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A NOVEL MGF BASED ANALYSIS OF CHANNEL CAPACITY OF GENERALIZED-K FADING WITH MAXIMAL-RATIO COMBINING DIVERSITY

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Abstract—In this paper, we have analyzed the channel capacity by using the maximal-ratio combing (MRC) diversity scheme for communication systems operating over a composite fading environment modeled by the Generalized-K distribution at the receiver. For the Generalized-K fading channel with arbitrary values for small and large scale fading parameters, we have derived a closed-form expression for the moment generating function (MGF) of the received signal-to-noise ratio (SNR) and utilized it to obtain a novel closed-form expressions for the channel capacity under different adaptive transmission schemes. The result of the proposed methods is compared with other reported literature to support the analysis.

1. INTRODUCTION

The received signal over a wireless channel is usually characterized by the joint effect of two independent random processes such as small scale fading due to the arrival of multiple, randomly delayed, reflected and scattered signal components at the receiver side and large scale fading due to shadowing from various obstacles in the propagation path. Therefore, it is useful for various wireless system designers to have a general statistical model that encompasses both of these random processes. To model the small-scale fading channel, various fading models such as Rayleigh, Rician and Nakagami have been proposed [1–5]. In addition to the multipath fading in the wireless

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environment, the quality of signal is also affected due to the shadowing from various obstacles in the propagation path [2]. The Nakagami-m and Rayleigh-lognormal (R-L) are well-known composite statistical distribution to model the multipath fading and shadowing [6–8]. As these distributions do not have closed-form mathematical solution, so it is difficult to use it widely. However, they have been approximated by the Generalized-K distribution [6] and K-distribution [7, 8]. Diversity reception is increasingly becoming a primary technique for improving the performance of radio communication systems in multipath propagation environments. Therefore, the performance of diversity schemes has recently received considerable research efforts. The diversity combining [9–13] is an effective technique for mitigating the detrimental effects of the multipath fading and shadowing in the wireless mobile channels.

In general, the channel capacity in fading channel is a complex expression in terms of the channel variation in time and/or frequency depending also upon the transmitter and/or receiver knowledge of the channel side information. For the various channel side information assumptions that have been proposed, several definitions of the channel capacity have been provided. These definitions depend on the different employed power and rate adaptation policies and the existence, or not, an outage probability [1–5]. Earlier, the channel capacity has been studied by various researchers for several fading environment [14–26]. Goldsmith and Varaiya [14], have examined the channel capacity of the Rayleigh fading channels under different adaptive transmission techniques. Lee [15], has derived an expression for the channel capacity of the Rayleigh fading channel. In [16], Gunther has extended the results presented in [15] by deriving the channel capacity of the Rayleigh fading channels under diversity scheme. In [17], Alouini and Goldsmith have derived the expression for the channel capacity of Rayleigh fading channels under various diversity schemes and different rate adaptation as well as transmit power schemes. Other fading channels like the Nakagami, Weibull, Rician, and Hoyt fading channels were studied in detail in [18–20]. Ref. [21, 22] is main source in which author's emphasis on the channel capacity over Generalized-K fading. In [21], the channel capacity under different diversity schemes and different rate adaptation and transmit power schemes for k-fading channel has been derived but it has limitation that the channel capacity has been analyzed only for the special value of shaping parameter (i.e., $m = 2$). Moreover, in [21], for the calculation of channel capacity under the optimal rate adaptation (C_{ora}) policy, Laourine et al have explored two methods for the calculation of C_{ora}. First method involves the Lommel function and second method shows that, when the shadowing parameter, k, is an integer-plus-one and half, the channel capacity can be expressed in term of the more familiar sine and cosine integrals and these two methods having complex expressions for it. In [22], the channel capacity under different diversity schemes and different rate adaptation and transmit power schemes for k-fading channel has been derived. For calculation of the C_{ora} in [22], Efthymoglou et al. have obtained the approximate value by calculating the limit at $(a \to 1)$ and formula for C_{ora} is valid for non-integer value of the shaping parameters (k) and (m). If k and m are integers then formula for C_{ora} fails. In [23], the characteristics function (CF) is developed for computing the ergodic channel capacity. In [24, 25], the moment generating function based (MGF) approach is proposed for the computation of the channel capacity only for C_{ora} scheme by using numerical techniques. In [26], a novel MGF based approach is developed for evaluation of channel capacity for various rate adaptations and transmit power. In [26], the integral is evaluated by using mainly two type of numerical techniques, both the numerical techniques are lengthy and very much complex.

