The Potential of Moving Relays— A Performance Analysis

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***Abstract*—In this paper we show the potential of moving relay nodes (MRNs), i.e., relays mounted on top of public transportation vehicles, to improve capacity, reliability and coverage for vehicular users in future wireless networks. To this end, we study and compare the performance of dual-hop MRN assisted transmission, dual-hop transmission assisted by a fixed relay node (FRN) deployed on the street, as well as of the baseline single-hop direct transmission. For an accurate comparison, we optimize the FRN position in terms of outage probability (OP). This position is a function of the pathloss, transmit power and vehicle penetration loss (VPL). The problem is investigated for Rayleigh fading under a fixed cell coverage. When VPL is moderate to high, MRN assisted transmission greatly outperforms transmission assisted by an FRN as well as direct transmission, hence it is very promising for future wireless systems.**

I. Introduction

Relaying techniques in wireless communication have a long history [1]. Together with other low power nodes, such as pico and femto nodes, the relay node (RN) is a key component of heterogeneous networks (HetNets), as introduced in release 10 of the 3GPP Long Term Evolution (LTE) standards [2]. However, only RNs deployed at fixed positions, here denoted as fixed RNs (FRN), are standardized whereas RNs with mobility are still under investigation [3], [4]. Preliminary studies have shown the potential capacity and coverage improvement with deploying coordinated and cooperative relays on top of trains [5]. Furthermore, it was shown that dynamically deployed relays can achieve significant performance gains even when the allowed overheads are very limited. In addition, several studies have considered the use of FRNs to either maximize capacity or extend the coverage of wireless networks [6]. In [7], the authors investigate the optimal FRN position with respect to system capacity maximization when coverage extension is aimed, but only numerical solutions were obtained.

The aforementioned works, however, did not consider the effects of outdoor to indoor penetration loss, which is an important factor affecting system performance in practice. More specifically, measurements have shown that the vehicle penetration loss (VPL) can be as high as 25 dB for user equipment (UE) inside a minivan at the frequency of 2.4 GHz [8]. It should be noted that we foresee higher VPLs in higher frequencies, e.g., for the 4.0 GHz bands allocated to next generation mobile communication systems, and for some well isolated vehicles, e.g., buses or trams. Therefore the deployment of moving relay nodes (MRNs) on top of public transportation vehicles is very beneficial as it can eliminate VPL. This can be achieved by employing two separate indoor and outdoor antenna elements that are connected through a cable introducing negligible losses. The indoor antenna is inside the vehicle, communicating with the UE, and the outdoor antenna communicates with the base station (BS).

In this paper, we investigate a general scenario that considers deploying the MRN on top of a public transportation vehicle, e.g., a bus or a tram. We derive closed-form expressions for the outage probability (OP) of the direct single-hop BS-to-UE transmission and the dual-hop FRN and MRN assisted transmission as a function of the VPL. To facilitate comparisons we optimize the FRN position and we also obtain a lower bound for the achieved OP via an FRN. The analytical results for the OP are validated through Monte-Carlo simulations. Furthermore, we evaluate numerically the ergodic capacity of the considered schemes. We show that as the VPL increases, MRN assisted transmission outperforms the conventional single-hop as well as the FRN assisted scheme, hence it is very promising for future wireless systems.

II. System Model

We consider a scenario where the BS has fixed coverage of D m while vehicles move along a highway as depicted in Fig. 1. We assume a dual-hop system where the BS transmits to a vehicular UE via an RN. Following the 3GPP convention, the link between the BS and the MRN or FRN is defined as the *backhaul link* and the link between the RN and the UE as the *access link*. It is assumed that the MRN and the FRN are half-duplex and employ the decode-and-forward (DF) protocol.

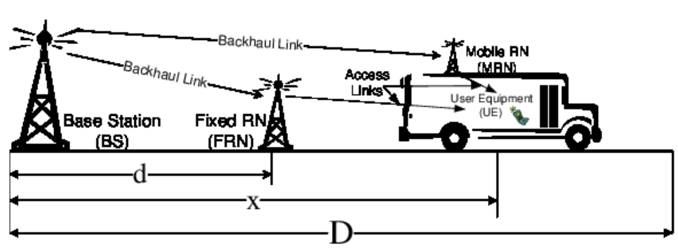

Figure 1. An illustration of the considered system scenario.

