The Energy Efficiency Potential of Moving and Fixed Relays for Vehicular Users

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Abstract—**In future wireless networks a significant number of wireless broadband users will be vehicular, i.e., they will be in public transportation vehicles like buses, trams or trains. In this paper, we show that the efficient use of relay nodes to serve vehicular users can greatly improve the energy efficiency of the network while maintaining the required quality-of-service (QoS). We consider vehicular users moving along a road within the coverage of a base station (BS). Communication can take place in a single-hop fashion (baseline case) or can be assisted by a single relay node (dual-hop), which can either be a fixed relay node (FRN) deployed at a specific position on the road or a moving relay node (MRN) mounted on top of the vehicle. We compare the required overall transmit energy for direct transmission, FRN and MRN assisted transmission in a noise limited system under Rayleigh fading while assuming an outage probability (OP) target. A lower bound is derived for the required energy of the FRN assisted transmission. It is shown that as the vehicular penetration loss (VPL) increases, both FRN and MRN assisted transmission can significantly lower the overall transmit energy compared to the conventional one-hop case. Moreover, transmission relying on an MRN outperforms the FRN assisted case when VPL is moderate to high.**

I. INTRODUCTION

As the demand for ubiquitous high quality wireless services increases unprecedentedly, the density of the deployed base stations (BSs) has been increasing drastically. Although new BSs are more energy efficient, their increasing number inevitably burdens the environment. Furthermore, the energy costs for operating mobile networks is constantly growing. Various solutions, ranging from energy efficient hardware designs to new network architectures, have been considered by both major operators and vendors to develop an "Eco-Smart solution" for future networks [1].

Currently, a significant number of mobile users are vehicular, i.e., they use wireless broadband while riding public transportation vehicles. Moreover, it is expected that the number of vehicular users will greatly rise due to the high penetration of smartphones and the increasing portability of laptops. Hence public vehicles are expected to evolve into wireless hotspots. A significant problem, however, is that radio signals traveling from the BS into the vehicle are severely attenuated by the vehicular penetration loss (VPL). Measurements show that VPL can be as high as 25 dB in a minivan at the frequency of 2.4 GHz [2]. Higher VPLs are foreseeable in the well isolated vehicles of interest here, and in higher frequency bands [3], e.g. the 3.6 GHz band allocated to next generation mobile communication. In order to meet the quality-of-service (QoS) requirement for a user equipment (UE) inside a vehicle, more radio frequency (RF) power needs to be transmitted to compensate the VPL, which can boost the energy consumption. As vehicular UEs (VUEs) will represent a significant portion of broadband UEs in the near future, it is crucial to design wireless systems in a way that minimizes the energy consumption while guaranteeing required QoS for these VUEs.

Previous works showed that using fixed relay nodes (FRNs) can improve the energy efficiency of wireless networks, as properly deployed FRNs can effectively compensate pathloss [4], [5]. However, as FRNs are deployed on the street level, they cannot combat VPL that attenuates received signals at vehicular UEs. An effective way to combat VPL is through the deployment of moving relay nodes (MRNs) on top of public transportation vehicles. MRNs consist of outdoor and indoor antenna units. The indoor antenna is inside the vehicle communicating with the vehicular UEs, while the outdoor antenna is outside the vehicle communicating with the BS, hence the VPL is circumvented. MRNs can also provide other benefits such as group handover, and collective channel state information (CSI) feedback [6], [7]. Preliminary studies have shown the potential capacity and coverage improvement of using coordinated and cooperative MRNs on top of trains [8]. In [9], it is shown that MRNs can improve the spectral efficiency and lower the outage probability (OP) when the average transmit power of the BS and the relay node is fixed. However, none of the aforementioned contributions studies the benefit of MRNs from an energy efficiency point of view.

Contributions: we argue that relay nodes in general can significantly reduce the transmit energy of the network and maintain the desired QoS for VUEs. We consider a scenario where a VUE is moving along a road, and can be served either directly by the BS in one hop (baseline case) or via a single relay node, either an FRN or an MRN, in two hops. We investigate how to serve the VUE energy efficiently under an OP constraint. To this end, we compare the required overall transmit energy for the considered schemes. For a fair comparison, we optimize the position of the FRN when only the UE position distribution is known. Furthermore, to facilitate comparisons we derive a lower bound for the required energy of the FRN assisted transmission. We show that the FRN assisted transmission, when the relay node position is optimized, can provide significant gains in terms of energy consumption. Moreover, as the VPL increases, both FRN and MRN assisted transmission can significantly lower the overall transmit energy compared to the direct transmission.

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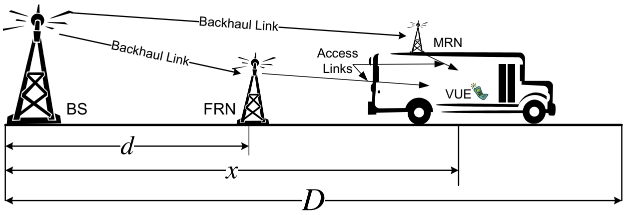

Figure 1. An illustration of the considered system scenario with the different kinds of nodes

We also show that the use of MRN outperforms FRN assisted transmission when VPL is moderate to high.

II. SIGNAL AND SYSTEM MODEL

The considered system setup is depicted in Fig. 1, where the BS has a fixed coverage of D meters. We consider a noise limited system with frequency flat fading. The noise is assumed to be additive white Gaussian noise (AWGN) of zero mean and variance N_0, and the envelope of the channel coefficients is assumed to follow the Rayleigh distribution. In wideband systems employing orthogonal frequency-division multiple access (OFDMA), this can be seen as a subchannel or a subchannel group whose bandwidth is much smaller than the coherence bandwidth [10, Ch. 12]. We assume that the transmitter (TX) has full knowledge of the average received power $\bar{P}_{\mathrm{r}}$ at the receiver (RX), i.e., it knows the pathloss. In practice, this corresponds to employing a slow feedback channel carrying information on the average received power. For simplicity, we assume that there are no power constraints at the BS, FRN and MRN.

