = \frac{\eta_S}{\gamma} \tag{14}$$

From the definition of (11) and energy efficiency (14), the upper bound of energy efficiency for a realistic wireless communication system can be expressed as

$$\eta_{E_G} = \frac{\log_2(1+\gamma)}{\gamma}, \qquad (bit/TNEU) \tag{15}$$

C. Energy and Spectral Efficiency over Urban Shadowed Channel Based on MGF approach

For practical wireless communication channel where the SNR is degraded by the channel impairments, the upper bounds of SE and EE are also deteriorated depending on the channel conditions which are characterized by the pdf. The SE bounds can be obtained using [15].

$$\eta_{S_F} = \frac{1}{\log 2}\int_0^\infty E_i(-s)\, M_\gamma^{(1)}(s)\; ds \tag{16}$$

where $E_i(.)$ denotes the exponential integral function. The quantity $M_\gamma^{(1)}(s)$ is the first derivative of the MGF. For urban shadowing environment where the pdf is given by (2), the first derivative of MGF can be derived using[20, eq.(07.34.20.0001.01)] and is given by

$$M_\gamma^{(1)}(s) = \frac{s}{\Gamma(c+1)} G_{3,2}^{1,3}\left(\frac{s\overline{\gamma}}{c}\,\middle|\, \begin{matrix} -1,-c,-1 \\ -1,0 \end{matrix}\right) \tag{17}$$

By expressing $E_i(-s) = -G_{1,2}^{2,0}\left(s\middle|\, \begin{smallmatrix} 1 \\ 0,0 \end{smallmatrix}\right)$ [19, eq.(8.4.11/1)] in (16), a closed form expression for spectral efficiency bounds are obtained with the aid of [20, eq.(07.34.21.0011.01)] as:

$$\eta_{S_F} = \frac{1}{\log 2\Gamma(c)} G_{4,2}^{1,4}\left(\frac{\overline{\gamma}}{c}\,\middle|\, \begin{matrix} 1,1,1-c,0 \\ 1,0 \end{matrix}\right) \tag{18}$$

Whereas, upper bound of energy efficiency (bit/TNEU) for wireless shadowed fading channel can be derived using (14) where its numerator is (16) and the denominator is the average SNR which can be obtained using the MGF as $E[\gamma^r] = M_\gamma^{(r)}(0)$. Thus, the EE bounds can be derived as

$$\eta_{E_F} = \frac{\int_0^\infty E_i(-s)\, M_\gamma^{(1)}(s)\; ds}{\log 2 \lim\limits_{s\to 0} M_\gamma^{(1)}(s)} \tag{19}$$

where $M_\gamma^{(1)}(s)$ is given in (17). The upper bound of SE and EE for AWGN that is expressed in (11) and (15) and the for urban shadowing environment that are given in (18) and (19) are plotted in Fig.1 as a function of SNR and several channel parameters.

As it clear from Fig.1, the EE and SE are deteriorated by urban channel effects which the bit/TNEU is significantly reduced for severity shadowing conditions $c = 1$ at high and low SNR values. For instance, at 20 dB of SNR, the SE is decreased by 2 bit/s/Hz for $c = 1$ compared to AWGN whereas the EE is diminished by about 25% in the low SNR range.

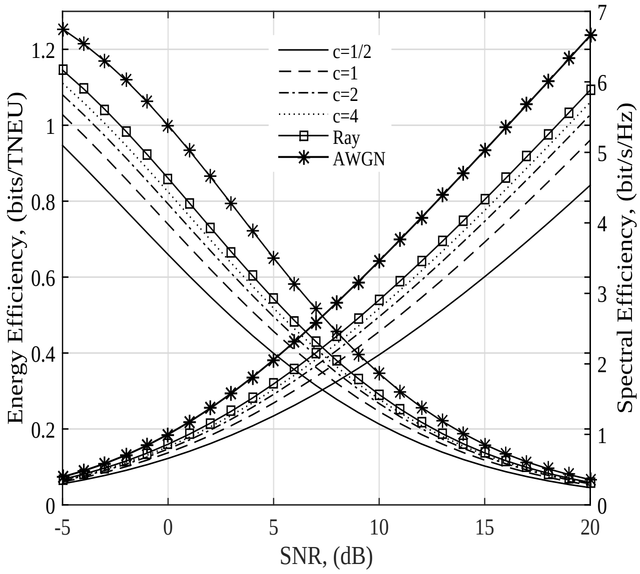

Fig. 1: Spectral and energy efficiency bounds for AWGN and RG channels as a function of SNR for different values of c

