The Potential of a Hybrid Fixed/User Relay Architecture— A Performance Analysis

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***Abstract*—Future wireless systems are likely to comprise a dense grid of fixed relay nodes (FRNs) and contain a large number of user terminals (UTs) that can act as user relay nodes (URNs) under certain circumstances. In this paper, we argue that significant gains can be attained if FRNs and URNs act together under the umbrella of a hybrid architecture. To this end, we perform an exact and asymptotic outage probability (OP) analysis of a dual hop system with single relay selection under Rayleigh fading. Furthermore, we derive an ergodic capacity upper bound as a function of the number of FRNs and URNs. We show that in low signal-to-noise ratio (SNR), FRNs are much more effective in reducing OP than URNs. Although it is always more beneficial to employ FRNs instead of URNs, in high SNR URNs are almost equally as effective as FRNs in reducing OP. In terms of ergodic capacity, FRNs achieve higher performance than URNs in all SNR regimes. We conclude that from a system design viewpoint, if the aim is to meet certain quality-of-service constraints, FRNs can be reserved to serve low SNR users, while URNs could be employed when channel conditions to destination UTs are more favorable.**

***Index Terms*—Fixed relay nodes (FRNs), user relay nodes (URNs), relay selection, outage probability, ergodic capacity.**

I. Introduction

The value of employing relay nodes (RNs) to improve performance of wireless networks has been well appreciated [1]–[6]. RNs can bring diversity and other gains to a wireless system, i.e., can increase capacity, extend coverage and improve quality-of-service (QoS). Therefore this technology can significantly enhance the user experience in a cost-efficient manner as it does not require costly multi-antenna wireless nodes [3]–[6]. Therefore, not surprisingly, RNs will play a significant role in future 4G systems and beyond as shown by the amount of attention they have received by wireless standardization [7]–[10].

RNs can be grouped into three categories, *fixed RNs* (FRNs), *user RNs* (URNs), and *moving RNs* (MRNs). FRNs are part of the system infrastructure and are deployed in fixed positions of the cell area [7]–[11], while URNs are user terminals (UTs) that relay signals to other UTs or base stations (BSs) under certain circumstances [3]–[6]. The difference between FRNs and URNs is that the wireless links between a BS and an FRN can be designed to achieve certain quality, e.g., FRNs can be placed at positions that have line-of-sight (LOS) connection to the serving BS, whereas this is not possible for URNs as their position changes. Furthermore, being part of the system infrastructure, FRNs can have a constant availability, which is not the case for URNs [3]–[6]. MRNs are RNs mounted on top of public transportation vehicles in order to boost the user experience of vehicular UTs [12]. Although MRNs are very promising, their study is beyond the scope of this paper which focuses on FRNs and URNs.

As the demand for high quality and ubiquitous wireless services constantly rises, it is envisaged that future systems will employ a dense grid of BSs and FRNs to meet the demand [13]–[15]. At the same time, the evergrowing number of wireless nodes provides a serious potential for improving system performance, as these nodes can act as URNs when they are in idle mode [4], [6]. This potential should be exploited as it adds a new promising dimension to the way that a wireless system can be designed. In this paper we argue that significant gains can be attained if we allow users to profit both from FRNs and URNs at the same time. In order for this to materialize, we propose a novel hybrid system architecture allowing the interplay between FRNs and URNs. This can result in substantial performance gains and can be viable from the system overhead point of view. The system can be designed to adaptively employ FRNs and URNs depending on what is more beneficial under certain circumstances and constraints.

More specifically, we propose that UTs can receive/transmit signals from/to FRNs and URNs. We consider a dual-hop system where a number of FRNs and URNs are available to serve a specific UT employing decode-and-forward (DF). We assume a downlink scenario where FRNs are always able to decode the signal transmitted by the source, while the decoding capability of URNs depends on the state of the source-to-URN channel. To investigate the achievable performance of such architecture, we perform an exact and asymptotic outage probability (OP) analysis that sheds some light to the impact of the system parameters to the overall performance. Furthermore, we derive an ergodic capacity upper bound as a function of the number of FRNs and URNs. We show that in low signal-to-noise ratio (SNR), FRNs are much more effective in reducing OP than URNs. Although employing FRNs always results in an advantage, as shown by the asymptotic OP analysis, in high SNR URNs are almost equally as effective as FRNs in reducing OP. In terms of ergodic capacity, FRNs achieve higher performance than URNs in all SNR regimes. We conclude that from a system design viewpoint, if the aim is to meet certain QoS constraints, e.g., constraining OP under a specific threshold, FRNs can serve low SNR users, while URNs could be employed when channel conditions to destination users are less adverse.

