Coverage-Improvement of V2I Communication through Car-Relays in Microcellular Urban Networks

Blanca Ramos Elbal†, Martin Klaus Müller†, Stefan Schwarz† and Markus Rupp

† Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion
TU Wien, Institute of Telecommunications
Gusshausstrasse 25/389, A-1040 Vienna, Austria
Email: {brelbal, mmueller, sschwarz, mrupp}@nt.tuwien.ac.at

***Abstract*—In this paper, we consider a microcellular urban network, where micro-cells provide a wireless connection to vehicular users. We focus on vehicular relaying to enhance the quality of the V2I link and therefore to improve the overall coverage in the network. To quantify the coverage gain, we compare the performance of direct communication between micro-cell and vehicular user with the relay-aided communication. In the examined scenario, we create a Manhattan grid of streets where in each street micro-cell base stations and vehicular users are randomly placed according to a Poisson point process. The employed pathloss distinguishes whether the transmitter is in the same street as the receiver, in a crossing or in a parallel street. We investigate our model analytically by leveraging tools from stochastic geometry as well as by Monte Carlo system level simulations. We compare results for the relay-assisted link and the direct link depending on the user density in terms of pathloss, SINR and coverage.**

***Index Terms*—vehicle-to-vehicle communications, stochastic geometry, system level simulation, coverage improvement**

I. Introduction

Vehicular communications has steadily increased in the last years. It is widely used in road safety applications such as potential collision warning, lane change assistance or speed adaptation. Such applications can support not only human drivers but also self-driving vehicles, which may have multiple advantages in the transport safety field [1]. In addition, vehicular communications can also be exploited to improve the coverage of mobile networks, by relaying the information from the Base Station (BS) to the users which are close to the cell boundary [2]. Network-to-User relays not only improve the coverage in the cell, but also allow to space out and reduce the number of BSs, leading to a reduction in the deployment costs for mobile operators. The amount of relays in the network is one of the key aspects in this field. The more available relays are in the network, the more likely it is that the user has one nearby relay, but it also increases the interference level and the overhead in the system.

The LTE standard supports both TDD and FDD systems. In LTE FDD, the Vehicle-to-vehicle (V2V) communication takes place in the uplink band of the network [3], since the majority of the traffic and control signalling of the system is conveyed in the downlink band. Therefore, the transmission and the reception of the V2V link share the same carrier frequency with a half duplex scheme. In [4], the authors deal with the resource allocation in uplink and propose an optimal and a heuristic algorithm for the resource allocation to maximize the number of D2D pairs allowed. In [5] the authors propose a model selection criteria to employ full-duplex instead of half-duplex under particular conditions.

In order to capture the spatial randomness of networks, stochastic geometry (SG) has emerged as a common technique to attain a tractable analysis. The distance distribution of a homogeneous Poisson point process (PPP) in $\mathbb{R}^2$ was investigated in [6, 7]. Existing work as proposed in [8] presents a tractable downlink analysis of the mean rate, outage probability and Signal-to-interference and noise ratio (SINR) when the BSs are randomly distributed according to a 2-dimensional (2D) PPP. In [9, 10] the authors analyze a microcellular urban network by modelling the streets as a Manhattan Poisson line process where the BSs are located according to a 1-D PPP in each street. In [11] the analysis is extended to a multi-lane scenario and takes into account the height of the vehicles to end up with line-of-sight (LOS) and non line-of-sight (NLOS) cases for the Vehicle-to-infrastructure (V2I) communication. The work done in [12] models BSs as a PPP in $\mathbb{R}^2$ and deals with the interference considering a guard region around each BS. The referred-to literature focuses on the downlink band, however there exist research evaluating the uplink band with BS placed randomly in $\mathbb{R}^2$ as well [13].

The above-mentioned contributions evaluate V2I links using SG tools. This paper is focused on the coverage gain assessment exploiting V2V car-relay communication. We consider a Manhattan grid with randomly placed streets, BSs and users similar to [9]. Whereas the authors in [9] evaluate the direct link, we extend the analysis for the constraints of a V2V communication. We derive the probability of the direct link to be in LOS or NLOS and compare it to simulations results. We also show the probability to have a cell without any relay. We quantify the SINR and coverage improvement with V2V communications depending on BS-, street- and user density.

