Performance Comparison of Fixed and Moving Relays under Co-channel Interference

Yutao Sui, Agisilaos Papadogiannis, Wei Yang, and Tommy Svensson
Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden
Email:{sui.yutao, agisilaos.papadogiannis, ywei, tommy.svensson}@chalmers.se

***Abstract*—In this paper, we study and compare the outage probability (OP) of a vehicular user of dual-hop moving relay node (MRN) assisted transmission, dual-hop transmission assisted by a fixed relay node (FRN), as well as of the baseline single-hop direct transmission under of co-channel interference. For an accurate comparison, we numerically optimize the FRN position which minimizes the average vehicular user OP. When vehicular penetration loss is moderate to high, MRN assisted transmission is shown to greatly outperform transmission assisted by an FRN as well as direct transmission. Hence the use of MRNs is very promising for improving the quality-of-service of vehicular users for future mobile communication systems.**

I. Introduction

With the introduction of the fixed relay node (FRN) in the release 10 of the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) standards, relaying techniques in mobile communication systems received extensive attention recently [1]–[5]. Together with other low power nodes, such as pico and femto nodes, the FRN is a key component of heterogeneous networks introduced in release 10 of 3GPP LTE standards [2]. On the other hand, the use of moving relay nodes (MRNs) in cellular systems is still under discussion in the release 11 of the 3GPP LTE [3]. Studies have shown that by deploying coordinated and cooperative relays on top of trains, the quality-of-service (QoS) of a user equipment (UE) inside the vehicle can be significantly improved [4]. Furthermore, in [5] it was shown that dynamically deployed relays can bring large performance gains to mobile communication systems.

One of the major advantages of using MRNs is the elimination of vehicular penetration loss (VPL) which significantly reduces the signal strength. Nowadays, public transportation vehicles, e.g., buses, trams, or trains, become natural hotspots for wireless data traffic, since a large number of mobile users are using their wireless data services while commuting or traveling. This makes the signal attenuation caused by the VPL a big challenge for future wireless communication systems. Measurements show that VPL can be as high as 25 dB in a minivan at the frequency of 2.4 GHz [6] and higher VPLs are foreseeable in the well isolated vehicles of interest in higher frequency bands[1]. By using two separate indoor and outdoor antennas connected through a cable introducing negligible losses, the MRNs can reduce or eliminate VPL. Furthermore, since the MRN can create its own cell within the vehicle, it has the potential to provide very high data rates to the connected vehicular UEs. MRNs can also provide other benefits such as group handover, reducing the signaling overhead of the network, and collective channel state information (CSI) feedback for advanced backhaul design [7].

In [8], we showed that in a noise limited system, using MRNs can improve the spectral efficiency and lower the outage probability (OP) for vehicular UEs when the average transmit power of the base station (BS) and the relay node (RN) is fixed. In this study, we extend our analysis to a scenario that the communication is corrupted by co-channel interference (CCI). This can be seen as a worst case scenario, since in practice CCI can be partly reduced by using various Inter Cell Interference Coordination (ICIC) techniques. We investigate a general scenario that considers deploying MRNs on top of public transportation vehicles, i.e., buses, trams or trains, and compare the OP performance of a vehicular UE of the dual-hop FRN and MRN assisted transmission and the baseline direct single-hop BS-to-UE transmission. Moreover, different links are modeled by considering different propagation conditions. To facilitate our comparisons, we numerically optimize the FRN position to minimize the average end-to-end OP for the vehicular UE. We show that as the VPL increases, an MRN is better at lowering the OP of vehicular UEs than the BS-to-UE direct transmission as well as the FRN assisted scheme. Hence the use of MRNs is very promising for future mobile communication systems.

This paper is organized as follows. In Section II we present the system models followed by propagation models and outage analysis in Section III. In Section IV, techniques used to optimize the FRN position in the presence of CCI are introduced and the optimal FRN position that minimize the average end-to-end OP at UE is obtained. In Section V, we present the OP performance of the considered schemes and Section VI concludes the paper.

II. System model

We consider the downlink of an RN assisted system with two cells: one primary cell where the OP performance at the vehicular UE is investigated and one interfering cell (see Fig. 1). For convenience, we label all the nodes in the primary cell with number 1 and nodes in the interfering cell with number 2. We assume that all transmitters, i.e., BSs, FRNs and MRNs, are transmitting at fixed average power and no power control schemes are considered. The BSs in both cells

[1] The 3.6 GHz frequency band has been allocated to next generation mobile communication at World Radio Communication Conference in 2007.

