On the Performance of Cascaded Generalized $\mathcal{K}$ Fading Channels

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***Abstract*—A novel distribution referred to as $N*$generalized $\mathcal{K}$, constructed as the product of N statistically independent, but not necessarily identically distributed, generalized $\mathcal{K}$ random variables (RVs) is introduced. Statistical characterization of the proposed distribution is carried out via the derivation of closed-form expressions for its moment generating, probability density, cumulative distribution and moment functions. Using the obtained formulas, we present new closed-form expressions for the outage probability, the bit error probability and the average channel capacity of a digital communication system operating over the N cascaded generalized $\mathcal{K}$ distributed channels.**

***Index Terms*—Average bit error rate, channel capacity, cascaded fading, outage probability, composite channels.**

I. Introduction

Recently, the concept of multiple scattering radio propagation channels [1] has been found useful in many scientific fields of communications and to fit many propagation scenarios. For example, in multi-hop communications [2], the source terminal communicates with the destination terminal trough a given number of nodes. When those nodes are analog repeaters (amplify and forward) with fixed gains, the resulting channel is a cascaded one and can be modeled as a product of fading amplitudes. The concept of cascaded channels can also be useful in modeling propagation via keyholes [3] or via diffracting wedges such as street corners or rooftops [1]. The statistical characterization of the products of RVs has been addressed many times recently. In the case of fading-only propagation, previous work encompassed the performance analysis of cascaded Rayleigh [4], Nakagami-m [5] and weibull channels [6]. The double Rayleigh model has been recently used for keyhole channel modeling of multiple-input multiple-output (MIMO) systems [3,7]. This model has been extended to the double Nakagami-m model in [8]. Interestingly enough, the product of Nakagami-m and weibull RVs has been used to analyze the performance of multihop systems [9,10] as well as to derive closed-form upper bounds for the distribution of the sum of RVs [11]. In addition to multipath fading, cascaded channels may suffer from shadowing. In such settings, each receiver is subject to a composite multipath/shadowing signal [12]. When short- and long- term fading conditions coexist in wireless communications, several compound models have been proposed to model both fading impairment types. Namely, the Suzuki [13], Nakagami-lognornal [14] and Rice-lognormal [15]. For all these models, the resulting composite probability density function (PDF) is unfortunately not in closed form, thereby making the performance evaluation of communication links over these channels unpractical. In this paper, the generalized $\mathcal{K}$ distribution [16] is used to model the composite fading shadowing channels. To the best of our knowledge, the case of cascaded fading/shadowing channels has never been addressed before.

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In this paper, we propose a statistical characterization of a new distribution constructed as the product of N statistically independent but not necessarily identically distributed generalized $\mathcal{K}$ RVs. In this context, the statistics of this distribution are derived through its moment-generating (MGF), PDF, cumulative distribution function (CDF), and moments. The proposed formulas are obtained using the Meijer's G function [17]. Moreover, considering the fact that the proposed model can describe a variety of digital communication systems, a performance analysis is carried out including the derivation of closed-form expressions for the outage probability, the symbol error rate and the channel capacity.

The remainder of this paper is organized as fellows. In section II, the statistics of the $N*$generalized $\mathcal{K}$ distribution are presented and analyzed. Section III provides the performance analysis of a communication system operating over a $N*$generalized $\mathcal{K}$ channel. Section IV concludes the paper while summarizing the main results.

II. The $N*$Generalized $\mathcal{K}$ distribution

Let us consider a random variable Y, constructed as the product of $N \geq 1$ independent but not necessarily identically generalized $\mathcal{K}$ distributed RVs $\{R_i\}_{i=1}^{N}$, each with pdf [16]

$$f_{R_i}(r) = C_i r^{\beta_i} K_{\alpha_i}(a_i r_i), \tag{1}$$

where $C_i = \frac{a_i^{\beta_i+1}}{2^{\beta_i}\Gamma(m_i)\Gamma(\lambda_i)}$ and m_i and λ_i are the shaping parameters of the distribution, $\alpha_i = \lambda_i - m_i$, $\beta_i = \lambda_i + m_i - 1$ and $a_i = \sqrt{\frac{4\lambda_i m_i}{\Omega_i}}$, where Ω_i is the mean power. In (1), $K_\alpha(\cdot)$ is the modified Bessel function of the second kind and order α, and $\Gamma(\cdot)$ is the gamma function [17]. As a compound distribution, the generalized $\mathcal{K}$ is able to model a great variety of fading and shadowed environments. Indeed, this versatile distribution proved to be particularly useful in evaluating the performance of the Nakagami-lognormal channel [16].