Without loss of generality, we consider downlink transmission where communication to the VUE can either be direct or assisted by an FRN or an MRN. The RNs are assumed to be decode-and-forward (DF) and half-duplex. In the first time slot, the RN receives and decodes the signal from the BS, and in the second slot the RN forwards the decoded symbol to the VUE. Following the 3GPP convention, we refer to the link between the BS and the RN as the *backhaul link*, and the link between the RN and the UE as the *access link*. In all cases we consider a VUE moving along a road (see Fig. 1) where the distance between the BS and the UE is x.

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 N_0 is the noise power at RX; h represents the channel coefficient, and $\beta L^{-\alpha}$ models the pathloss when the RX is at distance L from the TX. Moreover, α denotes the pathloss exponent, where usually $2 \leq \alpha \leq 4$, and β is the pathloss constant [10, Ch. 4]. The pathloss model $\beta L^{-\alpha}$ is only valid when the distance between RX and TX is greater than a certain value d_{break}, also known as the *break point* [10, Ch. 4], which is usually observed at 20 to 35 meters [11]. When the RX is at a smaller distance than d_{break}, there is no universally accepted model for the pathloss in outdoor cellular systems. As the detailed pathloss modeling is out of scope in this study, for simplicity, we conservatively assume that the pathloss within the break point is a constant K which equals the pathloss at a distance equal to the break point. In addition, ε denotes the VPL attenuating radio signals coming into the vehicle, where $0 < \varepsilon \leq 1$. As both the FRN and the outdoor antenna of the MRN are deployed outside the vehicle, there is no penetration loss affecting the backhaul links.

III. OUTAGE AND ENERGY CONSUMPTION ANALYSIS

In this section, under a given outage probability (OP) target, we investigate the required overall average transmit power of the system which directly relates to the energy consumption of the considered schemes. In the presence of fading, there is always a probability that a source transmit rate of R cannot be supported by the channel. OP can be expressed as $P_{\mathrm{out}} = \Pr\{\gamma < \gamma_{\mathrm{th}}\}$ [10, Ch. 5], where $\Pr\{\cdot\}$ denotes probability, and γ_{th} is the required SNR threshold at the UE. From a QoS point of view, all kinds of services have minimum bit error rate (BER) or codeword error rate (CWER) requirements which can be translated into a required average minimum received SNR at the UE side [10, Ch. 12.2.3]. In a noise limited system, if the instantaneously received power is P_{r}, the corresponding received SNR is $\gamma = P_{\mathrm{r}}/N_0$. As the RX noise figure is fixed at the manufacturing stage, the OP can be calculated with respect to a minimum required received power threshold $\Gamma = \gamma_{\mathrm{th}} N_0$. Thus the OP can be expressed as $P_{\mathrm{out}} = \Pr\{P_{\mathrm{r}} < \Gamma\}$. To keep notation compact, we shall abbreviate in mathematical formulas the acronyms UE, BS, MRN, and FRN as U, B, M, and F, respectively.

A. Direct Transmission

Since the envelope of the channel coefficients follows the Rayleigh distribution by assumption, the instantaneously received power $P_{\mathrm{r_U}}$ of a UE located at distance x from the BS follows an exponential distribution with probability distribution function (pdf)

$$p_{\mathrm{r_u}}(z) = \frac{1}{\bar{P}_{\mathrm{r_U}}(x)} \exp\left(-\frac{z}{\bar{P}_{\mathrm{r_U}}(x)}\right), \tag{2}$$

where $\bar{P}_{\mathrm{r_U}}(x)$ is the average received signal power at the UE based on pathloss alone,[1] and $\exp(\cdot)$ denotes the exponential function [10, Ch. 5]. The OP can be expressed as

$$P_{\mathrm{out}} = \Pr\{P_{\mathrm{r_U}} < \Gamma_{\mathrm{D}}\} = 1 - \exp\left(-\frac{\Gamma_{\mathrm{D}}}{\bar{P}_{\mathrm{r_U}}(x)}\right). \tag{3}$$

In order to meet the OP target t, it follows that $P_{\mathrm{out}} = t$. Thus, the required average received power at the UE needs be

$$\bar{P}_{\mathrm{r_U}}(x) = -\frac{\Gamma_{\mathrm{D}}}{\ln(1-t)}, \tag{4}$$

where $\ln(\cdot)$ denotes the natural logarithmic function. The total required minimum average transmit power at the BS is

$$P_{\mathrm{D}}(x) = P_{\mathrm{t_B}}(x) = -\frac{\Gamma_{\mathrm{D}}\, x^{\alpha_{\mathrm{D}}}}{\ln(1-t)\, \varepsilon\, \beta_{\mathrm{D}}}. \tag{5}$$

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[1] As we do not consider shadowing, the received power is averaged over all possible small scale fading realizations.

We consider that for all schemes, whether relay assisted or not, transmission has the same duration of T. Thus, for direct transmission, the consumed energy in each transmission frame when the VUE is at position x is $E_{\mathrm{D}}(x) = P_{\mathrm{D}}(x)\,T$. We assume that T is fairly short within which the average transmit power does not change. This is a reasonable assumption as the pathloss, determining the average transmit power, changes in the order of seconds while in practical wireless systems, e.g., the 3rd Generation Partnership Project Long Term Evolution system, the frame duration for one transmission is in the order of milliseconds [12, Ch. 10].

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 some other factors [13, Ch. 3]. As we consider a VUE moving along a road, it is reasonable to assume a uniform distribution of the UE position along the road. The pdf $p_x(x)$ of the UE distance distribution can be expressed as

$$p_x(x) \;=\; \begin{cases} \frac{1}{D}, & 0 \le x \le D \\ 0, & \text{otherwise} \end{cases}. \tag{6}$$

Thus, if the BS has a fixed coverage of D meters, the expectation of the average transmit power of the system is

$$\bar{P}_{\mathrm{D}} \;=\; \mathbb{E}_x\left[P_{\mathrm{D}}(x)\right] = -\frac{\Gamma_{\mathrm{D}}\, D^{\alpha_{\mathrm{D}}}}{\ln(1-t)\,\varepsilon\,\beta_{\mathrm{D}}\,(1+\alpha_{\mathrm{D}})}, \tag{7}$$