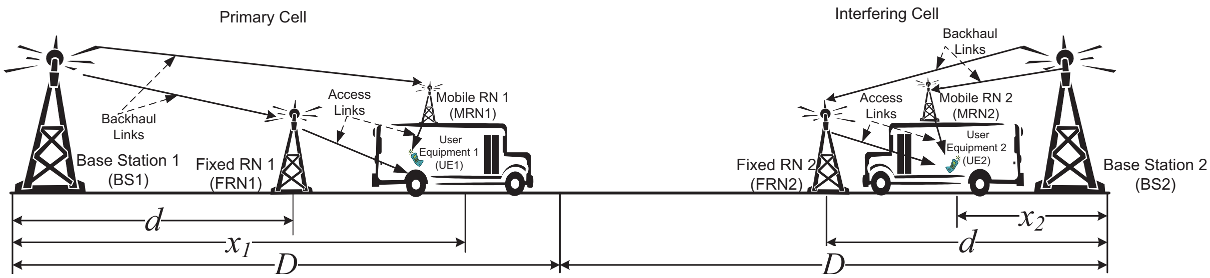

Figure 1. System model

have fixed coverage of D meters while vehicles move along a highway. Regarding FRN assisted transmission, we constrain our study to a symmetric deployment of the FRNs, i.e., each of the FRNs is at the same distance d meters from its serving BS. For MRN assisted transmission, we assume that the MRN is deployed on top of a vehicle and it eliminates the VPL by properly separating its indoor and outdoor antennas. Following the 3GPP convention, the BS-RN and RN-UE links are denoted as *backhaul* and *access links*, respectively.

It is assumed that both the MRN and the FRN are decode-and-forward (DF) and half-duplex, i.e., 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. Moreover, we assume no direct link between the BS and the UE in the RN assisted transmission. The same type of RNs are assumed to be used in the two cells, i.e., scenarios such as one cell is equipped with MRN while the other uses FRN is not considered in this work. Furthermore, in the study of RN assisted transmissions, we assume that the downlinks of the two cells are synchronized in time, which means that in both cells, the backhaul links are only active in the first time slot and access links are only active in the following slot. Thus, backhaul links and access links will not interfere with each other. In addition, we consider the impact of pathloss and small scale flat fading on the end-to-end OP at the vehicular UE.

In general, if the transmitter (TX) has an average transmit power $P_{\rm t}$ and the interference source has an average transmit power $P_{\rm t_I}$, the received signal-to-interference-plus-noise ratio (SINR) can be expressed as

$$\gamma = \frac{P_r\left(y\right)}{P_{r_{\rm I}}\left(y_{\rm I}\right)+N_0} = \frac{P_{\rm t}\, L(y)\, |h|^2\, V}{P_{\rm t_I}\, L_{\rm I}\left(y_{\rm I}\right)\, |h_{\rm I}|^2 V' + N_0}, \quad (1)$$

where $P_r\left(y\right)$ denotes the received desired signal power and and $P_{r_{\rm I}}\left(y_{\rm I}\right)$ is interference power at the receiver; y is the distance between the TX and the receiver (RX) and $y_{\rm I}$ represents the distance between the interference source and the RX. Moreover, N_0 is the average background noise power; $L\left(y\right)$ models the pathloss when an RX is at distance y from the TX and $L_{\rm I}\left(y_{\rm I}\right)$ models the pathloss when an RX is at distance $y_{\rm I}$ from the interference source. In addition, h and $h_{\rm I}$ represent the respective channel coefficients of the desired and interference links and will be detailed in Section III. We consider a flat fading environment. In wideband systems employing orthogonal frequency-division multiple access (OFDMA), this setup can be seen as a subchannel or a subchannel group whose bandwidth is much smaller than the coherence bandwidth of the channel [9, Ch. 12].

In (1), V and V' denote the VPL affecting communication, where $0 < V \leq 1,\ 0 < V' \leq 1$. We assume that both vehicles have the same VPL of a value ε. The RNs are assumed to be deployed outdoors, so no VPL affects the backhaul links of the RN assisted transmission, i.e., $V_{\rm R_{bk}} = V'_{\rm R_{bk}} = 1$. For the direct transmission, and the FRN access link, obviously we have $V_{\rm D} = V'_{\rm D} = \varepsilon,\ V_{\rm F_{ac}} = V'_{\rm F_{ac}} = \varepsilon$. For the MRN assisted transmission, as we assumed the antenna communicating with the UE is deployed inside the vehicle, there is no VPL affecting the desired signal, i.e., $V_{\rm M_{ac}} = 1$; however, the interfering signal of the MRN access link is attenuated twice by both vehicles, which gives $V'_{\rm M_{ac}} = \varepsilon^2$.

III. Propagation Models and Outage analysis

A. Propagation Models

In this section, we discuss the different propagation models employed for each of the links. For BS to UE direct transmission and the access link of an FRN, a non-line-of-sight (NLOS) propagation environment is considered. For the backhaul link of an FRN, we consider a line-of-sight (LOS) propagation environment. This is motivated that if we have a proper site planning, the probability for the FRN backhaul link to have a LOS connection is relatively high. The interference of the FRN backhaul link, i.e., BS2 to FRN1, is considered as NLOS, since the FRN is far away from the interfering BS and LOS probability in this case is very low (see [10, Table A.2.1.1.2-3]). Such a setup is the best scenario an FRN can experience in practice.