IV. Spectral and Energy Efficiency of M-QAM in the Shadowed Urban Environment

In this section, the SE and EE for M-QAM modulation technique are addressed and investigated in shadowing urban environment. From (12), the SE can be derived by estimating the maximum average mutual information rate and determining the normalized channel bandwidth. To estimate the average mutual information, the M-QAM system is modeled as Discrete-Input Continuous-Output Memoryless Channel (DCMC) which the M-ary input signals are assumed equiprobable signals and its probability is given as

$$p\left(\mathbf{x}_m\right) = \frac{1}{M}, \quad m = 2, ..., M. \tag{20}$$

The channel's transition probability of M-QAM is given by

$$p\left(\mathbf{y}|\mathbf{x}_m\right) = \prod_{n=1}^{D} \frac{1}{\sqrt{\pi N_o}} \exp\left(\frac{-\left(y_n - x_{mn}\right)^2}{N_o}\right), \tag{21}$$

where $\mathbf{y}$ is the received signal vector for given $\mathbf{x}$ was transmitted vector. For $D = 2$ M-ary QAM signaling, the maximum mutual information can be found in [23] and hence by using (12) the bandwidth efficiency is obtained as

$$\eta_{S_M} = \frac{\log_2(M)}{1+\rho} - \frac{1}{M(1+\rho)} \times \sum_{k=1}^{M} E\left\{\log_2\left[\sum_{i=1}^{M} \exp\left(\Phi_i^m\right)\right]\right\} \tag{22}$$

with

$$\Phi_i^m = \frac{-|\boldsymbol{\alpha}(\mathbf{x}_k - \mathbf{x}_i) + \boldsymbol{n}|^2 + |\boldsymbol{n}|^2}{N_o}$$

where $\mathbf{x}_i$ is the M-QAM symbols and $\boldsymbol{n}$ is a complex AWGN having a variance $N_o/2$ and $\boldsymbol{\alpha}$ is the complex channel gain which can be modeled using a given fading distributions. The expectation $E[.]$ is taken over $\boldsymbol{n}$ and $\boldsymbol{\alpha}$. The spectral efficiency of M-QAM, (22), is evaluated using Monte Carlo simulation which is performed using MATLAB. The channel gain, ($\boldsymbol{\alpha}$), which represents the shadowed urban channel can be modeled using

$$\boldsymbol{\alpha} = \sqrt{\left(E \times G_c\right)/c} \tag{23}$$

where E and G_c represent the pdf of α^2 for small and large scale fading and it can be generated using *exppdf* and *gamrnd* functions ,respectively, which are available in MATLAB toolbox. For AWGN channel, the channel factor is set to 1 ($\boldsymbol{\alpha} = 1$). The energy efficiency of M-QAM can be evaluated using (14) where $\gamma = \overline{\alpha}^2|x|^2/N_o$. The simulation of (22) is carried out for one million M-QAM symbols and the roll-off factor is chosen as $\alpha = 1/3$. Also, the SE and EE are investigated for several fading shadowing channel parameters, c. The SE of a square constellation for M-QAM is plotted for $M = 4, 16$ and 64 in Fig.2 whereas the EE is plotted in Fig.3. For comparison propose the SE and EE of M-QAM for AWGN and Rayleigh channels are also plotted. Fig.2 shows the impact of urban shadowing channel on the achieved SE. It is obvious that as c increases the SE improves; however, it is Always below the Rayleigh and AWGN channels bounds. Also, it is observed that as SNR increases SE approaches to its maximum value which is given by $\frac{\log_2 M}{1+\alpha}$.