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II. System Model

A. Pathloss model

In this work the pathloss is modelled as a distance-dependent function, similar to the model based on ray tracing and measurement results developed in [9]. The path between transmitter and receiver is divided into different segments x_n. Such N segments represent the streets that the transmitter signal has to travel across on a 2D-Manhattan grid to reach the receiver. The path composed by the segments x_n is the shortest between transmitter and receiver and we assume that signals that travel different paths from transmitter to receiver are weak enough to be neglected. In a Manhattan grid scenario, $\max(N) = 3$ since the transmitter and receiver can be in the same street, in a perpendicular street or in a parallel street. The first segment is considered to have a pathloss exponent α_L whereas pathloss exponent of the remaining segments is α_N. The pathloss expression is given by

$$L(x_n) = x_1^{\alpha_L} \prod_{n=2}^{N} x_n^{\alpha_N}. \tag{1}$$

A graphical example is shown in Figure 1. In a LOS link, $N = 1$ and $x_n^{"} = x_1^{"}$. In the NLOS link depicted on the picture $N = 3$ and $x_n = \{x_1, x_2, x_3\}$.

B. Network Deployment and Relay Association

Our scenario comprises a 2D Manhattan grid where the streets are generated according to a Poisson line process (PLP) with density λ_s, as depicted in Figure 1. In each street, the BSs are deployed following a PPP with density λ_b. The users are distributed in the same way with density λ_u. They are divided into two groups: *relays* and *transmitters*. *Relays* are idle and available to boost the signal from the BS to the users and *transmitters*, conversely, have data to send to their BS. We follow the LTE standard and assume that V2V communication takes place in the side-link, which is integrated into the uplink. Therefore the transmitters convey to their BS in the uplink band and act as interferers in the relay-user link. Therewith the BS-relay communication occurs in downlink while the relay-user communication takes place in uplink, following a decode-and-forward scheme for the BS-relay-user communication. We consider half of the users to be relays, that is, $\lambda_r = 0.5\lambda_u$, and consequently the transmitters density is $\lambda_t = 0.5\lambda_u$.

All users are attached to the BS that provides the smallest pathloss following (1). Since the streets and BSs are deployed according to a PLP and a PPP, respectively, we use the equations for the cumulative distribution function (CDF) of the largest channel gain for BSs in LOS and NLOS derived in [9] as

$$F_{LOS_{BS}}(u) = \exp\left(-2\lambda_b u^{-\frac{1}{\alpha_L}}\right) \tag{2}$$

and

$$F_{NLOS_{BS}}(u) = \exp\left(-2\lambda_s (2\lambda_b)^{\frac{\alpha_L}{\alpha_N}} u^{-\frac{1}{\alpha_L}} \Gamma\left(1 - \frac{\alpha_L}{\alpha_N}\right)\right), \tag{3}$$

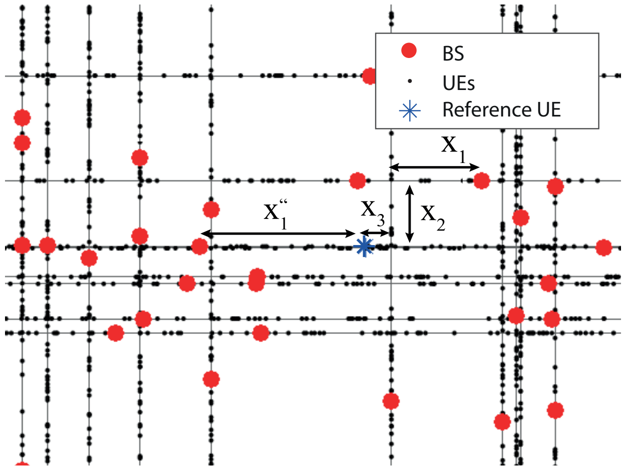

Fig. 1: System model comprising streets, BSs and users with two examples of BS-user paths, x_n and $x_n^{"}$.