In this paper, we have presented the MGF based channel capacity analysis over the Generalized-K fading channel with L-branch maximal-ratio combining (MRC) diversity at receiver. The main contribution of this paper consists in the evaluation the MGF function and the derived MGF function is used to evaluate a closed-form expression for the channel capacity under optimal rate adaptation (C_{ora}) and channel inversion with fixed rate (C_{cifr}). The Closed form expression for C_{ora} is in this paper is valid for integer and non integer value of the shaping parameter k and m. The MGF based method proposed in this paper, for calculation of the channel capacity is simpler than PDF based approach as reported in [21, 22] as well as MGF based approach as discussed in [26]. The derived results are obtained in the terms of well known Meijer G function, which can be easily, implemented using Maple or Mathematica software. The paper is organized as follows. Section 2 describes the channel model and MGF. The channel capacity evaluation under different policies is performed in Section 3. Numerical results are discussed in Section 4. Finally, Section 5 concludes the work and recommends the future directions.

2. GENERALIZED-K FADING CHANNEL MODEL

Let us consider the L-branch MRC diversity receiver operating over the Generalized-K fading channel. If we assume that in the Generalized-K fading environment, the amplitude of received signal envelop, X, which is a random variable that has probability density function (PDF) is given by [23]:

$$f_X(x) = \frac{4\, x^{Lm\,+k-1}}{\Gamma(mL)\Gamma(k)} \left(\frac{m}{\Omega}\right)^{\frac{k+mL}{2}} K_{k-mL}\left[2\left(\frac{m}{\Omega}\right)^{1/2} x\right] \quad x \geq 0 \quad (1)$$

where k and m are the shaping parameters of the distribution. $K_\nu(\cdot)$ is the $\nu(\cdot)$ order modified Bessel function of of the second kind and $\Gamma(\cdot)$ is the Gamma function [27, 28]. In the Equation (1), $\Omega = E[X^2]/k$ is the mean power and $E[\cdot]$ denotes the expectation. Note that the parameter $m \geq 1/2$ inversely reflects the small-scale fading severity, whereas parameter $k > 0$ inversely reflects the shadowing severity. Since Generalized-K fading is the distributions based on two parameters (k and m), Equation (1) can be used to describe different fading and shadowing models for combination of k and/or m. For example, as $k \to \infty$, it approximates the well known Nakagami-m distribution [1]. For $m = 1$, it coincides with the k-distribution and approximately models the R-L fading condition while for $m \to \infty$ and $k \to \infty$, Equation (1) approaches the additive white Gaussian noise (AWGN) channel. The instantaneous SNR per received symbol at output of the diversity branch is:

$$\gamma = X^2 E_S/N_0$$

where E_S is the average symbol energy and N_0 is single-sided power spectral density of the additive white Gaussian noise. Assuming all the branches are identical and corresponding average SNR is given as:

$$\bar{\gamma} = k\,\Omega\, E_S/N_0$$

By changing variables, the PDF of γ from the Equation (1) can be written as:

$$f_\gamma(\gamma) = \frac{2\ (\gamma)^{(\alpha-1)/2}}{\Gamma(mL)\Gamma(k)} (\,\Xi)^{(\alpha+1)/2} K_\beta\left[2\sqrt{\Xi\,\gamma}\right] \qquad \gamma \geq 0 \qquad (2)$$

where $\alpha = mL+k-1$, $\beta = k-mL$ and $\Xi = k\,m/\bar{\gamma}$. The MGF is one of most important characteristics of the any distribution function because it helps in the bit-error-rate as well as channel capacity performance evaluation of the wireless communication systems. The MGF of γ is defined as [1]:

$$M_\gamma(s) = \int_0^\infty \exp(-s\gamma)\, f_\gamma(\gamma)\, d\gamma \qquad (3)$$