For both RN assisted schemes, in the first hop the BS transmits to the RN and the RN decodes the received signal, while in the second hop the RN forwards the decoded symbol to the vehicular UE. For these cases we assume no direct link between the BS and the UE. In a flat fading noise limited system, if the average transmit power is P_{t}, the received signal-to-noise ratio (SNR) can be expressed as

$$\gamma=\frac{P_{\mathrm{t}}|h|^{2}\beta L^{-\alpha}\varepsilon}{N_{0}}, \tag{1}$$

where h represents the channel coefficient and $\beta L^{-\alpha}$ models the pathloss when the receiver (RX) is at distance L from the transmitter (TX). Moreover, α denotes the pathloss exponent, where usually $2 \leq \alpha \leq 4$ and β denotes the pathloss constant [9]. The pathloss model $\beta L^{-\alpha}$ is only valid when the distance between RX and TX is greater than a certain value, also known as the *break point* [9]. The 3GPP spatial channel model (SCM) for urban microcell environments considers that the break point is at 20 meters; for $L<20$ a constant loss is assumed [10]. In addition, ε denotes the VPL affecting communication, where $0<\varepsilon \leq 1$ and N_0 represents the one side noise power density at RX.

As shown in Fig. 1, the FRN is at distance d and the UE is at distance x from the BS. The capacities of the backhaul and access links can be expressed as $C_{\mathrm{bk}}=\log_2(1+\gamma_{RN})$ and $C_{\mathrm{ac}}=\log_2(1+\gamma_{UE})$ respectively, where $\gamma_{\mathrm{RN}}=\frac{P_{\mathrm{t}}^{\mathrm{eNB}}|h_1|^2\beta_1 d_1^{-\alpha_1}}{N_0}$ [11]. Regarding γ_{UE}, for FRN we have $\gamma_{\mathrm{UE}}^{\mathrm{FRN}}=\frac{P_{\mathrm{t}}^{\mathrm{RN}}|h_2|^2\beta_2|x-d|^{-\alpha_2}\varepsilon}{N_0}$ and for MRN, as the distance between the TX and RN is short (5 meters at most), and there is almost always a line-of-sight (LOS) link, we simply assume a constant loss K, hence $\gamma_{\mathrm{UE}}^{\mathrm{MRN}}=\frac{P_{\mathrm{t}}^{\mathrm{RN}}K}{N_0}$. $P_{\mathrm{t}}^{\mathrm{e}NB}$ and $P_{\mathrm{t}}^{\mathrm{RN}}$ denote the average transmit power of the BS and the RN respectively. In addition, h_1 denotes the channel coefficient of the backhaul link and h_2 denotes the channel coefficient of the access link in the case of FRN assisted transmission. We assume the RNs are deployed outdoors, hence there is no VPL for the backhaul links. The ergodic capacity of the considered dual-hop RN-assisted scenarios can be expressed as

$$C_{\mathrm{DF}}=\mathbb{E}\left[\frac{1}{2}\min\{C_{\mathrm{bk}},C_{\mathrm{ac}}\}\right], \tag{2}$$

where $\mathbb{E}[\cdot]$ denotes expectation.

III. Outage Analysis

OP is defined as $P_{\mathrm{out}}=\Pr\{\gamma<\gamma_{\mathrm{th}}\}$, where γ is the instantaneous received SNR and γ_{th} is the required SNR threshold at RX to support a given target rate. In a half-duplex RN-assisted system with DF, to support a given end-to-end rate of $\mathcal{R}$ bits/sec/Hz at the UE, both the backhaul and the access links need to support a rate of $2\mathcal{R}$. Thus, it is required that $\min(\gamma_{\mathrm{RN}},\gamma_{\mathrm{UE}})\geq\gamma_{\mathrm{th}}$, where $\gamma_{\mathrm{th}}=2^{2\mathcal{R}}-1$ [11].