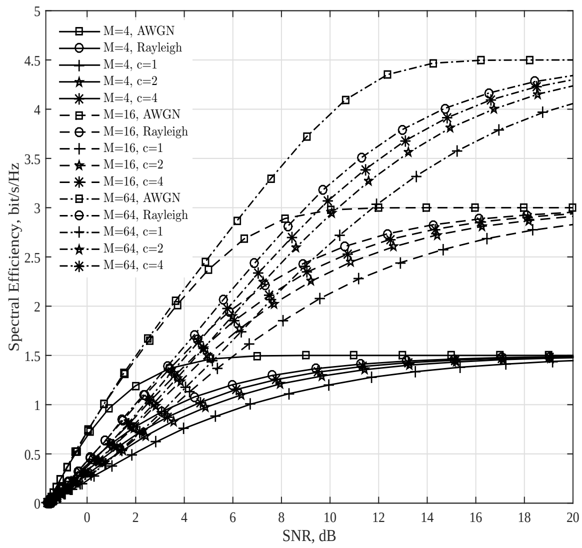

Fig. 2: Spectral efficiency of M-QAM for AWGN and RG channels as a function of SNR for different values of c

The effect of normalized bandwidth on the SE is also investigated by varying the roll-off factor from 0 to 1. SE as a function of SNR and α is plotted in Fig.3 for 4-QAM constellation and $c = 1$ and 4. The maximum SE is achieved when the lowest bandwidth is occupied i.e., $\alpha = 0$ and SE reduces as the normalized bandwidth increases. The EE of M-QAM constellation is evaluated and plotted in Fig.4 in terms of SNR and channel parameters. It is noted that each modulation level, M, attains the maximum EE in a certain SNR range which are specified by boundaries, γ_n.

The negative influence of the shadowed urban channel is clearly high. For instance, in a case of $c = 1$, the EE is degraded by 58% compared to AWGN channel. Also, it

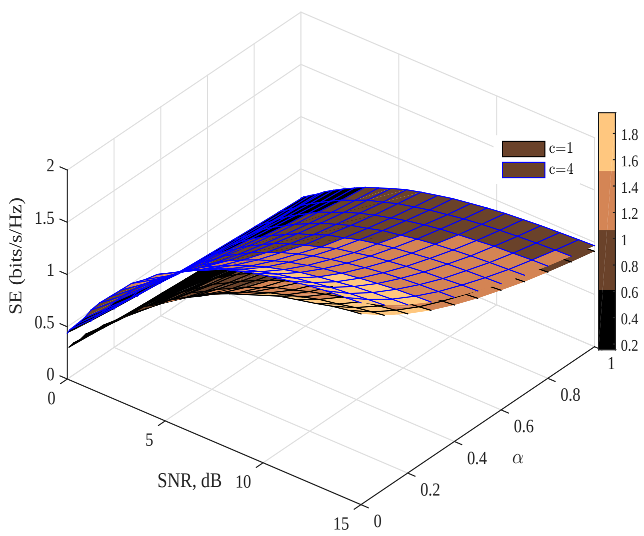

Fig. 3: Spectral efficiency of 4-QAM over RG channel as a function of SNR and α for $c = 1$ and 4

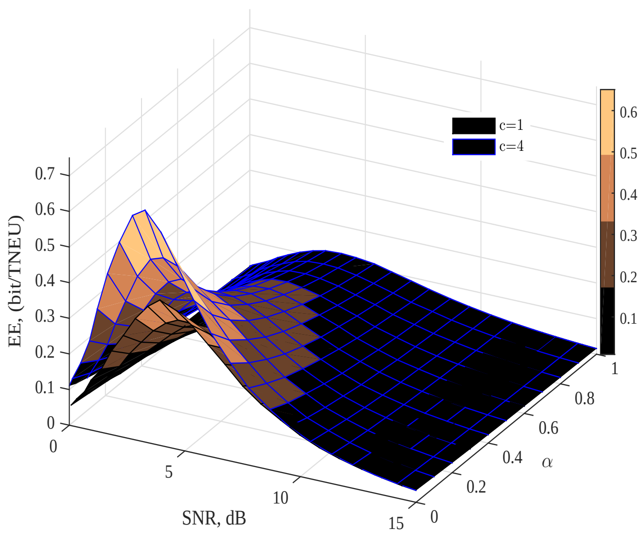

Fig. 5: Energy efficiency of 4-QAM over RG channel as a function of SNR and α for $c = 1$ and 4

