EAI Endorsed Transactions
on Industrial Networks and Intelligent Systems Research Article **EAI.EU**

Outage Probability of Vehicular Networks under Unreliable Backhaul

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Abstract

This paper presents for the first time a heterogeneous vehicular model with multiple moving small cells and a moving receiver with unreliable backhaul. In this system, a macro-base station connects to multiple moving small cells via wireless backhaul links. A Bernoulli process is adopted to model the backhaul reliability. A selection combining protocol is used at the receiver side to maximize the received signal-to-noise ratio. We investigate the impact of the number of moving small cells, the position of the receiver and the backhaul reliability on the system performance over double- Rayleigh fading channels. Expressions for outage probability are derived.

Received on 04 December 2018; accepted on 12 December 2018; published on 19 December 2018

Keywords: V2V, Double-Rayleigh fading channels, unreliable backhaul, outage probability

doi:10.4108/eai.19-12-2018.156077

1. Introduction

Future wireless networks are expected to be more dense and heterogeneous to satisfy the growing data demand. Heterogeneous networks (HetNets) can be exploited to cope with the increasing demand. In HetNets, small cells with low power are deployed within the high power macro cell coverage area to increase gain in coverage and capacity [1] [2] [3]. In vehicular networks these small cells can also be deployed on the move. The traditional way to connect small cells and macro cells is to utilize a wired backhaul. However, the cost for deployment and maintenance is high. Wireless backhaul has emerged as a suitable and flexible solution to overcome the high cost. However, wireless backhaul is not as reliable as wired backhaul because of non-line of sight (nLOS) and channel fading[4]. In this way, the impact of wireless backhaul on the system performance of a mobile receiver such as a vehicle in is a concern.

Vehicular communications and vehicular ad-hoc networks (VANETs) are gaining increasing interests [5][6]. Vehicular communications can enable the wireless transmission between high mobility vehicles. Vehicle-to-vehicle communication (V2V) is important because the technology can enable application to enhance the road safety, efficiency and reduce the traffic congestion[7]. Therefore, the system performance of heterogeneous vehicular networks is worth studying. Because of the high mobility of the vehicles, channel models for stationary objects such as Rayleigh, Rician or Nakagami-m can not be applied to V2V communications. Double-Rayleigh fading channels have been proposed for vehicles transmission links [8].

Previous research has studied the impact of wireless backhaul on system performance over Rayleigh fading channels [9] and Nakagami-m fading channels [10]. Research has shown that backhaul reliability is a key factor on system performance[4, 9–12] . This motivates us to study the backhaul reliability in vehicular networks. To the best of the authors' knowledge, the impact of wireless backhaul on system performance over double-Rayleigh fading channels for vehicular communications has not been studied yet.

Notation: $P[\cdot]$ is the probability of occurrence of an event. For a random variable X, $F_X(\cdot)$ denotes its cumulative distribution function (CDF) and $f_X(\cdot)$ denotes the corresponding probability density function (PDF). $\max(\cdot)$ and $\min(\cdot)$ denote the maximum and minimum of their arguments, respectively.

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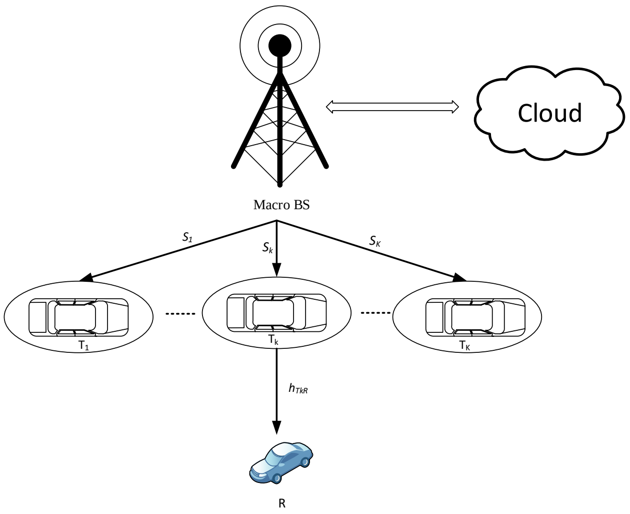

Figure 1. Vehicular network system model with mobile small cells and unreliable backhaul