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Next, we define the distribution of Y given by:

$$Y=\prod_{i=1}^{N}R_i, \tag{2}$$

as the $N*$generalized $\mathcal{K}$ distribution.

Theorem 1 The MGF (moment-generating function) of Y is given by:

$$M_Y(s)=\frac{1/\sqrt{\pi}}{\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)} G_{2,2N}^{2N,2}\left(\frac{4\prod_{i=1}^{N}\frac{m_i\lambda_i}{\Omega_i}}{s^2}\middle| \begin{array}{c}1,\frac{1}{2}\\ \lambda_1,m_1,\ldots\ldots,\lambda_N,m_N\end{array}\right), \tag{3}$$

where $G[\cdot]$ is the Meijer's G-function [17] . The proof of (3) is given in the Appendix.

The pdf of Y can be derived as

$$f_Y(y)=L^{-1}[M_Y(s),y], \tag{4}$$

where $L^{-1}(\cdot;\cdot)$ is the inverse Laplace transform [17]. By the help of [18, eq. 3.38.1], the pdf of Y can be expressed in closed-form as

$$f_Y(y)=\frac{2}{\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)y} G_{0,2N}^{2N,0}\left(y^2\prod_{i=1}^{N}\frac{m_i\lambda_i}{\Omega_i}\middle| \begin{array}{c}-\\ \lambda_1,m_1,\ldots\ldots,\lambda_N,m_N\end{array}\right). \tag{5}$$

As a verification, note that for $N=1$, and by using the fact that

$$G_{0,2}^{2,0}\left(z\,|b,c\right)=2z^{\frac{(b-c)}{2}}K_{b-c}(2\sqrt{z}), \tag{6}$$

(5) simplifies to (1). Also using [17, eq. 7.811.4], it can be easily verified that $\int_0^\infty f_Y(y)dy=1$ and therefore $f_Y(\cdot)$ is a valid pdf. In (1), as $\lambda_i\longrightarrow\infty$, the generalized $\mathcal{K}$ distribution reduces to the well known Nakagami-m distribution, and consequently, Y reduces to the $N*$Nakagami-m distribution. By applying an N-fold limit operation based on the fact that:

$$\lim_{b_j\longrightarrow\infty}\frac{1}{\Gamma(b_j)}G_{p,q}^{m,n}\left(b_jz\middle| \begin{array}{c}a_1...a_p\\ b_j,..,b_m,\ldots,b_q\end{array}\right)= G_{p,q-1}^{m-1,n}\left(z\middle| \begin{array}{c}a_1...a_p\\ b_{j+1},..,b_m,\ldots,b_q\end{array}\right), \tag{7}$$

(5) reduces to the pdf of the $N*$Nakagami-m distribution recently found in [5].

The cumulative density function of Y is defined as

$$F_Y(y)=\int_0^y f_Y(z)dz. \tag{8}$$

By substituting (5) in (8) and with the aid of [19], we find that:

$$F_Y(y)=\frac{1}{\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)} G_{1,2N+1}^{2N+1,1}\left(y^2\prod_{i=1}^{N}\frac{m_i\lambda_i}{\Omega_i}\middle| \begin{array}{c}1\\ \lambda_1,m_1,\ldots\ldots,\lambda_N,m_N,0\end{array}\right). \tag{9}$$

The above CDF expression can be very useful mainly in deriving closed-form expressions for the average outage duration of a multihop non-regenerative communication system over composite fading channels. So far, only short-term fading conditions have been considered.

III. Performance analysis

Let us consider a digital communication system operating over an $N*$generalized $\mathcal{K}$ fading channel. In (1), the distribution shaping parameters m_i and λ_i correspond, respectively, to the fading severity and the shadowing spread parameters of the $i-$th composite channel. In this section, some performance criteria, namely the outage probability, the symbol error rate and the channel capacity are derived for a digital system operating over N cascaded composite channels. Interestingly enough, these new formulas can be used to find some tight upper bounds on the performances of a fixed gain amplify and forward communication system operating over fading/shadowing generalized $\mathcal{K}$ distributed channels.

