A Hybrid Satellite-Terrestrial Cooperative Network over Non Identically Distributed Fading Channels

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Abstract— **This paper investigates a hybrid satellite-terrestrial cooperative relaying communications network (HSTCN) under independent and non-identical shadowed Rician and Nakagami-m fading channels. It evaluates the performance of such a network using amplify-and-forward (AF) cooperative relaying protocol. The maximal ratio combining (MRC) technique is used at the destination to combine the signals received from the source and cooperating relay nodes. An analytical approach is derived to evaluate the performance of the system in terms of outage probability and symbol error rate (SER). The closed form expressions for the probability density function (PDF), cumulative distribution function (CDF) and moment generating function (MGF) of the end-to-end signal to noise ratio (SNR) are also derived. The derived analytical expressions are applied to the general operating conditions with the help of satellite channel data available from the literature. The analytical results are compared with Monte Carlo simulations. The results show the improvement in the performance of the HSTCN under challenging fading conditions with the help of fixed multiple terrestrial relay nodes.**

Index Terms— **Hybrid satellite-terrestrial, cooperative relay, amplify and forward, fading channels, combined probability density function, moment generating function, outage probability, symbol error rate.**

I. Introduction

The demand for high bit rate transmission supporting a variety of multimedia services is increasing day by day. Satellite technology can address this concern as it can be used to develop a global communication system. In this scenario, the differences between terrestrial and satellite communication systems as well as between fixed and mobile networks will cease to exist in the global coverage by wireless communication system.

Cooperative relaying networks are useful in the satellite-terrestrial networks as it can extend the satellite coverage especially in the areas where terrestrial networks are not able to provide services due to lack of coverage, emergency conditions, and network overloads. Many efficient physical layer techniques like adaptive coding and modulation (ACM), satellite channel modeling, synchronization and estimation are proposed, but these techniques are not able to provide satellite coverage inside buildings and shopping malls due to lack of signal from the satellites [1]. In such situations, a cooperative relaying satellite-terrestrial network can play an important role as it offers services inside covered areas as well as supports low cost user terminals with satellite transmission and reception capabilities. The relay node operates in two strategies, i.e. Amplify and Forward (AF), and Decode and Forward (DF) [2]. Hence, diversity gain can be achieved through multiple signal paths. As a result, a high data rate is achieved and transmission becomes more reliable in terms of symbol error rate (SER) and outage probability [2]. Many standardization groups have incorporated relaying techniques into their emerging standards such as IEEE 802.16 and IEEE 802.11 [3].

The concept of a hybrid satellite-terrestrial cooperative system is presented in [4]–[7]. In [4], transmit diversity technique using space time coding (STC) is proposed and diversity gain is achieved with the use of multiple terrestrial relay nodes with encoding capabilities, while additional coding gain can be achieved at the destination node by combining different parity symbols as shown in [5]. Moreover, a comparison of AF and DF techniques in a cooperative satellite communication network is discussed in [6]. In [8], the architecture of a satellite based mobile multimedia broadcasting is presented, while cooperative relaying for DVB-SH is discussed in [9] - [10]. The outage performance of multiple relay cooperative system using Nakagami-m fading channel is discussed in [11] - [12].

In a cooperative relaying satellite-terrestrial system, a hybrid channel consisting of satellite and terrestrial components is perceived by the destination node. Furthermore, the conventional channel models used in terrestrial radio propagation cannot be used to characterize the satellite channel because of the remarkable differences observed in the line-of-sight (LOS) and shadowing links. In order to model such a satellite channel, a combination of different probability distributions is necessary [13]. In [5]–[7] and [14], a hybrid satellite-terrestrial channel is considered in which fadings in the source(satellite)-relay (S-R) and source(satellite)-destination (S-D) links are assumed to be Rician distributed, while Rayleigh fading is assumed between the relay-destination (R-D) link. In [4], [10] and [15], lognormal distribution is considered in S-R and S-D links. While evaluating the BER performance of single

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and multichannel reception, lognormal based models can be complex especially for the mathematical computations. Thus, the shadowed Rician channel model [16] which is simple and accurate in terms of mathematical computations and much closer to the measured satellite data can be used.

In this paper, we investigate the performance of multi-hop AF HSTCN under non-identically distributed fading links between $S \rightarrow D$, $S \rightarrow R_i$ and $R_i \rightarrow D$. To the best of our knowledge, the performance analysis of a HSTCN over independent and non-identically shadowed Rician and Nakagami-m fading channels with closed form analytical expressions has not yet been investigated. Hence, we derive the closed form expressions to evaluate the performance in terms of outage probability and SER for some important modulation schemes under various fading scenarios. We also compare the theoretical results with Monte Carlo simulations of these different scenarios.

Section II of this paper introduces the network and fading models. In Section III, we derive the closed form expressions for the combined PDF, CDF and MGF of the bounded end-to-end SNR of the relay path. The Land Mobile satellite Channel (LMSC) parameters for various fading conditions are used to analyze the performance of the system in Section IV. Finally, concluding remarks are given in Section V.

Mathematical Notations and Functions: $X \rightarrow Y$ describes the link between node X and Y, $E[\cdot]$ denotes the expectation. $K_v(\cdot)$, ${}_1F_1(\cdot,\cdot,\cdot)$, $\Gamma(\cdot)$, γ_{xy}, $\bar{\gamma}_{xy}$, $\mathcal{M}_\gamma(s)$ and ${}_2F_1(\cdot,\cdot,\cdot;\cdot)$ denote the vth order modified Bessel function of the second kind, the hypergeometric function, gamma function, instantaneous SNR of the $X \rightarrow Y$ link, average SNR of the $X \rightarrow Y$ link, the MGF of the equivalent SNR (γ) and the Gauss hypergeometric function, respectively.

II. SYSTEM MODEL

A. Network Model

A HSTCN with multiple cooperative terrestrial fixed relays (R_i) where $i = 1...,N$ and single destination (D) is assumed as shown in Fig. 1. Independent and non-identical fading paths exist between the source (S), N relay nodes and the destination. It is assumed that each node is equipped with single antenna. The source transmits information signal to the relay nodes and the destination. The independent faded copies of the information signal are received at the destination node, one directly from the satellite and the other through the N relay nodes. This technique of transmitting information from different locations makes communication possible even in bad channel conditions and provides spatial diversity at the destination. To explain the system in a less complex manner, the AF cooperative protocol is used at all relay nodes to forward information received from a source to the destination node, where the distance between the relay nodes and a stationary destination node is same. Specifically, the whole transmission is accomplished in two phases as illustrated in Fig. 1. In the first phase

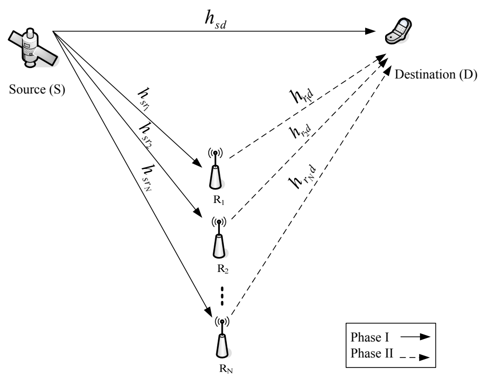

Figure 1. System model of a hybrid satellite-terrestrial cooperative network

of cooperative communication, the source broadcast the signal (information), destination and N terrestrial relay nodes receive. In the second phase, the relay nodes amplified the receive signal and forward the scaled version of the signal to the destination while the source keeps silent. The destination node combines all received signals from the source and N relays using MRC. Further, for the sake of mathematical tractability it is assumed that the signals transmitted by the source and relay nodes are perfectly synchronized at the destination node.