The remainder of this paper is structured as follows. In Section II the considered signal and system model is presented and in Section III performance is analyzed in terms of outage probability and ergodic capacity. Section IV presents the performance evaluation and Section V concludes the paper.

II. Signal and system model

We consider a dual-hop system comprising a source node S, a destination node D and $F+M$ RNs in total. The RNs are divided into a set $\mathbb{F}$ of FRNs with cardinality F and a set $\mathbb{M}$ of URNs with cardinality M. All RNs operate in half-duplex mode employing the DF protocol and it is assumed that there is no direct $S \rightarrow D$ connection, i.e., S communicates with D only via the RNs. We assume downlink transmission, where S is the BS and D is a destination UT. Communication between S and D takes place in two time slots. In the first slot S transmits a symbol s of energy E_s while all RNs receive the message of S and attempt to decode it. The FRNs of $\mathbb{F}$ are assumed to always be able to decode s, whereas the likelihood for the URNs of $\mathbb{M}$ decoding s depends on the quality of the S-to-URN channels[1]. This setup creates in effect $F+M$ dual-hop end-to-end links.

Flat fading channels are considered and $h_{1,r}$, $h_{2,r}$, for $r \in \{\mathbb{F}, \mathbb{M}\}$, denote the channel coefficients modeling the S-to-RN and the RN-to-D links respectively. Note that as FRNs are assumed to always decode the symbol of the source, it follows that only $h_{2,r}\ \forall\ r \in \mathbb{F}$ of the RN-to-D link affects performance. The channel coefficients are modeled as independent zero mean complex Gaussian random variables (RVs), i.e., $h_{1,r} \sim \mathcal{CN}\left(0, \Omega_{1,r}/2\right)$, $h_{2,r} \sim \mathcal{CN}\left(0, \Omega_{2,r}/2\right)$, where $\Omega_{1,r} = \mathbb{E}\left[\left|h_{1,r}\right|^2\right] \frac{E_s}{N_0}$, $\Omega_{2,r} = \mathbb{E}\left[\left|h_{2,r}\right|^2\right] \frac{E_s}{N_0}$ represent the average SNR of the corresponding links. N_0 denotes the one side power spectral density of the zero-mean circularly symmetric additive white Gaussian noise and $\mathbb{E}\left[.\right]$ denotes expectation. The signal envelope of these links follows the Rayleigh distribution. The end-to-end SNR of each of the $F+M$ end-to-end dual-hop links can be expressed as

$$\gamma_r = \begin{cases} \gamma_{2,r}\,, & \text{if r} \in \mathbb{F} \\ \min\left\{\gamma_{1,r}, \gamma_{2,r}\right\}, & \text{if r} \in \mathbb{M} \end{cases} \tag{1}$$

where $\gamma_{1,r}$ and $\gamma_{2,r}$ represent the instantaneous SNR of the S-to-RN and RN-to-D links respectively. The FRNs are assumed always to decode successfully the signal of the source, hence the end-to-end SNR in this case only depends on the SNR of the FRN-to-D link, $\gamma_{2,r}$. This represents a performance upper bound for the FRNs (lower bound if OP is the considered metric) as it implies perfect backhaul. Although perfect wireless backhaul cannot be easily achieved, the backhaul for FRNs can be designed to be of very high quality, e.g., by properly positioning the FRN to guarantee high degree of LOS to the BS and by employing highly directive antennas. From the Rayleigh fading assumption, it follows that the SNRs of the end-to-end links are exponentially distributed RVs whose cumulative distribution function (CDF) is

$$F_{\gamma_r}\left(x\right) = \begin{cases} 1 - e^{-\lambda_{2,r}\,x}, & \text{if r} \in \mathbb{F} \\ 1 - e^{-\lambda_{\min,r}\,x}, & \text{if r} \in \mathbb{M} \end{cases} \tag{2}$$

where $\lambda_{1,r} = \frac{1}{\Omega_{1,r}}\ \forall\ r \in \mathbb{M}$, $\lambda_{2,r} = \frac{1}{\Omega_{2,r}}\ \forall\ r \in \{\mathbb{M}, \mathbb{F}\}$. From order statistics, it follows that $\lambda_{\min,r} = \lambda_{1,r} + \lambda_{2,r}\ \forall\ r \in \mathbb{M}$ [16, ch. 4].

