Computer Networks 106 (2016) 122–133

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Review article

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

Jun Zheng[a,b], Peng Yang[a], Jingjing Luo[a], Qiuming Liu[a], Li Yu[a,*]

[a] School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan 430074, China

[b] School of Science, Zhejiang A & F University, Hangzhou 310013, China

ARTICLE INFO

Article history:
Received 8 June 2015
Revised 8 February 2016
Accepted 15 February 2016
Available online 10 March 2016

Keywords:
Cognitive radio
Multi-hop wireless networks
Throughput bound

ABSTRACT

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.

1. Introduction

With the advent of cognitive radio technologies [1], the under-utilized 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 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

* Corresponding author. Tel.: +86 13871235115.
E-mail addresses: junzheng@hust.edu.cn (J. Zheng), yangpeng@hust.edu.cn (P. Yang), luojingjing@hust.edu.cn (J. Luo), liuqiuming@hust.edu.cn (Q. Liu), hustlyu@hust.edu.cn (L. Yu).

http://dx.doi.org/10.1016/j.comnet.2016.02.015
1389-1286/

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 PU, SUs transmit over the channel. Moreover, a smaller average arrival rate implies longer inter-arrival time resulting in more transmission opportunities for SUs, while a larger arrival rate means less opportunities.

In the secondary network, we adopt a homogeneous network, i.e., SUs have identical behavior. Packets initiated from a SU, identified as source-SU, are transmitted to a destination SU in a hop-by-hop manner, where the packets traverse through a sequence of intermediate SUs, denoted as relay-SUs, see Fig. 2. Both source-SU and relay-SUs are named as transmit-SUs. Since all SUs share the same spectrum, we define a contention set based on the following protocol model whose prototype is proposed in [20].

Protocol model: Let X_i and X_j be the position of i-th and j-th SU, and let $|X_i - X_j|$ be the distance between them. Given that the transmission range is identical for all SUs, denoted as r, when SU X_i transmits to X_j, the transmission is successfully received by X_j if

$$|X_i - X_j| \leq r.$$

According to the protocol model, we define the following contention set

Contention set: Given a transmit-SU X_i, there exists an amount of SUs locating within the transmission range of X_i. These SUs have packets to transmit over the channel, consequently, they share the spectrum with transmit-SU under a certain media access scheme. These SUs form a set named as contention set.

In each hop, the transmit-SU carries out transmission following two phases, i.e., spectrum sensing and spectrum contention. For the first phase of spectrum sensing, the transit-SU senses the state of channel cooperatively with other SUs. If channel is sensed to be idle, the transmit-SU comes into the second phase of spectrum contention. The transmit-SU competes with SUs belonging to contention set to access to the channel. After a successful contention, packets are transmitted to a relay-SU in one hop distance. The multi-hop transmission is accomplished as long as the packets are received at the destination. During the transmission, cooperative spectrum sensing is employed to guarantee the spectrum sensing which is suited to the distributed secondary network. In addition, since the SUs in contention set attempt to transmit over the channel, a media access scheme is required to share the spectrum among SUs. To fit for the decentralized secondary network, we adopt the CSMA regime to provide fair resource allocation for SUs.

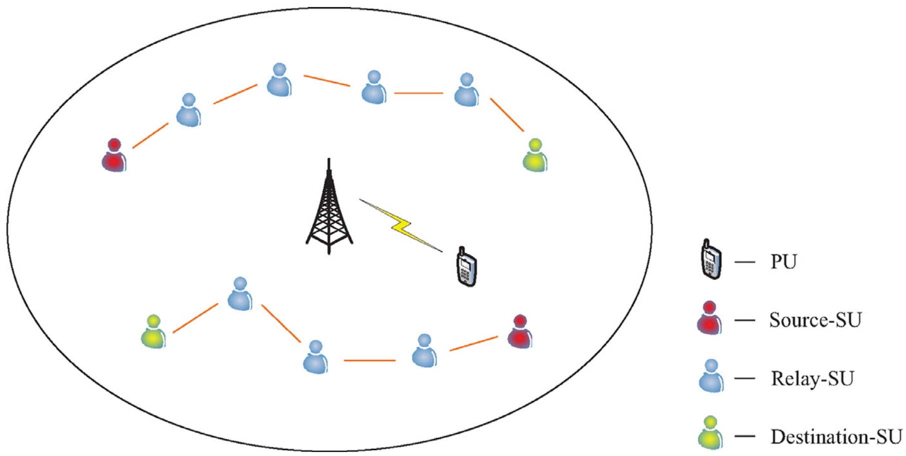


Fig. 1. The cognitive radio network comprises single PU and multiple SUs. SUs form a cognitive radio ad hoc network, each SU transmits packets to destination in a multi-hop way.