By substituting $f_\gamma(\gamma)$ given by Equation (2) into Equation (3) then the MGF of Equation (3) can be expressed as:

$$M_\gamma(s) = \frac{2\,(\,\Xi)^{(\alpha+1)/2}}{\Gamma(mL)\Gamma(k)} \int_0^\infty \exp(-s\gamma)\ (\gamma)^{(\alpha-1)/2} K_\beta\left[2\sqrt{\Xi\,\gamma}\right] d\gamma \quad (4)$$

The normalized average channel capacity can be easily obtained as $\overline{C}/BW$ in terms of b/s/Hz. As expected, average channel capacity is always less than the capacity provided by the additive white Gaussian noise channel. Moreover, for $k = m = 1$, the obtained average channel capacity is less than that in the Rayleigh fading channel, while it improve as k and/or m increases. By expressing $K_\beta(\cdot)$ in terms of Meijer's G-function as [27] and from [28], we get:

$$M_\gamma(s) = \frac{(\Xi/s)^{\frac{\alpha+1}{2}}}{\Gamma(mL)\Gamma(k)} G\begin{matrix} 2 & 1 \\ 1 & 2 \end{matrix} \left[\frac{\Xi}{s} \middle| \begin{matrix} (1-\alpha)/2 & \\ \beta/2 & -\beta/2 \end{matrix} \right] \tag{5}$$

where $G(\cdot)$ is the Meijer's G function as given in [27] which is easy to evaluate by itself using the modern mathematical packages such as Mathematica and Maple.

3. MGF-BASED CHANNEL CAPACITY ANALYSIS

The channel capacity has been regarded as the fundamental information theoretic performance measure to predict the maximum information rate of a communication system. It is extensively used as a basic tool for the analysis and design of new and more efficient techniques to improve the spectral efficiency of modern wireless communication systems and to gain insight into how to counteract the detrimental effects of the multipath fading propagation via opportunistic and adaptive communication methods. The MGF based approach for the channel capacity analysis is the most significant technique. The MGF based approach for the analysis of spectral efficiency over fading channels is represented due to the fact that most of the frameworks described in literature make use of the so-called PDF based approach of the received SNR, which is a task that might be very cumbersome for most system setups and often require to manage expression including series. It is also well known that a prior knowledge of channel state information at the transmitter may be exploited to improve the channel capacity, such that in the low SNR regime, the maximum achievable data rate of a fading channel might be much larger than when there is no fading. The MGF and CF (characteristics function) based approaches have extensively been used for analysing average bit error rate probability and outage probability. Alouini et al. [29], have also pointed out the complexity of using and generalizing MGF and CF based approaches for channel capacity computation. Moreover, the application of the pdf based approach for channel capacity computation turns out to be in evident counter tendency with recent advances on performance analysis of digital communication over fading channels.

Several researchers [30–33] have clearly shown the potential of using either an MGF or an CF-based approach for simplifying the analysis in most situation of interest with the computation of important performance parameters where the application of pdf based approach seems impractical. Recent advances on the performance analysis of digital communication systems in fading channels has recognized the potential importance of the MGF or Laplace transforms as a powerful tools for simplifying the analysis of diversity communication systems. This led to simple expressions to average bit and symbol error rate for wide variety of digital communication scheme on fading channels including multipath reception with correlated diversity [11, 34–35]. Key to these developments was the transformation of the conditional error rate expressions into different equivalent forms in which the conditional variable appears only as an exponent. In this section, we propose some alternative expressions for channel capacity computation by relying on the knowledge of the MGF $M_\gamma(.)$ of γ. In the following section we have presented closed from expression for C_{ORA} and C_{cifr} schemes. It is difficult to get closed form expression for the channel capacity using MGF based approach, for optimal simultaneous power and rate adaptation (C_{OPRA}) and the truncated channel inversion (C_{TCIFR}) schemes in future communication using a novel marginal MGF based channel capacity analysis approach.