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

B. MRN Assisted Transmission

Since we consider no fading for the transmission between the MRN and the VUE, the average transmit power of the MRN can be adjusted to provide the required data rate to the UE. Therefore we only need to guarantee that the OP constraint is satisfied for the backhaul link. With an OP target t at the VUE, it holds that $P_{\text{out}} = \Pr\{P_{\mathrm{r_M}} < \Gamma_{\mathrm{M}}\} = t$. By the same reasoning as in Section III-A, we have that the average received power at the MRN should be at minimum $\bar{P}_{\mathrm{r_M}}(x) = -\frac{\Gamma_{\mathrm{M}}}{\ln(1-t)}$, and $P_{\mathrm{t_{BM}}}(x) = -\frac{\Gamma_{\mathrm{M}}\, x^{\alpha_{\mathrm{M}}}}{\ln(1-t)\,\beta_{\mathrm{M}}}$. For the access link, as no fading is assumed, the average received power at the UE is $\bar{P}_{\mathrm{r_U}} = P_{\mathrm{t_M}}\,K$, where K is a constant pathloss value as outlined before. Thus, for a target received power $\bar{P}_{\mathrm{r_U}}(x)$ at the UE, the average transmit power of the indoor MRN is $P_{\mathrm{t_M}} = \frac{\bar{P}_{\mathrm{r_U}}(x)}{K}$. The total expended power for an end-to-end transmission when the UE is at position x is

$$P_{\mathrm{M}}(x) = P_{\mathrm{t_{BM}}}(x) + P_{\mathrm{t_M}} = -\frac{\Gamma_{\mathrm{M}}\, x^{\alpha_{\mathrm{M}}}}{\ln(1-t)\,\beta_{\mathrm{M}}} + \frac{\bar{P}_{\mathrm{r_U}}(x)}{K}. \tag{8}$$

Thus, for the MRN assisted transmission the average consumed energy per transmission frame for an end-to-end transmission is $E_{\mathrm{M}}(x) = \frac{1}{2}\left(P_{\mathrm{t_{BM}}}(x)\,T + P_{\mathrm{t_M}}\,T\right) = \frac{1}{2}\,P_{\mathrm{M}}(x)\,T$. Similarly to the direct transmission, the expectation of the average transmit power of the system becomes

$$\begin{aligned} \bar{P}_{\mathrm{M}} \;&=\; \mathbb{E}_x\left[\frac{1}{2}\,P_{\mathrm{M}}(x)\right] \\ &=\; -\frac{\Gamma_{\mathrm{M}}\, D^{\alpha_{\mathrm{M}}}}{2\,\ln(1-t)\,\beta_{\mathrm{M}}\,(1+\alpha_{\mathrm{M}})} + \frac{\bar{P}_{\mathrm{r_U}}(x)}{2\,K}. \end{aligned} \tag{9}$$

C. FRN Assisted Transmission

A DF FRN assisted transmission with a given OP target t at the UE entails that the received power of the backhaul and access links should meet the following constraint

$$P_{\text{out}} = \Pr\{\min(P_{\mathrm{r_F}}, P_{\mathrm{r_U}}) < \Gamma_{\mathrm{F}}\} = t. \tag{10}$$

The instantaneously received power at the FRN and the UE is denoted as $P_{\mathrm{r_F}}$ and $P_{\mathrm{r_U}}$, respectively. The random variable that is of interest for analyzing OP performance is $P_{\mathrm{r_{min}}} = \min(P_{\mathrm{r_F}}, P_{\mathrm{r_U}})$. Since $P_{\mathrm{r_F}}$ and $P_{\mathrm{r_U}}$ are assumed to be independently exponentially distributed with different parameters, by means of order statistics [14, Ch. 4], we obtain that $P_{\mathrm{r_{min}}}$ is also exponentially distributed with the pdf

$$p_{\mathrm{r_{min}}}(z) = \left(\frac{1}{\bar{P}_{\mathrm{r_F}}} + \frac{1}{\bar{P}_{\mathrm{r_U}}}\right)\exp\left(-\frac{\bar{P}_{\mathrm{r_U}} + \bar{P}_{\mathrm{r_F}}}{\bar{P}_{\mathrm{r_F}}\bar{P}_{\mathrm{r_U}}}\,z\right), \tag{11}$$

where $\bar{P}_{\mathrm{r_F}}$, $\bar{P}_{\mathrm{r_U}}$ denote the average received power at the FRN and the UE, respectively. For an OP target t at the UE, it follows that

$$P_{\text{out}} = \Pr\{P_{\mathrm{r_{min}}} < \Gamma_{\mathrm{F}}\} = 1 - \exp\left(-\frac{\bar{P}_{\mathrm{r_U}} + \bar{P}_{\mathrm{r_F}}}{\bar{P}_{\mathrm{r_F}}\bar{P}_{\mathrm{r_U}}}\Gamma_{\mathrm{F}}\right) = t, \tag{12}$$

which yields

$$\frac{1}{\bar{P}_{\mathrm{r_F}}} + \frac{1}{\bar{P}_{\mathrm{r_U}}} = -\frac{\ln(1-t)}{\Gamma_{\mathrm{F}}}. \tag{13}$$

Equation (13) can serve as the equivalent constraint of (10) for optimizing the position of the FRN (see Section IV). In FRN assisted transmission, the overall system average transmit power depends both on the position of the FRN and the UE, and can be expressed as $P_{\mathrm{F}}(x, d) = P_{\mathrm{t_{BF}}}(d) + P_{\mathrm{t_F}}(x, d)$. For the backhaul link, the average received power at the FRN can be expressed as

$$\bar{P}_{\mathrm{r_F}}(d) = P_{\mathrm{t_{BF}}}\,\beta_{\mathrm{F}}\,d^{-\alpha_{\mathrm{F}}},\;\; (d \ge d_{\text{break}}) \tag{14}$$

During the second hop, the average received power at the UE depends on the pathloss between FRN and UE and the VPL ε. Depending on whether the VUE is located at a smaller or greater distance than d_{break}, the average received power is

$$\bar{P}_{\mathrm{r_U}}(x) = \begin{cases} P_{\mathrm{t_F}}\,\varepsilon\,\beta_{\mathrm{U}}\,\mathrm{K} & |x-d| < d_{\text{break}} \\ P_{\mathrm{t_F}}\,\varepsilon\,\beta_{\mathrm{U}}\,|\,x-d\,|^{-\alpha_{\mathrm{U}}} & |x-d| \ge d_{\text{break}} \end{cases}. \tag{15}$$