For transmission we consider single relay selection, where a single RN is selected to forward the source's symbol, the one providing the maximum RN-to-D SNR. Therefore the end SNR is

$$\gamma_{\text{end}} = \max\left\{\gamma_1, \gamma_2, \ldots, \gamma_{F+M}\right\}. \tag{3}$$

The resulting mutual information is

$$\mathcal{I} = \frac{1}{2}\log_2\left(1 + \gamma_{\text{end}}\right). \tag{4}$$

III. Performance analysis

In this section we conduct analysis in order to assess performance of the proposed hybrid FRN/URN architecture. More specifically we derive closed-form expressions for the exact and asymptotic OP. We also derive an ergodic capacity upper bound as a function of the number of FRNs and URNs.

A. Outage Probability - Exact SNR Analysis

The OP for a source transmit rate of $\mathcal{R}$ bits/s/Hz of the considered single relay selection scheme is given by the following expression

$$\begin{aligned} P_{\text{out}}\left(\gamma_{\text{th}}\right) &= \Pr\left[\mathcal{R} > \frac{1}{2}\log_2\left(1 + \gamma_{\text{end}}\right)\right] \\ &= \Pr\left[\gamma_{\text{end}} < \gamma_{\text{th}}\right] = F_{\gamma_{\text{end}}}\left(\gamma_{\text{th}}\right), \end{aligned} \tag{5}$$

where $\gamma_{\text{th}} = 2^{2\,\mathcal{R}} - 1$ and $\Pr\left[.\right]$ denotes probability. $F_{\gamma_{\text{end}}}\left(x\right)$ in this case is the CDF of $\gamma_{\text{end}} = \max\left\{\gamma_1, \gamma_2, \ldots, \gamma_{F+M}\right\}$. From probability theory, the CDF of the maximum of a set of $F+M$ RVs equals the product of their individual CDFs [17], i.e., $F_{\gamma_{\max}}\left(x\right) = \prod_{r=1}^{F+M} F_{\gamma_r}\left(x\right)$. For the considered scenario this results in the following expression

$$F_{\gamma_{\text{end}}}\left(x\right) = \underbrace{\prod_{f \in \mathbb{F}}\left[1 - e^{-\frac{x}{\Omega_{2,f}}}\right]}_{\text{FRNs}}\underbrace{\prod_{m \in \mathbb{M}}\left[1 - e^{-\left(\frac{1}{\Omega_{1,m}} + \frac{1}{\Omega_{2,m}}\right)x}\right]}_{\text{URNs}}. \tag{6}$$

For the special case of independent and identically distributed (IID) channels[2], i.e., $\Omega_{1,r} = \Omega_{2,r} \equiv \Omega,\ \forall\ r \in \{\mathbb{F}, \mathbb{M}\}$, the CDF of (6) reduces to

$$F_{\gamma_{\text{end}}}\left(x\right) = \left(1 - e^{-\frac{x}{\Omega}}\right)^F \left(1 - e^{-\frac{2\,x}{\Omega}}\right)^M. \tag{7}$$

[1]The uplink case is similar, although decoding during the first hop is not guaranteed for any of the RNs.

[2]This assumption is made for analytical tractability and reflects the case of very dense URN and UT deployment.

By plugging (7) into (5) we obtain the following closed-form expression for the OP as a function of the source transmit rate $\mathcal{R}$ and the number of fixed and mobile RNs F and M respectively

$$P_{\text{out}}\left(\Omega\right)=\left(1-e^{-\frac{\gamma_{th}}{\Omega}}\right)^{F}\left(1-e^{-\frac{2\,\gamma_{\text{th}}}{\Omega}}\right)^{M}. \tag{8}$$

B. Outage Probability - Asymptotic Analysis

In the high SNR regime, P_{out} is given by the following expression [18], [19]

$$P_{\text{out}}^{\infty}\left(\Omega\right)=\left(G_c\cdot\Omega\right)^{-G_d}+o\left(\Omega^{-G_d}\right) \tag{9}$$

where G_d and G_c denote the *diversity order* and *coding gain* respectively.