B. Fading Model

In the proposed system independent and non-identical fading channels are assumed. The shadowed Rician distribution is assumed between $S \rightarrow D$, and $S \rightarrow R_i$, which is a more accurate distribution for analyzing the performance of wireless land mobile satellite communication (LMSC) systems [16]. The fading coefficient for $S \rightarrow D$ and R_i nodes are represented as h_{sd} and h_{sr_i} respectively as shown in Fig. 1. The channel coefficient between $R_i \rightarrow D$ follows the Nakagami-m distribution because there are multiple paths due to small buildings, trees and other objects and fading coefficient is denoted by $h_{r_i d}$. The instantaneous SNR of the combined signal at the output of MRC at the destination node can be written as:

$$\gamma_{\text{MRC}} = \gamma_{\text{sd}} + \sum_{i=1}^{N} \gamma_{r_i} \tag{1}$$

where $\gamma_{sd} = |h_{sd}|^2 E_s/N_0$ is the instantaneous SNR of the $S \rightarrow D$ and γ_{r_i} is the instantaneous SNR between the source and *i*th relay, and between the *i*th relay and destination. For the tractable analytical evaluation of outage probability and SER, γ_{r_i}, can be determined by

$$\gamma_{r_i} = \frac{\gamma_{\text{sr}_i}\gamma_{r_i d}}{\gamma_{\text{sr}_i} + \gamma_{r_i d}} \tag{2}$$

where $\gamma_{sr_i} = |h_{sr_i}|^2 E_s/N_0$ is the instantaneous SNR of $S \rightarrow R_i$ channel while $\gamma_{r_i d} = |h_{r_i d}|^2 E_{r_i}/N_0$ is the instantaneous SNR of $R_i \rightarrow D$ channel. While E_s and E_{r_i} are the transmit power of the S and the R_i node. The received noise at the *i*th relay and at the destination node is modeled as additive white Gaussian (AWGN) noise with variance N_0. Fading coefficients between the $S \to D$ and $S \to R_i$ are assumed as shadowed Rician distribution and PDF of SNR per symbol is given by [16] as

$$f_{\gamma_{\text{xy}}}(\gamma) = \frac{1}{2b_o\bar{\gamma}_{\text{xy}}}\left(\frac{2b_om_o}{2b_om_o+\Omega}\right)^{m_o}\exp\left(\frac{-\gamma}{2b_o\bar{\gamma}_{\text{xy}}}\right) \times {}_1F_1\left(m_o,1,\frac{\Omega\gamma}{2b_o\bar{\gamma}_{\text{xy}}\left(2b_om_o+\Omega\right)}\right) \quad (3)$$

Here, Ω is the average power of the LOS component, $2b_o$ is the average power of the multipath component. Here, m_o is allowed to vary over the wider range of $m_o \geq 0$. We can model different types of LOS conditions for the land mobile satellite channels, i.e. very small values of m_o corresponds to the urban areas, while the value of $0 < m_o < \infty$ is associated with suburban and rural areas with partial obstruction of the LOS.

The PDF of the instantaneous SNR per symbol between the $R_i \to D$ is distributed according to the Nakagami-m distribution which covers a broad variety of fading scenarios for the different values of m-fading parameter [17],

$$f_{\gamma_{r_id}}(\gamma) = \frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_{r_id}}\right)^m\gamma^{m-1}\exp\left(-\frac{m}{\bar{\gamma}_{r_id}}\gamma\right) \quad (4)$$

where m is the traditional Nakagami multipath fading parameter which ranges from ≥ 0.5 to ∞.

III. Performance Analysis

This section presents a comprehensive performance analysis of the proposed HSTCN. The PDF, CDF and MGF of the end-to-end relaying SNR, γ_{r_i}, are derived, and based on such statistics, we obtained exact closed form expressions of the outage probability and symbol error rate (SER).

A. Statistical characterization of end-to-end relaying SNR

The combined PDF of two independent and non-identical distributions (3) and (4), can be calculated by using [18], (as explained in Appendix A) and expressed as the following equation,

$$\begin{aligned} f_{\gamma_{r_i}}(\gamma) = {} & \frac{1}{2b_o\bar{\gamma}_{\text{sr}_i}}\left(\frac{2b_om_o}{2b_om_o+\Omega}\right)^{m_o}\frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_{r_id}}\right)^m \\ & \times \exp\left[-\left(\frac{1}{2b_o\bar{\gamma}_{\text{sr}_i}}+\frac{m}{\bar{\gamma}_{r_id}}\right)\gamma\right]\sum_{x=0}^{\infty}\frac{1}{(x!)} \\ & \times \frac{\Gamma(m_o+x)}{\Gamma(m_o)\Gamma(1+x)}\lambda^x\sum_{y=0}^{m+x+1}\binom{m+x+1}{y} \\ & \times 2\gamma^{m+x}\left(\sqrt{\frac{\bar{\gamma}_{r_id}}{2b_om\bar{\gamma}_{\text{sr}_i}}}\right)^{m-y} \\ & \times K_{(m-y)}\left(2\gamma\sqrt{\frac{m}{2b_o\bar{\gamma}_{\text{sr}_i}\bar{\gamma}_{r_id}}}\right) \end{aligned} \quad (5)$$

where $\lambda = \left(\frac{\Omega}{2b_o\bar{\gamma}_{\text{sr}_i}(2b_om_o+\Omega)}\right)$. The average SNR between $S \to R_i$ is represented by $\bar{\gamma}_{sr_i} = E_s/N_0$ while $\bar{\gamma}_{r_id} = E_{r_i}/N_0$ is the average SNR between $R_i \to D$. The following are some special cases where the above derived PDF can be applicable.