Assume that the source terminal is transmitting a signal with an average power normalized to unity. Then the end-to-end SNR can be written as [12]

$$\gamma=\frac{Y^2}{N_0}, \tag{10}$$

where N_0 is the single-sided AWGN power spectral density. The corresponding average SNR is given by

$$\bar{\gamma}=\frac{E[Y^2]}{N_0}=\frac{\prod_{i=1}^{N}E[R_i^2]}{N_0}=\frac{\prod_{i=1}^{N}\Omega_i}{N_0}. \tag{11}$$

Tacking this into account in (5) yields the pdf of γ given by

$$f_\gamma(y)=\frac{1}{y\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)} G_{0,2N}^{2N,0}\left(\frac{y}{\bar{\gamma}}\prod_{i=1}^{N}m_i\lambda_i\middle| \begin{array}{c}-\\ \lambda_1,m_1,\ldots\ldots,\lambda_N,m_N\end{array}\right). \tag{12}$$

With the aid of [17, eq. 7.811.4], the n-th moment of γ can be easily derived as

$$E\langle\gamma^n\rangle=\overline{\gamma}^n\prod_{i=1}^{N}\frac{\Gamma(n+m_i)\Gamma(n+\lambda_i)}{\Gamma(m_i)\Gamma(\lambda_i)m_i^n\lambda_i^n}. \tag{13}$$

A. Amount of Fading

Using (13), the amount of fading defined as the ratio of the variance to the square average SNR can be derived as

$$\begin{aligned}AoF&=\frac{E[\gamma^2]-E[\gamma]^2}{\bar{\gamma}^2}\\ &=\prod_{i=1}^{N}(1+\frac{1}{m_i})(1+\frac{1}{\lambda_i})-1.\end{aligned} \tag{14}$$

B. Outage Probability

The outage probability is an important performance measure of communication links operating over composite fading/shadowing channels. It is defined as the probability that the output SNR falls below a given threshold γ_{th}, i.e.,

$$P_{out}=F_\gamma(\gamma_{th}), \tag{15}$$

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where $F_\gamma(y)$ is the CDF of γ which is shown to be given by:

$$F_\gamma(\gamma) = F_Y\left(\sqrt{\frac{\gamma}{\bar{\gamma}}\prod_{i=1}^{N}\Omega_i}\right) = \frac{G_{1,2N+1}^{2N+1,1}\left(\frac{\gamma}{\bar{\gamma}}\prod_{i=1}^{N} m_i\lambda_i \middle| \begin{matrix} 1 \\ \lambda_1, m_1, \ldots\ldots, \lambda_N, m_N, 0 \end{matrix}\right)}{\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)}. \quad (16)$$

In Figs. 1 and 2, the outage probability is plotted as a function of the inverse normalized threshold $\frac{\bar{\gamma}}{\gamma_{th}}$ for the $N*$generalized $\mathcal{K}$ distributed channel with $N = 2, 3,$ and 4. For the sake of conciseness here and in all the following simulations, we assume without loss of generality that the channels are independent and identically distributed, i.e., $m_i = m$ and $\lambda_i = \lambda$. In Fig. 1, we notice that P_{out} improves as m increases and/or N decreases. Indeed, as fading becomes less severe and/or the number of cascaded channels decreases, the probability that any of the cascaded channels is in deep fade decreases significantly. In Fig. 2, the probability of outage deteriorates as shadowing becomes heavier, i.e., when λ decreases. Notice that the effect of the shadowing spread is more pronounced compared to the effect of the fading severity.

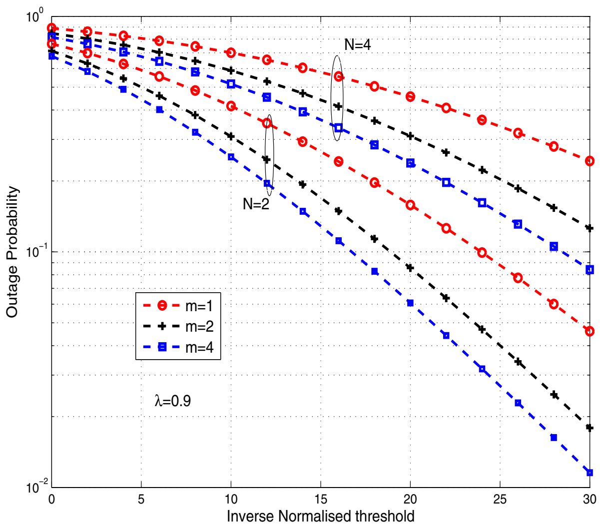

Fig. 1. Outage probability as a function of the inverse normalized threshold for $N*$generalized channels with different values of N and the fading severity parameter m.