Proposition 1: The P_{out}^{∞} of the considered hybrid relay architecture is given by the following expression

$$P_{\text{out}}^{\infty}\left(\Omega\right)=2^{M}\,\gamma_{\text{th}}^{F+M}\,\Omega^{-(F+M)}+o\left(\Omega^{-G_d}\right) \tag{10}$$

where the diversity order and coding gain are respectively

$$G_d=F+M \tag{11}$$
$$G_c=2^{-\frac{M}{F+M}}\,\gamma_{\text{th}}^{-1}. \tag{12}$$

Proof: Following the definition, the diversity order G_d is derived as follows

$$\begin{aligned}G_d&=-\lim_{\Omega\to\infty}\frac{\log_2 P_{\text{out}}\left(\Omega\right)}{\log_2\left(\Omega\right)} &(13)\\&=-\lim_{\Omega\to\infty}\frac{\log_2\left(\left(1-e^{-\frac{\gamma_{th}}{\Omega}}\right)^{F}\left(1-e^{-\frac{2\,\gamma_{th}}{\Omega}}\right)^{M}\right)}{\log_2\left(\Omega\right)} &(14)\\&=\lim_{\Omega\to\infty}\left[\frac{\gamma_{\text{th}}\,e^{-\frac{\gamma_{th}}{\Omega}}\,F}{\left(1-e^{-\frac{\gamma_{th}}{\Omega}}\right)\Omega}+\frac{2\,\gamma_{\text{th}}\,e^{-\frac{2\,\gamma_{th}}{\Omega}}\,M}{\left(1-e^{-\frac{2\,\gamma_{th}}{\Omega}}\right)\Omega}\right] &(15)\end{aligned}$$

where from (14) to (15) we have applied the L'Hopital's rule. After some further algebraic manipulations the diversity order of (11) can be easily obtained.

From (9), we derive the coding gain G_c as follows

$$\begin{aligned}G_c&=\lim_{\Omega\to\infty}\frac{P_{\text{out}}\left(\Omega\right)^{-\frac{1}{G_d}}}{\Omega} &(16)\\&=\lim_{\Omega\to\infty}\frac{\left(1-e^{-\frac{\gamma_{th}}{\Omega}}\right)^{-\frac{F}{F+M}}\left(1-e^{-\frac{2\,\gamma_{th}}{\Omega}}\right)^{-\frac{M}{F+M}}}{\Omega}. &(17)\end{aligned}$$

■

From (10), we observe that P_{out}^{∞} is a monotonically increasing function of the number of URNs M, showing that when the sum of the employed FRNs and URNs is constant it is always more beneficial to employ FRNs instead of URNs. This is reflected by the coding gain of (12) and results from the fact that URNs under DF are not guaranteed to decode the symbol of the source.

C. Ergodic Capacity

The ergodic capacity of the considered scheme is defined as

$$\begin{aligned}\bar{C}&=\mathbb{E}\left[\frac{1}{2}\log_2\left(1+\gamma_{\text{end}}\right)\right] &(18)\\&=\frac{1}{2}\int_0^{\infty}\log_2\left(1+x\right)f_{\gamma_{\text{end}}}\left(x\right)dx,\end{aligned}$$

where $f_{\gamma_{\text{end}}}\left(x\right)$ is the probability density function (PDF) of the end-to-end SNR of (3). By definition $f_{\gamma_{\text{end}}}\left(x\right)\triangleq\frac{dF_{\gamma_{\text{end}}}(x)}{dx}$. Hence, by differentiating the CDF of (7), we obtain

$$f_{\gamma_{\text{end}}}\left(x\right)=A\left(x\right)+B\left(x\right), \tag{19}$$

where

$$\begin{aligned}A\left(x\right)&=\frac{F}{\Omega}e^{-\frac{x}{\Omega}}\left(1-e^{-\frac{2x}{\Omega}}\right)^{M}\left(1-e^{-\frac{x}{\Omega}}\right)^{F-1} &(20)\\B\left(x\right)&=\frac{2M}{\Omega}e^{-\frac{2x}{\Omega}}\left(1-e^{-\frac{2x}{\Omega}}\right)^{M-1}\left(1-e^{-\frac{x}{\Omega}}\right)^{F}. &(21)\end{aligned}$$