where u indicates the pathloss and $\Gamma(z)$ denotes the gamma function. The expression (2) represents the link of the closest BS to the user in the same street and (3) the link for the BS in a perpendicular street with the largest channel gain. We assume the signal coming from parallel streets to be negligible [14]. Therefore, the CDF of the largest channel gain is given by

$$F_{BS}(u) = F_{LOS_{BS}}(u) F_{NLOS_{BS}}(u). \tag{4}$$

By calculating the derivative of (2) and (3), we can determine the probability density functions (PDFs) $f_{LOS_{BS}}(u)$ and $f_{NLOS_{BS}}(u)$. Since being attached to a LOS or a NLOS BS are mutually exclusive events, we can compute the probability of being attached to a LOS or a NLOS BS as follows:

$$p_{LOS_{BS}} = \int_0^\infty F_{NLOS_{BS}}(u) f_{LOS_{BS}}(u) du, \tag{5}$$

$$p_{NLOS_{BS}} = \int_0^\infty F_{LOS_{BS}}(u) f_{NLOS_{BS}}(u) du. \tag{6}$$

Once the user is attached to the BS, the user-relay attachment should be done. Since the relay conveys the signal coming from the BS, we assume that the chosen relay has to be within the same cell as the user. For this reason, albeit relays and BSs are both modelled as a PPPs, we cannot reuse the results (2) and (3).

If λ_u is very low, there might not be any relay in the cell. In order to compute the probability of having any relay inside the cell, we assume that the user is attached to a BS in the same street, that is, $p_{LOS_{BS}} = 1$. As we show in the following section, this assumption is very likely. We can split the probability to have no relays in the cell into the probability to have no relays in LOS and the probability to have no relays in NLOS. As already mentioned, the PDF of the channel gain from our attached BS is $f_{LOS_{BS}}(u)$. To compute the probability to have no relays in LOS, we should find the channel gain of the second BS in LOS. In [6], we can find the distance to a second neighbour in a PPP. According to (1), in LOS the channel gain depending of the distance is given by $u = x_1^{-\alpha_L}$. Performing this change of variable, we can

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compute the channel gain from the second neighbour in LOS:

$$f_{LOS_{BS-2}}(u) = \frac{(2\lambda_b)^2}{\alpha_L} u^{-\frac{1}{\alpha_L}} \exp\left(-2\lambda_b u^{-\frac{1}{\alpha_L}}\right). \quad (7)$$

In order to find the cell edge, we consider that the user is attached to the BS with the largest channel gain. Therefore the channel gain from the neighbouring BS given by (7) should be smaller than the channel gain from the attached BS while the user is in the cell. At the cell edge, both channel gains will be equal, that is, $f_{LOS_{BS-2}}(u) = f_{LOS_{BS}}(u)|_{u=u_{cell-LOS}}$. In this way we can compute the lower bound of the channel gain in LOS for the relay-user link, $u_{cell-LOS} = 2\lambda_b^{\alpha_L}$. The probability that the closest relay has a channel gain lower than this bound and therefore, is out of the cell is given by

$$\begin{aligned} p_{no-relay_{LOS}} &= \int_0^{u_{cell-LOS}} f_{LOS_{relay}}(u) du \\ &= \int_0^{u_{cell-LOS}} \lambda_r u^{-\frac{1+\alpha_L}{\alpha_L}} \exp\left(-2\lambda_r u^{-\frac{1}{\alpha_L}}\right) du. \end{aligned} \quad (8)$$

Following the same procedure and under the assumption that the user is attached to a BS in LOS, the channel gain associated to the nearest neighbor in NLOS is equal to the channel gain from the attached BS at the cell edge, that is, $f_{LOS_{BS}}(u) = f_{NLOS_{BS}}(u)|_{u=u_{cell-NLOS}}$. With that approach the probability to have any relay inside the cell placed in a perpendicular street is given by

$$\begin{aligned} p_{no-relay_{NLOS}} &= \int_0^{u_{cell-NLOS}} f_{NLOS_{relay}}(u) du \\ = \int_0^{u_{cell-NLOS}} &\frac{2}{\alpha_N} u^{-\frac{\alpha_N+1}{\alpha_n}} \Gamma[1-\frac{\alpha_L}{\alpha_N}]\lambda_s (2\lambda_r)^{\frac{\alpha_L}{\alpha_N}} \quad (9) \\ \exp &\left(-2\lambda_s (2\lambda_b)^{\frac{\alpha_L}{\alpha_N}} u^{-\frac{1}{\alpha_L}} \Gamma\left(1-\frac{\alpha_L}{\alpha_N}\right)\right) du, \end{aligned}$$

where $f_{NLOS_{relay}}(u)$ follows the same derivation as $f_{NLOS_{BS}}(u)$, but considering the density λ_u instead of λ_b. Consequently the probability to have a cell empty of relays is expressed as

$$p_{empty} = p_{no-relay_{LOS}} p_{no-relay_{NLOS}}. \quad (10)$$

Regarding the interferers, we assume that our attached BS performs perfect scheduling in the uplink band, which eliminates intra-cell-interference and only leaves inter-cell-interference for the relay-assisted link.