3.1. Optimal Rate Adaptation

When the transmitter power remains constant, usually as a result of channel state information (CSI) being available at receiver side, the channel capacity with optimal rate adaptation (C_{ORA}) in terms of the MGF based approach can be expressed as [26]:

$$C_{ORA} = \frac{1}{\ln(2)} \int_0^\infty E_i(-s)\ M_\gamma^{(1)}(s)\, ds \tag{6}$$

where $E_i(\cdot)$ denotes the exponential integral function defined in [28] and $M_\gamma^{(1)}(s)$ is the first derivative of the MGF. The integral in Equation (6) is called E_i-transform, as an $E_i(\cdot)$ kernel function defines this integral transform. Moreover, in those scenarios where very complicated expressions of the MGF of the received SNR do not allow easily computing the aforementioned integral in closed form, the result in Equation (6) can efficiently and easily be obtained by using standard computing environments, such as Wolfram MATHEMATICA. In fact, we point out that the (logarithmic) singularity of the $E_i(\cdot)$ kernel function around zero is removed by the integral operation and does not provide, in general, numerical problems. By expressing $E_i(-s)$ as in [28, Equation (8.44.11.1)] and from Equation (3), the integral in the Equation (6), can be expressed as:

$$I = -\frac{(\Xi)^{\frac{\alpha+1}{2}}}{\Gamma(mL)\Gamma(k)} \int_0^\infty G\,{}^{2\ 0}_{1\ 2}\left[s\middle|\begin{matrix}1\\0\ \ 0\end{matrix}\right] \frac{d}{ds}\left((s)^{-(\alpha+1)/2} G\,{}^{2\ 1}_{1\ 2}\left[\frac{\Xi}{s}\middle|\begin{matrix}(1-\alpha)/2 & \\ \beta/2 & -\beta/2\end{matrix}\right]\right) ds \quad (7)$$

Using [28 Equation (8.2.1.35)] along with [28, Equation (8.2.1.14)] and by putting $s = \Xi t$, the integral given in Equation (7) can be expressed as:

$$I = \frac{1}{\Gamma(mL)\Gamma(k)} \int_0^\infty (t)^{-(\alpha+3)/2} G\,{}^{2\ 0}_{1\ 2}\left[\Xi t\middle|\begin{matrix}1\\0\ \ 0\end{matrix}\right] G\,{}^{1\ 2}_{2\ 1}\left[t\middle|\begin{matrix}1-\beta/2 & 1+\beta/2\\ 1+(\alpha+1)/2 & \end{matrix}\right] dt \quad (8)$$

From [28, Equation (2.24.1)], the integral I given in the Equation (8), can be expressed as:

$$I = \frac{(\Xi)^{\frac{\alpha+1}{2}}}{\Gamma(mL)\Gamma(k)} G\,{}^{1\ 4}_{4\ 2}\left[\frac{1}{\Xi}\middle|\begin{matrix}1-\beta/2 & 1+\beta/2 & 1+(\alpha+1)/2 & 1+(\alpha+1)/2\\ 1+(\alpha+1)/2 & (\alpha+1)/2 & & \end{matrix}\right] \quad (9)$$

By putting the value of I in Equation (6), the C_{ora} can be expressed as:

$$C_{ora} = \frac{1}{\ln(2)} \frac{(\Xi)^{\frac{\alpha+1}{2}}}{\Gamma(mL)\Gamma(k)} G\,{}^{1\ 4}_{4\ 2}\left[\frac{1}{\Xi}\middle|\begin{matrix}1-\beta/2 & 1+\beta/2 & 1+(\alpha+1)/2 & 1+(\alpha+1)/2\\ 1+(\alpha+1)/2 & (\alpha+1)/2 & & \end{matrix}\right] \quad (10)$$

The above formula for the channel capacity with ORA policy evaluates correctly for arbitrary non-integer values of k and m, approach for evaluation of C_{ora} in this much simpler than [21, 22]. Equation (10) is also valid for integer values of k and m.

