Ergodic Capacity Analysis for Interference-Limited AF Multi-Hop Relaying Channels in Nakagami-m Fading

Imène Trigui, *Member, IEEE*, Sofiène Affes, *Senior Member, IEEE*, and Alex Stéphenne, *Senior Member, IEEE*

***Abstract*—An analytical characterization of the ergodic capacity of interference-limited multihop wireless networks with amplify-and forward (AF) relaying is presented. In our analysis, we consider that transmissions are performed over Nakagami-m fading where channel state information is only known at the receiving terminals. We derive an exact expression for the ergodic capacity by exploiting the moment generating function (MGF) of the inverse signal-to-interference ratio (SIR). The result is applicable for arbitrary numbers of interfering signals at the receiving terminals and can be efficiently evaluated. Furthermore, considering the special case of dual-hop transmission, we propose a more refined characterization where the high-SIR capacity is expanded as an affine function. The zero-order term or the power offset for which we find insightful closed-form expressions, is shown to play a chief role in understanding the impact of interference and power on the system's capacity. Finally, some simulation results sustaining our analysis are provided.**

***Index Terms*—Amplify-and-forward (AF), cochannel interference, ergodic capacity, high-SIR capacity, multihop wireless networks, Lauricella hypergeometric functions.**

I. Introduction

MULTIHOP communications have been an outstanding topic of research in the last years due to their ability to provide broader coverage and higher reliability for many wireless communication systems (see e.g., [1] and [2] and references therein). The key advantage of relaying is to enable high capacity where traditional architectures are unsatisfactory due to location constraints (e.g., cell-edge, shadowing, indoor), leading to a more homogenous user experience. Depending on the nature and complexity of the relaying technique, relay nodes can be broadly categorized as either amplify and forward (AF) or decode and forward (DF) [3]. While AF relays act as repeaters, DF relays decode and recode the received signal prior to forwarding it to the receiver, thereby implying a larger delay than with a simple repeater.

In the open literature, several works investigating multihop communications exist (cf. [1]- [5] and references therein). Despite their importance, many of the existing results have been based on the assumption that the system is thermal-noise limited. However, relaying-access capacity is also affected by strong co-channel interference (CCI) due to the aggressive frequency reuse in cellular networks. Cochannel interference, which is an essential feature of wireless networks, can cause more severe performance degradation than thermal noise in many wireless networks.

Apart from the very recent works of [6] and [7], most of the performance analysis of multihop systems in the presence of interference has been restricted to dual-hop relay systems. In this case, contributions range from the analysis of interference-limited relay [8] or destination [9], [10] scenarios, to multiple interferers at both sides [11]. In this context, multiple closed-form expressions for the outage and error probabilities were derived. As far as the multihop case is considered, [6] analyzed the effect of co-channel interference assuming Rayleigh fading interfering signals affecting the relays. Specifically, the outage and error probabilities were investigated. An extension of [6] to the Nakagami-m fading scenario has been carried out in [7]. From the aforementioned up-to-date technical literature, it is fairly evident that this large number of contributions provide either outage or bit error rate analysis and that the ergodic capacity is almost unexplored from the analytical point of view.

This paper goes toward filling this gap by deriving a new exact analytical expression and insightful closed-form high-SIR approximations for the ergodic capacity of channel-assisted AF multihop relay systems in interference-limited Nakagami-m fading. It turns out that the ergodic capacity belongs to a special class of generalized hypergeometric series. These are the first Lauricella's multivariate hypergeometric functions of $N+1$ variables $\mathrm{F}_{\mathrm{A}}^{(\mathrm{N}+1)}$ [12], where N is the number of multihop links. This result is subsequently employed to derive simplified closed-form expressions for the ergodic capacity in the high-SIR regime.

Based on our analytical expressions, we investigate the impact of the prominent interference-relay channel features on the ergodic capacity. In the high-SIR regime, we present simple closed-form expressions for the key capacity parameters; the high-SIR slope and the high-SIR power offset. Whilst the former is fixed, the latter is a more intricate function capturing all the interference-relay channel features, namely the interferers number, the power gain and the fading severity.

The remainder of this paper is organized as follows: In Section II, the basic definitions and background related to multihop AF relaying suffering interference are provided. In section III, a closed-form expression for the the ergodic capacity of interference-limited multihop systems subject to

Manuscript received November 22, 2012; revised March 5, 2013. The editor coordinating the review of this paper and approving it for publication was A. Nallanathan.

I. Trigui and S. Affes are with INRS, Montreal, Quebec, Canada (e-mail: itrigui@emt.inrs.ca).

A. Stéphenne is with Huwaei, Ottawa, Ontario, Canada.

Digital Object Identifier 10.1109/TCOMM.2013.052013.120900

Nakagami-m fading is derived. In Section VI, this general closed-form expression is reduced in the dual-hop case to an elegant and simple expression that is suitable for the high-SIR regime. Section V assesses the performance analysis by numerical examples. Finally, some concluding remarks are presented in Section VI.

II. Interference-Limited Relaying: System Model

Let us consider a communication system where several AF relays $\{R_n, n = 1, N-1\}$ are employed to assist a generic transmitter send an encoded message to a remote destination. We assume that the relays and the destination are affected by $\{L_n, n = 1, N\}$ co-channel interferers (CCI). At the n-th time slot, the n-th relay node R_n receives a faded signal from the immediately preceding transmitting terminal R_{n-1} and L_n faded co-channel interfering signals written as

$$y_n = \sqrt{E_{n-1}} h_n x_{n-1} + \sqrt{E_{I_n}} \sum_{l=1}^{L_n} c_{l,n} g_{l,n}, \qquad (1)$$

where h_n denotes the fading gain of the channel between terminals R_{n-1} and R_n, following a flat Nakagami-m fading distribution; x_{n-1} denotes the unit-energy signal transmitted from the $(n-1)$th node; and E_{n-1} indicates the transmit energy from the said node. In the second term of the right-hand-side (RHS) of (1), $c_{l,n}$ is the l-th cochannel interferer's signal affecting the nth relay with energy equal to E_{I_n}, and $g_{l,n}$ is the flat Nakagami-m fading coefficient of the l-th interference channel affecting the nth relay. In an interference-limited wireless communication system, the effect of additive white Gaussian noise can usually be neglected. Interference-limited scenarios, in fact, are very relevant to modern cellular systems, which tend to operate precisely in such conditions.

The amplification process at the nth relay consists of generating the signal $x_n = (1/\sqrt{E_{n-1}|h_n|^2}) y_n$ and transmitting it to the next node. In this case, a relay just amplifies the incoming signal with the inverse of the channel of the previous hop, regardless of the interference level of that hop.