To guarantee a certain average received power $\bar{P}_{\mathrm{r_F}}$ at the FRN and $\bar{P}_{\mathrm{r_U}}$ at the UE, it follows from (14) and (15) that the average BS and FRN transmit power should be at minimum

$$P_{\mathrm{t_{BF}}}(d) = \frac{\bar{P}_{\mathrm{r_F}}\,d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}, \tag{16}$$

and

$$P_{\mathrm{t_F}}(x, d) = \begin{cases} \frac{\bar{P}_{\mathrm{r_U}}}{\varepsilon\beta_{\mathrm{U}}\mathrm{K}}, & |x-d| < d_{\text{break}} \\ \frac{\bar{P}_{\mathrm{r_U}}\,|\,x-d\,|^{\alpha_{\mathrm{U}}}}{\varepsilon\beta_{\mathrm{U}}}, & |x-d| \ge d_{\text{break}} \end{cases}. \tag{17}$$

Hence, the total expended minimum average power at a given UE position x is $P_{\mathrm{F}}(x, d) = P_{\mathrm{t_{BF}}}(d) + P_{\mathrm{t_F}}(x, d)$. Note that all the values above depend on the position of the FRN d,

$$\begin{aligned}\bar{P}_{\mathrm{F}}(d) &= \mathbb{E}_x\left[\frac{1}{2}P_{\mathrm{F}}(x,\,d)\right]\\ &= \frac{1}{2}\int_0^D \left(P_{\mathrm{t_{BF}}}(d)+P_{\mathrm{t_F}}(x,\,d)\right)p_x(x)\,dx\\ &= \frac{\bar{P}_{\mathrm{r_F}}d^{\alpha_{\mathrm{F}}}}{2\,\beta_{\mathrm{F}}}+\frac{\bar{P}_{\mathrm{r_U}}}{2\,D\,\varepsilon\,\beta_{\mathrm{U}}}\left[\int_0^{d-d_{\mathrm{break}}}(d-x)^{\alpha_{\mathrm{U}}}\,dx+\int_{d-d_{\mathrm{break}}}^{d+d_{\mathrm{break}}}\frac{1}{\mathrm{K}}\,dx+\int_{d+d_{\mathrm{break}}}^{D}(x-d)^{\alpha_{\mathrm{U}}}\,dx\right]\\ &= \frac{1}{2}\left[\frac{\bar{P}_{\mathrm{r_F}}d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}+\frac{\bar{P}_{\mathrm{r_U}}\left(d^{\alpha_{\mathrm{U}}+1}\,\mathrm{K}+(D-d)^{\alpha_{\mathrm{U}}+1}\,\mathrm{K}+2\,d_{\mathrm{break}}\left(\alpha_{\mathrm{U}}+1-d_{\mathrm{break}}^{\alpha_{\mathrm{U}}}\,\mathrm{K}\right)\right)}{D\,\varepsilon\,\beta_{\mathrm{U}}\left(\alpha_{\mathrm{U}}+1\right)\mathrm{K}}\right].\end{aligned} \tag{18}$$

and that of the VUE x relative to the BS. Thus it is crucial to select a position d for the FRN to minimize $P_{\mathrm{F}}(x,\,d)$. Similar to the MRN assisted scheme, we have $E_{\mathrm{F}}(x,\,d)=\frac{1}{2}\left(P_{\mathrm{t_{BF}}}(d)\,T+P_{\mathrm{t_F}}(x,\,d)\,T\right)=\frac{1}{2}P_{\mathrm{F}}(x,\,d)\;T$. As the same end-to-end transmission frame duration T is assumed for all three schemes, it is enough to compare their total average system transmit power (see Sec. V), i.e., $P_{\mathrm{D}}(x)$, $\frac{1}{2}P_{\mathrm{M}}(x)$ and $\frac{1}{2}P_{\mathrm{F}}(x,\,d)$.

With a uniform UE distribution, we obtain the expectation of the overall average transmit power of the system in (18). Note that, in this case, the expectation of the average transmit power of $\bar{P}_{\mathrm{F}}(d)$ is a function of d. In Section IV we address the optimization of the FRN position in order to minimize $\bar{P}_{\mathrm{F}}(d)$.

IV. Optimizing the Energy Efficiency of FRN Assisted Transmission

In order to profit from FRN assisted transmission and allow a fair comparison, the FRN should be deployed at an optimal position that minimizes the total transmit power while meeting the OP target. To this end, we consider the following two cases: 1) the exact UE position is known and the FRN is deployed accordingly. This serves a transmit power lower bound for the FRN assisted transmission that assists comparisons; 2) the optimal positioning of the FRN when only the UE position distribution is known, as this represents the realistic case where the statistics of the position of the VUE moving along a straight road is known.

A. FRN Power Lower Bound

The considered transmit power lower bound for the FRN assisted transmission is obtained assuming the position of the vehicular is known and then the FRN is deployed accordingly, i.e., d_{opt} is a function of x. Although such a scheme cannot be implemented in practice, it serves as a performance bound and thus a good tool for comparisons. More specifically, for a given UE position x and OP target t, the optimal position $d_{\mathrm{opt}}(x)$ for the FRN can be obtained as

$$d_{\mathrm{opt}}(x)=\quad \arg\min_{d}\;P_{\mathrm{F}}(x,\,d)\,, \tag{19}$$

with constraints $P_{\mathrm{out}}=\mathrm{t}$, $P_{\mathrm{t_{BF}}}>0$, and $P_{\mathrm{t_F}}>0$. In order to compensate for the pathloss, the average transmit power grows as the distance between TX and RX increases. Hence, in a dual-hop system if we know the UE position x, the FRN should always be placed between BS and UE, i.e., $d\leq x$, to minimize $P_{\mathrm{F}}(d,\,x)$. Moreover, as within d_{break} meters from the UE pathloss is assumed to be constant, the FRN should be placed at a distance of at least d_{break} meters from the UE. Otherwise, more BS transmit power is required to compensate for the pathloss of the backhaul link to meet the OP constraint.