The pathloss $L\left(y\right)$ between a TX and an RX depends on several factors, e.g., antenna heights, propagation conditions, etc., and is usually determined by measurements [9, Ch. 4]. In this study, a carrier frequency of 2.0 GHz is considered. The pathloss models can usually be expressed as

$$L\left(y\right)[\mathrm{dB}] = A\, \log_{10}\left(y\right) + B, \quad (2)$$

where A is the pathloss exponent, B is the pathloss constant and y is the distance between TX and RX in kilometers. For direct and FRN assisted transmissions, we follow the pathloss models given in [10]. Regarding the MRN assisted transmission, the pathloss of the backhaul link and its interference are modeled in the same way as the direct transmission. For the access link, since the distance between the MRN and the UE

Table I
SUMMARY OF THE PATHLOSS MODELS

Scenario	LOS / NLOS	A	B	Break Point [km]
Direct transmission and its interference (BS1–UE1 and BS2–UE1)	NLOS	42.8	131.1	0.035
MRN backhaul link and its interference (BS1–MRN1 and BS2–MRN2)				
FRN backhaul link (BS1–FRN1)	LOS	23.5	100.7	0.035
Interference to the backhaul link of FRN (BS2–FRN1)	NLOS	36.3	125.2	0.035
FRN access link and its interference (FRN1–UE1 and FRN2–UE1)	NLOS	37.5	145.4	0.035
Interference to the access link of MRN (MRN2–UE1)	LOS	26	108.6	0.02
Access link of MRN (MRN1–UE1)	LOS	Constant power loss $G = -84$ dB		

is short (up to around 5 meters), and there is almost always a LOS link, we simply assume a constant power loss G which includes the effect of pathloss and fading. We set $G = -84\,\mathrm{dB}$ which approaches the measurement lower bound shown in [11] in the presence of fading. As for the interference between the access link of two MRNs, i.e., MRN2 to UE1, we use the LOS COST 231–Walfish–Ikegami pathloss model [12, Ch. 7]. This is considered to be the worst case scenario since lower interference power is expected for the NLOS transmission. The values of A and B for different propagation scenarios are summarized in Table I.

It is worth mentioning that pathloss models are usually valid when the distance between a TX and an RX is greater than a certain value, also known as the break point [9, Ch. 4]. As the detailed pathloss modeling is out of the scope of this study, for simplicity, within the break point, we conservatively assume that the pathloss is constant and equals the pathloss at the break point distance, i.e., $L\left(y\right) = L\left(y_{\mathrm{break}}\right),\ y \le y_{\mathrm{break}}$.

The amplitude of the channel coefficients are considered to be Rayleigh distributed in a NLOS propagation environment and to be Rician distribution with different K factors in the LOS propagation environment [9, Ch. 5]. Based on the studies of stationary feeder links in typical urban scenarios [13, pp. 17-18], we consider $K_{\mathrm{F_{bk}}} = 10$ for the FRN backhaul in this study. On the other hand, for the street level LOS propagation, the K factor depends on the distance between the TX and the RX. In our study, we adopt the model given in [13, pp. 73] and the K factor for the interference to access link of the serving MRN is given as follows.

$$K_{\mathrm{M_{I_{ac}}}} = \begin{cases} 10 & L_{\mathrm{M_I}}\left(y_{\mathrm{I}}\right) < 85\,\mathrm{dB} \\ 2 & 85\,\mathrm{dB} \le L_{\mathrm{M_I}}\left(y_{\mathrm{I}}\right) < 110\,\mathrm{dB} \\ 1 & L_{\mathrm{M_I}}\left(y_{\mathrm{I}}\right) \ge 110\,\mathrm{dB} \end{cases}. \quad (3)$$

B. Outage Analysis

In the presence of fading, there is always a probability that the received SINR γ falls below a given threshold γ_{th}, which is usually referred as OP. For direct transmission, the end-to-end OP at the UE is given as

$$P_{\mathrm{out_D}}\left(\gamma_{\mathrm{th_D}}\right) = \Pr\left(\gamma < \gamma_{\mathrm{th_D}}\right). \quad (4)$$

On the other hand, in a half-duplex DF RN-assisted system, outage takes place if either the backhaul or access link is in outage. Thus, in the FRN or MRN assisted transmission, OP can be expressed as

$$P_{\mathrm{out_R}}\left(\gamma_{\mathrm{th_R}}\right) = \Pr\left(\min\left(\gamma_{\mathrm{bk}},\, \gamma_{\mathrm{ac}}\right) < \gamma_{\mathrm{th_R}}\right). \quad (5)$$