3.2. Channel Inversion with Fixed Rate

The channel capacity for channel inversion with fixed rate (C_{cifr}) requires that the transmitter exploits the channel state information so that constant SNR is maintained at the receiver. This method uses fixed transmission rate since the channel after fading inversion appears. The channel capacity with the fixed channel inversion rate in terms of the MGF can be expressed as given in [26]:

$$C_{cifr} = \log_2\left(1 + \frac{1}{\int\limits_0^\infty M_\gamma(s)\,ds}\right) \tag{11}$$

$$I_2 = \int\limits_0^\infty M_\gamma(s)\,ds \tag{12}$$

By substituting the value of $M_\gamma(s)$ from the Equation (5) to Equation (12), I_2 can be expressed as:

$$I_2 = \int\limits_0^\infty \frac{(\Xi/s)^{\frac{\alpha+1}{2}}}{\Gamma(mL)\Gamma(k)} G\ {}^{2\ \ 1}_{1\ \ 2}\left[\frac{\Xi}{s}\middle|\ \begin{matrix}(1-\alpha)/2 & \\ \beta/2 & -\beta/2\end{matrix}\right] ds \tag{13}$$

By putting $t = 1/s$ in above integral and using [27], the integral given by Equation (13) can be expressed as:

$$I_2 = \frac{\Xi\,\Gamma\left((\alpha+\beta-1)/2\right)\Gamma\left((\alpha-\beta-1)/2\right)}{\Gamma(mL)\,\Gamma(k)} \tag{14}$$

By substituting the value of I_2 in Equation (11), we get:

$$C_{CIFR} = \log_2\left(1 + \frac{\Gamma(mL)\,\Gamma(k)}{\Xi\,\Gamma\left((\alpha+\beta-1)/2\right)\Gamma\left((\alpha-\beta-1)/2\right)}\right) \tag{15}$$

For $L = 1$ and if m is integer in Equation (15), we get:

$$C_{CIFR} = \log_2\left(1 + \frac{\bar{\gamma}\ (m-1)\,(k-1)}{km}\right) \tag{16}$$

Equation (16) is similar to [21, Equation (29)] and [22, Equation (27)]. The approach for the derivation of this equation as compared to [21] and [22] is quite simple.

4. RESULT AND DISCUSSION

In this section, we present some numerical results for the channel capacity with MRC diversity over the Generalized-K fading channel. Fig. 1 shows the capacity for optimal rate adaptation (C_{ora}) versus SNR heavy shadowing ($k = 1.0931$) and light shadowing ($k = 75.11$) as L increases form $L = 1$ to $L = 3$ channel capacity improves significantly.

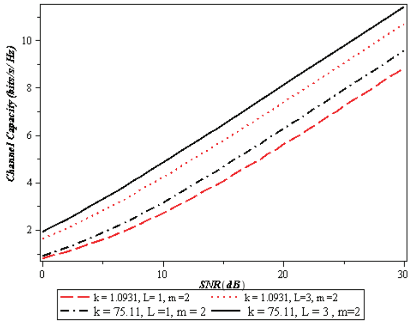

Figure 1. Channel capacity for the optimal rate adaptation (C_{ora}) versus SNR for heavy shadowing ($k = 1.0931$) and light shadowing ($k = 75.11$).

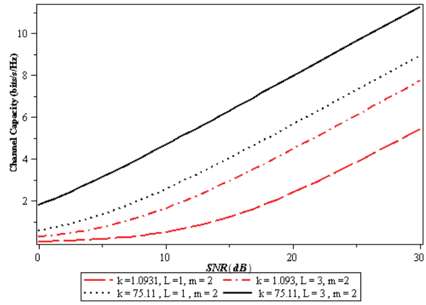

Figure 2. Channel capacity for channel inversion with fixed rate (C_{cifr}) versus SNR for the light shadowing ($k = 75.11$) and heavy shadowing ($k = 1.0931$).

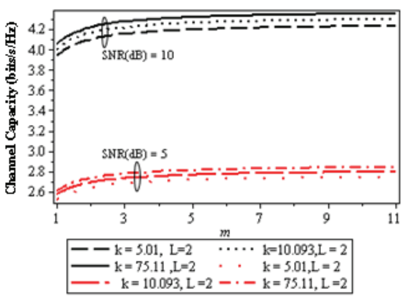

Figure 3. Channel capacity for optimal rate adaptation (C_{ora}) versus fading parameter for various values of the SNR.