Let $C_1=\frac{d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}$, $C_2=\frac{(x-d)^{\alpha_{\mathrm{U}}}}{\varepsilon\beta_{\mathrm{U}}}$, $a=\frac{1}{P_{\mathrm{r_F}}}$ and $b=\frac{1}{P_{\mathrm{r_U}}}$. Then, the optimization problem (19) becomes

$$\begin{aligned} d(x)= \quad & \arg\min_{d}\;\left(\tfrac{C_1}{a}+\tfrac{C_2}{b}\right) \\ & \text{subject to} \qquad \mathrm{a}+\mathrm{b}=\lambda \\ & \qquad\qquad\qquad a>0 \\ & \qquad\qquad\qquad b>0 \\ & x-d>d_{\mathrm{break}},\; d\geq d_{\mathrm{break}},\; d\leq \mathrm{D}. \end{aligned} \tag{20}$$

where $\lambda=-\frac{\ln(1-t)}{\Gamma_{\mathrm{F}}}$ follows from (13) reflecting the OP constraint t. The problem (20) is in general non-convex. For the parameters of interest, however, we show that it is convex in the following paragraphs.

To make this problem mathematically tractable, we solve it in two steps. In the first step, we derive the transmit power allocation scheme between the BS and FRN. In the second step, we show that if the position x of the UE is known, by employing this power allocation scheme, we can find a unique optimal FRN location d_{opt}, between d_{break} and x, which yields a global minimum total average transmit power. Notice that $a=\lambda-b$. If we fix C_1 and C_2 to be positive constants, the objective function becomes a function of b, given as $g(b)=\frac{C_1}{\lambda-b}+\frac{C_2}{b}$. Taking the second order derivative of $g(b)$ with respect to b we have $\frac{\partial^2 g(b)}{\partial b^2}=\frac{2\,C_1}{(\lambda-b)^3}+\frac{2\,C_2}{b^3}$. In general, $g(b)$ is not convex, but $\frac{\partial^2 g(b)}{\partial b^2}>0$ within the given parameter range, i.e., $b>0,\;\lambda-b>0$, $g(b)$ is convex in b, and it has a global minimum value. Solving $\frac{\partial g(b)}{\partial b}=0$ for b, we obtain

$$\hat{b}=\frac{\sqrt{C_2}\,\lambda}{\sqrt{C_1}+\sqrt{C_2}}. \tag{21}$$

The corresponding value of the objective function is given as

$$P_{\mathrm{F}}(x,\,d)=\frac{\left(\sqrt{C_1}+\sqrt{C_2}\right)^2}{\lambda}. \tag{22}$$

As the UE position x is assumed to be known, C_1 and C_2 depend only on the position of the FRN. Thus, the convexity

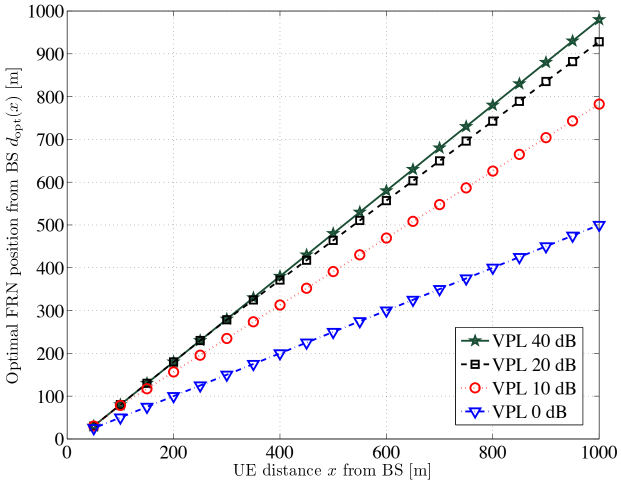

Figure 2. Optimal FRN position $d_{\mathrm{opt}}(x)$ when the UE position is known with $\alpha_{\mathrm{F}} = \alpha_{\mathrm{U}} = 3.8$ and $\beta_{\mathrm{F}} = \beta_{\mathrm{U}} = 3.5237 \times 10^{-4}$

of $g(b)$ indicates that if x is known and we follow the power allocation scheme of (21), when the FRN position d is fixed, there is a unique minimum total average transmit power of the system at each of the possible FRN positions.

Next we examine how to find d_{opt} among all the possible positions that we can place the FRN between d_{break} and x, and achieve the global minimum of $P_{\mathrm{F}}(x, d)$. Plugging C_1 and C_2 back to the objective function (22), we obtain

$$P_{\mathrm{F}}(d) = \frac{\left(\sqrt{\frac{d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}} + \sqrt{\frac{(x-d)^{\alpha_{\mathrm{U}}}}{\varepsilon\beta_{\mathrm{U}}}}\right)^2}{\lambda}. \qquad (23)$$

To minimize $P_{\mathrm{F}}(d)$ is equivalent to minimize $f(d) = \sqrt{\frac{d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}} + \sqrt{\frac{(x-d)^{\alpha_{\mathrm{U}}}}{\varepsilon\beta_{\mathrm{U}}}}$. The second order derivative of $f(d)$ with respect to d is

$$\frac{\partial^2 f(d)}{\partial d^2} = \frac{1}{4d^2(x-d)^2} \cdot \left[\underbrace{\alpha_{\mathrm{F}}(\alpha_{\mathrm{F}}-2)\sqrt{\frac{d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}}(x-d)^2}_{\overset{\text{(a)}}{>0}} + \underbrace{(\alpha_{\mathrm{U}}-2)\alpha_{\mathrm{U}} d^2\sqrt{\frac{(x-d)^{\alpha_{\mathrm{U}}}}{\varepsilon\,\beta_{\mathrm{U}}}}}_{\overset{\text{(b)}}{>0}}\right] > 0, \qquad (24)$$

where (a), (b) follows because $x \geq d$, $2 < \alpha_{\mathrm{F}} \leq 4$ and $2 < \alpha_{\mathrm{U}} \leq 4$. Thus, $f(d)$ is convex in d and has a global minimum. Setting $\frac{\partial f(d)}{\partial d} = 0$, we obtain

$$\alpha_{\mathrm{F}}\beta_{\mathrm{F}}^{-\frac{1}{2}} d^{\frac{\alpha_{\mathrm{F}}-2}{2}} = \alpha_{\mathrm{U}}(\varepsilon\beta_{\mathrm{U}})^{-\frac{1}{2}}(x-d)^{\frac{\alpha_{\mathrm{U}}-2}{2}}. \qquad (25)$$

