# System Performance of Relay-Assisted Heterogeneous Vehicular Networks with Unreliable Backhaul over Double-Rayleigh Fading Channels

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**Abstract.** This paper introduces for the first time a relay-assisted heterogeneous vehicular model including numerous stationary small cells, a mobile relay and a mobile receiver with unreliable backhaul. In this proposed system model, a macro-base station connected to the cloud communicates to numerous small cells through wireless backhaul links. A Bernoulli process is utilized to model the backhaul reliability. A relay using decode-and-forward protocol is considered to help the transmission from the stationary small cells to the mobile receiver. Moreover, at the mobile relay side, a selection combining protocol is applied to maximize the received signal-to-noise ratio. The links between stationary small cells and mobile relay are Rayleigh fading channels, and the link between mobile relay and mobile receiver is double-Rayleigh fading channel. A closed-form expression for outage probability is provided to evaluate the influence of the number of small cells and the backhaul reliability on the proposed system performance.

**Keywords:** Relay · Double-Rayleigh fading channels · Unreliable backhaul · Outage probability

## 1 Introduction

With the fast increasing amount of smart devices, future networks will be more dense and heterogeneous [5,12]. In heterogeneous networks (HetNets), the adoption of backhaul to connect the macro-base station and small cells is gaining interest. The conventional wired backhaul can provide stable transmissions, but

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it costs a lot to deploy and maintain it. Alternatively, wireless backhaul is flexible and cost-effective, but because of non-line of sight (nLOS) and channel fading [6] wireless backhaul can not ensure a transmission as reliable as wired backhaul.

In recent years, the increasing number of vehicles has caused traffic congestion, traffic accidents and resource consumption. Therefore, future vehicular communication networks and vehicular ad-hoc networks (VANETs) which can provide information transmission through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) have been widely investigated [16]. Many applications are available to improve road safety and resource management in vehicular networks [1]. Hence, it is essential to study the performance of heterogeneous vehicular network. In vehicular networks, vehicles are mobile so channel models for static objects, such as, Rayleigh, Rician and Nakagami-m are not suitable for vehicular communications. Instead, double-Rayleigh fading channel was introduced and can be utilized for mobile transmission links [2].

In heterogeneous vehicular networks, relays also attract interest because they can help to improve the system coverage and overall system performance [3,11]. In vehicular networks, relays are likely to exist in abundance as vehicles are scattered around a geographical area. There are two well known relay protocols, amplify-and-forward (AF) and decode-and-forward (DF) [10]. Networks with DF relays can achieve better system performance than AF because of the lower interference [14]. The authors in [15] studied the impact of backhaul reliability on vehicular networks, but the benefit of using relays was not investigated. This motivates us to consider exploiting cooperative DF relays in heterogeneous vehicular networks.

In recent research, the influence of wireless backhaul on system performance over Rayleigh fading channels [14] and Nakagami-m fading channels [8] was investigated and the conclusion of this research shows that backhaul reliability is a crucial parameter which can influence the system model significantly [6–9,13,14]. Hence, in our proposed relay-assisted heterogeneous vehicular networks, the backhaul reliability parameter should be well studied.

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

## 2 System Model

We propose a relay-assisted heterogeneous vehicular network including a Macro-Base station ($BS$) linked to the cloud, $K$ stationary small cells $\{T_1, ...T_k, ...T_K\}$, a mobile DF relay $R$ and a mobile receiver $D$ as shown in Fig. 1. $s_k$ represents the backhaul reliability for small cell $T_k$ and it denotes the probability that the small cell $T_k$ can decode the $k$th $T_k$'s information successfully from $BS$ through unreliable backhaul. The relay $R$ selects a best small cell $T_k$ with the highest SNR using selection combining protocol. All nodes are assumed to be equipped with single antenna. Because the small cells $T_k$ are stationary and the relay is mobile,