By following the same procedure as in [6], the end-to-end signal-to-interference ratio (SIR) at the destination can be obtained as [7], [9]

$$\gamma = \left[\sum_{n=1}^{N} \frac{\sum_{l=1}^{L_n} Z_{l,n}}{Y_n} \right]^{-1} = \left[\sum_{n=1}^{N} \frac{1}{\gamma_n} \right]^{-1}, \qquad (2)$$

with $Y_n = E_{n-1}|h_n|^2$ being the fading amplitude of the desired signal at the n-th node and $Z_{l,n} = E_{I_n}|g_{l,n}|^2; l = 1, \ldots, L_n, n = 1, \ldots, N$ being the instantaneous power of the l-th interferer to the n-th node. Accordingly, γ_n represents the instantaneous SIR at the n-th hop. Hereafter, we consider that the cooperative links undergo independent and non-identically distributed (i.n.i.d.) Nakagami-m fading with arbitrary fading parameters and arbitrary average powers. Nonetheless, for the sake of simplicity, we assume that the interference links are subject to identically-distributed Nakagami-m fading. Thus, Y_n and $\tilde{Z}_n = \sum_{l=1}^{L_n} Z_{l,n}$, follow a Gamma distribution with probability density functions given by

$$\begin{aligned} p_{Y_n}(y) &= \frac{m_{r,n}^{m_{r,n}}}{\Gamma(m_{r,n}) \Omega_{r,n}^{m_{r,n}}} y^{m_{r,n}-1} \exp\left(-\frac{m_{r,n} y}{\Omega_{r,n}}\right) \\ p_{\tilde{Z}_n}(z) &= \frac{m_{I,n}^{L_n m_{I,n}} z^{L_n m_{I,n}-1}}{\Gamma(L_n m_{I,n}) \Omega_{I_n}^{L_n m_{I,n}}} \exp\left(-\frac{m_{I,n} z}{\Omega_{I,n}}\right), \end{aligned} \qquad (3)$$

where $\Gamma(\cdot)$ is the Gamma function [16, Eq.(8.310.1)]. Furthermore in (3), $m_{r,n}$ and $\Omega_{r,n}$ are, respectively, the Nakagami fading parameter and the average power of the desired signal at the n-th relay. Similarly, $m_{I,n}$ and $\Omega_{I,n}$ are the Nakagami fading parameter and the average power of each interfering signal at the n-th relay, respectively. The total interference at each hop $\tilde{Z}_n$ is the sum of L_n independent Gamma distributed random variables with parameters $L_n m_{I,n}$ and $L_n \Omega_{I,n}$. The average SIR of each interferer at the n-th relay is defined as $\Lambda_n \triangleq \Omega_{r,n}/\Omega_{I,n}$.

III. Multihop Performance

Capacity analysis is of extreme importance in the design of wireless systems since it determines the maximum achievable rates in the network. A reliable capacity performance study has to take into account important issues such as co-channel interference. In this context, we propose hereafter new closed-form expressions for the ergodic capacity of multihop AF systems suffering interference in Nakagami-m fading.

A. Ergodic Capacity

In a N-hop cooperative relaying system, the end-to-end ergodic capacity can be expressed as

$$C_E = \frac{1}{N} \mathrm{E}\left[\log_2(1+\gamma)\right], \qquad (4)$$

in which the factor $1/N$ accounts for the total number of time slots required for the transmission and $\mathrm{E}[\cdot]$ denotes mathematical expectation.

Theorem 1: Let Z be an arbitrary non-negative random variable. Then

$$\mathrm{E}\left[\ln(1+Z)\right] = \int_0^\infty \frac{1-e^{-s}}{s} M_{\frac{1}{Z}}(s) ds, \qquad (5)$$

where $M_z(\cdot)$ stands for the MGF of z.

Proof: In order to give a formal proof of (5), consider the following Taylor series expansion of $\ln(1+z)$ valid for all $z \geq 0$, [16, Eq. (4.1.25)]

$$\ln(1+Z) = \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{Z}{Z+1}\right)^n, \qquad \forall Z \geq 0. \qquad (6)$$

Then, by taking the expectation at both sides of (6), we obtain (5) when we substitute

$$\mathrm{E}\left\{\left(\frac{1}{1+Z^{-1}}\right)^n\right\} = \frac{1}{(n-1)!} \int_0^\infty s^{n-1} e^{-s} M_{Z^{-1}}(s) ds. \qquad (7)$$

The interchange of summation and integration is valid since the series $\sum_{n=1}^{\infty} s^{n-1}/n!$ is uniformly convergent for $s \geq 0$.

Corollary 1: The ergodic capacity of an interference-limited multi-hop AF relaying system in arbitrary Nakagami-m fading is given by

$$C_E=\frac{1}{N\ln(2)}\sum_{\eta\in\mathcal{P}_N}\Gamma(\Omega(\eta)+1)\prod_{n=1}^{N}\left(\frac{\Gamma(-m_{r,n})\left(\frac{m_{r,n}}{m_{I,n}\Lambda_n}\right)^{m_{r,n}}}{\mathrm{B}(m_{r,n},L_n m_{I,n})}\right)^{1-\eta_n}$$
$$\mathrm{F}_{\mathrm{A}}^{(\mathrm{N+1})}\Bigg(\Omega(\eta)+1;1,L_1 m_{I,1}+(1-\eta_1)m_{r,1},\ldots,L_N m_{I,N}+(1-\eta_N)$$
$$m_{r,N};2,1-\delta_{\eta_1}m_{r,1},\ldots,1-\delta_{\eta_N}m_{r,N};1,\frac{m_{r,1}}{m_{I,1}\Lambda_1},\ldots,\frac{m_{r,N}}{m_{I,N}\Lambda_N}\Bigg), \quad (8)$$

where $\delta_{\eta_k}=\mathrm{sign}(\eta_k-1/2), k=1,...,N$ and $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ is the first Lauricella hypergeometric function of r variables [12].

Proof: Recalling (4) and applying *Theorem 1* yields

$$C_E=\frac{1}{N\ln(2)}\int_0^\infty\frac{1-e^{-s}}{s}M_{\gamma^{-1}}(s)ds. \quad (9)$$

Since the cooperative links are statistically independent, the MGF of γ^{-1} can be expressed by the product of the corresponding marginal MGFs pertaining to the N hops as follows

$$M_{\gamma^{-1}}(s)=\prod_{n=1}^{N}M_{\gamma_n^{-1}}(s)ds, \quad (10)$$

where $M_{\gamma_n^{-1}}$ can be expressed, using (3) and exploiting [16, Eqs. (3.351.3) and (9.211.4)], as

$$M_{\gamma_n^{-1}}(s)=\frac{\Gamma(m_{r,n}+L_n m_{I,n})}{\Gamma(m_{r,n})}\Psi\left(L_n m_{I,n};1-m_{r,n};\frac{m_{r,n}}{m_{I,n}\Lambda_n}s\right), \quad (11)$$

with $\Psi(a;b;z)$ being the Triconomi confluent hypergeometric function [16, Eq. (9.211.1)]. Next, a closed-form expression for (9) will be derived. Making use of [16, Eq. (9.210.2)], we start by representing the Triconomi function in terms of the confluent Hypergeometric function ${}_1\mathrm{F}_1(a;b;z)$ [16, Eq. (9.210.1)][1], as

$$\Psi\left(L_n m_{I,n};1-m_{r,n};\frac{m_{r,n}}{m_{I,n}\Lambda_n}s\right)=\frac{\Gamma(m_{r,n})}{\Gamma(m_{r,n}+L_n m_{I,n})}$$
$${}_1\mathrm{F}_1\left(L_n m_{I,n};1-m_{r,n};\frac{m_{r,n}}{m_{I,n}\Lambda_n}s\right)+\frac{\Gamma(-m_{r,n})}{\Gamma(L_n m_{I,n})}\left(\frac{m_{r,n}}{m_{I,n}\Lambda_n}s\right)^{m_{r,n}}$$
$${}_1\mathrm{F}_1\left(m_{r,n}+L_n m_{I,n};1+m_{r,n};\frac{m_{r,n}}{m_{I,n}\Lambda_n}s\right). \quad (12)$$

Likewise, the function $(1-e^{-s})/s$ can be expressed in terms of ${}_1\mathrm{F}_1(a;b;z)$ as $(1-e^{-s})/s=e^{-s}{}_1\mathrm{F}_1(1;2;s)$. Thus, performing the necessary substitutions and simplifying leads to

$$C_E=\frac{1}{N\ln(2)}\int_0^\infty e^{-s}{}_1\mathrm{F}_1(1;2;s)$$
$$\prod_{n=1}^{N}\left[{}_1\mathrm{F}_1\left(L_n m_{I,n};1-m_{r,n};\frac{m_{r,n}s}{m_{I,n}\Lambda_n}\right)+\frac{\Gamma(-m_{r,n})\left(\frac{m_{r,n}s}{m_{I,n}\Lambda_n}\right)^{m_{r,n}}}{\mathrm{B}(L_n m_{I,n},m_{r,n})}\right.$$
$$\left.{}_1\mathrm{F}_1\left(m_{r,n}+L_n m_{I,n};1+m_{r,n};\frac{m_{r,n}s}{m_{I,n}\Lambda_n}\right)\right]ds. \quad (13)$$