For certain values of α_{F} and α_{U}, the real root $\hat{d}$ of (25) can be obtained analytically. In general, especially for non-integer values of α_{F} and α_{U}, numerical methods, such as bisection search [15, Ch. 9], can be used to obtain $\hat{d}(x)$. With the given constraint $x - d > d_{\mathrm{break}}$, the optimal FRN position is then given as

$$d_{\mathrm{opt}}(x) = \min\left\{x - d_{\mathrm{break}},\ \hat{d}(x)\right\}. \qquad (26)$$

Fig. 2 plots the optimal FRN position $d_{\mathrm{opt}}(x)$ as a function of the UE position x for different values of VPL assuming $\alpha_{\mathrm{F}} = \alpha_{\mathrm{U}} = 3.8$ and $\beta_{\mathrm{F}} = \beta_{\mathrm{U}} = 3.5237 \times 10^{-4}$ [11]. We notice that the results in Fig. 2 suggest that when VPL increases, the FRN should be placed nearer to the UE in order to minimize the total average transmit power.

B. Optimal FRN position for known UE position distribution

In reality, the position of the FRN is fixed. In this section, we discuss the optimal FRN position which minimize the total average transmit power, when only the UE position distribution is known. As mentioned before, a uniform UE position distribution is assumed. The following optimization problem can be formulated

$$\begin{aligned} \bar{d}_{\mathrm{opt}} = \ & \arg\min_{d} \bar{P}_{\mathrm{F}}(d) \qquad (27)\\ \text{subject to} \quad & \frac{1}{\bar{\mathrm{P}}_{\mathrm{r_F}}} + \frac{1}{\bar{\mathrm{P}}_{\mathrm{r_U}}} = \lambda \\ & \frac{1}{\bar{P}_{\mathrm{r_F}}} > 0 \\ & \frac{1}{\bar{P}_{\mathrm{r_U}}} > 0 \\ & d \geq d_{break},\ d - d_{\mathrm{break}} \leq D, \end{aligned}$$

where $\bar{P}_{\mathrm{F}}(d)$ is given by (18). Problem (27) can be solved in a similar manner as problem (19) by denoting $C_1 = \frac{d^{\alpha_{\mathrm{F}}}}{\beta_{\mathrm{F}}}$, $C_2 = \frac{\left(d^{\alpha_{\mathrm{U}}+1}\,\mathrm{K} + (\mathrm{D}-d)^{\alpha_{\mathrm{U}}+1}\,\mathrm{K} + 2\,d_{\mathrm{break}}\left(\alpha_{\mathrm{U}}+1-d_{\mathrm{break}}^{\alpha_{\mathrm{U}}}\,\mathrm{K}\right)\right)}{\mathrm{D}\,\varepsilon\,\beta_{\mathrm{U}}\,(\alpha_{\mathrm{U}}+1)\,\mathrm{K}}$, $a = \frac{1}{\bar{P}_{\mathrm{r_F}}}$ and $b = \frac{1}{\bar{P}_{\mathrm{r_U}}}$. Following the arguments of Section IV-A, we conclude that the objective function is convex in d. The analytical solution to the optimization problem (27), however, is not as easily obtained as for problem (20). Thus, we resort to numerical methods [16, Ch. 10-11] to obtain the optimal FRN position.

Fig. 3 shows the optimal FRN positions as a function of VPL assuming that $\alpha_{\mathrm{F}} = \alpha_{\mathrm{U}} = 3.8$, $\beta_{\mathrm{F}} = \beta_{\mathrm{U}} = 3.5237 \times 10^{-4}$ and $\mathrm{D} = 1000$ m. The plot shows that when VPL is small, the FRN positions minimizing the overall OP tend to be nearer to the BS. This is because transmission always takes place in two hops via the FRN, even if the UEs are near the BS. It can be observed that as the VPL increases, the FRN position approaches $\mathrm{D}/2$.

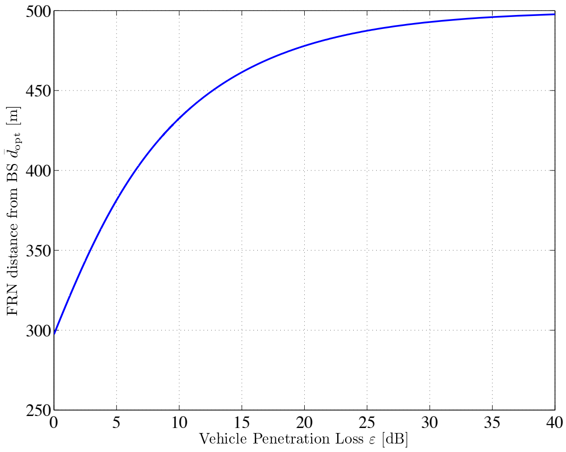

Figure 3. Optimal FRN position when the UE is uniformly distributed along the road with $\alpha_{\mathrm{F}} = \alpha_{\mathrm{U}} = 3.8$ and $\beta_{\mathrm{F}} = \beta_{\mathrm{U}} = 3.5237 \times 10^{-4}$

Table I
EVALUATION PARAMETERS

Parameter	Value
Pathloss model	$PL_{\mathrm{dB}} = 34.53 + 38\log_{10}(d)$
Pathloss break point	$d_{\mathrm{break}} = 20$ m
Constant power loss K within break point, and between MRN and UE	$34.53 + 38\log_{10}(d_{\mathrm{break}}) =$ 83.9691 dB
Receiver noise figure for RNs and UE	9 dB
Outage probability target	0.05
Required rate at the UE	$R = 1$bit/sec/Hz

V. PERFORMANCE EVALUATION

In this section, we evaluate the energy efficiency performance of the considered schemes using the 3GPP SCM urban NLOS microcell channel model. The employed evaluation parameters are summarized in Table I [11]. In practice, the SNR threshold can be chosen to satisfy different QoS constraints, such as a BER target, a CWER target or an achievable rate under a particular modulation and coding scheme [10, Ch. 12.2.3]. For simplicity, the SNR threshold used in our evaluation is based on the mutual information that $R = \log_2(1+\gamma)$, where γ is the received SNR [17]. Then, for direct transmission, the SNR threshold is $\gamma_{\mathrm{th1}} = 2^R - 1$ and the corresponding minimum received power threshold is $\Gamma_{\mathrm{D}} = \left(2^R - 1\right) N_0$. As the FRN and MRN are half-duplex, we need to guarantee a rate of $2R$ for both the backhaul and the access links in order to achieve the same rate of R at the UE side as the direct transmission. Thus, we have $\gamma_{\mathrm{th2}} = 2^{2R} - 1$ and $\Gamma_{\mathrm{F}} = \Gamma_{\mathrm{M}} = \left(2^{2R} - 1\right) N_0$.