2. System Model

We consider a heterogeneous vehicular network consisting of a Macro-base station (BS) connected to the cloud, K moving small cells which can be vehicles $\{T_1 ... T_k, ... T_K\}$ and a moving receiver R as shown in Fig.1. The backhaul reliability for T_k is provided by s_k, and it represents the probability that the T_k can successfully decode the kth T_k's signal from BS via unreliable backhaul. The best T_k with the highest SNR can be selected at R. All nodes are supposed to be equipped with a single antenna. Assuming all the channels are independent and identically distributed double-Rayleigh fading. Assume that the receiver R knows perfect CSI of the links from T_k to R. The CDF and PDF of the double-Rayleigh fading channels are given as [13]

$$F_X(x) = 1 - 2\sqrt{x}\mathcal{K}_1\left(2\sqrt{x}\right), \tag{1}$$

$$f_X(x) = 2\mathcal{K}_0\left(2\sqrt{x}\right). \tag{2}$$

The unreliable backhaul links can perform either success or failure transmission. So the reliability backhaul is modeled as Bernoulli process $\mathbb{I}_k$ with success probability s_k where $P(\mathbb{I}_{k^*} = 1) = s_k$ and $P(\mathbb{I}_{k^*} = 0) = 1 - s_k$ [4]. This indicates that the probability of the message successfully delivered over its dedicated backhaul is s_k, however, the failure probability is $1 - s_k$. Assuming x is the desired transmitted signal from BS to R. The received signal at the receiver R is given as

$$y_R = \sqrt{P_T d_{TR}^{-\beta}} h_{\mathrm{TR}} x \mathbb{I}_k + n, \tag{3}$$

where P_T is the transmission power at T_k, h_{TR} is the channel coefficient of the link from T_k to R, n is the complex additive white Gaussian noise (AWGN) with zero mean and variance σ^2, i.e., $n \sim CN(0, \sigma^2)$, d_{TR} is the distance from T_k to R and β is the path loss exponent. The received SNR at R is given as

$$\gamma_R = \frac{\gamma_I |h_{\mathrm{TR}}|^2 \mathbb{I}_k}{d_{TR}^{\beta}}, \tag{4}$$

where $\gamma_I = \frac{P_T}{n}$. Selection combining protocol is used at the destination R in order to select the best T_k that has the maximum SNR to transmit the signal. The T_{k^*} is selected as

$$k^* = \max_{k=1,...,K} \arg\left(\gamma_R\right). \tag{5}$$

In this way, the end to end SNR at the receiver R can be rewritten as

$$\gamma_{T_{k^*}R} = \frac{\gamma_I |h_{\mathrm{T_{k^*}R}}|^2 \mathbb{I}_{k^*}}{d_{TR}^{\beta}} \tag{6}$$

where $|h_{\mathrm{T_{k^*}R}}|^2$ is the channel coefficient from the selected T_{k^*} to R.

3. Outage Probability Analysis

In this section, outage probability [14] is derived to evaluate the system performance. Outage probability is an important performance metric and can be defined as the instantaneous mutual information rate falls below a certain threshold. Considering the CDF of SNR from T_k to R, it can be derived as,

$$F_{\gamma_T}(x) = P\left[\frac{\gamma_I |h_{\mathrm{TR}}|^2}{d_{TR}^{\beta}} < x\right] \tag{7}$$

$$= 1 - 2\sqrt{\frac{x d_{TR}^{\beta}}{\gamma_I}}\mathcal{K}_1\left(2\sqrt{\frac{x d_{TR}^{\beta}}{\gamma_I}}\right). \tag{8}$$

The above equation is the CDF of SNR without considering the unreliable backhaul, we now take into account the unreliable backhaul. Assuming success probability s for each link i.e., $s_k = s$, $\forall k$. The PDF of γ_R is modeled by the mixed distribution,

$$f_{\gamma_R}(x) = (1 - s)\delta(x) + s\frac{\partial F_{\gamma_T}(x)}{\partial x}, \tag{9}$$

where $\delta(x)$ is the Dirac delta function. According to (9), the CDF of the γ_R is given as

$$F_{\gamma_R}(x) = \int_0^x f_{\gamma_R}(t)dt. \tag{10}$$

The expressions are given as,

$$F_{\gamma_R}(x) = 1 - s + \frac{sd^{\beta}_{TR}}{\gamma_I}\int_0^x \mathcal{K}_0\left(2\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}\right)dt - \frac{sd^{\beta}_{TR}}{\gamma_I}$$
$$\int_0^x \frac{\mathcal{K}_1\left(2\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}\right)}{\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}}dt + \frac{sd^{\beta}_{TR}}{\gamma_I}\int_0^x \mathcal{K}_2\left(2\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}\right)dt. \tag{11}$$