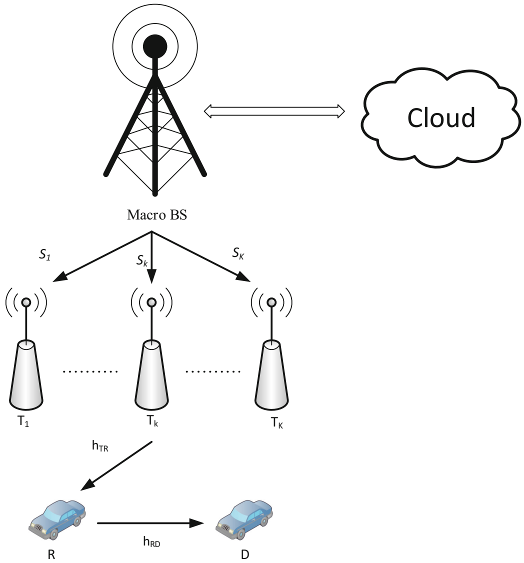

**Fig. 1.** Relay-assisted vehicular network system model with small cells and unreliable backhaul

we assume that the links from small cells $T_k$ to the mobile relay $R$ follow independent and identically distributed Rayleigh fading channels. Moreover, both the relay and receiver are mobile nodes, so we assume that the channel from the relay $R$ to the destination $D$ is independent and identically distributed double-Rayleigh fading channel. Assume that perfect CSI of the connections from $T_k$ to $R$ and $R$ to $D$ is available.

The channel from $T_k$ to $R$ is Rayleigh fading channel, and the CDF and PDF of Rayleigh fading channels are written as [13]

$$F_X(x) = 1 - \exp(-\lambda x), \tag{1}$$

$$f_X(x) = \lambda \exp(-\lambda x). \tag{2}$$

The channel from $R$ to $D$ is double-Rayleigh fading channel, and the CDF and PDF of double-Rayleigh fading channels are given as [1]

$$F_X(x) = 1 - 2\sqrt{x}\mathcal{K}_1\left(2\sqrt{x}\right), \tag{3}$$

$$f_X(x) = 2\mathcal{K}_0\left(2\sqrt{x}\right). \tag{4}$$

where $Kv(.)$ denotes the modified Bessel function of second kind with order $v$.

The unreliable backhaul links behave either a successful or failed transmission in a "one shot" communication fashion with no packet retransmission. Therefore, a Bernoulli process $\mathbb{I}_k$ is chosen to model backhaul reliability. The success probability of the transmission via wireless backhaul is $s_k$ where $P(\mathbb{I}_{k^*} = 1) = s_k$, similarly, the probability of failed transmission is $1 - s_k$ where $P(\mathbb{I}_{k^*} = 0) = 1 - s_k$ [6]. This represents that the probability of the signal successfully transmitted through wireless backhaul is $s_k$, however, the failure probability is $1 - s_k$ . $x$ is assumed to be the desired transmitted signal from $BS$ to mobile $D$. At the mobile relay $R$ side, the received signal is given as

$$y_R = \sqrt{P_T} h_{\mathsf{TR}} x \mathbb{I}_k + n. \tag{5}$$

Where $P_T$ represents the transmission power at $T_k$, $h_{\mathsf{TR}}$ represents the channel coefficient of the connection from $T_k$ to $R$, $n$ is the complex additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2$, i.e., $n \sim CN(0, \sigma^2)$.

At the mobile receiver side $D$, the received signal can be expressed as

$$y_D = \sqrt{P_R d_{RD}^{-\beta}} h_{\mathsf{RD}} x + n. \tag{6}$$

where $P_R$ represents the transmit power at $R$, $h_{\mathsf{RD}}$ is the channel coefficient of the link from $R$ to $D$, $d_{RD}$ represents the distance from $R$ to $D$ and $\beta$ is the path loss exponent.

Hence, the received SNR at the mobile relay $R$ is given as

$$\gamma_R = \gamma_I |h_{\mathsf{TR}}|^2 \mathbb{I}_k, \tag{7}$$

where $\gamma_I = \frac{P_T}{n}$.