Using the following alternate expression for the product involved in (13) which is of the form

$$\prod_{n=1}^{N}(X_n+Y_n)=\sum_{\eta\in\mathcal{P}_N}\prod_{n=1}^{N}X_n^{\eta_n}Y_n^{1-\eta_n}, \quad (14)$$

where $\mathcal{P}_N\triangleq\{\eta=(\eta_1,\eta_2,...,\eta_N):\eta\in\{0,1\}\}$, (13) can be rewritten, after some algebraic manipulations, as

$$C_E=\frac{1}{N\ln(2)}\sum_{\eta\in\mathcal{P}_N}\prod_{n=1}^{N}\left(\frac{\Gamma(-m_{r,n})\left(\frac{m_{r,n}}{m_{I,n}\Lambda_n}\right)^{m_{r,n}}}{\mathrm{B}(m_{r,n},L_n m_{I,n})}\right)^{1-\eta_n}\int_0^\infty s^{\Omega(\eta)}e^{-s}$$
$${}_1\mathrm{F}_1(1;2;s)\prod_{n=1}^{N}\left[{}_1\mathrm{F}_1\left(L_n m_{I,n};1-m_{r,n};\frac{m_{r,n}s}{m_{I,n}\Lambda_n}\right)\right]^{\eta_n}$$
$$\left[{}_1\mathrm{F}_1\left(L_n m_{I,n}+m_{r,n};1+m_{r,n};\frac{m_{r,n}s}{m_{I,n}\Lambda_n}\right)\right]^{1-\eta_n}ds, \quad (15)$$

where $\Omega(\eta)=\sum_{n=1}^{N}m_{r,n}-\sum_{n=1}^{N}m_{r,n}\eta_n$ and $\mathrm{B}(a,b)=\Gamma(a)\Gamma(b)/\Gamma(a+b)$ is the Beta function [16, Eq. (8.380.1)]. A careful inspection of (15) reveals that the modified version of the first Lauricella hypergeometric function, which is given by [12, Eq. (2.4.2)]

$$\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}\left(a;b_1,\ldots,b_r;c_1,\ldots,c_r;\frac{x_1}{\nu},\ldots,\frac{x_r}{\nu}\right)=\frac{\nu^a}{\Gamma(a)}$$
$$\int_0^\infty e^{-\nu t}t^{a-1}\left(\prod_{k=1}^{r}{}_1F_1(b_k;c_k,x_k t)\right)dt;$$
$$(\mathfrak{Re}(a)>0), \quad (16)$$

can be applied to solve the integrals involved in (15). Therefore, with the help of (16) and after some manipulations, a closed-form expression for the ergodic capacity is obtained as in (8). To the best of the authors' knowledge, this result is new. In addition, it is worthwhile to mention that, even in the Rayleigh case, such closed-form expression was not proposed in the technical literature before.

Reminiscent that the outage probability of this system has recently been expressed in terms of the second Lauricella function of r variables $\mathrm{F}_{\mathrm{B}}^{(\mathrm{r})}(\cdot)$ in [7]. In an interference-free environment, the authors of [2] have shown that the error probability of the multihop AF system can be described by the Lauricella function of the third type $\mathrm{F}_{\mathrm{C}}^{(\mathrm{r})}(\cdot)$.

B. One-Term Continuation Relation for $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$

The multivariable Lauricella function $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ is usually defined via its series representation given by [12, Eq. (2.1.1)], and its convergence is assured whenever $\sum_{i=1}^{r}|x_i|<1$. Under its

[1]Note that (12) is valid only for real-valued non-integer values of $m_{r,n}$. However, practically, very similar results are obtained for integer values of $m_{r,n}$ and $m_{r,n}+\epsilon$ for sufficiently small ϵ values.

Laplace-type integral representation (16), the $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ is convergent whenever $\mathfrak{Re}\left(\sum_{i=1}^{r} x_i\right) < 1$ [17, Eq.(2)]. Nevertheless, the convergence of $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ may often be improved by the use of analytic continuations formulas. In this section, a one-term continuation relation is obtained for the Lauricella $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ by making use of its Barnes integral representation. In what follows, let us assume that only one argument of the Lauricella function is greater that one (say x_r) and the remaining are less than one with $\mathfrak{Re}\left(\sum_{i=1}^{r-1} x_i\right) < 1$. We shall obtain one-term continuation relation for the F_{A} function by using the Barnes integral representation given by [12, Eq. (2.5.3)]

$$\frac{\Gamma(a)\Gamma(b_r)}{\Gamma(c_r)}\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}\left(a; b_1, \ldots, b_r; c_1, \ldots, c_r; x_1, \ldots, x_r\right) = \frac{1}{2\pi i} \int_{-i\infty}^{i\infty} \mathrm{F}_{\mathrm{A}}^{(\mathrm{r-1})}\left(a+t; b_1, \ldots, b_{r-1}; c_1, \ldots, c_{r-1}; x_1, \ldots, x_{r-1}\right) \times \frac{\Gamma(a+t)\Gamma(b_r+t)}{\Gamma(c_r+t)}\Gamma(-t)(-x_r)^t dt. \tag{17}$$

Apart from the numerical integration of (16), the integrand $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r-1})}$ in (17), which converges uniformly, can readily be computed via Gauss-Laguerre quadrature (GLQ)[2], as suggested in [14, Eq. (44)], according to

$$\mathrm{F}_{\mathrm{A}}^{(\mathrm{r-1})}\left(a+t; b_1, \ldots, b_{r-1}; c_1, \ldots, c_{r-1}; x_1, \ldots, x_{r-1}\right) \approx \sum_{k=0}^{N_p} w_k \xi_k^{a+t-1} \prod_{i=1}^{r-1} {}_1F_1(b_i; c_i; x_i \xi_k), \tag{18}$$

where t_k and w_k are, respectively, the $k-$th zero and weight of the Laguerre polynomial of order N_p [18]. Then, after plugging (18) into (17) and using [12, Eq. (1.21.7)], we obtain

$$\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}\left(a; b_1, \ldots, b_r; c_1, \ldots, c_r; x_1, \ldots, x_r\right) \approx \sum_{k=0}^{N_p} w_k \xi_k^{a-1} \left(\prod_{i=1}^{r-1} {}_1F_1(b_i; c_i; x_i \xi_k)\right) {}_2F_1(a, b_r; c_r, x_r \xi_k), \quad \left(x_r \geq 1, \mathfrak{Re}\left(\sum_{i=1}^{r-1} x_i\right) < 1\right), \tag{19}$$

which is the the continuation of $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ to a different region of its arguments x_r. Note that one can always modify the arguments x_i in (17) in order for the convergence of the integrand $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r-1})}$ to be satisfied, by making use of the following Euler integral transformation [12, Eq. (4.2.2)]

$$\mathrm{F}_{\mathrm{A}}^{(\mathrm{r-1})}(a; b_1, \ldots, b_{r-1}, c_1, \ldots, c_{r-1}; x_1, \ldots, x_{r-1}) = (1-x_j)^{-a}\mathrm{F}_{\mathrm{A}}^{(\mathrm{r-1})}\left(a; b_1, \ldots, c_j - b_j, b_{r-1}; c_1, \ldots, c_{r-1}; \frac{x_1}{1-x_j}, \ldots, \frac{x_j}{x_j-1}, \frac{x_{r-1}}{x_j-1}\right). \tag{20}$$

Note that an r-fold repetition of the preceding operations can leads to the continuation of the Lauricella function outside its region of convergence. Nevertheless, the result is not necessarily convenient in form. Finally, the new continuation formula obtained in (19) can be used for calculating the Lauricella $\mathrm{F}_{\mathrm{A}}^{(\mathrm{r})}$ function occurring in the analysis of the ergodic capacity of interference-limited multihop AF network, as shown in (8).