The VUE is assumed to be uniformly distributed with respect to its distance from the BS. The MRN is mounted on top of a vehicle and is assumed to fully circumvent VPL. The position of the FRN is determined by the solution to the optimization problem (27). The FRN position in the FRN lower bound case is given by (26). It reflects the lower bound for the consumed power by the FRN, and represents an ideal situation for the FRN assisted transmission, as it requires knowing the UE position to minimize the total average transmit power of the system. In practice, this bound may be approached but not achieved by using relay selection where several FRNs are deployed along the vehicle route.

Figs. 4, 5, and 6 plot the overall system average transmit power, i.e., $P_{\mathrm{D}}(x)$, $\frac{1}{2}P_{\mathrm{M}}(x)$ and $\frac{1}{2}P_{\mathrm{F}}\left(x, \bar{d}_{\mathrm{opt}}\right)$, together with the FRN lower bound $\frac{1}{2}P_{\mathrm{F}}(x, d_{\mathrm{opt}}(x))$, in one time slot T, when the VPL is 0 dB, 10 dB, and 20 dB. The OP target is set to 0.05 for all three cases. If there is no power loss caused by VPL (Fig. 4), the conventional direct transmission (one-hop case) achieves the lowest total average transmit power when the UE is within about 410 meters from the BS. As the use of FRN compensates for the pathloss, the FRN assisted transmission outperforms the direct transmission when the UE is at a greater distance than 410 meters from the BS. The best energy savings are achieved by the unrealistic FRN lower bound case and this is due to the fact that the optimally placed FRN efficiently compensates for the pathloss.

When the VPL is 10 dB (Fig. 5), because more transmit power is needed to compensate the VPL, the average transmit power of all the schemes increase, except the MRN assisted transmission. As shown in Fig. 5, the MRN outperforms the direct transmission and approaches the FRN lower bound. This also verifies the result obtained in Section IV-A that an FRN placed near to the UE can lower the total average transmit power as VPL increases.

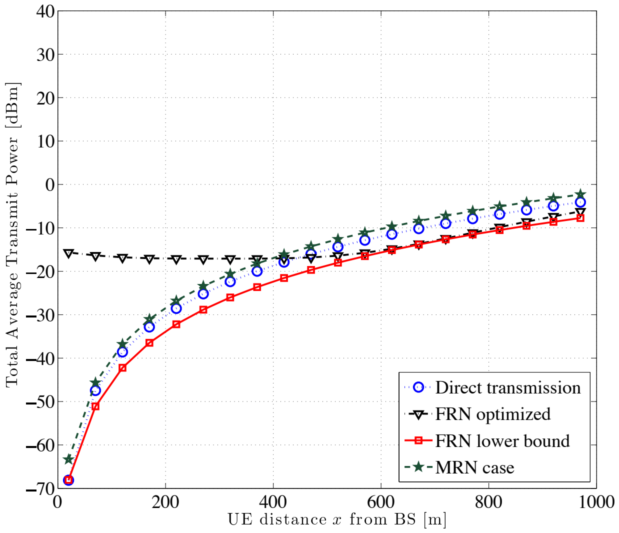

Figure 4. Total average transmit power $P_{\mathrm{D}}(x)$, $\frac{1}{2}P_{\mathrm{M}}(x)$, $\frac{1}{2}P_{\mathrm{F}}\left(x, \bar{d}_{\mathrm{opt}}\right)$, and $\frac{1}{2}P_{\mathrm{F}}(x, d_{\mathrm{opt}}(x))$with outage probability target of t = 0.05 when VPL = 0 dB

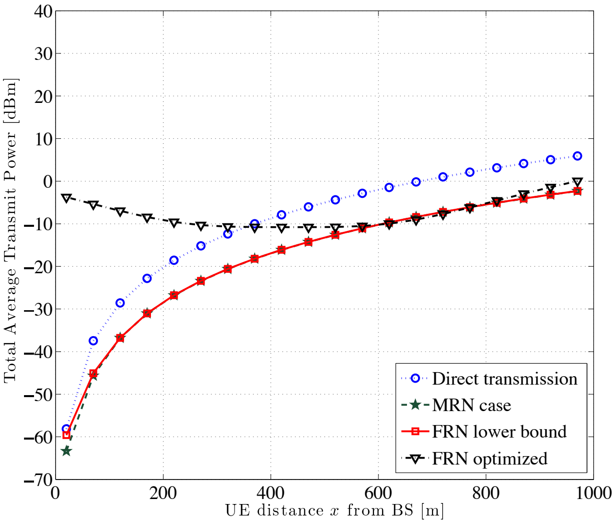

Figure 5. Total average transmit power $P_{\mathrm{D}}(x)$, $\frac{1}{2}P_{\mathrm{M}}(x)$, $\frac{1}{2}P_{\mathrm{F}}\left(x, \bar{d}_{\mathrm{opt}}\right)$, and $\frac{1}{2}P_{\mathrm{F}}(x, d_{\mathrm{opt}}(x))$ with outage probability target of t = 0.05 when VPL = 10 dB

As the VPL keeps increasing, more interesting trends can be observed. Fig. 6 shows the total average transmit power when VPL is 20 dB. In this case, the MRN assisted transmission requires the lowest overall average transmit power. Furthermore, as the FRN can effectively compensate the pathloss, the FRN assisted transmission requires lower overall average transmit power than the direct transmission, when the VUE is at a distance greater than 300 meters from the BS. We also observe that the overall average transmit power of MRN assisted transmission is even lower than the lower bound of the FRN case. This is mostly due to the fact that the MRN totally circumvents VPL.