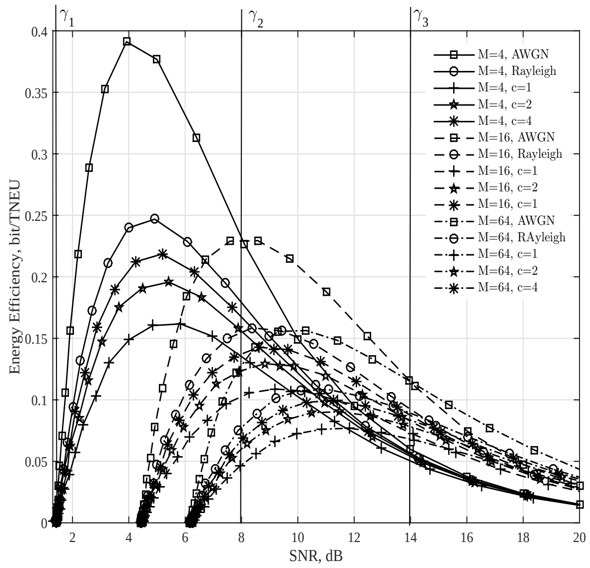

Fig. 4: Energy efficiency of M-QAM for AWGN and RG channels as a function of SNR for different values of c

is clear that lower modulation level provides high EE than the higher modulation levels. The EE of M-QAM is also examined regarding the normalized bandwidth. For example, the EE of 4-QAM is plotted as a function of SNR and the roll-off factor for the channel case $c = 1$ and 4 in Fig.5.

V. Efficiency metrics Improvement Using Adaptive M-QAM Technique

As shown in Figs.2 and 4, the SE and EE of M-QAM modulation system is very sensitive to the channel impairments and these metrics are significantly degraded over the urban channel. Thus, maximizing the SE and EE levels is an essential objective for any digital communication system. From Fig.4, we observe that the EE of each M-QAM has maximum value in a specific region of SNR. In this paper, an adaptive M-QAM modulation technique for shadowing fading channel is proposed to improve the efficiency metrics while maintaining a certain level of bit error rate performance. The technique is based on employing each M-QAM modulation level in the SNR region that provides the maximum EE.

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 γ estimation that is required to achieve the maximum EE as shown in Fig. 6. Therefore, mapping γ to the modulation level is the fundamental point to switch constellation size, M; thus, the range of γ is divided into N regions in order to decide which M-QAM is used when the estimated γ falls in the n^{th} region. Each region is specified with boundaries, γ_n, γ_{n+1}, which are determined to obtain the optimum values of EE and are indicated in Table I. It is assumed that when γ is estimated below γ_1 the transmission is suspended and the system suffers from an outage. The performance of proposed adaptive technique is evaluated in terms of average SE, average EE, outage probability and the average bit error probability.

TABLE I: γ_n BOUNDARIES

Mode n	M	γ_n–γ_{n+1} [dB]
1	4	1.4-8
2	16	8-14
3	64	14-∞

B. *Performance Analysis of Adaptive M-QAM technique*

In this section, the performance of adaptive M-QAM modulation in shadowing multi-path urban channel that is modeled by (2) is evaluated regarding the average SNR and the channel parameters.

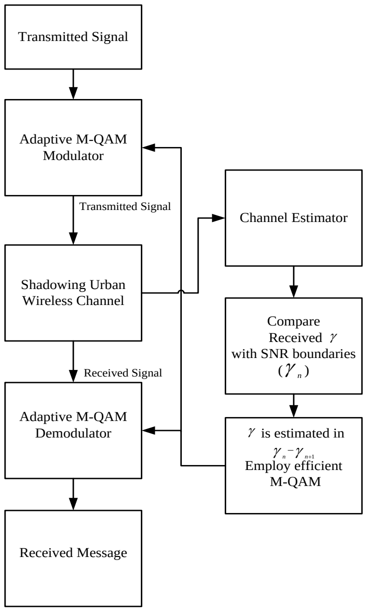

Fig. 6: Block diagram of an energy efficient M-QAM adaptive transmission technique

1) Average System Spectral Efficiency (bits/s/Hz): Average system SE $\overline{\eta_S}$ is the sum of data rates divided by the normalized bandwidth ($\log_2 M/(1+\rho)$) corresponding to N regions each weighted by the probability that γ falls in the n^{th} region, $P_r(n)$ and is given by [16] :

$$\overline{\eta_S} = \sum_{n=1}^{N} \left(\log_2 M/(1+\rho)\right) P_r(n) \tag{24}$$

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

$$P_r(n) = \frac{2}{\Gamma(c)} \Bigg\{ \left(\sqrt{\frac{c\gamma_n}{\overline{\gamma}}}\right)^c K_c\left(\sqrt{\frac{4c\gamma_n}{\overline{\gamma}}}\right) - \left(\sqrt{\frac{c\gamma_{n+1}}{\overline{\gamma}}}\right)^c K_c\left(\sqrt{\frac{4c\gamma_{n+1}}{\overline{\gamma}}}\right) \Bigg\} \tag{25}$$

Fig. 8 shows the average SE ($bits/s/Hz$) of adaptive M-QAM for three ($N = 3$) regions as a function of SNR for various channel parameters c. It is observed that the overall system SE is improved as the adaptive system utilizes high constellation size. Also, the adaptive modulation shows a good adaptation with channel conditions. The SE of Rayleigh and AWGN channels are also shown for comparison propose.