The relay-assisted link is composed of the BS-relay link and the relay-user link. The quality of the combined link is determined by the individual link with the lower channel gain. In order to compute the SINR, we assume a Rayleigh fading channel $h \sim exp(\mu, \sigma)$, noise and transmit powers P_{Tx_B} and P_{Tx_U}, for BS and users respectively. In that context, the relay-assisted communication will improve the coverage compared to the direct link communication when the following holds:

$$\min(\text{SINR}_{\text{BS-relay}}, \text{SINR}_{\text{relay-user}}) > \text{SINR}_{\text{BS-user}} \quad (11)$$

TABLE I: Simulation Parameters

Parameter	**Value**
α_L	2
α_N	4
P_{TX_b}	10 W
P_{TX_u}	0.2 W
N_0	-174 dBm/Hz
BW	10 MHz
$\{\mu, \sigma\}$	$\{1, 0\}$

III. Performance Evaluation

This section presents a comparison of the theorethical results derived in the previous section with Monte Carlo system level simulation results, as well as further simulations showing the SINR and coverage improvement. We perform 3.000 realizations for each parameter set $\{\lambda_s, \lambda_b, \lambda_u\}$, in a square simulation area of $4.8\,\text{km}^2$. Following [15], we select $P_{TX_U} = 200\,\text{mW}$. The simulation parameters are summarized in Table I.

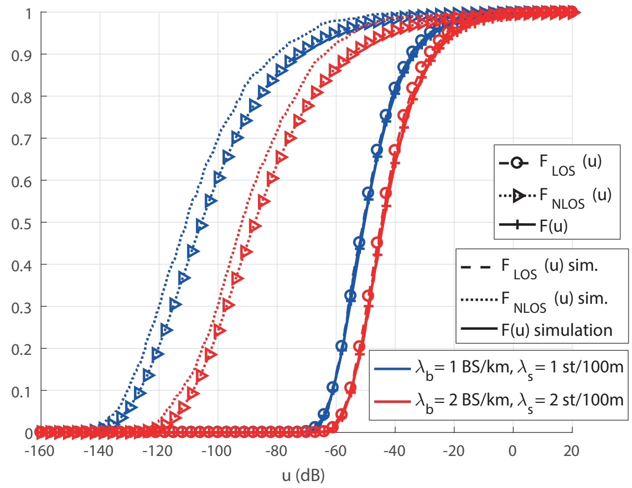

Fig. 2: Largest channel gain from BS in LOS, NLOS and the combined link. Theory and simulation results are plotted for two parameter sets.

Figure 2 provides the simulation results of the largest channel gain for the direct link and the comparison with the analysis given by (2), (3) and (4). Both simulation and theoretical channel gains are evaluated for 2 different parameter sets. The worst performance occurs when the BS and street density are very low ($\lambda_b = 1\,\text{BS/km}, \lambda_s = 1\,\text{street/100m}$). We must underline that the densities are given in units per length and not per area, as usual in the SG literature, since we use 1-D processes to generate both streets and BSs. The impact of increasing the street density is reflected in an improvement of the channel gain coming from perpendicular streets, $F_{NLOS}(u)$, since the probability to find a closer street increases with λ_s. In this case $F_{LOS}(u)$ is not affected.

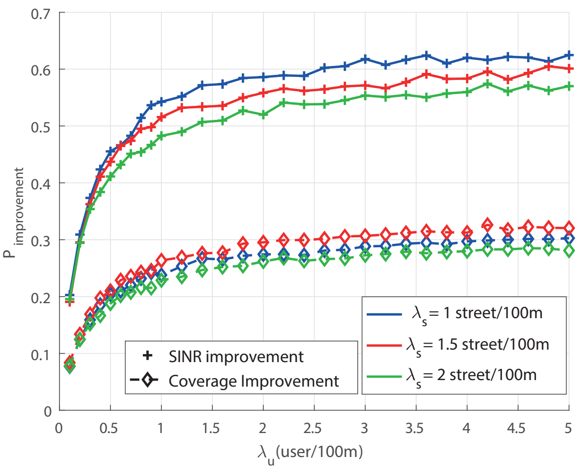

Fig. 3: Performance improvement with relay-assisted communication for a fixed $\lambda_b = 1\,\text{BS/km}$. For the coverage improvement, we assume an SINR threshold of $T = 5\,\text{dB}$.