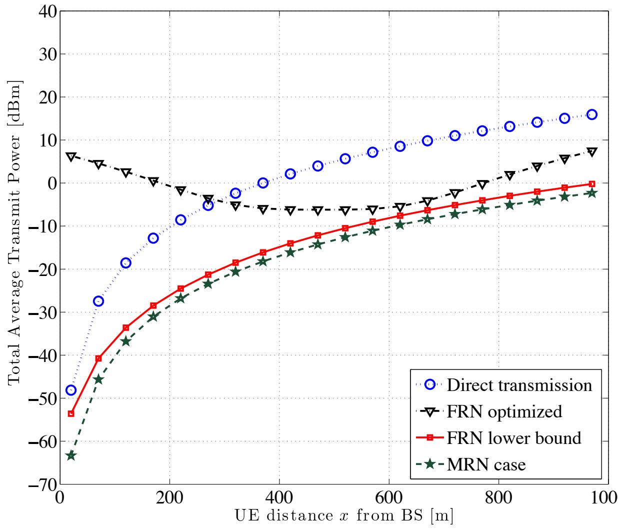

Figure 6. Total average transmit power $P_{\mathrm{D}}(x)$, $\frac{1}{2}P_{\mathrm{M}}(x)$, $\frac{1}{2}P_{\mathrm{F}}\left(x, \bar{d}_{\mathrm{opt}}\right)$, and $\frac{1}{2}P_{\mathrm{F}}\left(x, d_{\mathrm{opt}}(x)\right)$ with outage probability target of t = 0.05 when VPL = 20 dB

Table II
THE EXPECTATION OF THE OVERALL AVERAGE TRANSMIT POWER $\bar{P}_{\mathrm{D}}$, $\bar{P}_{\mathrm{M}}$ AND $\bar{P}_{\mathrm{F}}$ OF THE SYSTEM

	$\bar{P}$ [dBm] VPL=0 dB	$\bar{P}$ [dBm] VPL=10 dB	$\bar{P}$ [dBm] VPL=20 dB
Direct Transmission $\bar{P}_{\mathrm{D}}$	-10.38	-0.38	9.61
MRN case $\bar{P}_{\mathrm{M}}$	-8.62	-8.62	-8.62
FRN optimized $\bar{P}_{\mathrm{F}}$	-12.34	-5.93	1.60

In Table II we calculate the expectation of the overall average transmit power of the system i.e., $\bar{P}_{\mathrm{D}}$, $\bar{P}_{\mathrm{M}}$ and $\bar{P}_{\mathrm{F}}$, under different values of VPL. When there is no VPL, the FRN assisted transmission achieves the lowest expected value of the overall average transmit power, as the FRN can effectively compensate for the pathloss. But as VPL increases, the MRN case begins to outperform both the direct transmission and the FRN assisted transmission. This is because the MRN circumvents VPL while the other two schemes consume more transmit power to compensate for it. From the comparison between Figs. 5 and 6, and the results in Table II, we conclude that the higher the VPL is, the more energy savings the MRN can achieve compared to the other two schemes.

VI. CONCLUSION

In this paper we argued that relay nodes can bring significant benefits to future wireless networks in terms of energy efficiency, while maintaining the required QoS. As a significant number of users accessing wireless broadband will be vehicular, i.e., they will be located in public transportation vehicles like buses trams or trains, we have focused on this category of users. We compared the required average transmit power of the conventional single-hop transmission with that of dual-hop transmission assisted by either an MRN or an FRN under an outage probability constraint. The position of the FRN is optimized in terms of the consumed average transmit power in the considered scenario when only the UE position distribution is known. To assist comparisons, a lower bound for the power consumption of FRN assisted transmission has been derived. We have shown that dual-hop transmission via a relay node can significantly reduce the power consumption of the network under an outage probability constraint. More specifically, MRN assisted transmission performs best when the VPL is moderate to high. It can be concluded that MRNs and FRNs have a very good potential to minimize the average transmit power and maintain a certain QoS level in future wireless systems.

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REFERENCES

[1] J. Gozalvez, "Green radio technologies," *IEEE Veh. Technol. Mag.*, vol. 5, pp. 9–14, Mar. 2010.

[2] 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.

[3] S. Stavrou and S. Saunder, "Factors influencing outdoor to indoor radio wave propagation," in *Proc. 12th ICAP*, 2003.

[4] Q. Xue and A. Pantelidou, "Energy-efficient relay selection for multicast traffic," in *Proc. IEEE PIMRC Workshops*, 2010.

[5] W. Yang, L. Li, G. Wu, H. Wang, and Y. Wang, "Joint uplink and downlink relay selection in cooperative cellular networks," in *Proc. IEEE VTC 2010-Fall.*

[6] 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.

[7] W. Li, C. Zhang, X. Duan, S. Jia, *et al.*, "Performance evaluation and analysis on group mobility of mobile relay for LTE-Advanced system," in *Proc. IEEE VTC 2012-Fall.*

[8] 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.

[9] Y. Sui, A. Papadogiannis, and T. Svensson, "The potential of moving relays—a performance analysis," in *Proc. IEEE VTC 2012-Spring*.

[10] A. F. Molisch, *Wireless Communications*. West Sussex, UK: John Wiley & Sons Ltd., 2nd ed., 2010.

[11] 3GPP TR 25.996, "Spatial channel model for Multiple Input Multiple Output (MIMO) simulations," tech. rep. [Online] Available: http://www.3gpp.org, accessed 2013-01-28.

[12] E. Dahlman, S. Parkvall, and J. Skold, *4G LTE/LTE-Advanced for Mobile Broadband*. Oxford, UK: Elsevier, 2011.

[13] T. Rappaport, *Wireless Communications: Principles and Practice*. New Jersey, USA: Prentice Hall, 2nd ed., 2002.

[14] B. C. Arnold, N. Balakrishnan, H. N. Nagaraja, and H. N. Nagaraja, *A First Course in Order Statistics*. Philadelphia, USA: SIAM-Society for Industrial and Applied Mathematics, 2008.

[15] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes: The Art of Scientific Computing*. New York, USA: Cambridge University Press, 3rd ed., 2007.

[16] S. Boyd and L. Vandenberghe, *Convex Optimization*. New York, USA: Cambridge University Press.

[17] T. M. Cover and J. A. Thomas, *Elements of Information Theory*. New York, USA: Wiley Interscience, 2nd ed., 2006.