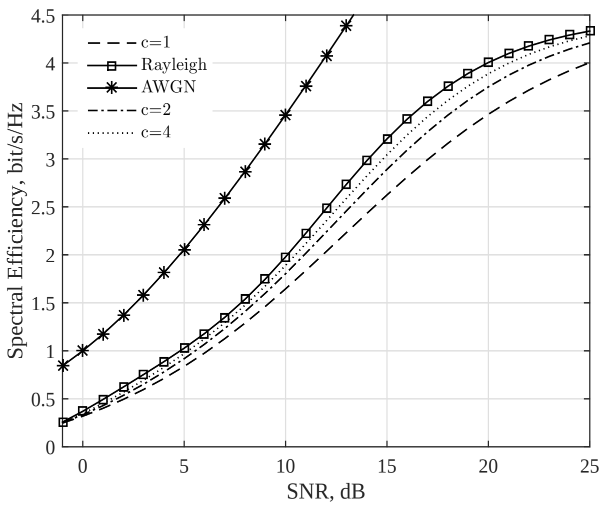

Fig. 7: Average spectral efficiency of adaptive modulation technique versus SNR for different wireless channels

2) Average System Energy Efficiency (bits/TNEU): Once the SE is obtained, the EE of adaptive transmission is directly evaluated by (14). The EE is illustrated in Fig.8 and it is evident that the EE is ameliorated for a wide estimated range of SNR. Fig.8 shows that EE is improved as the channel becomes less severe; however, it always below the EE of Rayleigh and AWGN channels.

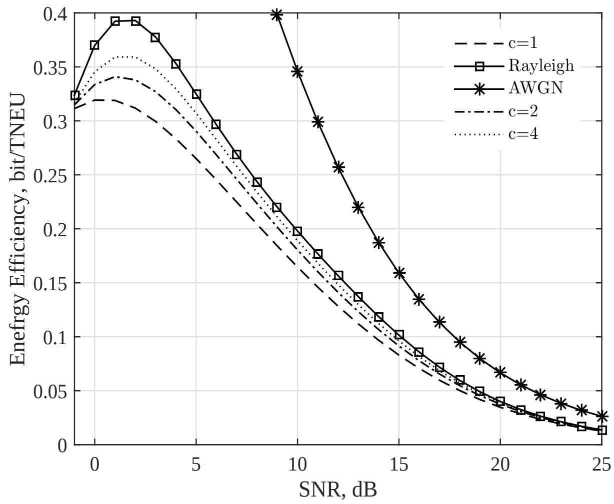

Fig. 8: Average energy efficiency of adaptive modulation technique versus SNR for different wireless channels

3) Outage probability: Since the transmission is suspended when the received γ falls below γ_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 $\gamma_1 = 1.4$ dB. P_o is plotted in Fig. 9 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.

C. Average Bit Error Rate

The proposed adaptive modulation technique is designed based on disjoint SNR regions for targeted maximum EE; however, it must satisfy certain QoS which is measured in terms of average BER. Thus, average BER, ($\overline{p}$), 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 average total number of transmitted bits and is given by [16]:

$$\overline{p} = \frac{1}{\overline{\eta_S}} \sum_{n=1}^{N} (\log_2 M)\overline{p}_n \tag{26}$$

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

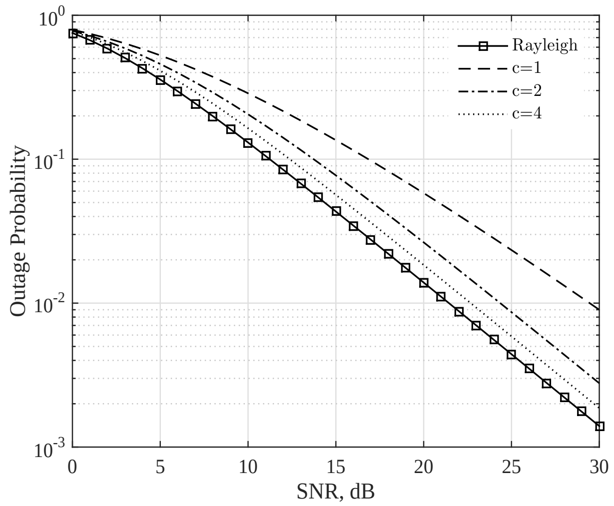

Fig. 9: Outage probability as a function of SNR for different values of several values of channel parameter c