As the evaluation of the integral of (18) is difficult, with the use of Jensen's inequality the ergodic capacity can be upper bounded as follows [20],

$$\mathbb{E}\left[\frac{1}{2}\log_2\left(1+\gamma_{\text{end}}\right)\right]\leq\frac{1}{2}\log_2\left(1+\mathbb{E}\left[\gamma_{\text{end}}\right]\right)=\bar{C}_{\text{UB}} \tag{22}$$

where

$$\mathbb{E}\left[\gamma_{\text{end}}\right]=\int_0^{\infty}x\,f_{\gamma_{\text{end}}}\left(x\right)dx. \tag{23}$$

In order to evaluate the integral of (23), we express $A\left(x\right)$ and $B\left(x\right)$ with the use of the standard binomial expansion $(a+b)^n=\sum_{k=0}^{n}\binom{n}{k}a^{n-k}\,b^k$ [21, eq. (1.111)], where $\binom{n}{k}=\dfrac{n!}{(n-k)!k!}$. After some algebraic manipulations we obtain

$$A\left(x\right)=\frac{F}{\Omega}\,e^{-\frac{x}{\Omega}}\sum_{m=0}^{M}\binom{M}{m}(-e^{-\frac{2x}{\Omega}})^m\sum_{f=0}^{F-1}\binom{F-1}{f}(-e^{-\frac{x}{\Omega}})^f \tag{24a}$$

$$=\frac{F}{\Omega}\sum_{m=0}^{M}\sum_{f=0}^{F-1}\binom{M}{m}\binom{F-1}{f}(-1)^{k+f}\,e^{-\frac{x}{\Omega}(1+2m+f)} \tag{24b}$$

$$B\left(x\right)=\frac{2M}{\Omega}\,e^{-\frac{2x}{\Omega}}\sum_{m=0}^{M-1}\binom{M-1}{m}(-e^{-\frac{2x}{\Omega}})^m\sum_{f=0}^{F}\binom{F}{f}(-e^{-\frac{x}{\Omega}})^f \tag{24c}$$

$$=\frac{2M}{\Omega}\sum_{m=0}^{M-1}\sum_{f=0}^{F}\binom{F}{f}\binom{M-1}{m}(-1)^{m+f}\,e^{-\frac{x}{\Omega}(2+2m+f)}. \tag{24d}$$

It should be noted that the expressions of (24) are valid for $F\geq 1$ and $M\geq 1$. Hence, the expectation of γ_{end} can be expressed as

$$\mathbb{E}[\gamma_{\text{end}}] = \int_0^\infty x\,[A(x) + B(x)]\,dx \quad (25)$$
$$= \int_0^\infty x\,A(x)\,dx + \int_0^\infty x\,B(x)\,dx.$$

By plugging the functions of (24) into (25) we obtain

$$\mathbb{E}[\gamma_{\text{end}}] = \int_0^\infty x\,\frac{F}{\Omega}\sum_{m=0}^{M}\sum_{f=0}^{F-1}\binom{M}{m}\binom{F-1}{f}(-1)^{m+f}\,e^{-\frac{x}{\Omega}(1+2k+j)}dx$$
$$+\int_0^\infty x\,\frac{2M}{\Omega}\sum_{m=0}^{M-1}\sum_{f=0}^{F}\binom{F}{f}\binom{M-1}{m}(-1)^{m+f}\,e^{-\frac{x}{\Omega}(2+2m+f)}dx. \quad (26)$$

After some manipulation we derive the closed-form expression for $\mathbb{E}[\gamma_{\text{end}}]$ of (27). Hence, the upper bound of the ergodic capacity of (22) can be evaluated in a straightforward manner.

IV. Performance Evaluation

In this section we evaluate the OP and the ergodic capacity of the proposed hybrid architecture as a function of the number of FRNs and URNs, F and M, respectively, and the average SNR Ω. Let K be the total number of RNs that serve a destination node D, i.e., $K = F + M$. For the present evaluation we assume the special case of IID Rayleigh channels, where $\Omega \equiv \Omega_{1,r} = \Omega_{2,r} = E_s/N_0,\ \forall\, r \in \{\mathbb{F}, \mathbb{M}\}$. This assumption, although simplistic, it provides very useful insights on how the proposed hybrid FRN/URN architecture can be best implemented.