Case 1: Applying $m_o = 0$ and $m = 1$ in (5), the link from $S \to R_i$ and $R_i \to D$ is converted into a Rayleigh distribution. The combined PDF of the independent and non-identical Rayleigh channels can be calculated using (6), the result of which is the same as that obtained in [12]

$$\begin{aligned} f_{\gamma_{r_i}}(\gamma) = {} & \frac{2\gamma}{\bar{\gamma}_{sr_i}\bar{\gamma}_{r_id}}\exp\left[-\left(\frac{1}{\bar{\gamma}_{sr_i}}+\frac{1}{\bar{\gamma}_{r_id}}\right)\gamma\right]\Bigg[2K_0 \\ & \times\left(\frac{2\gamma}{\sqrt{\bar{\gamma}_{sr_i}\bar{\gamma}_{r_id}}}\right)+\left(\sqrt{\frac{\bar{\gamma}_{sr_i}}{\bar{\gamma}_{r_id}}}+\sqrt{\frac{\bar{\gamma}_{r_id}}{\bar{\gamma}_{sr_i}}}\right) \\ & \times K_1\left(\frac{2\gamma}{\sqrt{\bar{\gamma}_{sr_i}\bar{\gamma}_{rd_i}}}\right)\Bigg] \end{aligned} \quad (6)$$

Case 2: In this case substituting $m_o = \infty$ in (5), the link between $S \to R_i$ act as Rician distribution. While if $m = 1$ in (5), the channel between $R_i \to D$ works as a Rayleigh distribution and the expression (7) is obtained,

$$\begin{aligned} f_{\gamma_{r_i}}(\gamma) = {} & \frac{(1+K_{sr_i})}{\bar{\gamma}_{sr_i}\bar{\gamma}_{r_id}}\exp\left(-K_{sr_i}-\mu\right)\sum_{x=0}^{\infty}\frac{1}{(x!)^2} \\ & \times\left(\frac{K_{sr_i}(1+K_{sr_i})}{\bar{\gamma}_{sr_i}}\right)^x\sum_{k=0}^{x+2}\binom{x+2}{k} \\ & \times 2\gamma^{x+1}\left(\sqrt{\frac{(1+K_{sr_i})\bar{\gamma}_{rd_i}}{\bar{\gamma}_{sr_i}}}\right)^{(1-k)} \\ & \times K_{(1-k)}\left(2\gamma\sqrt{\frac{(1+K_{sr_i})}{\bar{\gamma}_{sr_i}\bar{\gamma}_{r_id}}}\right) \end{aligned} \quad (7)$$

where $\mu = \frac{(1+K_{sr_i})\gamma}{\bar{\gamma}_{sr_i}} - \frac{\gamma}{\bar{\gamma}_{r_id}}$. This is the combined PDF of two independent and non-identical Rician and Rayleigh fading channels as shown in [19].

An exact closed form expression for the CDF of the end-to-end relaying SNR γ_{r_i}, in (2) can be derived as

$$\begin{aligned} F_{\gamma_{r_i}}(\gamma) = {} & 1-\frac{1}{2b_o\bar{\gamma}_{\text{sr}_i}}\left(\frac{2b_om_o}{2b_om_o+\Omega}\right)^{m_o}\sum_{n=0}^{m-1}\frac{1}{n!} \\ & \times\left(\frac{m}{\bar{\gamma}_{r_id}}\right)^n\text{Exp}\left[-\gamma\left(\frac{1}{2b_o\bar{\gamma}_{\text{sr}_i}}+\frac{m}{\bar{\gamma}_{r_id}}\right)\right] \\ & \times\sum_{k=0}^{\infty}\frac{1}{k!}\frac{\Gamma(m_o+k)}{\Gamma(m_o)\Gamma(1+k)}\lambda^k\sum_{j=0}^{n+k}\binom{n+k}{j} \\ & \times 2\gamma^{n+k+1}\left(\sqrt{\frac{2b_om\bar{\gamma}_{\text{sr}_i}}{\bar{\gamma}_{r_id}}}\right)^{k-j+1} \\ & \times K_{k-j+1}\left(2\gamma\sqrt{\frac{m}{2b_o\bar{\gamma}_{\text{sr}_i}\bar{\gamma}_{r_id}}}\right) \end{aligned} \quad (8)$$

*P*roof: The proof is provided in Appendix B

The MGF-based approach is a simple and efficient method to evaluate the average SER and outage probability in fading conditions and the MGF can be obtained from the expression given by

$$\mathcal{M}_{\gamma_{r_i}}(s) = E\left[e^{-s\gamma}\right] \quad (9)$$

$$\begin{aligned}\mathcal{M}_{\gamma_{r_i}}(s) =& \tfrac{1}{2b_o\bar{\gamma}_{sr_i}}\left(\tfrac{2b_om_o}{2b_om_o+\Omega}\right)^{m_o}\tfrac{1}{\Gamma(m)}\left(\tfrac{m}{\bar{\gamma}_{r_id}}\right)^{m}\sum_{x=0}^{\infty}\tfrac{1}{x!}\tfrac{\Gamma(m_o+x)}{\Gamma(m_o)\Gamma(1+x)}\lambda^x\sum_{y=0}^{m+x+1}\binom{m+x+1}{y}\\ &\times 2\left(\sqrt{\tfrac{\bar{\gamma}_{r_id}}{2b_om\bar{\gamma}_{sr_i}}}\right)^{m-y}\tfrac{\sqrt{\pi}(2\beta)^{m-y}}{(\alpha+\beta)^{2m+x-y+1}}\tfrac{\Gamma(2m+x-y+1)\Gamma(x+y+1)}{\Gamma(m+x+3/2)}\\ &\times {}_2F_1\left(2m+x-y+1, m-y+\tfrac{1}{2}, m+x+\tfrac{3}{2}, \tfrac{\alpha-\beta}{\alpha+\beta}\right)\end{aligned} \tag{10}$$

In order to provide a powerful tool for calculating the average SER and outage probability, a closed form expression for the MGF can be obtained using the combined PDF given in (5). After some mathematical manipulations and from [18], the MGF of γ_{r_i} is expressed as in (10). where

$$\alpha = \left[\frac{1}{2b_o\bar{\gamma}_{sr_i}} + \frac{m}{\bar{\gamma}_{r_id}} + s\right] \tag{11}$$

and

$$\beta = 2\sqrt{\frac{m}{2b_o\bar{\gamma}_{sr_i}\bar{\gamma}_{r_id}}} \tag{12}$$

After substituting (3) in (9) and using [18], the MGF of γ_{sd} can be shown as

$$\mathcal{M}_{\gamma_{\text{sd}}}(s) = \frac{(2b_om_o)^{m_o}(2b_os\bar{\gamma}_{\text{sd}}+1)^{m_o-1}}{[(2b_om_o+\Omega)(2b_os\bar{\gamma}_{\text{sd}}+1)-\Omega]^{m_o}} \tag{13}$$

where $\bar{\gamma}_{\text{sd}} = E_s/N_0$ is the average SNR of $S \to D$. Using the assumed non-identical fading channels, a closed form expression of the moment generating function of γ_{ub} can be obtained by multiplying the MGF of the γ_{sd} and γ_{r_i}

$$\mathcal{M}_{\gamma_{\text{ub}}}(s) = \mathcal{M}_{\gamma_{\text{sd}}}(s)\prod_{i=1}^{N}\mathcal{M}_{\gamma_{r_i}}(s) \tag{14}$$