The signal envelopes of the channel coefficients h_1 and h_2 are assumed to follow the Rayleigh distribution, hence the instantaneous received SNR γ follows an exponential distribution with probability density function (PDF) $p_\gamma(x)=\frac{1}{\bar{P}_{\mathrm{r}}}\exp\left(-x/\bar{P}_{\mathrm{r}}\right)$, where $\bar{P}_{\mathrm{r}}$ is the average received signal power [12, Chp. 3] and $\exp(\cdot)$ denotes the exponential function. The OP of a single-hop system is well studied and details can be found in various sources, e.g., [12, Chp. 3]. In an MRN assisted system, as we assume that the access link is not corrupted by multipath fading, the OP can be obtained similarly to the signle-hop system with the use of a higher threshold. In an FRN assisted system, the backhaul and access channel coefficients are considered to be independent and not identically distributed (INID), hence $\gamma_{\min}=\min(\gamma_{\mathrm{RN}},\gamma_{\mathrm{UE}})$ is also exponentially distributed with PDF $p_{\gamma_{\min}}(x)=\lambda\exp(-\lambda x)$. Here $\lambda=\frac{1}{\bar{P}_{\mathrm{r}}^{\mathrm{RN}}}+\frac{1}{\bar{P}_{\mathrm{r}}^{\mathrm{UE}}}$ where $\bar{P}_{\mathrm{r}}^{\mathrm{RN}}$, $\bar{P}_{\mathrm{r}}^{\mathrm{UE}}$ represent the average received power at the RN and UE respectively [13]. The OP for a given threshold γ_{th} is

$$P_{\mathrm{out}}=\Pr\{\gamma<\gamma_{\mathrm{th}}\}=1-\exp(-\lambda\gamma_{\mathrm{th}}). \tag{3}$$

As shown in Fig. 1, if the distance between BS and FRN is d and the distance between BS and UE is x, then

$$\bar{P}_{\mathrm{r}}^{\mathrm{RN}}=P_{\mathrm{t}}^{\mathrm{eNB}}\,\beta_1\,d^{-\alpha_1} \tag{4a}$$

$$\bar{P}_{\mathrm{r}}^{\mathrm{UE}}=P_{\mathrm{t}}^{\mathrm{RN}}\,\beta_2\,\varepsilon\,|x-d|^{-\alpha_2}. \tag{4b}$$

OP grows as γ diminishes and γ depends on the distance between TX and RX. As mentioned before, as within the break point of the TX the pathloss is assumed to be constant, the RN should at least be placed at the break point, here denoted as d_{break}, to minimize the OP. Thus, if we know the UE position x, the RN should always be placed between the BS and the UE, i.e., $d_{\mathrm{break}}\leq d\leq x$, to minimize the OP. The λ is given as follows

$$\lambda=\frac{1}{\bar{P}_{\mathrm{r}}^{\mathrm{RN}}}+\frac{1}{\bar{P}_{\mathrm{r}}^{\mathrm{UE}}}=\frac{\varepsilon\,\beta_2\,d^{\alpha_1}\,P_{\mathrm{t}}^{\mathrm{RN}}+\beta_1\,P_{\mathrm{t}}^{\mathrm{eNB}}\,(x-d)^{\alpha_2}}{\varepsilon\,\beta_1\,\beta_2\,P_{\mathrm{t}}^{\mathrm{eNB}}\,P_{\mathrm{t}}^{\mathrm{RN}}}. \tag{5}$$

By plugging (5) into (3) we express OP as a function of d as follows

$$P_{\mathrm{out}}(x,d)=1-\exp\left(-\frac{\varepsilon\,\beta_2\,d^{\alpha_1}\,P_{\mathrm{t}}^{\mathrm{RN}}+\beta_1\,P_{\mathrm{t}}^{\mathrm{eNB}}\,(x-d)^{\alpha_2}}{\varepsilon\,\beta_1\,\beta_2\,P_{\mathrm{t}}^{\mathrm{eNB}}\,P_{\mathrm{t}}^{\mathrm{RN}}}\gamma_{\mathrm{th}}\right). \tag{6}$$