Fig. 1 plots the exact P_{out} and asymptotic P_{out}^{∞} of the proposed architecture for a source transmit rate of $\mathcal{R} = 1$ bits/s/Hz as a function of the average SNR Ω for different values of F and M when $F+M = 20$. It can be clearly seen that as the coding gain of (12) is a monotonically decreasing function of M, increasing the number of URNs (under a constant sum of FRNs and URNs) results in a penalty in terms of OP. The derived asymptotic P_{out}^{∞} converges with the exact P_{out} approximately when Ω exceeds 10 dB.

Figs. 2 and 3 illustrate in three dimensions the OP trend in linear scale as a function of F and M when the average SNR Ω is 5 and 15 dB respectively. Both F and M vary from 1 to 20. It can be seen that when Ω is 5 dB (low SNR regime), if the network has either only URNs or FRNs, the URN-enabled network needs much more relays to achieve approximately the same OP as the FRN-enabled one. When the Ω is 15 dB (high SNR regime), FRNs and URNs achieve almost the same performance, suggesting that in a hybrid FRN/URN system architecture, URNs should be utilized to serve high SNR destination UTs whereas FRNs should be prioritized to serve UTs experiencing more adverse channel conditions.

Fig. 4 plots the ergodic capacity upper bound $\bar{C}_{\text{UB}}$ of (22) as a function of the average SNR Ω for different values of F and M when $F+M = 20$. To show the tightness of the bound, we plot in the same figure the ergodic capacity $\bar{C}$ of (18), where the involved integral is evaluated numerically. Ergodic capacity grows proportionally with Ω and as the number of FRNs

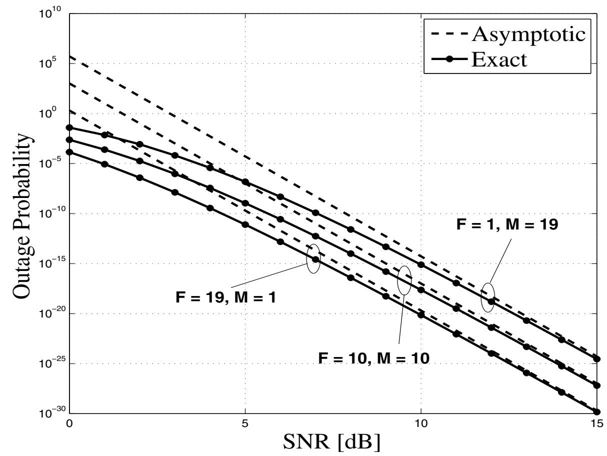

Fig. 1. P_{out} and P_{out}^{∞} vs. average SNR Ω for $\mathcal{R} = 1$ bits/s/Hz and different numbers of FRNs F and URNs M, when $F + M = 20$.

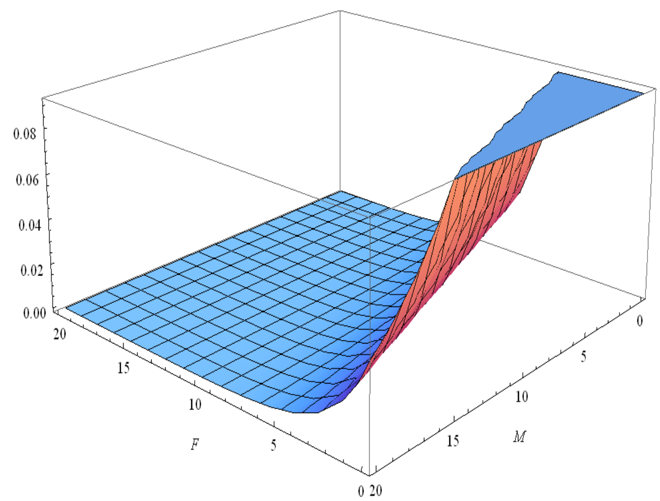

Fig. 2. A 3D illustration of P_{out} for $\mathcal{R} = 1$ bits/s/Hz as a function of the number of FRNs F and URNs M when average SNR $\Omega = 5$ dB.

grows and that of URNs diminishes (when their sum remains constant) ergodic capacity improves. Therefore in terms of ergodic capacity it is always better to employ FRNs instead of URNs, irrespective of the SNR of operation. We can also observe that the derived upper bound is tight.

