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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network to the primary user. The secondary network can use the spectrum if the interference from the secondary network to the primary user is below a maximum tolerable interference power (denoted as $P_{\text{max}}$).

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 $\{T_1, T_2, \ldots, T_K\}$, 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 $k$th 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],

$$F_x(\gamma) = 1 - 2\sqrt{\frac{\gamma_0}{\gamma_0^{2}}} \left(2\sqrt{\frac{\gamma_0}{\gamma_0^{2}}} \right), \quad (1)$$

$$f_x(\gamma) = 2\gamma\sqrt{\frac{\gamma_0}{\gamma_0^{2}}} \left(2\sqrt{\frac{\gamma_0}{\gamma_0^{2}}} \right). \quad (2)$$

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

$$y_D = \sqrt{P_T} d_{TD}^\beta h_{TD} x_k + n, \quad (3)$$

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 $\sigma^2$, i.e., $n \sim CN(0, \sigma^2)$. $d_{TD}$ is the distance from $T_k$ to $SU$. $\beta$ 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 $\pi_k$, and the success probability of the process is denoted as $s_k$ where $P(\{\pi_k = 1\}) = s_k$ and the failure probability of the process is denoted as $P(\{\pi_k = 0\}) = 1 - s_k$. [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

$$P_T = \frac{I_p d_{TP}^\beta}{|h_{TP}|^{2}}. \quad (4)$$

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 $\beta$ indicates the path loss exponent.

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

$$\gamma_T = \frac{\gamma I_p d_{TP}^\beta |h_{TD}|^2}{d_{TD}^\beta |h_{TP}|^{2}}, \quad (5)$$

where $\gamma = \frac{I_p}{\beta}$.

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

$$\gamma_{TD} = \frac{\gamma I_p d_{TP}^\beta |h_{TD}|^2 s_k}{d_{TD}^\beta |h_{TP}|^{2}}. \quad (6)$$

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

$$k^* = \max_{k=1,...,K} \arg \left(\gamma_{TD} \right). \quad (7)$$
Hence, the overall SNR with the selected $T_k$ of the proposed system model at $SU$ is rewritten as

$$\gamma_{TD}^{*} = \frac{\gamma_{I}^{d_{TD}} h_{TD}^{2} \|x_k\|^2}{d_{TD}^{2} h_{TD}^{2} \|x\|^2},$$

(8)

where $|h_{TD}|^2$ denotes the channel coefficient from the selected $T_k$ to $SU$ and $|h_{TD}|^2$ 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

$$F_{\gamma_{TD}}(x) = P\{\gamma_{TD} < x\} = \frac{1}{\pi} \left( \frac{1}{\pi} - \frac{1}{\pi} \right)$$

(9)

where $p = \frac{d_{TD}^{2} y_{D}^{2}}{d_{TD}^{2} y_{D}^{2}}$.

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]

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

(10)

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

$$F_{\gamma_{TD}}(x) = \int_{0}^{x} f_{\gamma_{TD}}(t) dt = 1 - s - \frac{spx^2 - 2x\gamma_I}{3(\gamma_I - px)^2} + \frac{2spx^3 - 3x\gamma_I^2}{3(\gamma_I - px)^3} \gamma_I$$

(11)

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

$$F_{\gamma_{TD}^{*}}(x) = F_{\gamma_{TD}}(x)^K.$$

The expression of CDF is derived as

$$F_{\gamma_{TD}^{*}}(x) = \left\{ \begin{array}{ll}
(1-s)^K, & \frac{x}{\gamma_I} p = 1. \\
\Theta, & \frac{x}{\gamma_I} p \neq 1.
\end{array} \right.$$
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 $\gamma_1 = 30 \, dB$, 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 $\gamma_1 = 10 \, dB$ and $\gamma_1 = 30 \, dB$, the system has a better performance when $\gamma_1 = 30 \, dB$. 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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