A. FRN Lower Bound

In this section we derive a lower bound for the OP of the FRN assisted transmission by finding analytically the position of FRN that minimizes OP. We assume that the exact UE position x is known and then place the FRN accordingly. As the exponential function is monotonically increasing, $P_{\mathrm{out}}(x,d)$ of (6) reaches its minimum when the exponential function argument is maximized. Let $f(x,d)=-\frac{\varepsilon\,\beta_2\,d^{\alpha_1}\,P_{\mathrm{t}}^{\mathrm{RN}}+\beta_1\,P_{\mathrm{t}}^{\mathrm{eNB}}\,(x-d)^{\alpha_2}}{\varepsilon\,\beta_1\,\beta_2\,P_{\mathrm{t}}^{\mathrm{eNB}}\,P_{\mathrm{t}}^{\mathrm{RN}}}\gamma_{\mathrm{th}}$. Then the problem becomes:

$$d_{\mathrm{opt}}(x)=\arg\max_{d_{\mathrm{break}}\leq d\leq x}f(x,d). \tag{7}$$

Without loss of generality let the ratio between the transmit power of RN and BS be $\rho=P_{\mathrm{t}}^{\mathrm{RN}}/P_{\mathrm{t}}^{\mathrm{eNB}}$, hence $P_{\mathrm{t}}^{\mathrm{RN}}=\rho P_{\mathrm{t}}^{\mathrm{eNB}}$. By taking the first and second order derivatives of $f(x,d)$ with respect to d we obtain:

$$\frac{\partial f(x,d)}{\partial d}=\frac{\alpha_2\,\beta_1\,(x-d)^{\alpha_2-1}-\alpha_1\,\beta_2\,\varepsilon\,\rho\,d^{\alpha_1-1}}{\beta_1\,\beta_2\,\varepsilon\,\rho\,P_{\mathrm{t}}^{\mathrm{eNB}}}\gamma_{\mathrm{th}} \tag{7a}$$

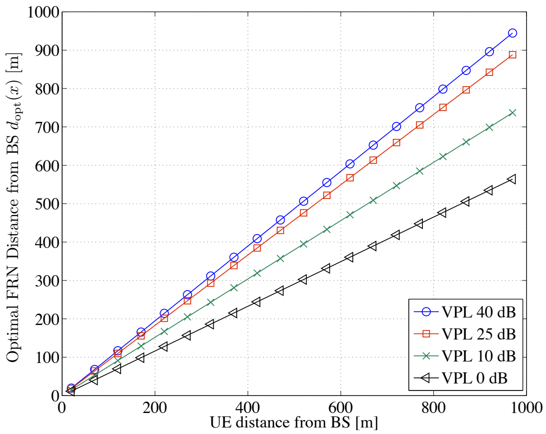

Figure 2. Optimal RN position when the UE position is known with $\alpha_1 = \alpha_2 = 3.8$ and $\beta_1 = \beta_2 = 3.5237 \times 10^{-4}$

$$\frac{\partial^2 f(x,d)}{\partial d^2} = -\frac{\gamma_{\rm th}}{\beta_1\,\beta_2\,d^2\,\varepsilon\,(x-d)^2\rho P_{\rm t}^{\rm eNB}}[-\alpha_1\,\beta_2\,d^{\alpha_1}\varepsilon\,\rho\,(x-d)^2 + \alpha_1^2\,\beta_2\,d^{\alpha_1}\,\varepsilon\,\rho\,(x-d)^2 +(\alpha_2-1)\,\alpha_2\,\beta_2\,d^2\,(x-d)^{\alpha_2}]. \quad (7b)$$

We observe that $\alpha_1^2\,\beta_2\,d^{\alpha_1}\,\varepsilon\,\rho\,(x-d)^2 - \alpha_1\,\beta_2\,d^{\alpha_1}\,\varepsilon\,\rho\,(x-d)^2 > 0$ when $2 \le \alpha \le 4$, which gives $\frac{\partial^2 f(x,d)}{\partial d^2} < 0$. Thus, $f(x,d)$ is concave in d and has a global maximum which is the positive root of the equation resulting from setting (7a) equal to zero. E.g., for $\alpha_1 = \alpha_2 = 2$, we have:

$$d_{\rm opt}(x) = \frac{\beta_1\,x}{\beta_1 + \beta_2\,\varepsilon\,\rho}. \quad (8)$$

For $\alpha_1 = \alpha_2 = 3$, we have:

$$d_{\rm opt}(x) = \frac{\beta_1\,x + \sqrt{\beta_1\,\beta_2\,\varepsilon\,\rho}\,x}{\beta_1 - \beta_2\,\varepsilon\,\rho}. \quad (9)$$

For non-integer values of α_1 and α_2, we can find the solution numerically. Fig. 2 shows the optimal FRN position as a function of VPL ε when assuming that $\alpha_1 = \alpha_2 = 3.8$ and $\beta_1 = \beta_2 = 3.5237 \times 10^{-4}$[10]. The employed transmit power of BS and RN is shown in Table I.