B. Outage Probability

1) Without direct link: In this scenario, it is assumed that the link between $S \to D$ is not available due to heavy shadowing and the source is communicating with destination node with the help of multiple fixed relay nodes. In noise limited systems, outage probability is an important performance measure and is defined as the probability that the received SNR, γ_{r_i}, falls below a certain threshold value γ_{th}. This threshold is a protection value for the SNR, below of which the quality of service is deemed to be unsatisfactory. The outage probability of dual hop system without direct link can be obtained by using (8) as follows

$$P_{\text{outage}}^{w/o} = F_{\gamma_{r_i}}(\gamma_{th}) \tag{15}$$

2) With MRC (direct and relaying path): Consider the case when the destination node is receiving the signal from multiple fixed relays and as well as from the source node. In this case the outage probability at the destination node is given by

$$P_{\text{outage}} = \Pr[\gamma_{\text{MRC}} < \gamma_{\text{th}}] \tag{16}$$

where $\gamma_{\text{th}} = 2^{2R} - 1$. The SNR can be approximated by its upper bound

$$\gamma_{\text{MRC}} = \gamma_{\text{ub}} = \gamma_{\text{sd}} + \gamma_{r_i} \tag{17}$$

Therefore, the outage probability can be written as

$$P_{\text{outage}} = \Pr[\gamma_{\text{ub}} < \gamma_{\text{th}}] \tag{18}$$

Moreover, the closed form expression of $\mathcal{M}_{\gamma_{\text{ub}}}(s)$ can be used to calculate the outage probability as

$$P_{\text{outage}} = \mathcal{L}^{-1}\left(\frac{\mathcal{M}_{\gamma_{\text{ub}}}(s)}{s}\right)\Bigg|_{\gamma_{\text{th}}} \tag{19}$$

where $\mathcal{L}^{-1}$ is the inverse Laplace transform. Using MGF-based approach, the end-to-end outage probability can be calculated by using any of the numerical techniques [20]-[21].

C. Symbol Error Rate

1) Without direct link: The average SER (ASER) rate is one of the important measures of the performance of wireless communication systems. The ASER of the various commonly used modulation schemes at certain SNR is shown in [17] and can be obtained as follows

$$P_{\text{ASER}}^{w/o} = aQ\left(\sqrt{b\gamma}\right) \tag{20}$$

where $Q(\cdot)$ is the Gaussian Q function which is defined as $Q(\alpha) = \frac{1}{\sqrt{2\pi}}\int_{\alpha}^{\infty}\exp\left(-\frac{t^2}{2}\right)dt$, and a and b are constants depending upon the specific modulation type. For example, $(a = 1, b = 2)$ and $(a = 1, b = 1)$ are used to calculate the exact bit error rate (BER) of binary phase shift keying (BPSK) and binary frequency shift keying (BFSK), respectively. Similarly, for the SER of M-PAM $(a = 2(M-1)/M)$ and $(b = 6\log_2 M \big/ M^2 - 1)$ are used. Further, the SER of other modulation schemes have approximate forms such as *M*-PSK $(a = 2, b = 2\sin^2\pi/M$ and *M*-ary quadrature amplitude modulation (M-QAM) $(a = 4, b = 3/(M-1))$. The results in this study show that there is a close approximation for these modulation schemes.

An accurate closed form expression for the average SER approximation can be obtained by integrating $P_{\text{ASER}}^{w/o}$ over the CDF of the relaying SNR γ_{r_i} as follows:

$$P_{\text{ASER}}^{w/o} = \frac{a}{\sqrt{2\pi}}\int_0^{\infty}F_{\gamma_{r_i}}\left(\frac{x^2}{b}\right)\exp\left(\frac{x^2}{2}\right)dx \tag{21}$$

By using (8) and after some variable transformations, and applying [18, eq.(6.619.3)], the exact closed form expression of the relaying path can be calculated as shown in (22), with the value of α and β given in (23) and (24)

$$\alpha = \frac{1}{2b_o\bar{\gamma}_{sr_i}b} + \frac{m}{b\bar{\gamma}_{r_id}} + \frac{1}{2} \tag{23}$$

$$\begin{aligned} P^{w/o}_{\text{ASER}} = & \frac{a}{2} - \frac{1}{2b_o\bar{\gamma}_{sr_i}} \left(\frac{2b_o m_o}{2b_o m_o+\Omega}\right)^{m_o} \sum_{n=0}^{m-1} \frac{1}{n!} \left(\frac{m}{\bar{\gamma}_{r_i d}}\right)^{n} \sum_{x=0}^{\infty} \frac{1}{x!} \frac{\Gamma(m_o+x)}{\Gamma(m_o)\Gamma(1+x)} \left(\frac{\Omega}{2b_o\bar{\gamma}_{sr_i}(2b_o m_o+\Omega)}\right)^{x} \sum_{y=0}^{n+x} \\ & \times \binom{n+x}{y} \left(\sqrt{\frac{2b_o m\bar{\gamma}_{sr_i}}{\bar{\gamma}_{r_i d}}}\right)^{x-y+1} \frac{a}{\sqrt{2}b^{n+2x-y+2}} \left(4\sqrt{\frac{m}{2b_o\bar{\gamma}_{sr_i}\bar{\gamma}_{r_i d}}}\right)^{x-y+1} \frac{\Gamma(n+2x-y+5/2)\Gamma(n+y+1/2)}{(\alpha+\beta)^{n+2x-y+5/2}\Gamma(n+x+2)} \\ & \times {}_2F_1\left(n+2x-y+5/2, x-y+3/2, n+x+2, \frac{\alpha-\beta}{\alpha+\beta}\right) \end{aligned} \quad (22)$$

and

$$\beta = \frac{2}{b}\sqrt{\frac{m}{2b_o\bar{\gamma}_{sr_i}\bar{\gamma}_{r_i d}}} \quad (24)$$

Equation (22) provides a simple and efficient way of evaluating the error rate performance of all modulation schemes that have SER of form indicated in (20).