According to selection combining, T_{k^*} is selected when γ_R achieves the maximum value, since for all random variables γ_R are independent and identically distributed. The CDF of the end-to-end SNR γ_{TR} can be written as

$$F_{\gamma_{T_{k^*}R}}(x) = F_{\gamma_R}(x)^k. \tag{12}$$

The expression is derived as

$$F_{\gamma_{T_{k^*}R}}(x) = \sum_{k=0}^{K}\binom{K}{k}\sum_{i=0}^{k}\binom{k}{i}(1-s)^{k-i}J_1^i \tag{13}$$
$$\sum_{j=0}^{K-k}\binom{K-k}{j}J_2^j\left(\frac{sd^{\beta}_{TR}}{\gamma_I}\right)^{i+K-k}(-1)^{K-k-j}J_3^{K-k-j}, \tag{14}$$

where

$$\begin{cases} J_1 = \int_0^x \mathcal{K}_0\left(2\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}\right)dt \\ J_2 = \int_0^x \mathcal{K}_2\left(2\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}\right)dt \\ J_3 = \int_0^x \frac{\mathcal{K}_1\left(2\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}\right)}{\sqrt{\frac{d^{\beta}_{TR}t}{\gamma_I}}}dt. \end{cases} \tag{15}$$

Mathematica software is used to derive the numerical results of J_1, J_2 and J_3.

4. Numerical Results

In this section, numerical results of the outage probability are studied to evaluate the impact of backhaul reliability and the number of mobile small cells on the system performance. The 'Sim' curves are the simulation results and 'Ana' curves are analytical results. In the figures, we can observe that both the simulation curves and analytical curves match very well. In this section, the threshold of outage probability is fixed at 1 bits/s/Hz. It is assumed that the location of the nodes in Cartesian coordinate system respectively are T_k = (0, 0), R =(0.4, 0). Hence, the normalized distance between two nodes can be found as $d_{TR}=\sqrt{(x_{T_k}-x_R)^2+(y_{T_k}-y_R)^2}$. Path loss exponent β = 4 is assumed. Fig. 2, 3, 4 and 5 show the impact of backhaul reliability, the number of small cells and the position of the receiver on the system performance.

In Fig. 2, s is fixed at 0.99. Assuming the number of small cells is $K = 1$, $K = 2$ to evaluate the impact of the number of small cells on system performance. In the figure, when the number of small cells increases, the outage probability decreases and the system can achieve a better performance due to the correlation of multiple signals at the receiver.

In Fig. 3 and Fig. 4, the outage probability with different backhaul reliability has been plotted. In Fig. 3, we assume that $K = 2$. It is obvious that the backhaul reliability has a significant impact on the outage probability. More specifically, when $\gamma_I = 10dB$, the outage probability drops from approximate 0.81 ($s = 0.1$) to 10^{-3} ($s = 0.9$). The system performance improves nearly 10^3 times when backhaul reliability increases from 0.1 to 0.9. Moreover, the system has a better performance when γ_I increases due to the high transmit power. In Fig. 4, the outage probability at different backhaul reliability has been investigated. $K = 3$ is assumed in this scenario. we assume that $s = 0.90$ and $s = 0.80$ to evaluate the impact of backhaul reliability on the system performance. When s increases, the system performs considerably better as the outage probability decreases significantly. As the probability of the information successfully delivered over the backhaul links gets higher, the system can achieve a better performance.

In Fig. 5, the outage probability with different receiver's position has been evaluated. s is fixed at 0.9, and $K = 2$. When the receiver moves from R= (0.4, 0) to R= (0.6, 0), outage probability increases significantly.

According to Fig. 2, 3, 4 and 5, the number of small cells, the position of the receiver and backhaul reliability can significantly affect system performance in terms of outage probability. Increasing backhaul reliability and the number of small cells and decreasing the distance between receiver and small cells can help the system to achieve a significantly better system performance.

