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Performance analysis of Cognitive Vehicular Networks under Unreliable Backhaul

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Abstract

This paper presents a comprehensive model including a wireless backhaul as a cost-effective backhaul alternative to wired backhaul for vehicular networks, a heterogeneous underlay cognitive vehicular network with multiple mobile secondary transmitters acting as mobile small cells, a mobile secondary receiver and a mobile primary user. To increase the spectrum utilization in this proposed vehicular network, multiple mobile secondary transmitters forward the signal to a mobile secondary receiver while using the same spectrum with a mobile primary user on the condition that the interference caused by secondary transmitters is tolerable at the primary user. A Bernoulli process is applied to model wireless backhaul reliability. The analytical closed-form expressions for outage probability as well as the asymptotic expression are derived to reveal the effects of backhaul reliability on the network performance over double-Rayleigh fading channels.

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1. Introduction

With scenarios such as 5G, Internet of Things, smart cities and smart vehicles, future wireless networks will be more heterogeneous and dense[1]. In heterogeneous networks (HetNets), backhauls are important to connect core networks to small cells. Conventional wired backhaul technologies ensure high reliability as well as high data rate, but they are costly, inconvenient to deploy and difficult to maintain. Wireless backhauls have attracted increasing attention in recent years and constitute a suitable alternative as they are cost-effective and flexible. However, wireless backhauls are not as reliable as wired backhauls due to non-LOS propagation and channel fading [2]. The influence of this unreliability upon system performance remains a concern [1] [2] [3].

In HetNets, the increasing number of terminals and data traffic lead to a shortage of spectrum. Cognitive radio networks (CRNs) [4] have been introduced to enhance the spectrum utilization. In underlay CRNs, secondary users are permitted to utilize the spectrum allocated to primary users as long as the interference they cause to primary users is tolerable, hence overall capacity can be improved. In heterogeneous CRNs, the effect of backhaul unreliability on the system performance has been presented [5–8]. In[5], a single small cell acting as a secondary transmitter was considered. As an extension to [5], multiple small cells acting as secondary transmitters were considered in the system model in [6]. Based on the research in [6], a relay was deployed between the transmitters and the receiver to enhance the coverage in [7]. The author in [8] considered both multiple small cells as well as multiple primary users and this scenario was more practical and realistic than the system models in [5–7]. Research in [5–8] proved that backhaul reliability is a vital parameter for heterogeneous cognitive network. However, it is important to note that the mentioned research in [5–8] considered Rayleigh and Nakagami-m fading channels, and they are only suitable for stationary communication connections but not to mobile communication connections.

Vehicular communications and vehicular ad-hoc networks (VANETs) are attracting increasing interest [9]. Vehicle-to-vehicle (V2V) can enable wireless communication between highly mobile vehicles and it can improve road safety, traffic efficiency and reduce traffic congestion [10]. With the fast growing number of connected vehicles, the deployment of VANETs will exhaust the radio spectrum. Applying CR technology in VANETs can enhance spectrum utilization in vehicular

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communications. Vehicles are able to opportunistically access licensed spectrum allocated prior to other systems, for example television stations, cellular networks or incumbent vehicles in the system[11]. Channel models for stationary communication links, for example Rician, Rayleigh or Nakagami-m is not suitable for V2V communications due to the high mobility of vehicles. Double-Rayleigh fading channel has been applied for mobile transmission connections [12].

CR-VANETs is an efficient approach to solve the spectrum scarcity. Wireless backhaul is an efficient way to enable vehicle to infrastructure (V2I) communications by connecting moving small cells to fixed macro-base stations. However, as mentioned previously, unreliable backhaul can affect the system performance significantly, so backhaul reliability is an essential parameter to be considered [5–8]. This motivates us to propose a heterogeneous underlay cognitive vehicular networks where the effects of backhaul reliability and the number of mobile secondary transmitters on system performance are examined.