2) With MRC (direct and relaying path): A unified MGF based approach which is an easy and efficient method to evaluate the SER performance of wireless systems, is given as:

$$P_{\text{ASER}} = a\int_0^{b\pi} \mathcal{M}_{\gamma_{\text{sd}}}(g; \bar{\gamma}_{\text{sd}}) \prod_{i=1}^{N} \mathcal{M}_{\gamma_{r_i}}(g; \bar{\gamma}_{\text{sr}_i}, \bar{\gamma}_{r_i d})\, d\theta \quad (25)$$

where the parameters a, b and g are determined by the the specific modulation type used. For *M*-ary phase shift keying (MPSK) and *M*-ary quadrature amplitude modulation (MQAM) these values are given as:

MPSK: $a = \frac{1}{\pi}$, $b_{PSK} = \frac{M-1}{M}$, $g = sin^2\left(\frac{\pi}{M}\right)$

MQAM:

$a_1 = \frac{4}{\pi}\left(1 - \frac{1}{\sqrt{M}}\right)$, $b_1 = \frac{1}{2}$, $g_1 = \frac{3}{2(M-1)}$

$a_2 = \frac{4}{\pi}\left(1 - \frac{1}{\sqrt{M}}\right)^2$, $b_2 = \frac{1}{4}$, $g_2 = \frac{3}{2(M-1)}$

IV. Numerical and Simulation Results

This section presents the numerical and simulation results of SER and the outage probability of a hybrid satellite-terrestrial cooperative system under non-identical fading channels. About 10^7 BPSK and QPSK symbols are randomly generated for simulation in the Matlab. The AWGN samples are complex Gaussian variables with zero mean and variance N_0, while the three channel variables, such as the shadowed Rician h_{sr_i}, h_{sd} and Nakagami $h_{r_i d}$ are independently generated. The analytical results are evaluated using the Mathematica program. The performance curves of the direct path under the shadowed Rician fading and the relaying path under shadowed Rician and Nakagami-m fading with cooperative MRC at destination are plotted in terms of outage probability and SER versus the average SNR of the transmitted signal. Since, the source transmits simultaneously to the destination and to the relay nodes, the signal energy through the links $S \rightarrow D$ and $S \rightarrow R$ is same. We have assumed that the channel between the source and the relay nodes has LOS communication $(m_o = 26)$ and the channel between the relay and destination node experience multipath fading. In this case we can allocate equal power at both the source and relay nodes [6]. The targeted threshold rate R is chosen as 1 bit/sec/Hz

TABLE I.
Land mobile satellite channel parameters [16]

Channel state	m_o	b_o	Ω
Frequent deep shadowing	2.56	0.0158	0.123
Moderate shadowing	7.64	0.0129	0.372
Infrequent light shadowing	26	0.005	0.515

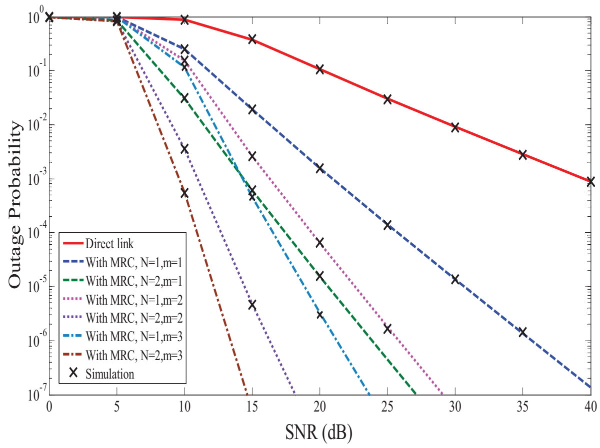

Figure 2. Outage probability versus the SNR performance of the proposed system when the direct channel experience the deep fading, $m_o = 2.56$, $S \rightarrow R_i$ channel have LOS, $m_o = 26$, and the $R_i \rightarrow D$ channel experience Nakagami-m fading associated with $m = 1, 2, 3$

to evaluate the outage probability of the system. The numerical values of the LMSC are taken from [16], as shown in Table. I. The LMSC parameter m_o in the direct channel and relay channel shows the intensity of fading. The m_o values in Table. I decreases as the amount of fading increases. We show the analytical results by the colored curves while the simulation results are shown by $(\times)$ mark on all the figures for comparison.

Firstly, the outage probability performance in relation to the average SNR using different number of relay nodes $(N = 1, 2)$ is determined. Fig. 2 compares the performance of the hybrid satellite-terrestrial cooperative system at multiple relay nodes in different and non-identical fading channels. The LMSC parameter $m_o = 2.56$ shows deep fading in the direct path while the path between $S \rightarrow R_i$ is under light fading $(m_o = 26)$. It is observed from the figure that the outage probability decreases as the number of relay nodes and m increase. The figure further show that the system with cooperation performs better than the system without any cooperation in terms of outage probability. For example, at the outage probability of 10^{-3}, the system with $(N = 1, m = 1)$ and $(N = 2, m = 1)$ offers a gain of 19 dB and 26

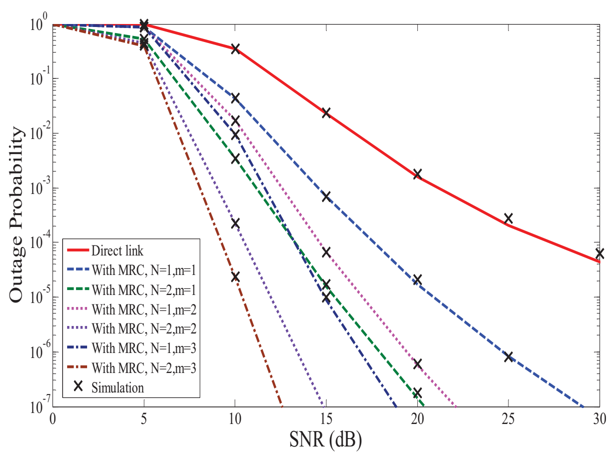

Figure 3. Outage probability versus the SNR performance of the proposed system when the direct channel experience the moderate fading, $m_o = 7.64$, $S \rightarrow R_i$ channel have LOS, $m_o = 26$, and the $R_i \rightarrow D$ channel experience Nakagami-m fading associated with $m = 1, 2, 3$

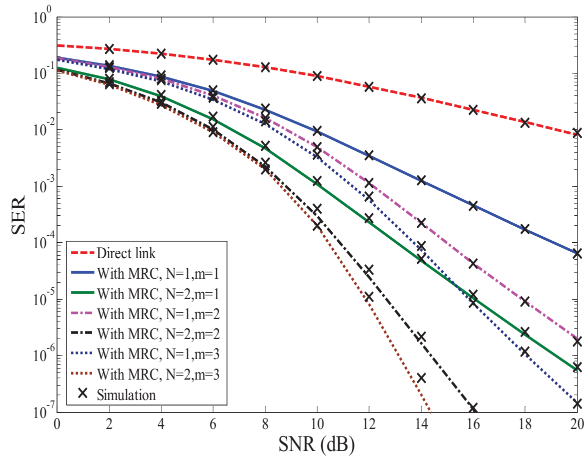

Figure 4. Symbol error rate (SER) versus the SNR performance of the proposed system using BPSK modulation scheme, when the direct channel experience the deep fading, $m_o = 2.56$, $S \rightarrow R_i$ channel have LOS, $m_o = 26$, and the $R_i \rightarrow D$ channel experience Nakagami-m fading associated with $m = 1, 2, 3$

dB over the system without cooperation. Similarly, the system with $(N = 2, m = 3)$ provides a gain of 3.5 dB over the system with $(N = 2, m = 2)$ at outage rate of 10^{-4}. At $m = 1$ the channel between $R_i \rightarrow D$ acts as Rayleigh fading. Fig. 3 illustrates the outage curves when the direct link of the destination with satellite suffers from moderate fading. It is also observed that the theoretical results agree quite well with the Monte Carlo simulations, confirming the accuracy of the analysis.