The threshold $\gamma_{\mathrm{th_D}}$ or $\gamma_{\mathrm{th_R}}$ varies according to different QoS requirements, e.g., a minimum error rate or a minimum data rate. In this study, the threshold is chosen based on the achievable rate in an LTE system investigated in [14] as

$$R\left(\mathrm{bits/s/Hz}\right) = B_{\mathrm{ef}}\,\eta\,\log_2\left(1 + \frac{\gamma}{\gamma_{\mathrm{ef}}}\right), \quad (6)$$

where B_{ef} adjusts for the bandwidth efficiency of the system, γ_{ef} corrects the SINR implementation efficiency of the system and η is a correction factor that is usually set to 1. In a single-input-single-out (SISO) LTE system with fast time and frequency domain packet scheduling, B_{ef} and γ_{ef} are found both to be 0.62 [14].

According to (6), if we require an end-to-end rate of R, the threshold $\gamma_{\mathrm{th_D}}$ for direct transmission is given as

$$\gamma_{\mathrm{th_D}} = \gamma_{\mathrm{ef}}\left(2^{\frac{R}{B_{\mathrm{ef}}\,\eta}} - 1\right). \quad (7)$$

On the other hand, in a half-duplex DF RN assisted transmission system, if we require an end-to-end rate of R, both the backhaul link and the access link should support at least a rate of $2\,R$. Thus, the threshold is

$$\gamma_{\mathrm{th_R}} = \gamma_{\mathrm{ef}}\left(2^{\frac{2\,R}{B_{\mathrm{ef}}\,\eta}} - 1\right). \quad (8)$$

IV. OPTIMIZING THE USE OF FRNS

In order to profit from the FRN and fairly compare the performance between the FRN assisted transmission and the other schemes, the FRN should be deployed in an optimal position that minimizes the average end-to-end OP at the UE, which is given as

$$\begin{aligned} \bar{P}_{\mathrm{out_F}}\left(d,\, \gamma_{\mathrm{th_R}}\right) &= \mathbb{E}_x\left[P_{\mathrm{out_F}}\left(d,\, x_1,\, \gamma_{\mathrm{th_R}}\right)\right] \\ &= \int_0^\infty P_{\mathrm{out_F}}\left(d,\, x_1,\, \gamma_{\mathrm{th_R}}\right)\, f_{x_1}(x_1)\, dx_1 \end{aligned} \quad (9)$$

where $\mathbb{E}\left[\cdot\right]$ denotes expectation and $f_{x_1}(x_1)$ is the probability density function (pdf) of the UE distance distribution. The probability of a UE being at a certain position in a cellular system is related to the distance between the UE and BS as well as other factors [9, Ch. 17]. Since we consider vehicular UEs moving along a road (see Fig. 1), it is reasonable to assume a uniform position distribution of the UE. Therefore, we have

$$f_{x_1}(x_1) = \begin{cases} \frac{1}{D}, & 0 \le x_1 \le D \\ 0, & \text{otherwise} \end{cases}. \quad (10)$$

By substituting (10) into (9), we obtain

$$\bar{P}_{\text{out}_\text{F}}(d,\, \gamma_{\text{th}_\text{R}}) = \frac{1}{D}\int_0^D P_{\text{out}_\text{F}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}})\, dx_1. \quad (11)$$

Thus, the optimal FRN position is obtained as

$$\bar{d}_{\text{opt}} = \arg \min_{d_{\text{break}} < d \le D} \bar{P}_{\text{out}_\text{F}}(d,\, \gamma_{\text{th}_\text{R}}). \quad (12)$$

In order to solve problem (12), $P_{\text{out}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}})$ needs to be determined. As mentioned in Section III-B, in a half-duplex DF RN-assisted system, outage takes place if ether the backhaul or access link is in outage. Hence, we have

$$\begin{aligned} &P_{\text{out}_\text{F}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}}) \\ &= \Pr\left(\min\left(\gamma_{\text{bk}}(d),\, \gamma_{\text{ac}}(d,\, x_1)\right) < \gamma_{\text{th}_\text{R}}\right) \\ &= 1 - \left(1 - F_{\gamma_{\text{bk}}}(d,\, \gamma_{\text{th}_\text{R}})\right)\left(1 - F_{\gamma_{\text{ac}}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}})\right) \\ &= F_{\gamma_{\text{bk}}}(d,\, \gamma_{\text{th}_\text{R}}) + F_{\gamma_{\text{ac}}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}}) \\ &\qquad - F_{\gamma_{\text{bk}}}(d,\, \gamma_{\text{th}_\text{R}})\, F_{\gamma_{\text{ac}}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}}), \end{aligned} \quad (13)$$

where $F_{\gamma_{\text{bk}}}(d,\, \gamma_{\text{th}_\text{R}})$ and $F_{\gamma_{\text{ac}}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}})$ are the cumulative distribution function (cdf) of the received SINR of the backhaul link and access link, respectively. The derivations of $F_{\gamma_{\text{bk}}}(d,\, \gamma_{\text{th}_\text{R}})$ and $F_{\gamma_{\text{ac}}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}})$ are given in the Appendix as