2. System Model

We present a heterogeneous underlay cognitive vehicular network with a Macro-base station (BS) connected to the cloud, K mobile secondary transmitters acting as mobile small cells $\{T_1, ...T_k, ...T_K\}$, a mobile secondary receiver SU and a mobile primary user PU. Mobile small cells play an important part in mobile vehicular communications and they are practical as they can be deployed in moving vehicles e.g., cars, buses and trains [13]. s_k represents the backhaul reliability for kth mobile secondary transmitter T_k and it means the probability that the signal transmitted from BS to T_k through wireless backhaul can be decoded successfully. The best T_{k^*} that has the highest SNR is chosen at the receiver side. In the proposed system model, all nodes have single antenna and all channels are independent and identically distributed double-Rayleigh fading. The CDF and PDF formulas of the double-Rayleigh fading channels are shown as [10],

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

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

In underlay CRNs, the mobile secondary network includes K mobile transmitters T_k and a secondary mobile receiver SU. To increase the spectrum utilization, the secondary network can use the spectrum licensed to PU if the interference from the secondary network to the primary user PU is below a maximum tolerable interference power (denoted as I_p).

Assuming x is the signal that forward from BS to SU with the help of T_k via wireless backhaul. The received signal at the secondary receiver SU is written as

$$y_D = \sqrt{P_T d_{TD}^{-\beta}} h_{\text{TD}} x \mathbb{I}_k + n, \tag{3}$$

where P_T denotes the transmit power at T_k. h_{TD} represents the channel coefficient of the link from T_k to SU. n denotes the complex additive white Gaussian noise (AWGN) with zero mean and variance σ^2, i.e., $n \sim CN(0, \sigma^2)$. d_{TD} is the distance from T_k to SU. β represents the path loss exponent.

The wireless backhaul can either result in a successful or a failed transmission, so this behaviour can be modeled as a Bernoulli process $\mathbb{I}_k$, and the success probability of the process is denoted as s_k where $P(\mathbb{I}_{k^*} = 1) = s_k$ and the failure probability of the process is denoted as $P(\mathbb{I}_{k^*} = 0) = 1 - s_k$ [3]. This illustrates that the probability of the desired signal from BS that transmitted to T_k successfully via the wireless backhaul is s_k and the failed transmission probability of a signal from BS to T_k over the backhaul link is $1 - s_k$.

In underlay CRN, the maximum tolerable interference power at PU is I_p, so the transmit power at the T_k should be limited as

$$P_T = \frac{I_p d_{TP}^{\beta}}{|h_{\text{TP}}|^2}. \tag{4}$$

where h_{TP} indicates the channel coefficient of the interference from T_k to PU; d_{TP} indicates the distance from T_k to PU and β indicates the path loss exponent.

In order to find the overall SNR at SU, firstly, we only consider the transmission link from Tk to SU and do not take backhaul reliability into consideration, the SNR at SU can be derived as

$$\gamma_T = \frac{\gamma_I d_{TP}^{\beta} |h_{\text{TD}}|^2}{d_{TD}^{\beta} |h_{\text{TP}}|^2}, \tag{5}$$

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

Secondly, we take backhaul reliability into consideration, the overall SNR from BS to SU with the help of T_k is written as

$$\gamma_{TD} = \frac{\gamma_I d_{TP}^{\beta} |h_{\text{TD}}|^2 \mathbb{I}_k}{d_{TD}^{\beta} |h_{\text{TP}}|^2}. \tag{6}$$

To choose the best T_{k^*} with the highest SNR among K mobile secondary transmitters at the secondary receiver SU, selection combining protocol is applied [2]. The best T_{k^*} is chosen based on selection combining as

$$k^* = \max_{k=1,\ldots,K} \arg\left(\gamma_{TD}\right). \tag{7}$$

Hence, the overall SNR with the selected T_{k^*} of the proposed system model at SU is rewritten as

$$\gamma_{T_k^* D} = \frac{\gamma_I d_{TP}^{\beta} |h_{\mathrm{T_k*D}}|^2 \mathbb{I}_k}{d_{TD}^{\beta} |h_{\mathrm{T_k*P}}|^2}, \tag{8}$$

where $|h_{\mathrm{T_k*D}}|^2$ denotes the channel coefficient from the selected T_{k^*} to SU and $|h_{\mathrm{T_k*P}}|^2$ denotes the channel coefficient from the selected T_{k^*} to PU.