Fig. 4 shows the SER performance of the hybrid satellite-terrestrial system with and without cooperation using the BPSK baseband modulation scheme when the direct link is under deep fading at $m_o = 2.56$. The figure shows that the performance of the system gets better as the Nakagami factor m increases and the slope of the curve gets deeper. The system with $N = 2$ and $m = 1$, $N = 2$ and $m = 2$, and $N = 2$ and $m = 3$, produces cooperation gain of about 6 dB at the SER of 10^{-4}, 7 dB at the SER of 10^{-5}, and 5 dB at the SER of 10^{-6} respectively, over the system using single relay cooperative communication.

The case when the direct link is under moderate fading at $m_o = 7.64$ is presented in Fig. 5, where the system with $N = 2$ and $m = 1$, $N = 2$ and $m = 2$, and $N = 2$ and $m = 3$, produce cooperation gain of about 4.5 dB, 3.6 dB , and 3 dB at 10^{-6} respectively, over the system using single relay cooperative communication.

Furthermore, Fig. 6 shows the SER performance of the system that uses the QPSK baseband modulation scheme when the direct link is under deep fading at $m_o = 2.56$. The multiple relay satellite-terrestrial cooperative communication system with $N = 2$ and $m = 1$, $N = 2$ and $m = 2$, and $N = 2$ and $m = 3$, produces cooperation gain of about 5 dB at the SER of 10^{-3}, 4.5 dB at the SER of 10^{-4}, and 4.3 dB at the SER of 10^{-5} respectively, over the system using single relay cooperative communication. The case when the direct link is under moderate fading at $m_o = 7.64$ is presented in Fig. 7. The exact agreement

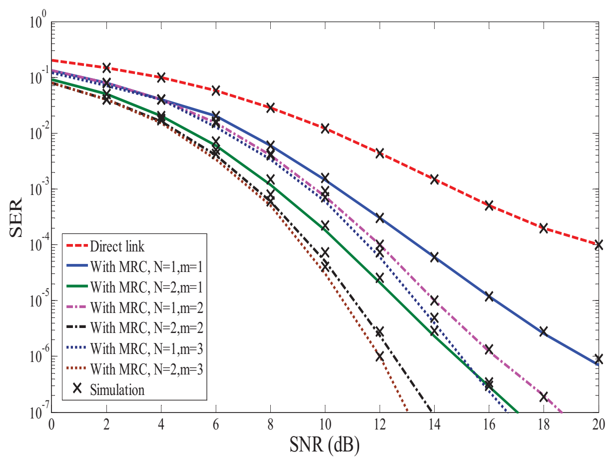

Figure 5. Symbol error rate (SER) versus the SNR performance of the proposed system using BPSK modulation scheme, when the direct channel experience the moderate fading, $m_o = 7.64$, $S \rightarrow R_i$ channel have LOS, $m_o = 26$, and the $R_i \rightarrow D$ channel experience Nakagami-m fading associated with $m = 1, 2, 3$

between the SER curves and the Monte Carlo simulation results validates the computational accuracy of our analysis.

V. Conclusion

In this paper, a rigorous analysis is carried out to derive the closed form expressions for the combined PDF, CDF and the MGF of non-identical relaying channel with bounded SNR. The results obtained are examined by evaluating the outage probability and the SER performances under various scenario of multiple relay hybrid satellite-terrestrial cooperative network using an AF protocol.

Using land mobile satellite channel statistical experimental data of different fading conditions obtained from literatures, the analyses of the study are verified using the results of the numerical computations and simulation.

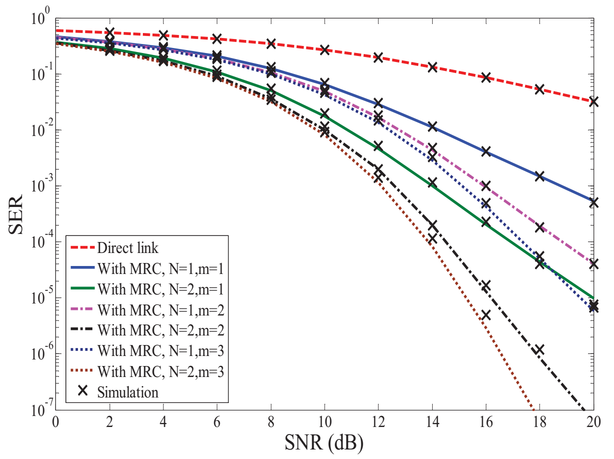

Figure 6. Symbol error rate (SER) versus the SNR performance of the proposed system using QPSK modulation scheme, when the direct channel experience the deep fading, $m_o = 2.56$, $S \rightarrow R_i$ channel have LOS, $m_o = 26$, and the $R_i \rightarrow D$ channel experience Nakagami-m fading associated with $m = 1, 2, 3$

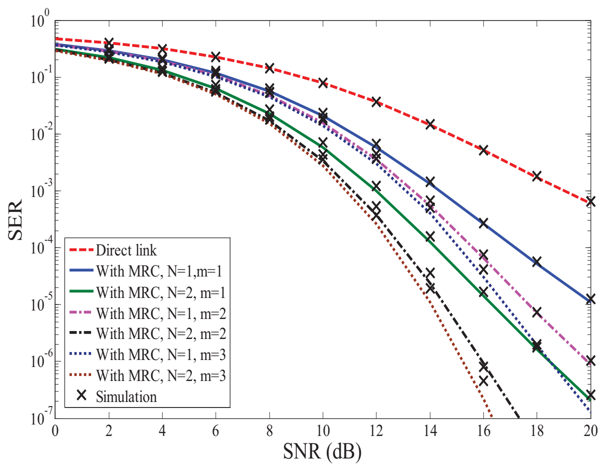

Figure 7. Symbol error rate (SER) versus the SNR performance of the proposed system using QPSK modulation scheme, when the direct channel experience the moderate fading, $m_o = 7.64$, $S \rightarrow R_i$ channel have LOS, $m_o = 26$, and the $R_i \rightarrow D$ channel experience Nakagami-m fading associated with $m = 1, 2, 3$

The results show that the multi-hop cooperative satellite-terrestrial communication has a diversity of advantages. The proposed system can provide a stable improved performance of future 4G services even in covered areas. The performance of the proposed system may also be extended to the DF cooperative communication scenario.