$$\begin{aligned} &F_{\gamma_{\text{bk}}}(d,\, \gamma_{\text{th}_\text{R}}) \\ &= \frac{P_{r_{\text{I}_{\text{bk}}}}(d)\, \gamma_{\text{th}_\text{R}}}{P_{r_{\text{I}_{\text{bk}}}}(d)\, \gamma_{\text{th}_\text{R}} + P_{r_{\text{bk}}}(d)} \exp\left(-\frac{K_{\text{F}_\text{b}}\, P_{r_{\text{bk}}}(d)}{P_{r_{\text{I}_{\text{bk}}}}(d)\, \gamma_{\text{th}_\text{R}} + P_{r_{\text{bk}}}(d)}\right), \end{aligned} \quad (14)$$

where K_{F_b} is the Rician K factor of the BS-FRN link and

$$\begin{aligned} &F_{\gamma_{\text{ac}}}(d,\, x_1,\, \gamma_{\text{th}_\text{R}}) \\ &= 1 - \frac{P_{r_{\text{ac}}}(d,\, x_1)}{P_{r_{\text{ac}}}(d,\, x_1) + P_{r_{\text{I}_{\text{ac}}}}(d,\, x_1)\, \gamma_{\text{th}_\text{R}}} \exp\left(-\frac{\gamma_{\text{th}_\text{R}}\, N_0}{P_{r_{\text{ac}}}(d,\, x_1)}\right). \end{aligned} \quad (15)$$

Hence, the OP at a given UE position can be obtained by plugging (14) and (15) into (13); however, the analytical solution to the optimization problem in (12) is not straightforward. In our study, $\bar{d}_{\text{opt}}$ is obtained numerically by a grid search with a resolution of 0.1 meters and an inter-site distance of 1732 meters, i.e., $D = 866$ m, is considered. Other employed parameters are given in Table II. Fig. 2 shows the optimal FRN position $\bar{d}_{\text{opt}}$ against different VPLs. As VPL grows, $\bar{d}_{\text{opt}}$ tends to move closer to the BS. This is due to the fact that, in order to compensate for the loss introduced by VPL, the FRN needs to be placed close to its serving BS to minimize the interference of the access link from the interfering FRN.

V. PERFORMANCE EVALUATION

In this section, we evaluate vehicular UE's OP of the considered schemes, i.e., direct transmission and FRN and MRN assisted transmission. The employed evaluation parameters are based on [10] and summarized in Table II. The corresponding FRN positions that minimize the average end-to-end OP at the UE are obtained by solving (12) numerically. The MRNs are placed on top of the vehicle and assumed to eliminate VPL.

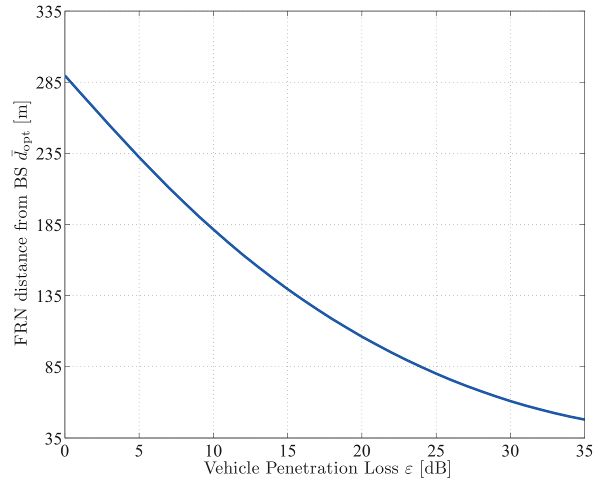

Figure 2. Optimal FRN position against different VPL with $D = 866$ m

For the direct transmission and FRN assisted transmission, the SINR at the FRN1 or the UE1 in the primary cell does not depend on the position of UE2 x_2. For the MRN case, however, the interference level experienced by UE1 depends on the position of UE2. Thus, for the evaluation of the MRN assisted transmission, we consider two setups: 1) UE2 is dropped uniformly in the interfering cell, and we obtain the average OP of UE1 in the primary cell by using the Monte Carlo method; 2) We place UE2 at the cell edge of the interfering cell, i.e., the nearest point to the primary cell, and obtain the OP of UE1. The second case can serve as the worst case scenario for the MRN performance, as it represents the largest interference that UE1 may experience from MRN2.