[2]Note that one could also use the semi-infinite GLQ method presented in [13] for higher accuracy.

IV. Dual-Hop Performance

Due to their practical merits, dual-hop AF relaying schemes have been adopted for cellular communications by next generation wireless standards, namely IEEE 802.16j and 3GPP-LTE [15]. In subsection IV.A, we analyze dual-hop performance in the general case of SIR values while in subsection IV.B, we restrict it to the high-SIR regime.

A. General case of SIR values

Assuming a dual-hop cooperative system ($N = 2$) and using (8) yields the ergodic capacity expression given by

$$C_E = \frac{1}{2\ln(2)} \sum_{\eta \in P_2} \Gamma(\Omega(\eta)+1) \prod_{n=1}^{2} \left(\frac{\Gamma(-m_{r,n})\left(\frac{m_{r,n}}{m_{I,n}\Lambda_n}\right)^{m_{r,n}}}{\mathrm{B}(m_{r,n}, L_n m_{I,n})}\right)^{1-\eta_n} \mathrm{F}_{\mathrm{A}}^{(3)}\left(\Omega(\eta)+1; 1, L_1 m_{I,1} + (1-\eta_1)m_{r,1}, L_2 m_{I,2} + (1-\eta_2)m_{r,2}; 2, 1-\delta_{\eta_1} m_{r,1}, 1-\delta_{\eta_2} m_{r,2}; 1, X_1, X_2\right), \tag{21}$$

where $X_1 = \frac{m_{r,1}}{m_{I,1}\Lambda_1}$ and $X_2 = \frac{m_{r,2}}{m_{I,2}\Lambda_2}$. By virtue of the decomposition formulas of the Lauricella function of three variables $F_A^{(3)}$ in [17], we obtain an alternative expression for the ergodic capacity in (21) given by

$$C_E = \frac{1}{2\ln(2)} \sum_{\eta \in P_2} \frac{\Gamma(\Omega(\eta)+1)}{(1-X_2)^{\Omega(\eta)+1}} \prod_{n=1}^{2} \left(\frac{\Gamma(-m_{r,n}) X_n^{m_{r,n}}}{\mathrm{B}(m_{r,n}, L_n m_{I,n})}\right)^{1-\eta_n} \sum_{i=0}^{\infty} A_{\eta,i} \left(\frac{X_2}{X_2-1}\right)^i \mathrm{F}_2\left(\Omega(\eta)+1+i; 1, L_1 m_{I,1} + (1-\eta_1)m_{r,1}, ; 2, 1-\delta_{\eta_1} m_{r,1}; \frac{1}{1-X_2}, \frac{X_1}{1-X_2}\right), \tag{22}$$

where $A_{\eta,i} = (\Omega(n)+1)_i (1-\delta_{\eta_2} m_{r,2} - L_2 m_{I,2} - (1-\eta_2)m_{r,2})_i / (1-\delta_{\eta_2} m_{r,2})_i\, i!$, with $(a)_n$ being the Pochhammer symbol. Moreover, in (22), F_2 is the Appell hypergeometric function of the second type [12]. In turn, the Appell's hypergeometric function F_2 in (22) verifies some reduction formulas involving series of simpler hypergeometric functions [19, Theorem 1]. Nevertheless, applying these reduction formulas requires separate treatment in the cases $\eta = \{1,1\}$ and $\eta \in \mathcal{P}_2 \backslash \{1,1\}$. Therefore, in order to proceed, it is adequate to rewrite (22) as

$$C_E = \frac{1}{2\ln(2)} \sum_{\eta \in P_2} \Psi_\eta = \frac{1}{2\ln(2)} \left\{\Psi_{\eta=\{1,1\}} + \sum_{\eta \in \mathcal{P}_2 \backslash \{1,1\}} \Psi_\eta\right\}, \tag{23}$$

where Ψ_η can be easily identified from (22). Now, by the help of [19, Theorem 1], and after several manipulations, we show that $\Psi_{\eta=\{1,1\}}$ and $\Psi_{\eta \in \mathcal{P}_2 \backslash \{1,1\}}$ can be expressed as in (24) and (25) at the top of the next page, where ${}_2F_1(a,b;c;z)$ and ${}_3F_2(a,b,c;d;z)$ denote the Gauss hypergeometric function and the generalized hypergeometric function, respectively. Plugging (24) and (25) into (23) yields an alternative expression for the ergodic capacity of interference-limited dual-hop

$$\Psi_{\eta=\{1,1\}} = -\ln\left(\frac{X_2}{X_2-1}\right) - \frac{L_1 m_{I_1}}{1-m_{r,1}}\left\{\frac{X_1}{X_2}{}_3F_2\left(L_1 m_{I,1}, 1, 1; 2-m_{r,1}, 2; -\frac{X_1}{X_2}\right) + \frac{X_1}{1-X_2}\right.$$
$$\left. {}_3F_2\left(L_1 m_{I,1}, 1, 1; 2-m_{r,1}, 2; \frac{X_1}{1-X_2}\right)\right\} + \sum_{i=1}^{\infty}\frac{A_{\eta=\{1,1\},i}}{i}\left\{{}_2F_1\left(i, L_1 m_{I,1}; 1-m_{r,1}; -\frac{X_1}{X_2}\right)\right.$$
$$\left. - \left(\frac{X_2}{X_2-1}\right)^i {}_2F_1\left(i, L_1 m_{I,1}; 1-m_{r,1}; \frac{X_1}{1-X_2}\right)\right\}. \tag{24}$$

$$\Psi_{\eta\in\mathcal{P}_2\setminus\{1,1\}} = \Gamma(\Omega(\eta)+1)(-1)^{\Omega(\eta)}\left(\frac{X_1}{X_2}\right)^{m_{r,1}(1-\eta_1)}\prod_{n=1}^{2}\left(\frac{\Gamma(-m_{r,n})}{\mathrm{B}(m_{r,n}, L_n m_{I,n})}\right)^{1-\eta_n}\sum_{i=0}^{\infty}\frac{A_{\eta,i}}{(\Omega(\eta)+i)}$$
$$\left\{{}_2F_1\left(\Omega(\eta)+i, L_1 m_{I,1}+(1-\eta_1)m_{r,1}; 1-\delta_{\eta_1}m_{r,1}; -\frac{X_1}{X_2}\right) - \left(\frac{X_2}{X_2-1}\right)^{\Omega(\eta)+i}{}_2F_1\left(\Omega(\eta)+i,\right.\right.$$
$$\left.\left. L_1 m_{I,1}+(1-\eta_1)m_{r,1}; 1-\delta_{\eta_1}m_{r,1}; \frac{X_1}{1-X_2}\right)\right\}. \tag{25}$$

relay channels. The latter involves common simple functions and thus has the advantage of being directly computable using mathematical software packages. Most importantly, in contrast to (8) and (21), the result in (23) allows for high-SIR performance analysis and hence gives more insights into the effect of the system parameters on the ergodic capacity.

B. High-SIR Regime

In the high-SIR regime, we consider two important scenarios; namely, one where the relay and destination SIRs grow large but in the same proportion, and one where the relay SIR grows large but the destination SIR is kept fixed.