C. Average Symbol Error Rate

The average symbol error probability constitutes probably the most important performance measure of a digital communication system and is given by:

$$P_{ae} = \int_0^\infty P_e(y) f_\gamma(y) dy, \quad (17)$$

where $P_e(y)$ is the conditional error probability (CEP) having generic expressions for different sets of modulation schemes.

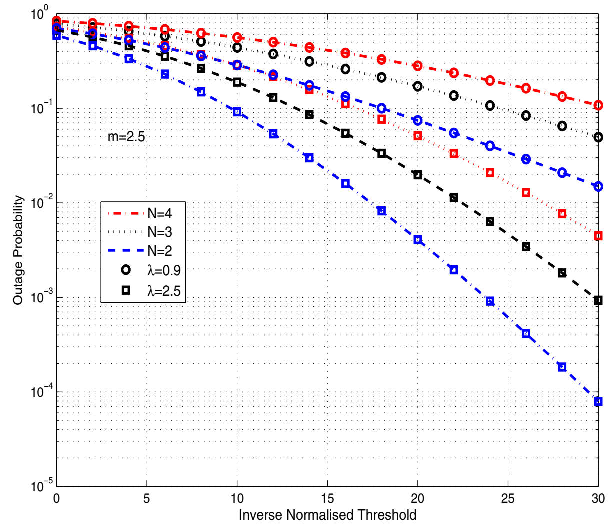

Fig. 2. Outage probability as a function of the inverse normalized threshold for $N*$generalized $\mathcal{K}$ channels with different values of N and the shadowing spread.

1) Binary modulations: For binary modulations, the CEP is given by [12]:

$$P_e(\gamma) = \frac{\Gamma(b, a\gamma)}{2\Gamma(b)}, \quad (18)$$

where $\Gamma(\alpha, x) = \int_x^\infty z^{\alpha-1}e^{-z}dz$ denotes the complementary incomplete gamma function, and $(a, b) = (1, 0.5)$ for binary phase shift keying (BPSK), $(a, b) = (0.5, 0.5)$ for coherent frequency binary shift keying (BFSK) and $(a, b) = (1, 1)$ for differential BPSK (DBPSK). By recognizing that

$$P_e(\gamma) = \frac{1}{2\Gamma(b)} G_{1,2}^{2,0}\left(a\gamma \middle| \begin{matrix} 1 \\ 0, b \end{matrix}\right), \quad (19)$$

the average bit error rate can be calculated by inserting (19) and (12) into (17), yielding with the help of [19], the following expression:

$$P_{ae} = \frac{1}{2\Gamma(b)\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)} G_{2,2N+1}^{2N,2}\left(\frac{\prod_{i=1}^{N} m_i\lambda_i}{a\bar{\gamma}} \middle| \begin{matrix} 1, 1-b \\ \lambda_1, m_1, \ldots\ldots, \lambda_N, m_N, 0 \end{matrix}\right). \quad (20)$$

2) M-ary modulations: For higher values of the average input SNR, the CEP for QPSK and M-QAM with rectangular constellation is given by [12] as

$$P_e(\gamma) = a\,\mathrm{erfc}(\sqrt{b\gamma}), \quad (21)$$

where $(a, b) = (1, \frac{1}{2})$ for QPSK and $(a, b) = (2(\sqrt{M} - 1)/\sqrt{M}, 3/2(M-1))$ for M-QAM. Recognizing that

$$\mathrm{erfc}(\sqrt{z}) = \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0}\left(z \middle| \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix}\right), \quad (22)$$

the average bit error rate simplifies to:

$$P_{ae} = \frac{a}{\sqrt{\pi}\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)} G_{2,2N+1}^{2N,2}\left(\frac{\prod_{i=1}^{N} m_i\lambda_i}{b\bar{\gamma}} \left| \begin{array}{c} 1, \frac{1}{2} \\ \lambda_1, m_1, \ldots\ldots, \lambda_N, m_N, 0 \end{array} \right.\right). \tag{23}$$

In Fig. 3, the average bit error rate of the $N*$generalized $\mathcal{K}$ channels with $N = 2, 3,$ and 4 is plotted. As expected, the average bit error probability deteriorates as the number of cascaded channels increases and the fading severity parameter m decreases. It is also noted that a similar behavior has also been observed for P_{out} (see Fig. 1).