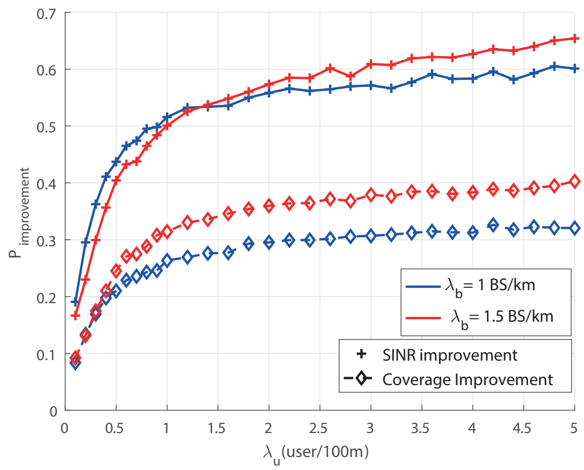

Fig. 4: Performance improvement with relay-assisted communication for a fixed $\lambda_s = 1.5\,\text{streets/100m}$. For the coverage improvement, we assume an SINR threshold of $T = 5\,\text{dB}$.

TABLE II: Probability to be attached in a LOS or NLOS BS. Theory (left) and simulations results (right) ($\lambda_b = 1\,\text{BS/km}$ and λ_s is given in streets/100m).

Link \ λ_s	1	1.5	2
LOS	0.9692‖0.9844	0.9543‖0.9801	0.9396‖0.9688
NLOS	0.0307‖0.0156	0.0457‖0.0184	0.0603‖0.0312

TABLE III: Probability to be attached to a LOS or NLOS BS. Theory (left) and simulations results (right) (λ_b = 2 streets/100m and λ_b is given in BS/km).

Link \ λ_b	1	1.5	2
LOS	0.9396‖0.9688	0.9396‖0.9607	0.9396‖0.9751
NLOS	0.0603‖0.0312	0.0603‖0.0328	0.0603‖0.0210

However, when λ_b increases, both $F_{LOS}(u)$ and $F_{NLOS}(u)$ improve. The curve shown for $F(u)$ overlaps with $F_{LOS}(u)$ since, as we show below, $p_{LOS_{BS}}$ is much larger than $p_{NLOS_{BS}}$. The theoretical curves for $F_{NLOS}(u)$ are less accurate due to our assumptions.

The LOS and NLOS probabilities derived in (5)- (6) is computed for different parameter sets and compared to simulation results. In Table II, λ_b is fixed while λ_s increases. That leads to a decreased probability of being attached to a LOS BS since the probability to have a street close to the user increases. In Table III, λ_s is fixed and λ_b varies. The repercussion in $p_{LOS_{BS}}$ and $p_{NLOS_{BS}}$ of such variation is negligible since both $F_{LOS}(u)$ and $F_{NLOS}(u)$ increase with λ_b.

Figure 3 and Figure 4 show performance results in terms of SINR for five different parameter sets over the users density. For each parameter set, two curves are shown. The SINR improvement curve represents the probability of (11). However, relay communication causes a significant overhead. The overhead increasement might not pay off if the direct link has already a good quality. Therefore we consider that direct links can be improved with V2V communication just when their SINR is below a threshold T, i.e., when a user is not in coverage. In Figure 3, for $\lambda_b = 1\,\text{BS/km}$ results the highest improvement of the SINR, but not of the coverage. That is due to the fact that when the BS-user link is already good enough, that is in coverage, we don not consider a possible coverage improvement with the relay-aided communication.

In both figures, the improvement of the relay-assisted communication for small λ_u is not significant, partly due to the high probability not to have any relays in the cell. In Figure 5, the outcome given by (9) is compared to simulation results. The higher the number of users, the larger is the probability to find one relay in the cell. When λ_b increases the cell becomes smaller and the probability to find a relay decreases. Since the BSs are placed randomly in each street, increasing λ_s has the same impact.

