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On the successful transmission probability of cooperative cognitive radio ad hoc networks

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ABSTRACT

We study the successful transmission probability of cognitive radio ad hoc networks in which secondary users assist primary users on transmitting packets. We propose a half-slotted ALOHA multiple access control protocol. Primary transmitters sacrifice second half slot for the reliability improved by the cooperative transmission of secondary users. We derive the closed-form expression of successful transmission probability for both primary and secondary network in the first-half slot. In the second half, we obtain the bounds of successful transmission probability for primary network and the closed-form expression of successful transmission probability for secondary network. Numerical results show that the successful transmission probability of both networks could achieve a maximum by optimizing the intensity of secondary users in the whole time slot.

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1. Introduction

Cognitive radio ad hoc networks (CRAHNs) is a network mode which combines cognitive radio and ad hoc technology. In recent years, with growing spectrum shortage and rapid development of wireless mobile communications, CRAHNs have attracted more and more concerns. How to improve the performance of CRAHNs has become a hot issue. Currently, research on the performance of CRAHNs focuses on network capacity which mainly includes two fields.

One field is the scaling law of CRAHNs. In 2000, Gupta and Kumar [1] provided the transport capacity of ad hoc networks based on signal to interference plus noise ratio (SINR) model. As λ being the density of transmitters in the network, they certified that the transport capacity scales as $\Theta\left(\sqrt{\lambda}\right)$. In [2], the scaling law of transport capacity were given about nodes density. In [3], the scaling law of transport capacity were analyzed about the transmission character of channel. With the development of CR technology, the researchers began to extend the achievement of ad hoc network to CRAHNs. In [4], a tradeoff was testified to exist between throughput and delay in an overlaid wireless network. In [5], the throughput of coexist two networks could achieve the same scaling law in a two-tier network which is same to that of single network. The scaling law were further studied in [6] in a two-tier network with cooperative transmission. They proved that throughput and delay had the same scaling law in the two networks when secondary nodes assisted primary nodes to send packets.

The other field focuses on the closed-form expression of network capacity of CRAHNs. In [7], Weber et al. analyzed the transmission capacity of single-hop network based on the theory of stochastic geometry [8]. In [9], Baccelli et al. proposed the spatial density of progress to measure the capacity of multi-hop network. These results were later spread to analyze the network capacity of CRAHNs. In [10], the transmission capacity was derived when an ad hoc network coexists with a cellular network. And the transmission capacity could be improved by changing some important parameters such as link diversity gain and link distance etc.. In [11], the throughput of CRAHNs was given to propose a distributed spectrum allocation policy. In [12], the upper bound of broadcast transmission capacity was studied in homogeneous network. In [13], transport capacity was redefined for CRAHNs as the product of transmission capacity times hop distance.

Considering all studies above, the closed-form expression of network capacity could be obtained by employing stochastic geometry. And this provides a method to study the relationship between the capacity and network parameters. We also find that the successful probability of one hop transmission is an important value whether for transmission capacity and spatial density of progress. And there is little research of the network performance for CRAHNs with cooperative transmission scene despite its wide application prospects.

In this paper, we analyze the successful transmission probability of CRAHNs in which secondary users cooperate primary users

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to transmit packets. Half-slotted ALOHA MAC protocol are adopted by both primary and secondary networks. In the first half slot, the closed-from expression of successful transmission probability is derived for primary and secondary transmitters whose distribution follow Poisson point process. In the second half slot, the bounds of successful transmission probability are obtained for cooperative transmission. And the successful transmission probability of secondary users is provided when employing nearest receiver routing strategy.

The paper is organized as follows. Section 2 gives the system model and the definition of some symbols. Section 3 analyzes the successful transmission probability of primary and secondary network in the first and second half slot, respectively. Section 4 presents the numerical results with some observations of them. Finally, conclusions are given in Section 5.

2. Network model

Consider the scenario where a network of primary users and a network of secondary users coexist on the same two-dimensional plane. Secondary users employ underlay spectrum sharing method to access the licensed channel, that is to say, transmit their packets while keeping quality of service (QoS) of primary network. In the following, we will define the primary and secondary network models, respectively.

2.1. Primary network

Assume that primary transmitters (PT) are distributed according to a Poisson point process (PPP) [8] with intensity λ_P, Φ_{1T}. Each primary receiver (PR) is paired with a primary transmitter with R_P distant away. Primary receivers are accordingly distributed as a PPP with intensity λ_P, Φ_{1R}.