From the obtained analytical, i.e., (8) and (9), and numerical results, i.e., Fig. 2, we can observe that the optimal FRN position depends on the pathloss model, the VPL and the transmit power ratio ρ between RN and BS. In all cases, as VPL increases the optimal FRN position approaches the UE. In the most extreme case, if we let the VPL approach infinity, i.e., $\varepsilon \to 0$, the optimal FRN position should coincide with that of the UE. Furthermore, in the HetNet concepts introduced by the 3GPP release 10, the RN nodes have much lower transmit power than BSs, i.e., $\rho < 1$ [14]. In such cases, as suggested by (8) and (9), the RN should be placed near the UE to minimize the OP.

These findings motivate the use of MRNs, especially when the RN transmit power is lower than that of the BS and VPL is high. Detailed simulation studies using the 3GPP specifications are presented in Section IV.

B. Optimal FRN Location for Known UE Position Distribution

To achieve a fair comparison between FRN and MRN assisted transmission, the FRN should be placed at a fixed position, unlike what has been assumed for obtaining the OP lower bound. Here we discuss what is the optimal FRN position, resulting in the minimum OP, when only the UE position distribution along the highway is known. Assuming that the probability of a UE being at a certain position in a cellular system is a function of the distance between the UE and the BS ([9, Chp. 3]), we denote the PDF of the UE distribution as $p_x(x)$. Thus, the average OP for our considered case is

$$\bar{P}_{\rm out}(d) = \int_0^D P_{\rm out}(x,d)\; p_x(x)\,dx, \quad (10)$$

where D is the radius of the cell. Thus, we can formulate the following optimization problem:

$$\bar{d}_{\rm opt} = \arg \min_{d_{\rm break} \le d \le D} \bar{P}_{\rm out}(d). \quad (11)$$

We assume vehicles moving along a highway, as shown in Fig. 1. Thus it is reasonable to assume a uniform distribution of the vehicles with respect to their distances from the BS. The problem becomes

$$\bar{d}_{\rm opt} = \arg \min_{d_{\rm break} \le d \le D} \int_0^D \frac{1}{D} P_{\rm out}(x,d)\;dx, \quad (12)$$

where $P_{\rm out}(x,d)$ is given by (6).

IV. Performance Evaluation

Table I
Simulation Parameters

Parameter	Value
Path Loss Model in [dB]	$PL_{\rm dB} = 34.53 + 38\log_{10}(d)$
Cell Radius D	1000 meters
BS transmit power P_t^{eNB}	24 dBm
RN transmit power P_t^{RN}	20 dBm
Receiver noise figure for both RN and UE	9 dB
Normalized minimum required rate $\mathcal{R}$ at UE	2 bits/s/Hz

In this section we present analytical and simulation results for the OP and ergodic capacity achieved by the considered schemes. The employed simulation parameters are given in Table I. As the RN radio TX and RX parts of 3GPP specifications are still under investigation [15], we refer to other low power nodes, i.e., Home BS, for the RN TX power [14]. The BS TX power is given in [14] and for the pathloss the employed model is the SCM urban non-line-of-sight (NLOS) microcell model [10][1].

For our evaluations the FRN minimizing the overall OP is placed according to the solution of (12). The optimal FRN position minimizing the OP assuming known UE position is given by (7) and the achieved OP serves as the OP lower bound for the FRN scheme. The MRN is placed on top of the vehicle and is assumed to eliminate VPL.

[1]The last access to all 3GPP specifications was on 17 Oct. 2011.