1) Large per Hop SIR: Here, we have $\Lambda_1 \to \infty$, $\Lambda_2 \to \infty$ with $\beta = \Lambda_2/\Lambda_1$ for some fixed β. In this case, the ergodic capacity can be expressed according to the affine expansion [20]

$$C_E^{\infty} = \mathcal{S}_\infty\left(\frac{\Lambda_1|\mathrm{dB}}{3\ \mathrm{dB}} - \mathcal{L}_\infty\right) + o(1), \tag{26}$$

with $\mathcal{S}_\infty$ denoting the high-SIR slope in bits/s/Hz/ (3 dB) given by

$$\mathcal{S}_\infty = \lim_{\Lambda_1\to\infty}\frac{C_E|_{\Lambda_2\to\infty,\Lambda_2/\Lambda_1=\beta}}{\log_2(\Lambda_1)}, \tag{27}$$

and $\mathcal{L}_\infty$ representing the high-SIR power offset in 3 dB units given by

$$\mathcal{L}_\infty = \lim_{\Lambda_1\to\infty}\left(\log_2(\Lambda_1) - \frac{C_E|_{\Lambda_2\to\infty,\Lambda_2/\Lambda_1=\beta}}{\mathcal{S}_\infty}\right). \tag{28}$$

From (24) and (25), we can evaluate $\mathcal{S}_\infty$ and $\mathcal{L}_\infty$ in closed-form as follows.

Theorem 2: When $\Lambda_1 \to \infty$ and $\Lambda_2 \to \infty$ with $\beta = \Lambda_2/\Lambda_1$, the high-SIR slope $\mathcal{S}_\infty$ and the high-SIR power offset $\mathcal{L}_\infty$ of interference-limited AF dual-hop systems are given by

$$\mathcal{S}_\infty = \frac{1}{2} \quad \text{b/s/Hz (3 dB)}, \tag{29}$$

and

$$\mathcal{L}_\infty(L_1, L_2) = \log_2\left(\frac{m_{r,2}}{m_{I,2}\beta}\right) + \frac{1}{\ln(2)}\Upsilon, \tag{30}$$

where Υ is given in (31) at the top of the next page with $\Delta = m_{r,2}m_{I,1}/m_{r,1}m_{I,2}$.

Proof: We start by applying the following identity to (24)

$$\ln\left(\frac{X_2}{X_2-1}\right) = \ln\left(\frac{m_{r,2}}{m_{I,2}\beta}\right) - \ln\left(\frac{m_{r,2}}{m_{I,2}\beta} - \Lambda_1\right)$$
$$\underset{\Lambda_1\longrightarrow\infty}{\simeq} \ln\left(\frac{m_{r,2}}{m_{I,2}\beta}\right) - \ln(\Lambda_1). \tag{32}$$

By performing the limit operations on the right hand side (R.H.S) of (24) and (25) and exploiting the result in (32), we obtain the ergodic capacity, in the high-SIR regime, as

$$\lim_{\Lambda_1,\Lambda_2\to\infty,\beta=\Lambda_2/\Lambda_1} C_E = \frac{1}{2}\left\{\log_2(\Lambda_1) - \log_2\left(\frac{m_{r,2}}{m_{I,2}\beta}\right) - \frac{1}{\ln(2)}\Upsilon\right\}. \tag{33}$$

Finally, by invoking (27) and (28), the claimed expressions of the high-SIR slope and the high-SIR power offset are found.

It is important to note that (29) and (30) allow an exact characterization of the key high-SIR ergodic capacity for arbitrary numbers of interferers at the relay and the destination and for an arbitrary Nakagami-m distribution of the interference-relay channel. In particular, (29) reveals the intuitive result that the multiplexing gain of dual-hop AF networks is unsensitive to the presence of interference. Indeed, the authors of [5] proved that the multiplexing gain of an interference-free dual-hop relaying system is also equal to $1/2$. On the other hand, the power offset in (30) is a more intricate function capturing all the interference and relay channels parameters.

For a fixed β, adding K interferers at the first hop and P interferers at the second hop, while not altering $\mathcal{S}_\infty$, would induce a high-SIR power offset shift given by

$$\delta\mathcal{L}_\infty(P, K) \triangleq \mathcal{L}_\infty(L_1+K, L_2+P) - \mathcal{L}_\infty(L_1, L_2). \tag{34}$$

Since the the computation of a closed-form expression of the high-SIR power offset shift in (34) is quite complicated, the

$$\Upsilon=\frac{L_1 m_{I_1}}{1-m_{r,1}}\frac{\beta}{\Delta}{}_3F_2\left(L_1 m_{I,1},1,1;2-m_{r,1},2;-\frac{\beta}{\Delta}\right)-\sum_{i=1}^{\infty}\frac{A_{\eta=\{1,1\},i}}{i}{}_2F_1\left(i,L_1 m_{I,1};1-m_{r,1};-\frac{\beta}{\Delta}\right)-\sum_{\eta\in\mathcal{P}_2\setminus\{1,1\}}\Gamma(\Omega(\eta)+1)$$
$$\frac{(-1)^{\Omega(\eta)}\prod_{n=1}^{2}\Gamma(-m_{r,n})^{1-\eta_n}}{\prod_{n=1}^{2}\mathrm{B}(m_{r,n},L_n m_{I,n})^{1-\eta_n}}\left(\frac{\beta}{\Delta}\right)^{m_{r,1}(1-\eta_1)}\sum_{i=0}^{\infty}\frac{A_{\eta,i}}{(\Omega(\eta)+i)}{}_2F_1\left(\Omega(\eta)+i,L_1 m_{I,1}+(1-\eta_1)m_{r,1};1-\delta_{\eta_1}m_{r,1};-\frac{\beta}{\Delta}\right). \quad (31)$$

effect of adding more interferers at each hop will be illustrated numerically in the next section.

Also of interest is the effect of the power gain β on the ergodic capacity. While the high-SIR slope is invariant to β, the power offset captures the sensitivity of the high-SIR capacity to the power gain. Indeed, asymptotically, the optimal power gain is the one that minimizes the power offset.

2) Large First-Hop SIR and Fixed Second-Hop SIR: : In this case, we have $\Lambda_1 \to \infty$ and Λ_2 is fixed. Considering the alternative expression for the ergodic capacity obtained in (23), then as $\Lambda_1 \to \infty$, we obtain

$$\lim_{\Lambda_1\to\infty} C_E=\frac{1}{2\ln(2)}\left\{\lim_{X_1\to 0}\Psi_{\eta=\{1,1\}}+\sum_{\eta\in P_2\setminus\{1,1\}}\lim_{X_1\to 0}\Psi_{\eta}\right\}. \quad (35)$$

Recalling the fact that ${}_2F_1\,(a,b;c;0) = 1$ and ${}_3F_1\,(a,b,c;e,f;0)=1$ yields

$$\lim_{X_1\to 0}\Psi_{\eta=\{1,1\}} = -\log_2\left(\frac{X_2}{X_2-1}\right)+ \sum_{i=1}^{\infty}\frac{A_{\eta=\{1,1\},i}}{i}\left(1-\left(\frac{X_2}{X_2-1}\right)^{i}\right), \quad (36)$$

and

$$\lim_{X_1\to 0}\Psi_{\eta\in\mathcal{P}_2\setminus\{1,1\}} = \frac{(-1)^{m_{r,2}}\Gamma(m_{r,2}+1)\Gamma(-m_{r,2})}{\mathrm{B}(L_2 m_{I,2},m_{r,2})} \sum_{i=0}^{\infty}\frac{A_{\eta=\{1,0\},i}}{(m_{r,2}+i)}\left(1-\left(\frac{X_2}{X_2-1}\right)^{m_{r,2}+i}\right). \quad (37)$$

Substituting (36) and (37) into (35), and performing some algebraic manipulations leads to the closed-form expression in (38) for the ergodic capacity of interference-limited AF dual-hop systems as the first hop SIR grows large for fixed relay and destination interference powers, where $\psi(\cdot)$ stands for the Digamma function [16, Eq. (8.361)]. The obtained result in (38) shows that if we fix Λ_2 and take large Λ_1, then the ergodic capacity of interference-limited AF dual-hop systems remains bounded (as a function of Λ_2). This confirms the intuitive notion that the capacity is restricted by the weakest link in the relay network; namely the relay-destination link in this case.