We move UE1 from its serving BS to the cell edge and plot its OP as a function of the distances from the serving BS for the considered setups. Figs. 3–5 show the average OP for UE1 at different positions from its serving BS with different VPLs. As we can see from the figures, the OPs of the UE with direct transmission and FRN assisted transmission increase significantly as VPL increases. When there is no VPL (Fig. 3), the direct transmission always gives the lowest OP. This is mostly due to the half-duplex loss of RN assisted schemes. As the VPL increases to 10 dB, the MRN and direct transmission almost have the same OP at the UE and when the VPL increases to 30 dB, the MRN assisted transmission significantly outperforms the direct transmission. On the other hand, the vehicular UE can only benefit from FRN assisted

Table II
SIMULATION PARAMETERS

Parameter	Value
Inter-site Distance	1732 meters
Average BS transmit power	46 dBm
Average FRN transmit power	30 dBm
Average MRN transmit power	20 dBm
Carrier Frequency	2.0 GHz
System Bandwidth	10 MHz
Receiver noise figure for both RN and UE	9 dB
Normalized Minimum Required Rate R at UE	1 bit/s/Hz

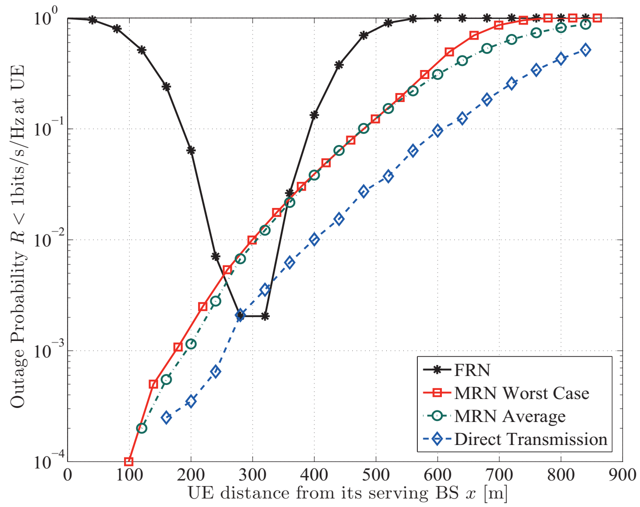

Figure 3. Outage Probability at UE when VPL = 0 dB

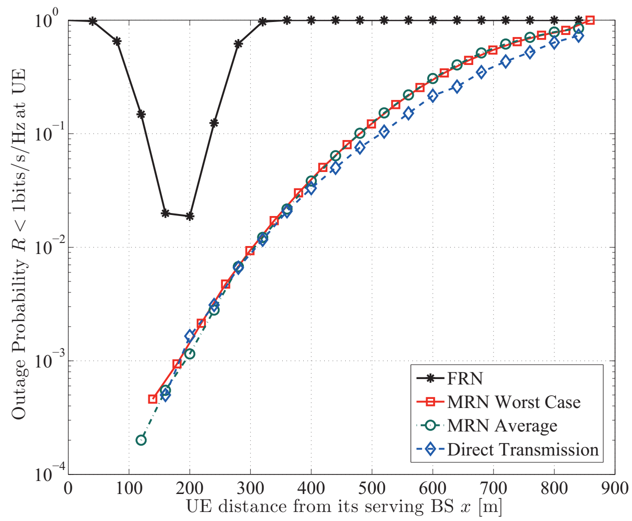

Figure 4. Outage Probability at UE when VPL = 10 dB

transmission when it is close to the FRN. This is mainly due to the low transmit power nature of the FRN, the half-duplex loss and the VPL.

Moreover, the interference power from the interfering MRN access link is attenuated twice by each of the vehicles. This effect can be observed by comparing the MRN worst case and MRN average case in Fig. 3. When there is no VPL, the quality of the MRN access link is significantly lowered, as there is no attenuation on the interference from the interfering cell. But as VPL increase, the interference generated by the access link of the interfering MRN can be well isolated inside the vehicle. As shown on Figs. 4–5, the difference between the MRN worst case and the MRN average case is barely noticeable. Therefore, the backhaul link is the bottleneck link that limits the performance of the MRN assisted transmission. If the reliability of the backhaul link is improved [7], lower OP can be expected at the UE.