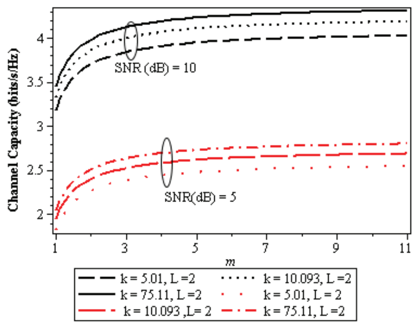

Figure 4. Capacity for channel inversion with fixed rate (C_{cifr}) versus fading parameter (m) for several values of the SNR.

Figure 2 shows the channel capacity with fixed channel inversion rate (C_{cifr}) versus SNR for the light shadowing ($k = 75.11$, $m = 2$) and heavy shadowing ($k = 1.0931$, $m = 2$) for $L = 1$, 3. By focussing on the effect of shadowing, in case heavy shadowing ($k = 1.0931$), the channel capacity degrades significantly as shown in Fig. 2 and channel capacity improves with the increase of L. The Fig. 3 and Fig. 4 shows plot of channel capacity verses fading parameters (m) under different transmission schemes, for the SNR (dB) = 10, the channel capacity is more than that of SNR (dB) = 5, for both the figures. As fading parameter (m) is increases, the channel capacity improves slightly and becomes almost constant for both the transmission schemes.

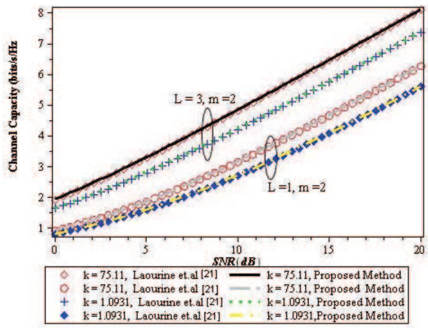

Figure 5. Comparison of the channel capacity for optimal rate adaptation (C_{ora}) with proposed method and PDF based method [21].

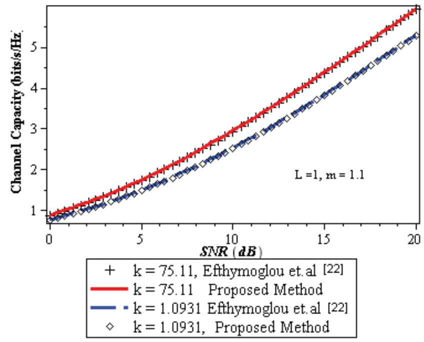

Figure 6. Comparison of the channel capacity for optimal rate adaptation (C_{ora}) with proposed method and PDF based method [22].

In Fig. 5, comparison of the channel capacity of proposed MGF based method and PDF based method [21] for various values of the shadowing parameters and diversity receivers is shown. The PDF based approach which is discussed in detail in [21] is only valid for fixed value of the shaping parameter (i.e., $m = 2$) but the MGF based proposed method given in this paper is valid for any arbitrary chosen values of the shaping parameter m. Fig. 6 shows the comparison of channel capacity of the proposed MGF based method and PDF based method [22]. Here, the PDF based method for $a = 1$ is merely an approximation of C_{ora}, and this approach is also valid only for non-integer values of k and m.

5. CONCLUSION

In this paper, a novel simple expression is derived to compute the channel capacity for Generalized-K fading with L-branch MRC under different adaptation policies by using MGF. We derived the mathematical expression for the channel capacity with optimal rate adaptation (C_{ora}) which is valid for arbitrary values of the shaping parameters k and m. We also derived an expression for the channel capacity for channel inversion with fixed rate (C_{cifr}). The C_{ora} and C_{cifr} are very easily computed by using the MGF based approach. For $L = 1$, (C_{cifr}) is computed by using Equation (16) which is similar to [21, Equation (29)] and [22, Equation (27)]. The derived mathematical expression can be useful in the performance evaluation of communication links over a composite fading environment. Due to their simple forms, these results offer a useful analytical tool for the accurate performance evaluation of various systems of practical interest.

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