5. Conclusion

In this paper, we propose a heterogeneous vehicular network with multiple mobile small cells and a moving receiver with unreliable backhaul over double-Rayleigh fading channels. Selection combining is used to choose the best small cell that has the maximum SNR at the receiver. The expression for outage probability is derived to evaluate the system performance. Results show that wireless backhaul reliability has a significant impact on system performance and this factor should be considered when designing heterogeneous vehicular network in the future. This paper also investigates that

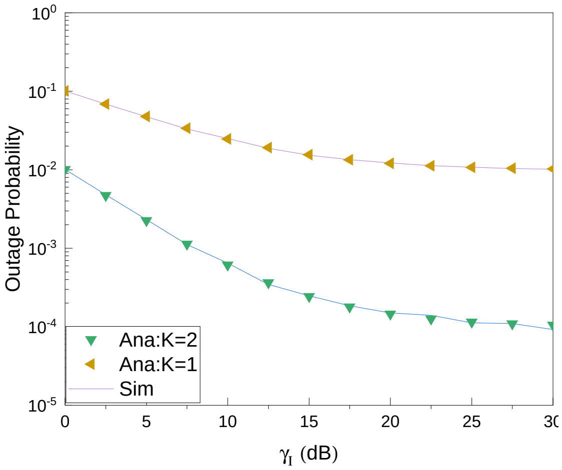

Figure 2. The impact of the number of small cells on system performance (s=0.99)

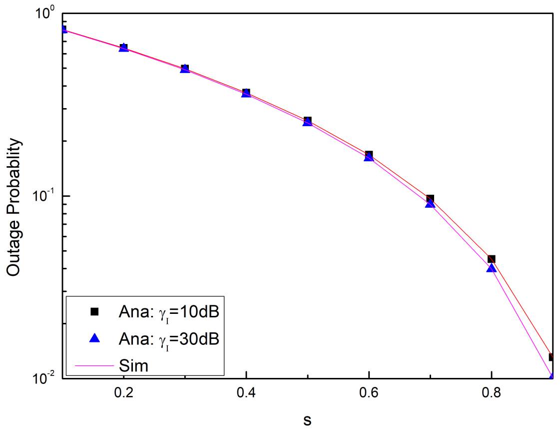

Figure 3. The impact of backhaul reliability on system performance (K=2)

adding moving small cells in vehicular networks and decreasing the distance between receiver and small cells result in a significantly better system performance.

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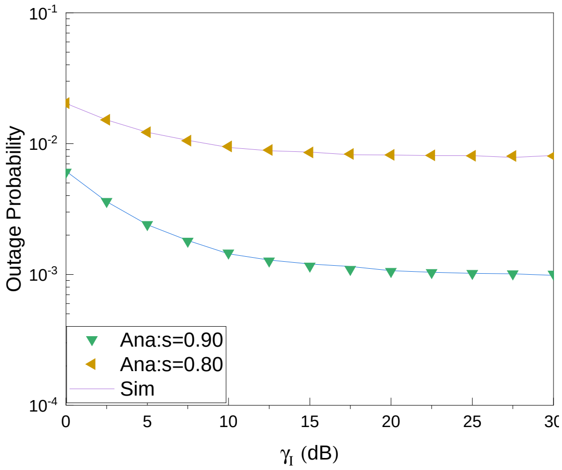

Figure 4. The impact of backhaul reliability on system performance (K=3)

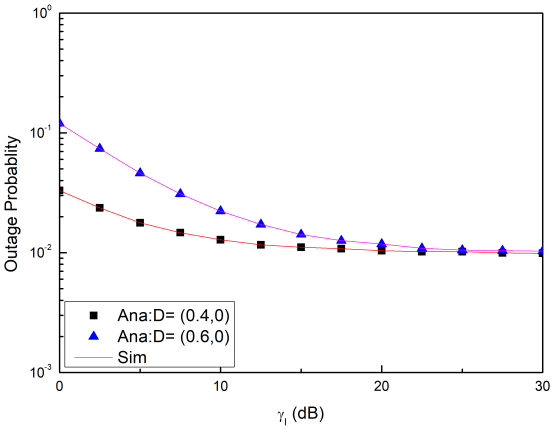

Figure 5. The impact of receiver's possition on system performance (s=0.9, K=2)

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