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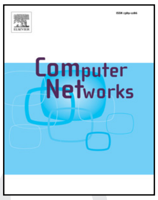

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Review article

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Per-user throughput analysis for secondary users in multi-hop cognitive radio networks

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A B S T R A C T

Cognitive radio networks (CRNs) allow secondary users (SUs) to opportunistically transmit over the channel to enhance the utilization of spectrum authorized to primary users (PUs). This paper investigates the throughput of SUs in ad hoc multi-hop CRNs. Specifically, we conduct a comprehensive analysis on per-user throughput for SUs, considering multiple factors that influence the SU transmissions, e.g., PU activity, spectrum sensing errors, media access for SUs and hop count. To model these factors, we develop an impairment process, which describes the service unused by SUs. For non-asymptotic analysis, numerical results reveal that the throughput decreases with the increase of average arrival rate of PU, sensing error probability, number of SUs and hop count. For asymptotic analysis, our theoretical results show that the throughput is dominantly impacted by the number of SUs, while independent with the hop count. Our study provides novel insights for the design of multi-hop cognitive radio networks.

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1. Introduction

With the advent of cognitive radio technologies [1], the underutilized spectrum [2] can be exploited by secondary users without interfering with primary users. In CRNs, PUs have priority to use the spectrum, and SUs are allowed to transmit over the spectrum holes left unused by PUs. A CRN usually consists of at least one PU and multiple SUs. When a SU attempts to transmit packets to destination, a multiple amount of intermediate SUs may act as relays for the transmission. As a result, the transmission is accomplished in a multi-hop manner. This multi-hop transmission occurs typically in cognitive wireless networks, such as cognitive radio ad hoc networks [3] and cognitive wireless mesh networks [4]. Since the SUs use the spectrum opportunistically, and the multi-hop transmission of SUs is influenced by several factors, it is crucial to provide QoS guarantees for SUs.

In the literature, a variety of researches have been conducted on the analysis of QoS performance for single-hop CRNs, such as delay [5–8] and throughput [5,8,9]. However, it is still a big challenge to investigate the performance of multi-hop CRNs, due to the fact that the multi-hop transmission of SUs is influenced by many factors, including PU activity, spectrum sensing errors, media access and hop count. Recently, studies on the end-to-end delay and throughput of multihop CRNs have attracted growing interest [10–14]. In [10], a cross-layer MAC is designed to get a near-optimal throughput. In [11], a hybrid MAC is proposed to guarantee the throughput. In [12], an end-to-end delay is derived considering the media access in an ad hoc CRNs. In [13], optimal throughput and average end-to-end delay is obtained under a scheduling policy for multi-hop CRNs. In [14], a performance analysis model, concentrating on PU and SU activities, is constructed. However, to the best

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of our knowledge, there is no prior work considering all the aforementioned factors in the performance analysis of multi-hop CRNs. These factors jointly affect the transmissions in multi-hop CRNs and make the multi-hop analysis non-trivial. In view of this, it is critically important to carry out a study providing a comprehensive investigation into the impact of these factors on performance.

In this paper, we aim at analyzing the per-user throughput of SUs, which is different from the throughput analysis in previous works. Since the per-user throughput captures the stochastic nature of arrivals of SUs and service provided to SUs. Moreover, the per-user throughput accounts for the impact on the transmission of SUs caused by PU activity, spectrum sensing errors, media access and hop count. Furthermore, the network throughput can be obtained by a summation of per-user throughput. It is notable that we derive the upper and lower bounds rather than average ones on the per-user throughput. This is due to the fact that the average throughput can only suggest the steady-state network performance. In practical, however, the packet forwarding is dynamic in multi-hop CRNs. In view of this, the upper and lower bounds can capture the performance more properly.