The selection combining protocol [4] is applied at $R$ to select the best $T_{k^*}$ with highest SNR to transmit the signal,

$$k^* = \max_{k=1,\ldots,K} \arg\left(\gamma_R\right). \tag{8}$$

Therefore, the received SNR at $R$ with the selected $T_{k^*}$ using selection combining protocol can be rewritten as

$$\gamma_{T_{K^*}R} = \gamma_I |h_{\mathsf{T_k * R}}|^2 \mathbb{I}_{k^*}, \tag{9}$$

where $|h_{\mathsf{T_k * R}}|^2$ represents the channel coefficient from the chosen $T_{k^*}$ to $R$. Similarly, the received SNR at the mobile receiver $D$ can be given as

$$\gamma_D = \frac{\gamma_S |h_{\mathsf{RD}}|^2}{d_{RD}^{\beta}}, \tag{10}$$

where $\gamma_S = \frac{P_R}{n}$.

We assume that the relay $R$ utilizes the DF protocol, so the overall SNR can be derived as

$$\gamma_{T_{K^*}D} = \min(\gamma_{T_{K^*}R}, \gamma_D). \tag{11}$$

## 3 Outage Probability Analysis

Outage probability is a key performance metric to figure out the system performance and is described as the probability that the instantaneous mutual information rate is below a certain threshold $\theta$. In this section, outage probability is utilized to investigate the proposed relay-assisted vehicular system performance.

Firstly, without considering the backhaul reliability, the CDF of SNR from $T_k$ to $R$ can be derived as,

$$\begin{aligned} F_{\gamma_T}(x) &= P[\gamma_I |h_{\mathsf{TR}}|^2 < x] \\ &= 1 - \exp(-\frac{\lambda x}{\gamma_I}). \end{aligned} \tag{12}$$

We now take into account the unreliable backhaul. We assume that success probability $s$ for each link from $BS$ to $T_k$ i.e., $s_k = s$, $\forall k$. The PDF of $\gamma_R$ is modeled by the mixed distribution [6],

$$f_{\gamma_R}(x) = (1-s)\delta(x) + s\frac{\partial F_{\gamma_T}(x)}{\partial x}, \tag{13}$$

where $\delta(x)$ denotes the Dirac delta function. As stated in (15), the CDF of $\gamma_R$ is given as

$$F_{\gamma_R}(x) = \int_0^x f_{\gamma_R}(t)dt. \tag{14}$$

According to selection combining protocol, $T_{k^*}$ with the highest SNR $\gamma_R$ will be chosen, because all random variables $\gamma_R$ are independent and identically distributed. Hence, the CDF of SNR $\gamma_{TR}$ can be given as

$$\begin{aligned} F_{\gamma_{T_{K^*}R}}(x) &= F_{\gamma_R}(x)^k \\ &= 1 + \sum_{k=1}^{K} \binom{K}{k} (-1)^k s^k \exp(-\frac{\lambda k x}{\gamma_I}). \end{aligned} \tag{15}$$

Moreover, the CDF of SNR from $R$ to $D$ is written as,

$$F_{\gamma_D}(x) = 1 - 2\sqrt{\frac{x d_{RD}^{\beta}}{\gamma_S}} \mathcal{K}_1 \left( 2\sqrt{\frac{x d_{RD}^{\beta}}{\gamma_S}} \right). \tag{16}$$

With the help of (11) (15) and (16), the CDF of our proposed model from $BS$ to $D$ is given as,

$$F_{\gamma_{T_{K^*}D}}(x) = 1 - (1 - F_{\gamma_{T_{K^*}R}}(x))(1 - F_{\gamma_D}(x))$$
$$= 1 + 2\sum_{k=1}^{K} \binom{K}{k} (-1)^k s^k \exp(-\frac{\lambda k x}{\gamma_I}) \sqrt{\frac{x d_{RD}^{\beta}}{\gamma_S}} \tag{17}$$
$$\mathcal{K}_1 \left( 2\sqrt{\frac{x d_{RD}^{\beta}}{\gamma_S}} \right).$$