3. Performance Analysis

3.1. Outage probability analysis

In this proposed heterogeneous underlay cognitive vehicular network, outage probability has been extensively used to represent the probability that the instantaneous mutual information rate is under a certain threshold [8]. In order to derive the outage probability, the CDF of the system overall SNR should be provided.

Firstly, without considering the backhaul reliability as well as selection combining, the CDF of the SNR (5) can be written as

$$\begin{aligned} F_{\gamma_T}(x) &= P[\frac{\gamma_I |h_{\mathrm{TD}}|^2}{|h_{\mathrm{TP}}|^2 p} < x] \\ &= \begin{cases} \frac{1}{2}, & \frac{x}{\gamma_I} p = 1. \\ \frac{\frac{x}{\gamma_I} p \left[\frac{x}{\gamma_I} p - 1 - \log(\frac{x}{\gamma_I} p)\right]}{(1-\frac{x}{\gamma_I} p)^2}, & \frac{x}{\gamma_I} p \neq 1. \end{cases} \end{aligned} \tag{9}$$

where $p = (\frac{d_{TD}}{d_{TP}})^{\beta}$.

The next step is to consider the backhaul and to find the CDF of the SNR (6) at SU. Assume equal success probability s for each link i.e., $s_k = s$, $\forall k$. The PDF of the SNR considering the backhaul reliability parameter is described by the following distribution [3]

$$f_{\gamma_{TD}}(x) = (1-s)\delta(x) + s \frac{\partial F_{\gamma_T}(x)}{\partial x}, \tag{10}$$

where $\delta(x)$ denotes the Dirac delta function. According to (10), the CDF of γ_{TD} (6) is given as

$$\begin{aligned} F_{\gamma_{TD}}(x) &= \int_0^x f_{\gamma_{TD}}(t)dt \\ &= 1 - s - \frac{sp^2x^2(p^2x - 3\gamma_I)}{3(\gamma_I - px)^3} - \frac{2sp^3x^3}{3(\gamma_I - px)^3} \\ &\frac{spx(px - 2\gamma_I)}{(\gamma_I - px)^2} - \frac{pxs\left[-\gamma_I + px + \gamma_I \log(\frac{px}{\gamma_I})\right]}{(\gamma_I - px)^2}. \end{aligned} \tag{11}$$

Applying selection combining protocol, the best T_{k^*} is selected when γ_{TD} is the highest as random variables follow independent and identically distributed. Therefore, the CDF of the overall SNR $\gamma_{T_{k^*}D}$ (8) is derived as

$$F_{\gamma_{T_{k^*}D}}(x) = F_{\gamma_{TD}}(x)^K. \tag{12}$$

The expression of CDF is derived as

$$F_{\gamma_{T_{k^*}D}}(x) = \begin{cases} (1-s)^K, & \frac{x}{\gamma_I} p = 1. \\ \Theta, & \frac{x}{\gamma_I} p \neq 1. \end{cases} \tag{13}$$

where

$$\begin{aligned} \Theta = &\sum_{k=0}^{K} \binom{K}{k} \sum_{i=0}^{k} \binom{k}{i} (1-s)^{k-i} \sum_{l=0}^{i} \binom{i}{l} \sum_{m=0}^{l} \binom{l}{m} \\ &\left[\frac{-sp^4x^3}{3(\gamma_I - px)^3}\right]^m \left[\frac{3sp^2\gamma_I x^2}{3(\gamma_I - px)^3}\right]^{l-m} \left[\frac{-2sp^3x^3}{3(\gamma_I - px)^3}\right]^{i-l} \\ &\sum_{j=0}^{K-k} \binom{K-k}{j} \left[\frac{-psx\gamma_I}{(\gamma_I - px)^2}\right]^j \left[\frac{-psx\gamma_I \log(\frac{px}{\gamma_I})}{(\gamma_I - px)^2}\right]^{K-k-j}. \end{aligned} \tag{14}$$

3.2. Asymptotic analysis

According to the closed-form expressions (13), in high SNR regime $\gamma_I \to \infty$, the asymptotic analysis can be derived as

$$P_{\gamma_{T_{k^*}D}}^{Asy}(x) = (1-s)^K. \tag{15}$$

From the equation of asymptotic analysis, the limitation of the outage probability in this proposed system is influenced by backhaul reliability s and the number of mobile secondary transmitters K. To be specific, when backhaul reliability s or K increased, the outage probability declines, hence, the system performance is improved.