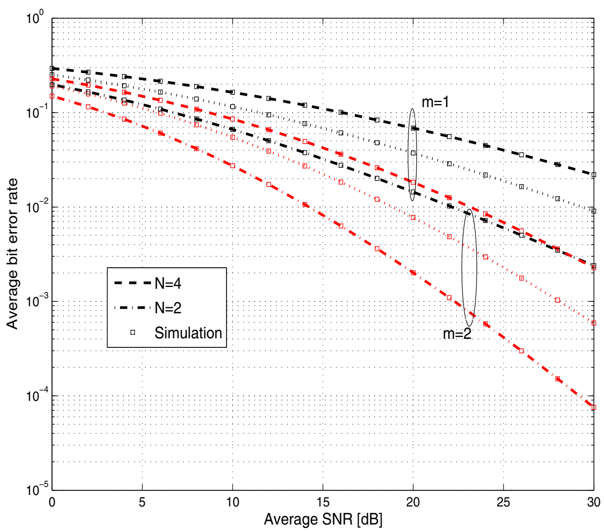

Fig. 3. BPSK error probability in N i.i.d generalized $\mathcal{K}$ channels ($\bar{\gamma}_i = \bar{\gamma}, \lambda_i = \lambda = 0.9$ and $m_i = m = \{1, 2\}$).

D. Average Channel Capacity

We consider an adaptive transmission scheme where optimal rate adaptation with constant transmit power is applied. This scheme entails variable-rate transmission relative to the channel, but is rather practical since the transmit power remains constant. The average channel capacity is known to be given by [12] as

$$C = \int_0^{\infty} \log_2(1+y) f_{\gamma}(y) dy. \tag{24}$$

After inserting (12) in (24), the logarithm function is firstly transformed as

$$\ln(1+z) = G_{2,2}^{1,2}\left(z \left| \begin{array}{c} 1, 1 \\ 1, 0 \end{array} \right.\right). \tag{25}$$

After using the classical Meijer's integral from two G functions [19], the channel capacity can be expressed as

$$C = \frac{1}{\ln(2)\prod_{i=1}^{N}\Gamma(m_i)\Gamma(\lambda_i)} G_{2,2N+2}^{2N,1}\left(\frac{\prod_{i=1}^{N} m_i\lambda_i}{\bar{\gamma}} \left| \begin{array}{c} 0, 1 \\ \lambda_1, m_1, \ldots\ldots, \lambda_N, m_N, 0, 0 \end{array} \right.\right). \tag{26}$$

In Fig. 4, the average channel capacity under optimal rate adaptation is plotted as a function of the average SNR for the cascaded $N*$generalized $\mathcal{K}$ channel with $N = 1, 3,$ and 6 and $m = 1$. Both heavy ($\lambda = 0.9$) and light ($\lambda = 2.5$) shadowed environments have been considered. The results indicate that the higher the value of N or/and the lower value of λ, the lower is the capacity. Moreover, we notice that the effect of the shadowing spread increases with N.

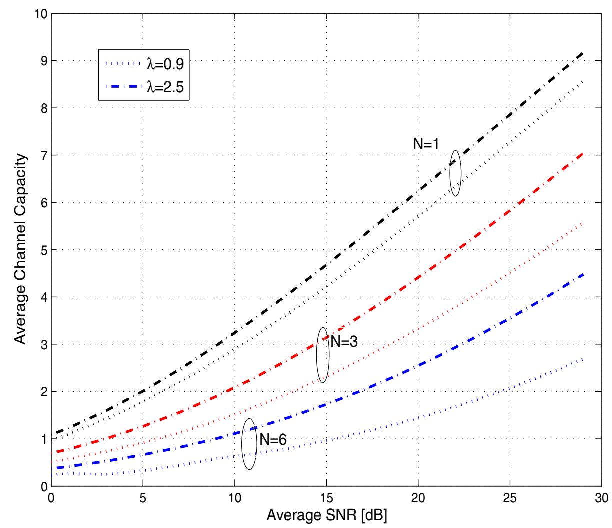

Fig. 4. Average channel capacity as a function of the average SNR for $m = 1$ and several values of N and λ.