V. Conclusion

It is foreseen that future wireless systems will comprise a large number of fixed relay nodes (FRNs) as well as user terminals that can act as user relay nodes (URNs). In this paper we proposed that it is beneficial from a system design viewpoint if FRNs and URNs act together under the umbrella of a hybrid fixed/user relay system architecture. To substantiate this, we assumed a dual-hop system employing single relay selection under DF and Rayleigh fading and performed exact and asymptotic outage probability (OP) analysis as a function of the number of FRNs and URNs. Furthermore we derived an ergodic capacity upper bound. We showed that

$$\mathbb{E}\left[\gamma_{\text{end}}\right] = F \sum_{m=0}^{M} \sum_{f=0}^{F-1} \binom{M}{m} \binom{F-1}{f} (-1)^{m+f} \frac{\Omega}{(1+f+2\,m)^2} + 2\,M \sum_{m=0}^{M-1} \sum_{f=0}^{F} \binom{F}{f} \binom{M-1}{m} (-1)^{m+f} \frac{\Omega}{(2+f+2\,m)^2}. \tag{27}$$

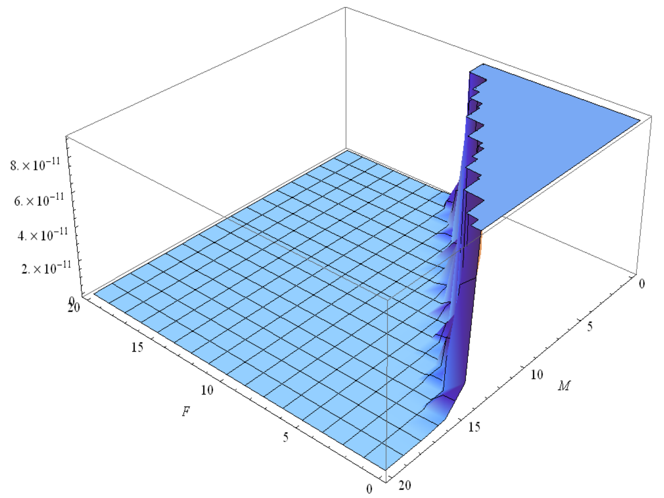

Fig. 3. A 3D illustration of P_{out} for $\mathcal{R} = 1$ bits/s/Hz as a function of the number of FRNs F and URNs M when average SNR = 15 dB.

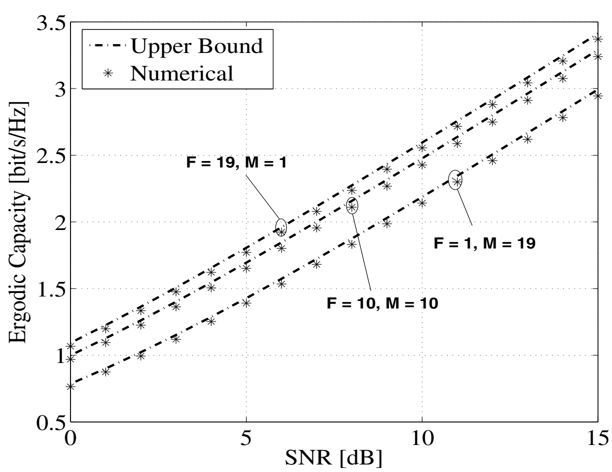

Fig. 4. Ergodic capacity $\bar{C}$ vs. average SNR Ω for different numbers of FRNs F and URNs M, when $F + M = 20$.

when the channel conditions are unfavorable (low SNR case), FRNs are much more effective in reducing OP. Although it is always preferable performance-wise to employ FRNs instead of URNs, in high SNR URNs are almost equally as effective as FRNs in reducing OP. In terms of ergodic capacity, FRNs perform better than URNs in all SNR regimes. We can conclude that if we are to meet certain quality-of-service constraints, FRNs can be reserved to serve low SNR users, while URNs could be utilized when channel conditions to destination users are less adverse.

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