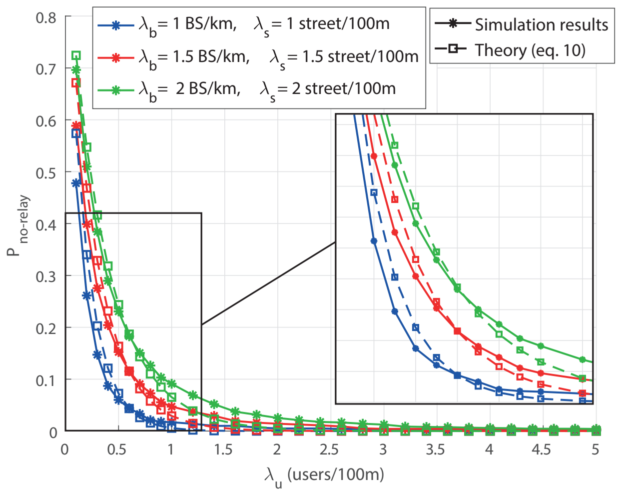

Fig. 5: Probability to have no relay in the cell over the user density for three parameter sets. Comparison of analytical and simulation results.

Figure 6 and Figure 7 show the coverage improvement

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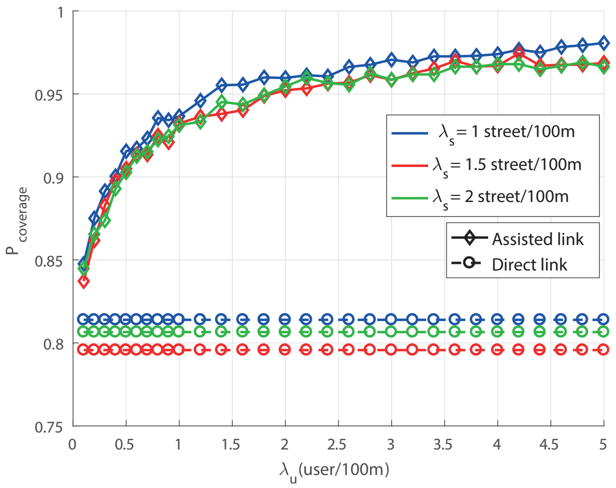

Fig. 6: Comparison of coverage probability of direct link and relay-assisted link for a fixed $\lambda_b = 1\,\text{BS/km}$ and $T = 0\,\text{dB}$.

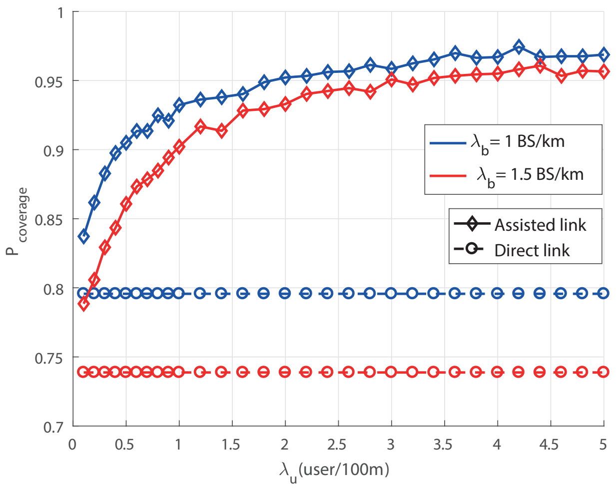

Fig. 7: Comparison of coverage probability of direct link and relay-assisted link for a constant $\lambda_s = 1.5\,\text{streets/100m}$ and $T = 0\,\text{dB}$.

with the relay-assisted link. Since in this work we analyse the downlink, the user density does not affect the direct link performance. The largest improvement is achieved with the lowest BS density and the highest user density.

IV. Conclusion

In this paper we investigated the coverage improvement when using car-relays. First, we found - from theory as well as simulations - that the probability for a user to be attached to a BS in LOS is significantly larger than to be in NLOS for all considered parameter combinations. We furthermore investigated the probability of improving SINR and coverage by utilizing relays and found that it largely depends on the relay density. To elaborate this, we introduced an approximation for the probability of not having a relay in the cell as a function of the relay density. Considering the absolute coverage probability values, we showed that they can be significantly improved when the relay density is large enough.

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