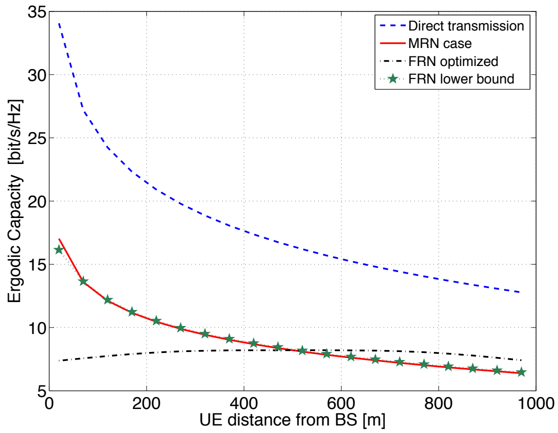

Figure 3. Ergodic Capacity when VPL = 0 dB

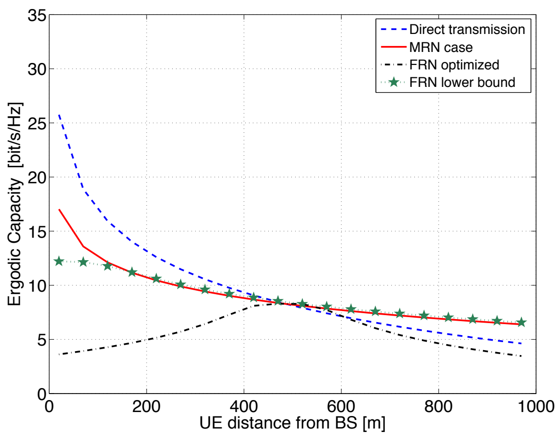

Figure 4. Ergodic Capacity when VPL = 25 dB

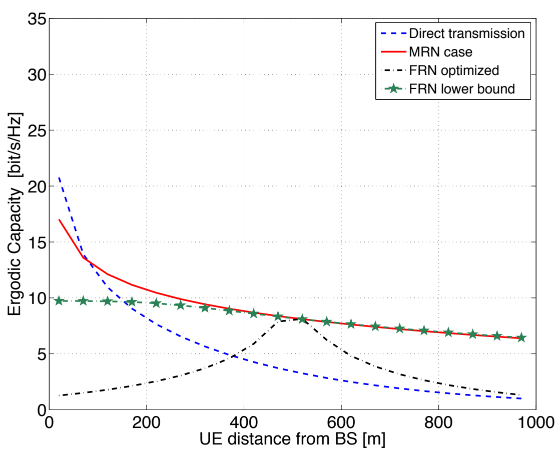

Figure 5. Ergodic Capacity when VPL = 40 dB

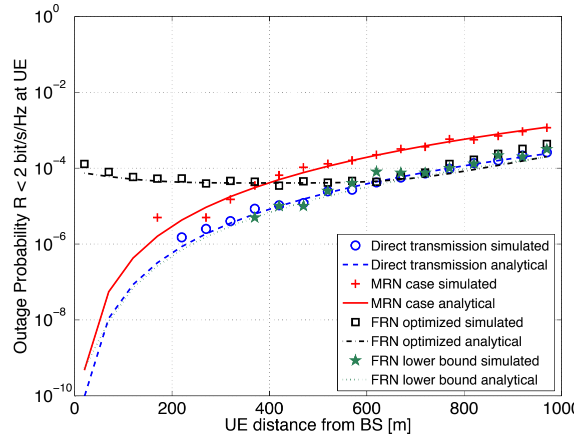

Figure 6. Outage Probability when VPL = 0 dB

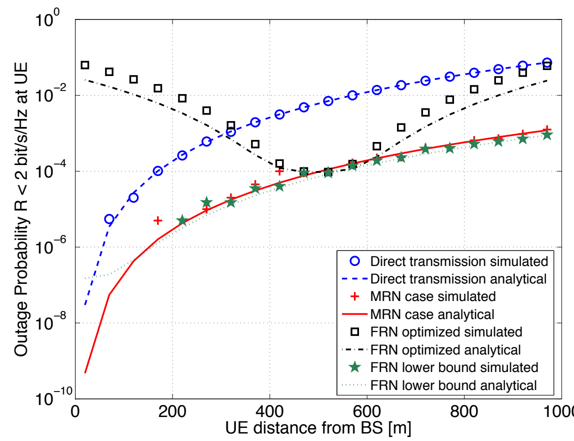

Figure 7. Outage Probability when VPL = 25 dB

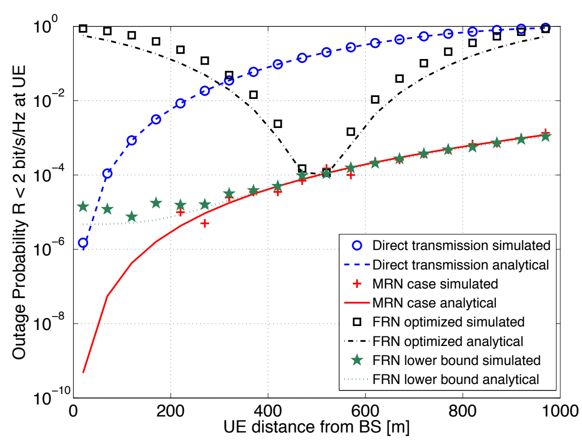

Figure 8. Outage Probability when VPL = 40 dB

Table II
OPTIMAL RN POSITION MINIMIZING THE AVERAGE OUTAGE PROBABILITY UNDER DIFFERENT VPL

VPL [dB]	$\bar{d}_{\mathrm{opt}}$ [m] $P_{\mathrm{t}}^{\mathrm{eNB}} = 24$ dBm $P_{\mathrm{t}}^{\mathrm{FRN}} = 24$ dBm	$\bar{d}_{\mathrm{opt}}$ [m] $P_{\mathrm{t}}^{\mathrm{eNB}} = 24$ dBm $P_{\mathrm{t}}^{\mathrm{FRN}} = 20$ dBm
0	341	398
10	460	482
25	495	498
40	500	500

As the analytical solution to optimization problem (12) is not straightforward, we solve it numerically by exhaustive grid search with a resolution of 1 meter. The results are given in Table II. It is shown that when the transmit power of the BS and FRN is the same and the VPL is small, the FRN positions minimizing the overall OP approach the BS. But as the VPL increases, the optimal FRN position is near the middle of the road. Similar results can be observed when the FRN transmit power is much lower than that of the BS. In the evaluations of this work, we consider $P_t^{eNB} = 24$ dBm and $P_t^{FRN} = 20$ dBm. The corresponding FRN positions are given in Table II.

Figs. 3, 4 and 5 show the simulated ergodic capacity under different VPLs. Figs. 6, 7 and 8 illustrate the OP performance for all the cases as calculated analytically, i.e., from equation (3), and also by simulation. We observe that there is a good match between the analytical and the simulation results. From Figs. 3 and 6 we can see that if there is no VPL, the baseline direct transmission always achieves the highest ergodic capacity and the lowest OP. As VPL increases, both RN assisted schemes achieve higher capacities as the UE moves away from the BS. Also from Fig. 4, we notice that the capacity of the dual-hop transmission via the MRN begins to overtake the direct transmission at a distance of around 550 meters from the BS when the VPL is moderate (25 dB). Furthermore, as VPL increases to 40 dB (see Fig. 5) the MRN assisted transmission outperforms the direct transmission even when the UE is about 100 meters away from the BS. In contrast, the FRN assisted transmission outperforms the direct transmission when the UE is around 390 meters away from the BS.