We employ stochastic network calculus (SNC) to conduct the throughput analysis. The SNC is a newly developed theory for performance analysis, where arrival curve and service curve are defined to bound the cumulative arrivals and service [15]. Based on these two curves, performance bounds, including backlog and delay bounds [15] and throughput bound [16,17], can be obtained, which means that the performance metrics can violate the bounds with a small probability. By employing the SNC, an attempt has been devoted to the delay and throughput analysis of single-hop CRNs with imperfect spectrum sensing in [18,19]. The most attractive feature of SNC is that an end-to-end service of a multi-hop path with concatenated servers can be derived by the min–plus convolution of each server's service curve. It is well known that the difficulty of multi-hop performance analysis is mainly caused by the correlated transmissions of neighboring links. The min–plus convolution can lead to a clean solution for this problem.

In multi-hop CRNs, packets from a SU traverse a sequence of SUs, which act as relays, until the packets are successfully received at the destination. Consequently, the per-user throughput can be viewed as the output rate of the destination. The point of departure of our efforts is the end-to-end service provisioned to the packet flow during the multi-hop transmission. However, the transmission is influenced by several factors, namely, PU activity, spectrum sensing errors, media access and hop count. PU activity determines the transmission opportunities provided to SUs. Spectrum sensing errors ruin the transmission for both PU and SUs. Media access scheme allocates transmission opportunities among SUs. Hop count represents the distance between source and destination. These factors influence the transmission in different ways, therefore, it is crucial to construct a model considering all these factors that jointly influence the transmission. From the perspective of SUs, various impact on the transmission ultimately results in a certain amount of service which cannot be utilized by SUs. Consequently, we introduce an impairment process to model the wasted service for a single-hop transmission, which accounts for all the factors as a whole. Based on the impairment process, service provided to SUs in each hop can be constructed, by which we then derive the end-to-end service using the min–plus convolution. Combined with the arrival process of packet flow, we can deduce the departure process using SNC. Finally, the per-user throughput bounds are obtained.

The main contributions are as follows:

- We present a per-user throughput analysis for SUs by considering several factors that influence the multi-hop transmission of SUs, including PU activity, spectrum sensing errors, media access and hop count.
- By introducing the impairment process to model the factors that influence the transmission, we derive the non-asymptotic upper and lower bounds of the throughput, which reveals that the throughput decreases with the increase of average arrival rate of PU, sensing error probability, number of SUs and hop count.
- Moreover, the asymptotic throughput bounds are obtained, which shows that the throughput is dominantly influenced by the number of SUs, while independent with the hop count.

The rest of this paper is organized as follows. In Section 2, we describe the multi-hop CRNs in details. In Section 3, a mathematical preliminary is presented. In Section 4, we first proclaim the arrival process for SUs, and then introduce the impairment process, after which the service process for SUs is obtained. In Section 5, we derive the upper bound and lower bound of the per-user throughput for SUs. In Section 6, a discussion is made on the numerical results. Lastly, we draw the conclusion in Section 7.

2. Network model

We consider an overlay CRN consisted of a primary network and a secondary network, as depicted in Fig. 1. The primary network provides a channel licensed to the primary source-destination pair. There are multiple SUs uniformly distributed in the secondary network. In order not to interfere with PU's transmission, the overlay CRN allows SUs to utilize the spectrum when PU is idle. The multi-hop CRN is assumed to be time slotted with slot size fixed to the duration of a packet transmission, and packet size is assumed to be identical for both PU and SUs. Due to the inherently hierarchical nature, SUs can only transmit over the channel when PU is idle. On the other hand, if packets from PU arrive within a time slot which is occupied by SUs, the packets will be transmitted in the next time slot.

For the primary network, PU transmits over the channel whenever packets arrive at the queue due to its priority to the channel, and only when PU is idle can SUs transmit. Therefore, the channel occupancy by PU determines transmission opportunities for SUs. To describe the channel occupancy, we assume that packet arrivals of PU follow a Poisson process, which is characterized by average arrival rate. Consequently, during the period of inter-arrivals of

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