V. Illustrative Numerical Results

The aim of this section is to illustrate the expressions derived in Sections III and IV using numerical examples and examine the effect of interference on the system's capacity. All the results shown here have been analytically obtained by the direct evaluation of the expressions developed in this paper: either (8) for an arbitrary number of hops N or (23), (26) and (38) for exact and asymptotic capacity of the dual-hop case. For the evaluation of (8) and (21), we exploit the algorithm proposed in Section III-B for the implementation of the Lauricella hypergeometric function F_A. Moreover, the accuracy of the proposed formulas have been verified by Monte Carlo simulations.

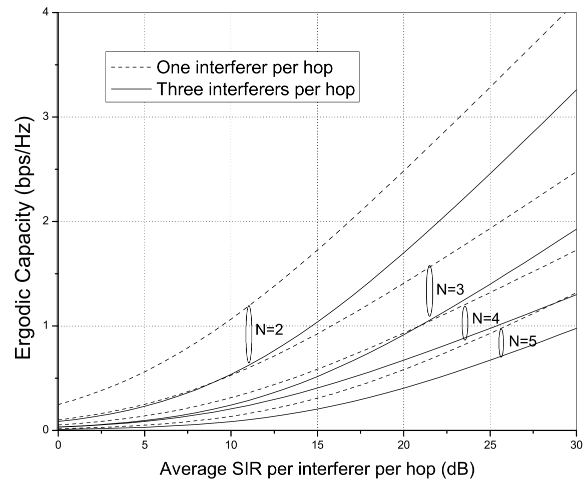


Fig. 1. Ergodic capacity of multihop AF relaying in the presence of cochannel interference for different numbers of hops N.

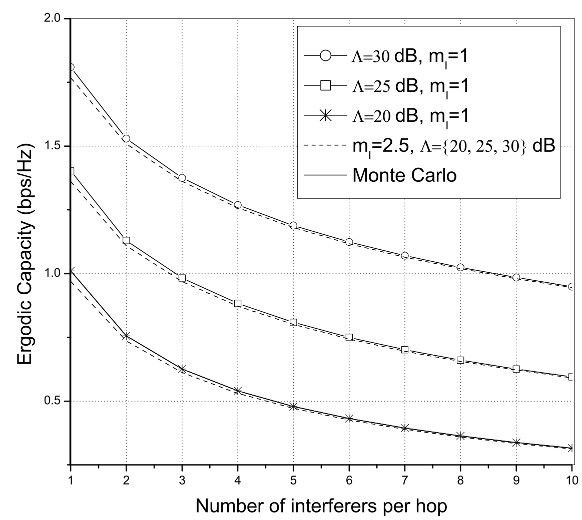


Fig. 2. Ergodic capacity of an interference-limited four-hop AF relay system against the number of interferers in each hop. Results are shown for i.i.d Nakagami-m faded links with $m_{r,n} = 1.5, n = 1, \ldots, 4$.

Fig. 1 shows the ergodic capacity of $N = \{2,3,4,5\}$-hop AF relaying system in an interference-impaired Nakagami-m fading channel with $L_n = \{1,3\}, n = 1,..,N$. The results are obtained in the case of i.i.d. channel gains and interfering signals between the relay links with $m_{r,n} = 1.5$ and $m_{I,n} = 2.5$. As observed, increasing N does not improve

$$\lim_{\Lambda_1\to\infty} C_E = -\frac{1}{2}\log_2\left(\frac{X_2}{X_2-1}\right)+\frac{1}{2\log(2)}\Bigg\{\psi(1-m_{r,2})-\psi(L_2m_{I,2})-\frac{X_2}{X_2-1}\left(1-\frac{L_2m_{I,2}}{1-m_{r,2}}\right)$$
$$ {}_3F_2\left(1,1,2-L_2m_{I,2}-m_{r,2};2,2-m_{r,2};\frac{X_2}{X_2-1}\right)+(-1)^{m_{r,2}+1}\Gamma(m_{r,2}+1)\Gamma(-m_{r,2})$$
$$\left(1-\frac{\left(\frac{X_2}{X_2-1}\right)^{m_{r,2}}}{m_{r,2}B(m_{r,2},L_2m_{I,2})}{}_2F_1\!\left(m_{r,2},1-L_2m_{I,2};1+m_{r,2};\frac{X_2}{X_2-1}\right)\right)\Bigg\}. \quad (38)$$

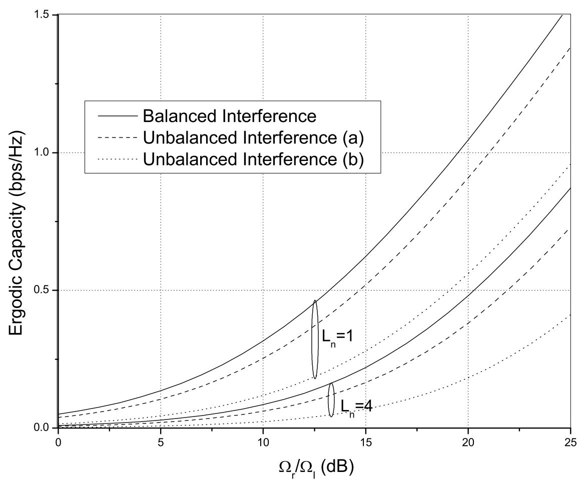


Fig. 3. Ergodic capacity of three-hop AF relaying in the presence of balanced and unbalanced cochannel interference for $L_n = \{1, 4\}, n = \{1, 2, 3\}$. Unbalanced (a): $\Omega_{I,n} = (0.45, 0.45, 0.1)\Omega_I$. Unbalanced (b): $\Omega_{I,n} = (0.9, 0.05, 0.05)\Omega_I$.

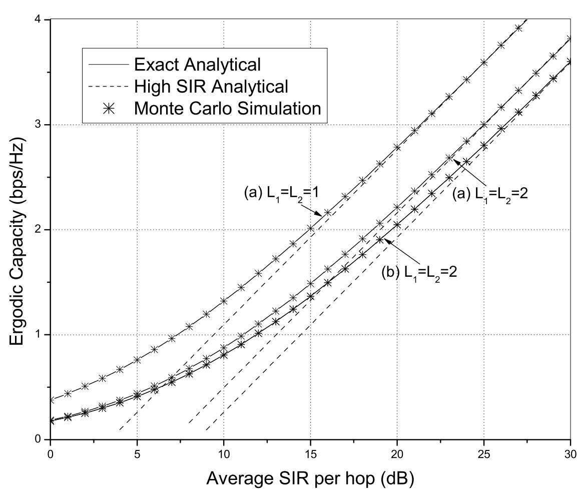


Fig. 4. Comparison of exact analytical, high-SIR analytical, and Monte Carlo simulation results for the ergodic capacity of interference-limited AF dual-hop systems with different interference and fading configurations. Results are shown for Rayleigh-faded interferers, $\Lambda_2/\Lambda_1 = 2$, (a): $m_1 = m_2 = 1.75$ and (b): $m_1 = m_2 = 0.75$.

the channel capacity, due to the fact that the number of orthogonal channels needed increases as the number of hops increases, thus decreasing the channel capacity by a factor of N. Nevertheless, increasing N reduces the effect of interference. Indeed, the capacity loss is halved when considering the five-hop scenario instead of the dual-hop scenario.