Regarding to the FRN assisted transmission, we notice

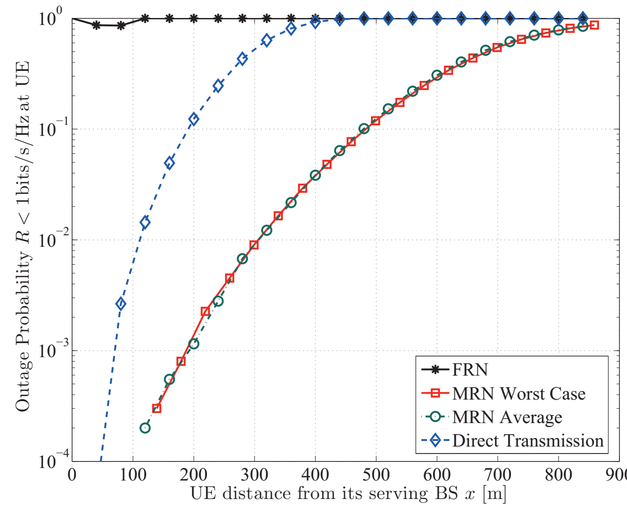

Figure 5. Outage Probability at UE when VPL = 30 dB

that only when there is no VPL (Fig. 3), the FRN can offer a better throughput than the direct and MRN assisted transmission when the vehicular UE is near to it. However, since the FRN is originally designed either to extend the cell coverage or increase the capacity of certain hotspot areas in cellular systems rather than to assist the vehicular UEs [2], the average high end-to-end vehicular UE OP of the FRN assisted transmission is not unexpected. It is worth mentioning that, as described in Section III, we model the backhaul link of the FRN assisted transmission as LOS but its interference is modeled as NLOS. This is the best case one can expect for the FRN assisted transmission but even with these assumptions, the contribution of FRN to the vehicular UE is very limited. Another thing that is worth mentioning is that the MRN is assumed to operate at a much lower transmit power than the FRN, but it serves vehicular UEs better than the FRN assisted transmission on average. Thus from an energy efficiency point of view, MRN is also a better choice for serving vehicular UEs.

VI. Conclusions

In this paper, we compared the end-to-end outage probability (OP) at the vehicular user equipment (UE) of single-hop direct transmission (baseline case), and dual-hop transmission via a moving relay node (MRN) as well as a fixed relay node (FRN). For a fair comparison, we numerically optimized the position of the FRN, which minimizes the average end-to-end OP at the vehicular UE. We showed that in the case of moderate to high vehicle penetration loss, an MRN deployed on top of a public transportation vehicle can bring significant enhancement to the quality-of-service of the vehicular UE. Thus, MRNs have a very good potential to boost performance of future mobile communication systems. Moreover, in the RN assisted transmission, we assume the access links are only deteriorated by the interference from other RN nodes and not from the BS. However, in practical systems, depending on the employed Inter Cell Interference Coordination techniques, the access links may be subjected to the interference from both the BS and RNs which may result in higher OPs at the UE. In order to fully understand the behavior of the RN assisted transmission, more sophisticated system level simulations need to be conducted.

ACKNOWLEDGMENT

This work has been supported by the Swedish Research Council (VR) project 621-2009-4555 Dynamic Multipoint Wireless Transmission and the EU FP7 project INFSO-ICT-247223 ARTIST4G.

APPENDIX

The outage probability (OP) is the probability that the received signal-to-interference-plus-noise ratio (SINR) falls below a given threshold γ_{th}, which can be written as

$$P_{\text{out}} = \Pr\left(\frac{x}{y+N_0} < \gamma_{\text{th}}\right), \tag{16}$$

where x is the desired signal power from the transmitter, y is the interference power from the interferer and N_0 is the average background noise power. The OP is the value of the cumulative distribution function (cdf) of the received SINR, when a threshold γ_{th} is given. In this paper, we only consider a single interferer and the cdf of the received SINR is calculated as follows. The expression (16) can be re-written as

$$\begin{aligned} P_{\text{out}} &= F_{\gamma}\left(\gamma_{\text{th}}\right) \\ &= \Pr\left(x < \gamma_{\text{th}}\left(y+N_0\right)\right) \qquad (17) \\ &= 1-\Pr\left(x > \gamma_{\text{th}}\left(y+N_0\right)\right) \\ &= 1-\int_0^{\infty} f_y\left(y\right) \int_{\gamma_{\text{th}}\left(y+N_0\right)}^{\infty} f_x\left(x\right) dx\, dy. \qquad (18) \end{aligned}$$

Regarding the FRN access link, the desired and interfering channel coefficients are considered to be independent and not identically distributed (INID) and both follow a Rayleigh distribution. Hence, the received power of the desired signal and the power of the interference signal follow INID exponential distributions [9, Ch. 4], which is given as,

$$f_{x_{\text{a}}}\left(x_{\text{a}}\right) = \frac{1}{P_r}\exp\left(-\frac{x_{\text{a}}}{P_r}\right), \tag{19}$$

where P_r is the average received signal power based on pathloss alone. Similary we have

$$f_{y_{\text{a}}}\left(y_{\text{a}}\right) = \frac{1}{P_{r_{\text{I}}}}\exp\left(-\frac{y_{\text{a}}}{P_{r_{\text{I}}}}\right), \tag{20}$$

where $P_{r_{\text{I}}}$ is the average received power from the interferer based on pathloss alone. By inserting (19) and (20) into (18), we can obtain the cdf of the access link as follows.

$$F_{\gamma_{\text{ac}}}\left(\gamma_{\text{th}}\right) = 1-\frac{P_{r_{\text{ac}}}}{P_{r_{\text{ac}}}+P_{r_{\text{I}_{\text{ac}}}}\gamma_{\text{th}}}\exp\left(-\frac{\gamma_{\text{th}}N_0}{P_{r_{\text{ac}}}}\right). \tag{21}$$