The OP plots show a more interesting trend. As we can see from Figs. 7 and 8, the OP of the MRN assisted transmission is always lower than that of the direct transmission and almost always lower than that of the FRN assisted transmission. This indicates that the MRN assisted system is better at maintaining a given rate, which can be translated to a quality-of-service (QoS) level, than the other two schemes.

We also observe that the FRN lower bound, based on the derivation of Section III, achieves a similar performance as the MRN when the UE is far from the BS. This can be explained by (2) showing that both the ergodic capacity and also the OP of RN assisted transmission under DF are limited by the worst link. Thus, as the UE moves away from the BS, the backhaul link is the main limitation for the system performance; this is also shown by the results of section III, suggesting that the FRN should be placed near the UE. These findings motivate the use of MRNs as they have great potential to provide significant performance gains for vehicular UEs.

V. CONCLUSION

In this paper we argued that MRNs can bring significant benefits to vehicular UEs in future wireless networks. To this end we compared the achievable ergodic capacity and OP of single-hop direct transmission (baseline case), and dual-hop transmission via an MRN as well as an FRN. For an accurate comparison, we optimized the FRN position in terms of OP and we also derived an OP lower bound for the FRN assisted case. By theoretical analysis and simulations we showed that in the cases of moderate to high VPL, MRN assisted transmission greatly outperforms FRN assisted transmission as well as direct transmission when the UE is moving away from the BS. We can conclude that MRNs have a very good potential to boost performance of future systems. In order to understand the performance of MRNs in a real cellular system, thorough system level evaluations will be conducted in the future.

ACKNOWLEDGMENT

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