Fig. 2 shows the ergodic capacity of four-hop AF relaying systems versus the number of interferers for i.i.d. Nakagami-m fading channels with $m_{r,n} = 1.5, n = 1, ..4$, $m_{I,n} = m_I = \{1, 2.5\}$ and $\Lambda_{I,n} = \Lambda = \{20, 25, 30\}$ dB. As can be seen, the analytical and simulation results are in excellent agreement. Moreover, we can quantify the performance degradation that occurs as the number of interferers increases. On the other hand, for a given interference power limit, it is seen that the ergodic capacity varies very slightly with the fading parameters of the interference channels.

Fig. 3 investigates the impact of interference power unbalance on the ergodic capacity of a three-hop AF relaying system. Different per hop interference power configurations have been considered while maintaining the overall interference power constant. The results are shown for $L_n = \{1, 4\}$, $m_{r,n} = 1.5$, and $m_{I,n} = 1$, $n = 1, 2, 3$. As can be seen, the ergodic capacity decreases as the links become highly unbalanced in terms of their perceived interference power, thereby highlighting the significance of the joint optimization of power allocation and relay location for AF network to enhance the system performance. It can also be seen that unbalanced interferers have less impact on the system's ergodic capacity as the interferers number increases.

Fig. 4 depicts the analytical high-SIR capacity approximations for interference-limited AF dual-hop systems, based on (29) and (30). The results are shown as a function of the first-hop SIR Λ_1 with $\beta = \Lambda_2/\Lambda_1 = 2$. These approximations are seen to converge to their respective exact capacity curves for quite moderate SIR levels (e.g., $\Lambda_1 \approx 15$ dB). We also see that when the number of interferers at the relay and/or the destination increases, the high-SIR power offset is increased, thereby yielding an overall deterioration of the ergodic capacity. Again, the analytical results match the simulation results perfectly. Fig. 4 also investigates the effect of the fading severity on every relay link which, in contrast to the fading severity of the interfering link, turns out to be considerable.
Fig. 5 illustrates the relationship in (34) where the high-SIR power offset shift is plotted against L_1, for $K = \{1, 2, 4\}$. It is clear that the excess power offset induced by interference is positive, thereby confirming the intuitive notion that the presence of more interferers has the effect of deteriorating the ergodic capacity. Moreover, for a fixed value of K, the high-SIR power offset shift is a decreasing function of L_1. We see that when L_1 (resp. L_2) is small, then a small increase in L_1 (resp. L_2) yields an important decrease in terms of the high-SIR power offset. However, in agreement with Fig. 5, as L_1 goes large, the impact of interference on the overall system's

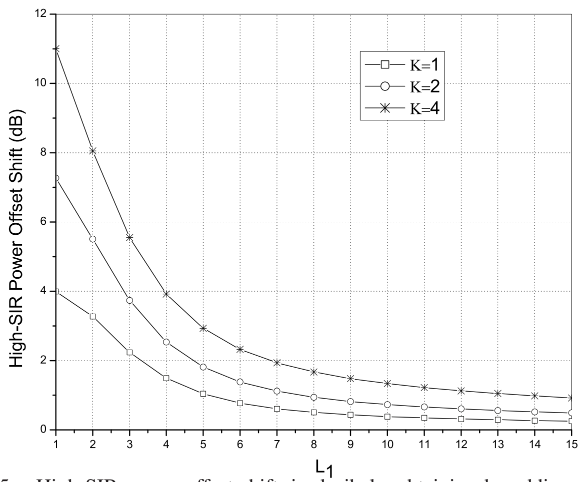


Fig. 5. High-SIR power offset shift, in decibels, obtaining by adding either (a) one interferer at the first hop ($K = 1$), (b) two interferers at the first hop ($K = 2$), or (c) four interferers at the first hop ($K = 4$). Results are shown for Rayleigh faded interferers with $L_2 = 1$, $m_{r,1} = m_{r,2} = 1.5$ and $\beta = 2$.

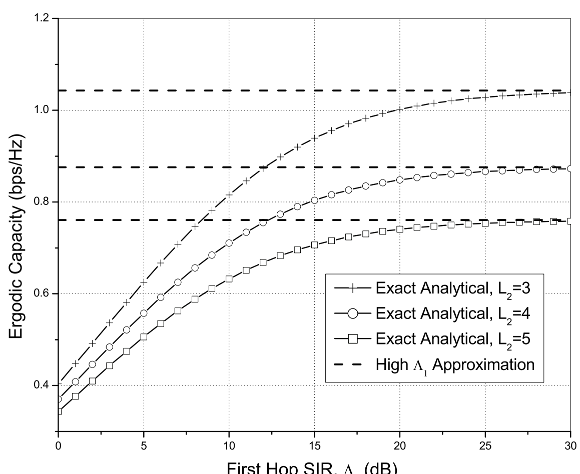


Fig. 6. Comparison of the high-SIR Λ_1 approximation and the exact analytical results for different numbers of interferers at the second hop. Results are shown for $L_1 = 1$, $\Lambda_2 = 10$ dB, $m_{r,1} = m_{r,2} = 1.5$, $m_{I,1} = 2$, and $m_{I,2} = 1.5$.

capacity approaches a limit.

Fig. 6 plots the closed-form high-SIR regime ergodic capacity based on (35) and the exact analytical ergodic capacity based on (21), for an AF dual-hop system suffering interference for different values of L_2. The results are presented as a function of the first-hop SIR Λ_1. It can be seen that the asymptotic approximations converge to their respective exact capacity curves for moderate values of λ_1 (e.g., within $\lambda_1 \approx 20$ dB).

VI. Conslusion

In this paper we presented an analytical characterization of the ergodic capacity of multihop AF relay channels with interference in Nakagami-m fading. The derived expression for the ergodic capacity provides a good match with the simulation results. Furthermore, exploiting recent advances in the hypergeometric functions theory, we derive simple and informative closed-form expressions for the high-SIR regime where the capacity is expanded as an affine function of the per hop $\mathrm{SIR}|_{\mathrm{dB}}$. The zero-order term or power offset for which we find insightful closed-form expressions, is shown to play a chief role in understanding the impact of interference and power on the system's capacity. Finally, it is worth remarking that the expressions presented in this paper have direct operational significance in ergodic interference-limited multihop channels.

References

[1] M. O. Hasna and M.-S. Alouini, “"Outage probability of multihop transmission over Nakagami fading channels,” *IEEE Commun. Lett.,* vol. 7, no. 5, pp. 216–218, May 2003.

[2] I. Trigui, S. Affes, and A. Stéphenne, “Closed-form error analysis of variable-gain multihop systems in Nakagami-m fading channels,” *IEEE Trans. Commun.,* vol. 59, no. 8, pp. 2285–2295, Aug. 2011.

[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: efficient protocols and outage behaviour,” *IEEE Trans. Inf. Theory,* vol. 50, pp. 3062–3080, Dec. 2004.

[4] I. Trigui, S. Affes, and A. Stéphenne, “Exact error analysis of dual-hop fixed-gain AF relaying over arbitrary Nakagami-m fading,” in *Proc. 2012 IEEE Vehicular Technolqgy Conf. – Fall*, pp. 1–5.

[5] S. Jin, M. R. McKay, C. Zhong, and K.-K. Wong, “Ergodic capacity cnalysis of amplify-and-forward MIMO dual-hop systems,” *IEEE Trans. Inf. Theory,* vol. 56, no. 5, May 2010.

[6] S. Ikki and S. Aissa, “Multihop wireless relaying systems in the presence of co-channel interferences: performance analysis and design optimization,” *IEEE Trans. Veh. Technol.*, vol 61, no. 2, Feb. 2012.

[7] T. Soithong, V. A. Aalo, G. P. Efthymoglou, and C. Chayawan, “Outage analysis of multihop relay systems in interference-limited Nakagami-m fading channels,” *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, Mar. 2012.