IV. Conclusion

A new distribution referred to as cascaded $N*$generalized $\mathcal{K}$, constructed as the product of N statistically independent generalized $\mathcal{K}$ RVs was analyzed in this paper. Statistical characterization of this distribution was performed by deriving its MGF, PDF and CDF. A number of open research problems could be addressed using the obtained closed-form formulas. Indeed, in this paper we were able to conduct a performance analysis of a digital communication system operating over an $N*$generalized $\mathcal{K}$ cascaded channel. Closed-form expressions for the outage probability, the average symbol error rate and the channel capacity were therefore derived.

V. Appendix

The MGF of Y is given by:

$$M_Y(s) = \int_0^{\infty} \ldots \int_0^{\infty} e^{-sy_1\ldots y_N} f_{R_1}(y_1)\ldots f_{R_N}(y_N) dy_1 \ldots dy_N. \tag{27}$$

The first integration in (27) is with respect to y_1 and is given by:

$$\begin{aligned} I_1 &= \int_0^{\infty} e^{-sy_1\ldots y_N} f_{R_1}(y_1) dy_1 \\ &= C_1 \int_0^{\infty} e^{-(sy_2\ldots y_N)y_1} y_1^{\beta_1} K_{\alpha_1}(a_1 y_1) dy_1 \end{aligned} \tag{28}$$

Recognizing that

$$e^{-sy_1\ldots y_N} = G_{0,1}^{1,0}\left(sy_1 \ldots y_N \left| 0 \right.\right), \tag{29}$$

I_1 can be written in closed-form using [19] as

$$I_1 = \frac{C_1(\frac{a_1}{2})^{-\beta_1-1}}{\sqrt{\pi}} G_{2,2}^{2,2}\left(\frac{(sy_2\ldots y_N)^2}{a_1^2} \middle| \begin{matrix} \frac{1-\beta_1-\alpha_1}{2}, \frac{1-\beta_1+\alpha_1}{2} \\ 0, \frac{1}{2} \end{matrix}\right). \quad (30)$$

After some simplifications, we get

$$I_1 = \frac{1/\sqrt{\pi}}{\Gamma(m_1)\Gamma(\lambda_1)} G_{2,2}^{2,2}\left(\frac{(sy_2\ldots y_N)^2}{a_1^2} \middle| \begin{matrix} 1-\lambda_1, 1-m_1 \\ 0, \frac{1}{2} \end{matrix}\right). \quad (31)$$

The second integration in (27) is with respect to y_2

$$I_2 = \int_0^\infty y_2^{\beta_2} K_{\alpha_2}(a_2 y_2) G_{2,2}^{2,2}\left(\frac{(sy_3\ldots y_N)^2}{a_1^2} y_2^2 \middle| \begin{matrix} 1-\lambda_1, 1-m_1 \\ 0, \frac{1}{2} \end{matrix}\right) dy_2. \quad (32)$$

Using [19], I_2 is derived as:

$$I_2 = \frac{1}{\Gamma(m_2)\Gamma(\lambda_2)} G_{4,2}^{2,4}\left(\frac{4(sy_3\ldots y_N)^2}{a_1^2 a_2^2} \middle| \begin{matrix} 1-\lambda_1, 1-m_1, 1-\lambda_2, 1-m_2 \\ 0, \frac{1}{2} \end{matrix}\right). \quad (33)$$

Following the same procedure, the N-fold integral in (27) yields the MGF of the $N*$generalized $\mathcal{K}$ distribution which can be expressed as

$$M_Y(s) = \frac{1/\sqrt{\pi}}{\prod_{i=1}^N \Gamma(m_i)\Gamma(\lambda_i)} G_{2N,2}^{2,2N}\left(\frac{4\prod_{i=1}^N \frac{m_i\lambda_i}{\Omega_i}}{s^2} \middle| \begin{matrix} 1-\lambda_1, 1-m_1, \ldots, 1-\lambda_N, 1-m_N \\ 0, \frac{1}{2} \end{matrix}\right). \quad (34)$$

Finally, using the analytical continuation of the G-function given by:

$$G_{p,q}^{l,m}\left(z \middle| \begin{matrix} a_q \\ b_p \end{matrix}\right) = G_{q,p}^{m,l}\left(\frac{1}{z} \middle| \begin{matrix} 1-b_p \\ 1-a_q \end{matrix}\right), \quad (35)$$

we obtain the MGF expression in (3).

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