## 4 Numerical Results

Numerical results of outage probability are investigated to study both the effect of backhaul reliability and number of stationary small cells on our proposed system performance. In this section, we have the following assumptions. The outage probability threshold is $\theta = 1$ bits/s/Hz. In a Cartesian coordinate system, the location of small cells, mobile relay and mobile receiver are: $T_k = (0,\ 0)$, $R = (0.8,\ 0)$ and $D = (1,\ 0)$. The path loss exponent is $\beta = 4$ and $\gamma_I = \gamma_S$. In the figures, 'Sim' is the results for simulation and 'Ana' is the results for analytical. The 'Sim' and 'Ana' match very well.

In Fig. 2, the influence of the number of small cells on system performance is presented. The backhaul reliability $s$ is fixed at 0.90. We assume the number of small cells is $K = 1$, $K = 2$ and $K = 3$. In the figure, we can observe that when $K$ increases, the outage probability drops. This is because the system can gain a superior performance because of the correlation of numerous signals at the mobile receiver side.

In Fig. 3, the effect of backhaul reliability $s$ on system performance is studied. We assume that $K = 3$. The level of backhaul reliability is various: $s = 0.90$, $s = 0.80$ and $s = 0.70$. We can observe in the figure that when the value of $s$ increases, the outage probability decreases, the system can achieve a significant superior performance. This is because when the signal has a higher probability to transmit successfully through the wireless backhaul the system can perform better.

As shown in Figs. 2 and 3, both the number of stationary small cells and the level of backhaul reliability have a significant influence on our proposed system performance. More specifically, in this relay-assisted heterogeneous vehicular network, adding more stationary small cells and increasing the backhaul reliability can result in a significant better system performance.

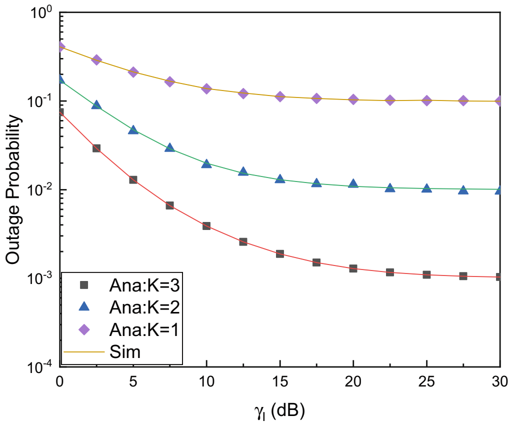

**Fig. 2.** The influence of the number of small cells on system performance (s = 0.90)

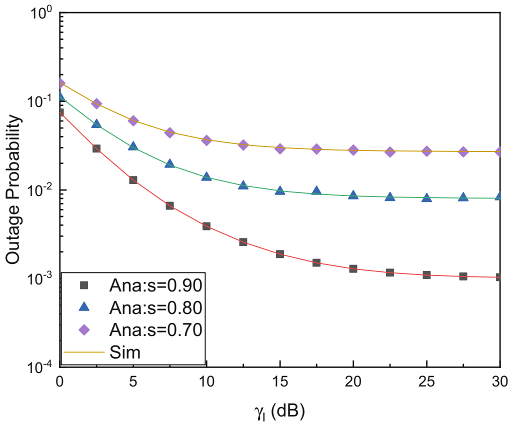

**Fig. 3.** The influence of backhaul reliability on system performance (K = 3)

## 5 Conclusion

We propose a relay-assisted heterogeneous vehicular network with a macro-base station, numerous stationary small cells, a mobile relay and a mobile receiver under unreliable backhaul over both Rayleigh fading channels and double-Rayleigh fading channels. At the mobile relay, selection combining protocol is utilized to select a best stationary small cell with the highest SNR. Outage probability is the metric to evaluate the system performance and the closed-form expression is provided. Our results prove that wireless backhaul reliability can affect the system performance significantly and this parameter should be considered when studying heterogeneous vehicular networks. Moreover, increasing the number of stationary small cells in our proposed system can help the system achieve a better performance.

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