[8] H. A. Suraweera, H. K. Garg, and A. Nallanathan, “Performance analysis of two hop amplify-and-forward systems with interference at the relay,” *IEEE Commun. Lett.,* vol. 14, no. 8, pp. 692–694, Aug. 2010.

[9] D. Lee and J. H. Lee, “Outage probability for dual-hop relaying systems with multiple interferers over Rayleigh fading channels,” *IEEE Trans. Veh. Technol.,* vol. 60, no. 1, pp. 333–338, Jan. 2011.

[10] C. Zhong, S. Jin, and K. K. Wong, “Dual-hop systems with noisy relay and interference-limited destination,” *IEEE Trans. Commun.,* vol. 58, no. 3, pp. 764–768, Mar. 2010.

[11] F. S. Al-Qahtani, T. Q. Duong, C. Zhong, K. A. Qaraqe, and H. Alnuweiri, “Performance analysis of dual-hop AF systems with interference in Nakagami-m fading channels,” *IEEE Signal Process. Lett.,* vol. 18, no. 8, pp. 454–457, Aug. 2011.

[12] H. Exton, *Multiple Hypergeometric Functions and Applications*. Jhon Wiley, 1976.

[13] Q. Shi and Y. Karasawa, “Some applications of Lauricella hypergeometric function F_A in performance analysis of wireless communications,” *IEEE Commun. Lett.*, vol. 16, no. 5, May 2012.

[14] J. M. Romero-Jerez and A. J. Goldsmith, “Performance of multichannel reception with transmit antenna selection in arbitrarily distributed Nagakami fading channels,” *IEEE Trans. Wireless Commun.,* vol. 8, no. 4, pp. 2006–2013, Apr. 2009.

[15] W. Chen, J. Montojo, A. Golitschek, C. Koutsimanis, and S. Xiaodong, “Relaying operation in 3GPP LTE: challenges and solutions,” *IEEE Commun. Mag.,* vol. 50, no. 2, pp. 156–162, Feb. 2012.

[16] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products,* 5th ed. Academic, 1994.

[17] A. Hasanov and H. M. Srivastava, “Some decomposition formulas associated with the Lauricella function F_A^r and other multiple hypergeometric functions,” *App. Math. Lett.*, vol. 19, pp. 113–121, 2006.

[18] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables,* 10th ed. Dover, 1972.

[19] S. B. Opps, S. Nasser, and H. M. Srivastava, “Some reduction and transformation formulas for the Appell hypergeometric function F_2,” *Math. Anal. Appl.*, vol. 302, pp. 180–195, 2005.

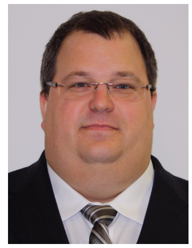
[20] A. Lozano, A. M. Tulino, and S. Verdu, “High-SNR power offset in multiantenna communication,” *IEEE Trans. Inf. Theory,* vol. 51, pp. 4134–4151, Dec. 2005.

Imene Trigui received the “Diplôme d'Ingénieur” in telecommunications (with Honors) from Tunisia's Communications School (Sup'Com) in 2006. In April 2010, she obtained her M.Sc. degree with the rate exceptional at the Institut National de la Recherche Scientifique, Centre Énergie, Matériaux, et Télécommunications (INRS-ÉMT), Université du Québec, Montréal, QC, Canada. She is currently pursuing her Ph.D. degree at INRS-EMT. Her research focuses on cooperative communications, performance analysis of wireless systems, channel coding and modulation. Ms. Trigui is currently the recipient of a top-tier Alexander-Graham-Bell Canada graduate scholarship from the National Sciences and Engineering Research Council (2012-2014). She had to decline another Ph.D. scholarship offered over the same period from the "Fonds de Recherche du Québec Nature et Technologies" (FRQNT). She was previously the recipient of an Undergraduate Student Fellowship from the Tunisian Ministry of Communications. She also received a best paper award at IEEE VTC'2010-Fall. Ms. Trigui serves regularly as a reviewer for many top international journals and conferences in her field.

Sofiène Affes (S-94–M'95–SM'04) received the Diplôme d'Ingénieur in telecommunications in 1992, and the Ph.D. degree with honors in signal processing in 1995, both from the École Nationale Supérieure des Télécommunications (ENST), Paris, France.

He has been since with INRS-EMT, University of Quebec, Montreal, Canada, as a Research Associate from 1995 till 1997, as an Assistant Professor till 2000, then as an Associate Professor till 2009. Currently he is a Full Professor in the Wireless Communications Group. His research interests are in wireless communications, statistical signal and array processing and adaptive space-time processing. From 1998 to 2002 he has been leading the radio design and signal processing activities of the Bell/Nortel/NSERC Industrial Research Chair in Personal Communications at INRS-EMT, Montreal, Canada. Since 2004, he has been actively involved in major projects in wireless of PROMPT (Partnerships for Research on Microelectronics, Photonics and Telecommunications).

Professor Affes was the co-recipient of the 2002 Prize for Research Excellence of INRS. From 2003 till 2013, he held a Canada Research Chair in Wireless Communications. From 2008 to 2011, he held a Discovery Accelerator Supplement (DAS) Award from NSERC (Natural Sciences & Engineering Research Council of Canada). Very recently, he has been awarded a second DAS from NSERC till 2016. In 2006, Professor Affes served as a General Co-Chair of the IEEE VTC'2006-Fall conference, Montreal, Canada. In 2008, he received from the IEEE Vehicular Technology Society the IEEE VTC Chair Recognition Award for exemplary contributions to the success of IEEE VTC. He currently acts as a member of the Editorial Boards of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the IEEE TRANSACTIONS ON SIGNAL PROCESSING, the IEEE TRANSACTIONS ON COMMUNICATIONS, and the *Wiley Journal on Wireless Communications & Mobile Computing*.



Alex Stéphenne was born in Quebec, Canada, on May 8, 1969. He received the B.Eng. degree in electrical engineering from McGill University, Montreal, Quebec, in 1992, and the M.Sc. degree and Ph.D. degrees in telecommunications from INRS-Télécommunications, Université du Québec, Montreal, in 1994 and 2000, respectively. In 1999 he joined SITA Inc., in Montreal, where he worked on the design of remote management strategies for the computer systems of airline companies. In 2000, he became a DSP Design Specialist for Dataradio Inc., Montreal, a company specializing in the design and manufacturing of advanced wireless data products and systems for mission critical applications. In January 2001, he joined Ericsson and worked for over two years in Sweden, where he was responsible for the design of baseband algorithms for WCDMA commercial base station receivers. From June 2003 to December 2008, he was still working for Ericsson, but was based in Montreal, where he was a researcher focusing on issues related to the physical layer of wireless communication systems. Since 2004, he is also an adjunct professor at INRS, where he has been continuously supervising the research activities of multiple students. His current research interests include Coordinated Multi-Point (CoMP) transmission and reception, Inter-Cell Interference Coordination (ICIC) and mitigation techniques in Heterogeneous Networks (HetNets), wireless channel modeling/characterization/estimation, statistical signal processing, array processing and adaptive filtering for wireless telecommunication applications. He joined Huawei Technologies Canada, in Ottawa, in Dec. 2009.

Alex has been a member of the IEEE since 1995 and a Senior member since 2006. He is a member of the "Ordre des Ingénieurs du Québec" (OIQ). He is a member of the organizing committee and a co-chair of the Technical Program Committee (TPC) for the 2012-Fall IEEE Vehicular Technology Conference (VTC'12-Fall), in Quebec City. He has served as a co-chair for the "Multiple antenna systems and space-time processing" track for VTC'08-Fall, in Calgary, and as a co-chair of the TPC for VTC'2006-Fall in Montreal.