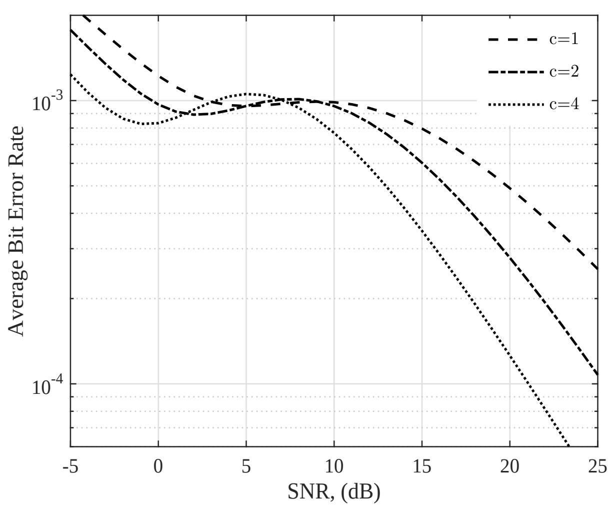

Fig. 10: Average bit error rate of adaptive modulation technique as function of SNR for several values of channel parameter c

$$\overline{p}_n = \int_{\gamma_n}^{\gamma_{n+1}} p_e(\gamma, M)\ p_\gamma(\gamma)\, d\gamma \quad (27)$$

where $p_\gamma(\gamma)$ is given by (2) and $p_e(\gamma, M)$ is the error probability of square M-QAM modulation and it is given by

$$p_e(\gamma, M) \leq 0.2\ \exp\left(-\frac{1.5\gamma}{M-1}\right),\ \gamma\ \geq 0,\ M\ \geq 4 \quad (28)$$

Thus, $\overline{p}_n$ can be written as:

$$\overline{p}_n = 0.2 \int_{0}^{\gamma_{n+1}} \exp\left(-\frac{1.5\gamma}{M-1}\right) p_\gamma(\gamma)\, d\gamma - 0.2 \int_{0}^{\gamma_n} \exp\left(-\frac{1.5\gamma}{M-1}\right) p_\gamma(\gamma)\, d\gamma \quad (29)$$

By comparing (29) with (6) which is the definition of truncated MGF, $\overline{p}_n$ can be directly obtained as:

$$\overline{p}_n = 0.2\widehat{M}_\gamma(s, \gamma_{n+1})|_{s=\frac{1.5}{M-1}} - 0.2\widehat{M}_\gamma(s, \gamma_n)|_{s=\frac{1.5}{M-1}} \quad (30)$$

The average bit error rate of the proposed adaptive M-QAM for n regions is derived by using truncated MGF and hence the total BER average of the adaptive system can be obtained by using (26). Fig. 10 shows $\overline{p}$ for $(N = 3)$ as a function of SNR and for different values of c. It is clear that the adaptive modulation technique maintains a certain QoS for all values of c in the targeted SNR range. Also, for high values of SNR, the performance is dominated by the highly utilized M-QAM modulation level.

VI. Conclusion

The spectral and energy efficiencies for a digital communication system have been investigated in multi-path superimposed on shadowing urban channel environment. The wireless channel was modeled by a composite Rayleigh-Gamma distribution. We have derived closed-form boundaries of SE and EE for the modeled channel. The SE and EE for M-QAM modulation technique have also been analyzed in terms of channel parameters, roll-off factor and SNR using Monte Carlo simulation. We found that SE and EE are deteriorated by channel impairments. Hence, adaptive transmission technique was proposed to enhance the efficiency of M-QAM system. The performance of adaptive technique has been evaluated concerning average SE, average EE, outage probability and average error probability. The results show that the proposed adaptive system not only improves system SE and EE but also provides the trade-off between efficiency metrics and BER performance; hence, offers flexibility in the design of digital communication system.

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