As for the backhaul link of the FRN assisted transmission, the amplitude of the desired signal is Rician distributed which results in a gamma distributed received signal power [9, Ch. 4] while the power of the interference signal follows the exponential distribution. However, in this case, an exact closed form of the received SINR distribution cannot be obtained by using (18) [15]. But due to the relatively small inter-site distance, low noise figure [2] and the high BS transmit power, the interference power is much larger than the background noise power, i.e., $y \gg N_0$. Thus, the outage probability of the backhaul link can be approximated as

$$P_{\text{out}_{\text{bk}}} = \Pr\left(\frac{x_{\text{b}}}{y_{\text{b}}+N_0} < \gamma_{\text{th}}\right) \approx \Pr\left(\frac{x_{\text{b}}}{y_{\text{b}}} < \gamma_{\text{th}}\right).$$

The OP for a Rician distributed desired signal and a Rayleigh distributed interferer with negligible background noise is studied in [15] and the cdf of the received SINR is

$$F_{\gamma_{\text{bk}}}\left(\gamma_{\text{th}}\right) = \frac{P_{r_{\text{I}_{\text{bk}}}}\gamma_{\text{th}}}{P_{r_{\text{I}_{\text{bk}}}}\gamma_{\text{th}}+P_{r_{\text{bk}}}}\exp\left(-\frac{K\,P_{r_{\text{bk}}}}{P_{r_{\text{I}_{\text{bk}}}}\gamma_{\text{th}}+P_{r_{\text{bk}}}}\right). \tag{22}$$

[2]The noise figure at the FRN can be as low as 5 dB, but a 9 dB noise figure is usually assumed at the UE [10, Table A.2.1.1.4-3].

REFERENCES

[1] A. Saadani, G. Liebl, *et al.*, "D3.4 relay configurations," tech. rep., Artist4G deliverable, Jul. 2011. [Online] https://ict-artist4g.eu/projet/deliverables accessed 2012-06-12.
[2] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, *et al.*, "A survey on 3GPP heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 18, pp. 10–21, Jun. 2011.
[3] 3GPP, "Overview of 3GPP release 11 v0.1.0," tech. rep. [Online] http://www.3gpp.org/ accessed 2012-06-12.
[4] V. V. Phan, K. Horneman, L. Yu, and J. Vihriala, "Providing enhanced cellular coverage in public transportation with smart relay systems," in *Proc. IEEE VNC*, 2010.
[5] A. Papadogiannis, A. Saadani, and E. Hardouin, "Exploiting dynamic relays with limited overhead in cellular systems," in *Proc. IEEE GLOBECOM Workshops*, 2009.
[6] E. Tanghe, W. Joseph, L. Verloock, and L. Martens, "Evaluation of vehicle penetration loss at wireless communication frequencies," *IEEE Trans. Veh. Technol.*, vol. 57, pp. 2036–2041, Jul. 2008.
[7] M. Sternad, M. Grieger, R. A. Olesen, T. Svensson, *et al.*, "Using 'predictor antennas' for long-range prediction of fast fading for moving relays," in *Proc. IEEE WCNC Workshop*, 2012.
[8] Y. Sui, A. Papadogiannis, and T. Svensson, "The potential of moving relays—a performance analysis," in *Proc. IEEE VTC 2012-Spring*.
[9] A. F. Molisch, *Wireless Communications*. West Sussex, UK: John Wiley & Sons Ltd., 2nd edition ed., 2010.
[10] 3GPP TR 36.814, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects," tech. rep. [Online] http://www.3gpp.org/ accessed 2012-06-12.
[11] H. Masui, T. Kobayashi, and M. Akaike, "Microwave path-loss modeling in urban line-of-sight environments," *IEEE J. Sel. Areas Commun.*, vol. 20, pp. 1151–1155, Aug 2002.
[12] A. F. Molisch, *Supplementary Material for 2nd Edition of Wireless Communications*. West Sussex, UK: John Wiley & Sons Ltd., 2011. [Online] http://www.wiley.com/ accessed 2012-03-28.
[13] P. Kyösti, J. Meinilä, L. Hentilä, X. Zhao, *et al.*, "WINNER II Channel Models Part II, Radio channel measurement and analysis results," tech. rep., IST-4-027756 WINNER II, 2007. [Online] http://www.ist-winner.org/deliverables.html accessed 2012-06-12.
[14] P. Mogensen, W. Na, I. Kovacs, *et al.*, "LTE capacity compared to the shannon bound," in *Proc. IEEE VTC 2007-Spring*, 2007.
[15] Y.-D. Yao and A. Sheikh, "Outage probability analysis for microcell mobile radio systems with cochannel interferers in Rician/Rayleigh fading environment," *Electronics Letters*, vol. 26, pp. 864 –866, Jun. 1990.