2.2. Secondary network

Consider the locations of secondary users (SU) follow a PPP with intensity λ_S, Φ_2. All secondary users are split into two categories based on the locations of them. Those locate in the coverage range of primary transmitters are defined as the cooperative SU (CSU). The Others are ordinary SU (OSU). The coverage range of PT is defined as the circle of radius R_P centered in PT. According to the thinning theory [8], CSU are distributed as a PPP with intensity $\lambda_S p_c$, Φ_{2C}. And OSU are distributed as a PPP with intensity $\lambda_S(1-p_c)$, Φ_{2O}. p_c is the probability of a secondary user being a CSU, and

$$\begin{aligned} p_c &= P(\text{A secondary user to be one of a CSU}) \\ &= 1 - P(\text{No PT lie in the coverage area of SU}) \\ &= 1 - e^{-\lambda_P \pi R_P^2}. \end{aligned} \tag{1}$$

R_S is the maximum of transmission distance of SU.

2.3. Half-slotted ALOHA protocol

Time is divided into slot and all users are synchronized to one clock. In one slot, primary users sacrifice half slot transmission for the reliability which is improved by SU' cooperative transmission. Or to be more precise, we further divide one slot into two parts: the first half slot and the second half slot.

In the first half slot, PT send their packets, while CSU keeping silent to receive the packets of PT. OSU transmit with a probability of p. Therefore, secondary transmitters formulate a PPP with intensity $\lambda_S p(1-p_c)$, Φ_{2T}. Secondary receivers formulate another PPP with intensity $\lambda_S(1-p)(1-p_c)$, Φ_{2R}.

In the second half slot, CSU send the packets received from PT with a probability p_0 while OSU transmitting. Thus the transmitters of CSU are distributed as a PPP Φ'_{2T} with intensity $\lambda_S p_0$. p_0 is related to the successful transmission probability of PT in the first half slot and will be given in detail in Section 3.

2.4. SIR based successful transmission

In this paper, we focus on the interference-limited case and the ambient noise is ignored. The wireless channel undergoes both large scale path-loss and small scale Rayleigh fading. Power gain of the channel in both networks is given by

$$G(r) = hr^{-\alpha}, \tag{2}$$

where r is the link distance.

- Considering a typical primary receiver y on the origin, its transmitter s can successfully send the packets to it if and only if

$$\text{SIR}_y = \frac{\rho_1 h R_P^{-\alpha}}{I} \geqslant \beta, \tag{3}$$

- For a certain secondary receiver z on the origin, its transmitter t can successfully send the packets to it if and only if

$$\text{SIR}_z = \frac{\rho_2 h d^{-\alpha}}{I} \geqslant \beta, \tag{4}$$

where I is the sum of interference coming from other concurrent transmitters. ρ_1 and ρ_2 are transmission power of primary and secondary network, respectively. d is the transmission distance from t to z.

3. Analysis of the network performance

In this paper, the network performance is characterized by successful transmission probability which is the probability that a receiver could catch the packets successfully from its transmitter in a shot. Since half-slotted ALOHA protocol is adopted, the analysis of the successful transmission probability is divided for the first half slot and the second half slot, respectively.

3.1. Successful transmission probability for the first half slot

- Successful transmission probability of PT. In the first half slot, PT and OSU transmit their packets to their receivers at the same time. Therefore, we obtain the successful transmission probability of the PT as

$$\begin{aligned} \mathbf{P}_{f1} &= \mathbf{P}\big(\text{SIR}_{f1} \geq \beta_1\big) \\ &= \mathbf{Pr}\left(\frac{\rho_1 h R_P^{-\alpha}}{\sum_{x\in\Phi_{1T}} \rho_1 h\|x\|^{-\alpha} + \sum_{y\in\Phi_{2T}} \rho_2 h\|y\|^{-\alpha}} \geq \beta_1\right), \end{aligned} \tag{5}$$

where $\|x\|(\|y\|)$ is the distance between PT (OSU transmitters) and the typical receivers. According to Lemma 1 in [9],

$$\mathbf{P}_{f1} = e^{-\left(\lambda_P + \lambda_S(1-p_c)p(\rho_2/\rho_1)^{2/\alpha}\right)K_\alpha \beta_1^{2/\alpha} R_P^2}, \tag{6}$$

where $K_\alpha = \frac{2\pi^2}{\alpha \sin(2\pi/\alpha)}$.

- Successful transmission probability of the OSU. For OSU transmission, the interference come from PT and other OSU transmitting the packets at that time. Hence the successful transmission probability of the OSU is

$$\begin{aligned} \mathbf{P}_{f2} &= \mathbf{P}\big(\text{SIR}_{f2} \geq \beta_2\big) \\ &= \mathbf{P}\left(\frac{\rho_2 h r^{-\alpha}}{\sum_{x'\in\Phi_{1T}} \rho_1 h\|x'\|^{-\alpha} + \sum_{y'\in\Phi_{2T}} \rho_2 h\|y'\|^{-\alpha}} \geq \beta_2\right) \\ &= e^{-\left(\lambda_P(\rho_1/\rho_2)^{2/\alpha} + \lambda_S(1-p_c)p\right)K_\alpha \beta_2^{2/\alpha} r^2}, \end{aligned} \tag{7}$$

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