4. Numerical Results

The numerical results in terms of the outage probability are evaluated to investigate the effect of backhaul reliability on the proposed heterogeneous cognitive vehicular network in Fig. 1 and 2. In the figures of this section, 'Sim', 'Ana' and 'Asy ' indicate the curves of simulation, analysis and asymptotic. The curves of simulation and analytical match precisely. The parameters are designed as: 1) The threshold for the outage probability is 1 bits/s/Hz. 2) The position of the nodes in the proposed system model are assumed as T_k = (0, 0), PU =(0.5, 0.5), SU =(0.4, 0) in a Cartesian coordinate system. Therefore, the normalized distance d_{ab} between two nodes is described as $\sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}$, where $ab = \{T_kSU, T_kPU\}$. 3) Path loss exponent is assumed as $\beta = 4$.

In Fig. 1, the influence of different values of backhaul reliability on system performance is presented. The value of backhaul reliability is changed from $s = 0.90$, $s = 0.80$ to $s = 0.70$, and $K = 2$. In Fig.1, when s increases, the outage probability drops significantly, and the system performance is improved significantly. The is because a higher s indicates a higher probability that messages could be delivered via wireless backhaul.

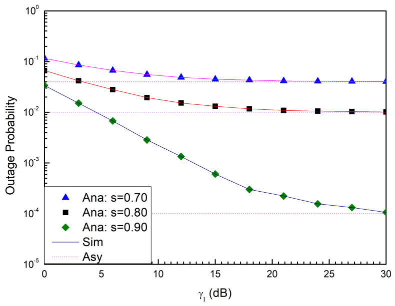

Figure 1. The effect of backhaul reliability s on system performance (K=2)

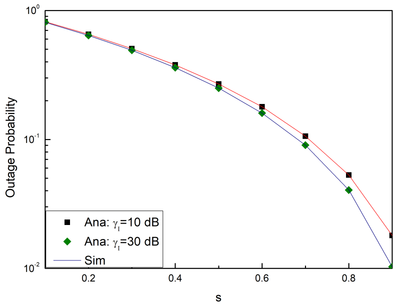

Figure 2. The effect of backhaul reliability s and peak tolerable interference at primary user on system performance (K=2)

In order to see how the backhaul reliability influence the system performance visually, in Fig. 2, the outage probability for various levels of backhaul reliability is provided. In this scenario, the number of secondary transmitters T_k is fixed at $K = 2$. The backhaul reliability varies from 0.10 to 0.90. Obviously, the backhaul reliability parameter can influence the outage probability significantly in the proposed heterogeneous cognitive vehicular network. To be specific, when $\gamma_I =$ 30 dB, the outage probability decreases from nearly 0.80 ($s = 0.10$) to 10^{-2} ($s = 0.90$). The system performance can achieve approximate 10^2 times improvement when the backhaul reliability is improved from 0.10 to 0.90. Also, compared the two curves when $\gamma_I = 10dB$ and $\gamma_I = 30dB$, the system has a better performance when $\gamma_I = 30dB$. This is because the transmit power at T_k can be increased when PU has a higher maximum tolerable interference power.

As shown in the figures and asymptotic analysis, backhaul reliability influence the system performance significantly. Increasing the backhaul reliability can improve system performance dramatically.

5. Conclusions

A heterogeneous cognitive vehicular network with multiple mobile secondary transmitters, a mobile secondary receiver and a mobile primary receiver under unreliable backhaul is proposed. Closed-form expressions and asymptotic analysis for outage probability are derived to investigate the system performance and also obtain the insight of the proposed system model. The results reveal that wireless backhaul reliability influences the proposed system performance dramatically, more specifically, in our scenario the system performance can improve nearly 10^2 times when backhaul reliability increases from 0.10 to 0.90. Therefore, this factor should be taken into consideration when investigating heterogeneous cognitive vehicular networks. The results also reveal that adding more mobile secondary transmitters results in a significant performance improvement.

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