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Appendix I
Derivation of the Combined PDF of Relay Path $f_{\gamma_{r_i}}(\gamma)$

The combined PDF of two independent and non-identical distributions is given in [12] as

$$f_{\gamma_{r_i}}(\gamma) = \int_{\gamma}^{\infty} \frac{z^2}{(z-\gamma)^2} f_{\gamma_{\mathrm{sr}_i}}\left(\frac{\gamma z}{z-\gamma}\right) f_{\gamma_{r_i}}(z) dz \quad (26)$$

After applying $f_{\gamma_{\mathrm{sr}_i}}$ and $f_{\gamma_{r_i d}}$ from (3) and (4) in the above equation and carrying out some variable transformations, (26) can be written as

$$\begin{aligned} f_{\gamma_{r_i}}(\gamma) = &\frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}}\left(\frac{2b_o m_o}{2b_o m_o + \Omega}\right)^{m_o}\frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_{r_i d}}\right)^{m} \\ &\times \exp\left[-\left(\frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} + \frac{m}{\bar{\gamma}_{r_i d}}\right)\gamma\right]\int_0^{\infty}\left(\frac{z+\gamma}{z}\right)^{m+1} \\ &\times z^{m-1}\exp\left[-\left(\frac{\gamma^2}{2b_o\bar{\gamma}_{\mathrm{sr}_i} z} + \frac{mz}{\bar{\gamma}_{r_i d}}\right)\right] \\ &\times {}_1F_1\left(m_o, 1, \frac{\Omega\gamma(z+\gamma)}{2b_o\bar{\gamma}_{\mathrm{sr}_i}(2b_o m_o + \Omega) z}\right) dz \end{aligned} \quad (27)$$

Now substituting ${}_1F_1(\cdot,\cdot,\cdot)$ with series expression by using [18, eq.(9.14.1)], (27) can be written as

$$\begin{aligned} f_{\gamma_{r_i}}(\gamma) = &\frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}}\left(\frac{2b_o m_o}{2b_o m_o + \Omega}\right)^{m_o}\frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_{r_i d}}\right)^{m} \\ &\times \sum_{x=0}^{\infty}\frac{1}{x!}\gamma^{x}\frac{\Gamma(m_o + x)}{\Gamma(m_o)\Gamma(1+x)}\lambda^{x} \\ &\times \int_0^{\infty}\left(\frac{z+\gamma}{z}\right)^{m+x+1} z^{m-1} \\ &\times \exp\left[-\left(\frac{\gamma^2}{2b_o\bar{\gamma}_{\mathrm{sr}_i} z} + \frac{mz}{\bar{\gamma}_{r_i d}}\right)\right] dz \end{aligned} \quad (28)$$

Upon expanding the term $\left(1 + \frac{\gamma}{a}\right)^{m+x+1}$ according to [18, eq.(1.111)], we can reach

$$\begin{aligned} f_{\gamma_{r_i}}(\gamma) = &\frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}}\left(\frac{2b_o m_o}{2b_o m_o + \Omega}\right)^{m_o}\frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_{r_i d}}\right)^{m} \\ &\times \exp\left[-\left(\frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} + \frac{m}{\bar{\gamma}_{r_i d}}\right)\gamma\right]\sum_{x=0}^{\infty}\frac{1}{x!} \\ &\times \frac{\Gamma(m_o + x)}{\Gamma(m_o)\Gamma(1+x)}\lambda^{x} \\ &\times \sum_{y=0}^{m+x+1}\binom{m+x+1}{y}\gamma^{x+y}\int_0^{\infty} z^{m-y-1} \\ &\times \exp\left[-\left(\frac{\gamma^2}{2b_o\bar{\gamma}_{\mathrm{sr}_i} z} + \frac{mz}{\bar{\gamma}_{r_i d}}\right)\right] dz \end{aligned} \quad (29)$$

Now with the help of [18, eq.(3.471.9)], the combined PDF of $f_{\gamma_{r_i}}(\gamma)$ can be shown as (5).

Appendix II
Derivation of Relay Path CDF $F_{\gamma_{r_i}}(\gamma)$

The PDF of SNR per symbol of $S \rightarrow R_i$ link is given in (4) and the CDF of $R_i \rightarrow D$ link for the integer values of m is given by

$$\Gamma\left(m, \frac{m\gamma}{\bar{\gamma}_{r_i d}}\right) = 1 - \exp\left(-\frac{m\gamma}{\bar{\gamma}_{r_i d}}\right) \sum_{n=0}^{m-1} \frac{1}{n!} \left(\frac{m\gamma}{\bar{\gamma}_{r_i d}}\right)^n \tag{30}$$

Then, the CDF of the relaying path can be calculated with the help of (2) as

$$\begin{aligned}
F_{\gamma_{r_i}}(\gamma) &= \Pr\left(\gamma_{r_i} \le \gamma\right) = \Pr\left(\frac{\gamma_{\mathrm{sr}_i}\gamma_{r_i d}}{\gamma_{\mathrm{sr}_i} + \gamma_{r_i d}} \le \gamma\right) \\
&= \int_0^{\gamma} \Pr\left(\gamma_{r_i d} \ge \frac{\gamma\gamma_{\mathrm{sr}_i}}{\gamma_{\mathrm{sr}_i} - \gamma}\right) f_{\gamma_{\mathrm{sr}_i}}\left(\gamma_{\mathrm{sr}_i}\right) d\gamma_{\mathrm{sr}_i} \\
&+ \int_{\gamma}^{\infty} \Pr\left(\gamma_{r_i d} \le \frac{\gamma\gamma_{\mathrm{sr}_i}}{\gamma_{\mathrm{sr}_i} - \gamma}\right) f_{\gamma_{\mathrm{sr}_i}}\left(\gamma_{\mathrm{sr}_i}\right) d\gamma_{\mathrm{sr}_i} \\
&= 1 - \int_{\gamma}^{\infty} \Pr\left(\gamma_{r_i d} \ge \frac{\gamma\gamma_{\mathrm{sr}_i}}{\gamma_{\mathrm{sr}_i} - \gamma}\right) f_{\gamma_{\mathrm{sr}_i}}\left(\gamma_{\mathrm{sr}_i}\right) d\gamma_{\mathrm{sr}_i} \\
&= 1 - \frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} \left(\frac{2b_o m_o}{2b_o m_o + \Omega}\right)^{m_o} \sum_{n=0}^{m-1} \frac{1}{n!} \left(\frac{m}{\bar{\gamma}_{r_i d}}\right)^n \\
&\times \int_{\gamma}^{\infty} \exp\left[-\left(\frac{\gamma_{\mathrm{sr}_i}}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} + \frac{m\gamma\gamma_{\mathrm{sr}_i}}{\bar{\gamma}_{r_i d}\left(\gamma_{\mathrm{sr}_i} - \gamma\right)}\right)\right] \\
&\times \left(\frac{\gamma\gamma_{\mathrm{sr}_i}}{\gamma_{\mathrm{sr}_i} - \gamma}\right)^n \\
&\times {}_1F_1\left(m_o, 1, \frac{\Omega\gamma_{\mathrm{sr}_i}}{2b_o\bar{\gamma}_{\mathrm{sr}_i}\left(2b_o m_o + \Omega\right)}\right) d\gamma_{\mathrm{sr}_i}
\end{aligned} \tag{31}$$

After integral substitution $x = \gamma_{sr_i} - \gamma$ and applying [18, eq.(9.14.1)] and [18, eq.(1.111)] we can reach

$$\begin{aligned}
F_{\gamma_{r_i}}(\gamma) &= 1 - \frac{1}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} \left(\frac{2b_o m_o}{2b_o m_o + \Omega}\right)^{m_o} \sum_{n=0}^{m-1} \frac{1}{n!} \\
&\times \left(\frac{m}{\bar{\gamma}_{r_i d}}\right)^n \exp\left[-\left(\frac{\gamma}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} + \frac{m\gamma}{\bar{\gamma}_{r_i d}}\right)\right] \\
&\times \sum_{k=0}^{\infty} \frac{1}{k!} \frac{\Gamma(m_o + k)}{\Gamma(m_o)\Gamma(1+k)} \left(\frac{\Omega}{2b_o\bar{\gamma}_{\mathrm{sr}}\left(2b_o m_o + \Omega\right)}\right)^k \\
&\times \sum_{j=0}^{n+k} \binom{n+k}{j} \gamma^{n+j} \\
&\times \int_0^{\infty} \exp\left[-\left(\frac{x}{2b_o\bar{\gamma}_{\mathrm{sr}_i}} + \frac{m\gamma^2}{x\bar{\gamma}_{r_i d}}\right)\right] x^{k-j} dx
\end{aligned} \tag{32}$$

Now with the aid of [18, eq.(3.471.9)] and solving the above integral, we can get the closed form CDF expression in (8).

REFERENCES

[1] A. Vanelli-Coralli, G. Corazza, G. Karagiannidis, P. Mathiopoulos, D. Michalopoulos, C. Mosquera, S. Papaharalabos, and S. Scalise, "Satellite communications: Research trends and open issues," in *proceeding of the International Workshop on Satellite and Space Communications, IWSSC'07.*, 2007, pp. 71–75.

[2] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[3] V. Genc, S. Murphy, Y. Yu, and J. Murphy, "IEEE 802.16 j relay-based wireless access networks: an overview," *IEEE Wireless Communications*, vol. 15, no. 5, pp. 56–63, 2008.

[4] S. Kim, H. Kim, and K. Kang, "Performance enhancement in future mobile satellite broadcasting services," *IEEE Communications Magazine*, vol. 46, no. 7, pp. 118–124, 2008.

[5] D. Ahn, S. Kim, H. Kim, and D. Park, "A cooperative transmit diversity scheme for mobile satellite broadcasting systems," *International Journal of Satellite Communications and Networking*, vol. 28, no. 5-6, pp. 352–368, 2010.

[6] Y. Labrador, M. Karimi, D. Pan, and J. Miller, "An approach to cooperative satellite communications in 4G mobile systems," *Journal of Communications*, vol. 4, no. 10, pp. 815–826, 2009.

[7] C. Warty, "Cooperative communication for multiple satellite network," in *porceeding of the IEEE Aerospace Conference*, 2010, pp. 1–7.

[8] S. Lee, S. Lee, K. Kim, and J. Seo, "Personal and mobile satellite DMB services in Korea," *IEEE Transactions on Broadcasting*, vol. 53, no. 1, pp. 179–187, 2007.

[9] N. Chuberre, O. Courseille, P. Laine, L. Roullet, T. Quignon, and M. Tatard, "Hybrid satellite and terrestrial infrastructure for mobile broadcast services delivery: an outlook to the unlimited mobile TV system performance," *International Journal of Satellite Communications and Networking*, vol. 26, no. 5, pp. 405–426, 2008.

[10] S. Morosi, E. Del Re, S. Jayousi, and R. Suffritti, "Hybrid satellite/terrestrial cooperative relaying strategies for DVB-SH based communication systems," in *proceeding of the European Wireless Conference,. EW'09.*, 2009, pp. 240–244.

[11] S. Ikki and M. Ahmed, "Performance analysis of cooperative diversity wireless networks over Nakagami-m fading channel," *IEEE Communications Letters*, vol. 11, no. 4, pp. 334–336, 2007.

[12] L. Yang and H. Chen, "Error probability of digital communications using relay diversity over Nakagami-m fading channels," *IEEE Transactions on Wireless Communications*, vol. 7, no. 5, pp. 1806–1811, 2008.

[13] F. Fontán, M. Vazquez-Castro, C. Cabado, J. Garcia, and E. Kubista, "Statistical modeling of the LMS channel," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 6, pp. 1549–1567, 2001.

[14] H. Kim, K. Kang, and D. Ami, "Distributed space-time coded transmission for mobile satellite communication using ancillary terrestrial component," in *proceeding of the IEEE International Conference on Communications,. ICC'07.*, 2007, pp. 4426–4431.

[15] A. Perez-Neira, C. Ibars, J. Serra, A. del Coso, J. Gomez, and M. Caus, "MIMO applicability to satellite networks," in *in proceeding of the IEEE 10th International Workshop on Signal Processing for Space Communications, 2008. SPSC.*, 2008, pp. 1–9.

[16] A. Abdi, W. Lau, M. Alouini, and M. Kaveh, "A new simple model for land mobile satellite channels: first-and second-order statistics," *IEEE Transactions on Wireless Communications*, vol. 2, no. 3, pp. 519–528, 2003.

[17] M. Simon and M. Alouini, *Digital communication over fading channels*. Wiley-IEEE Press, 2005, vol. 86.

[18] I. Ryzhik, A. Jeffrey, and D. Zwillinger, *Table of integrals, series and products*. Academic Press, 2007.

[19] A. Iqbal and K. Ahmed, "SER analysis of cooperative satellite-terrestrial network over non identical fading channels," in *proceeding of the IEEE 5th Advanced satellite multimedia systems conference (ASMA) and the 11th signal processing for space communications workshop (SPSC)*, 2010, pp. 329–334.

[20] J. Abate and W. Whitt, "Numerical inversion of Laplace

transforms of probability distributions," *ORSA Journal on Computing*, vol. 7, pp. 36–36, 1995.

[21] Y. Ko, M. Alouini, and M. Simon, "Outage probability of diversity systems over generalized fading channels," *IEEE Transactions on Communications*, vol. 48, no. 11, pp. 1783–1787, 2000.

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