Further, we present some notations for our network model here. The channel provides a constant service rate C, PU and SUs have fixed packet length L, consequently, the time slot δ can be expressed as $\delta = \frac{L}{C}$. For the multi-hop transmission, let H be the total hop count. In each hop, there are N_h $(h = 1, 2, \dots, H)$ SUs competing the channel for transmission opportunities.

3. Preliminary

In this section, we introduce necessary notations and results for the stochastic network calculus.

Consider a time-slotted system, the input and output of system are described by arrival process $A(t)$ and departure process $D(t)$, and system provides a service, denoted as $S(t)$, to the input. $A(t)$, $D(t)$ and $S(t)$ are cumulative arrivals, departures and service during period of $(0, t]$, therefore, they are non-negative and nondecreasing for all $t > 0$, and $A(0) = D(0) = S(0) = 0$. Moreover, for a time interval $(s, t]$, they satisfy $A(s,t) = A(t) - A(s)$, $D(s,t) = D(t) - D(s)$ and $S(s,t) = S(t) - S(s)$. Due to the causality of a system, the departures can be related to the arrivals by the service process as

$$D(t) = A \otimes S(t) \tag{1}$$

where $\otimes$ is the min–plus convolution operator. The convolution of two real-valued functions $f(s, t)$ and $g(s, t)$ for a period of $(s, t]$ is defined as

$$f \otimes g(s,t) = \inf_{s \le u \le t} \{f(s,u) + g(u,t)\}. \tag{2}$$

Based on the min–plus convolution, a system consisting of concatenated servers can be transformed into an equivalent single server system, which is the most prominent feature of SNC for performance analysis. This concatenation property is claimed as [21].

Lemma 1. *Consider packet arrivals passing through a system with concatenated N servers, if each server n* $(n = 1, 2, \dots, N)$ *provides a service process* $S_n(t)$ *to its input, then the arrivals is provisioned with an equivalent end-to-end service process as follows*

$$S(t) = S_1 \otimes S_2 \otimes \cdots \otimes S_N(t). \tag{3}$$

Since $D(t)$ is related with arrival process $A(t)$ and service process $S(t)$ in (1), the departure process captures the stochastic nature of arrivals and service. Based on departure process, the non-asymptotic upper bound and lower bound of throughput can be defined as follows.

Definition 1 ([16]). Consider a system with an arrival process $A(t)$, the system provides a service $S(t)$ to the arrivals, for some fixed violation probability ε, the non-asymptotic upper bound of throughput $\lambda_{U,t}$ satisfies

$$P\{D(t) \ge \lambda_{U,t} t\} \le \varepsilon, \qquad \text{for all } t \ge 0 \tag{4}$$

and the non-asymptotic lower bound of throughput $\lambda_{L,t}$ satisfies

$$P\{D(t) \le \lambda_{L,t} t\} \le \varepsilon, \qquad \text{for all } t \ge 0 \tag{5}$$

where the value of violation probability ε is close to zero.

The definition provides a probabilistic upper bound on the cumulative departures during period $(0, t]$ in that the departures $D(t)$

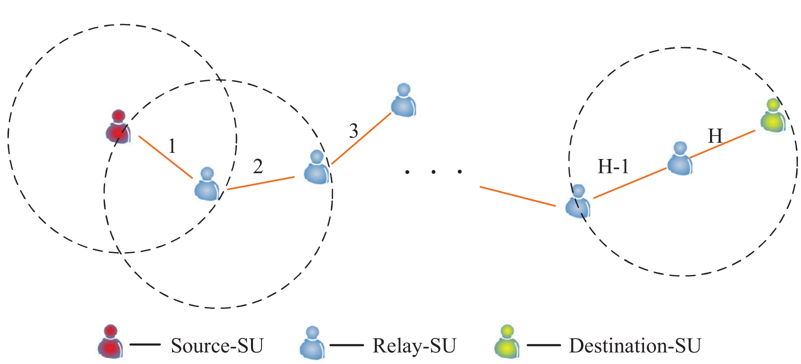


Fig. 2. The dotted circle represents the transmission range of source-SU or relay-SUs in each hop. For the first hop, the source-SU competes with the SUs belonging to contention set, after a successful contention, the packets are sent to the relay-SU. The relay-SU transmits packets to the next one, until the packets are received at the destination-SU after H hops.

can violate $\lambda_{U,t}t$ with a small probability of ε like 10^{-3}. In other words, the departures till time t are smaller than $\lambda_{U,t}t$ with high probability, which implies the upper bound of throughput $\lambda_{U,t}$. Similarly, $\lambda_{L,t}$ can be viewed as the lower bound of throughput.

The two non-asymptotic throughput bounds $\lambda_{U,t}$ and $\lambda_{L,t}$ can also cover the asymptotic results when we let subscript t go to infinity, i.e., $\lambda_U = \lim_{t\to\infty} \lambda_{U,t}$ and $\lambda_L = \lim_{t\to\infty} \lambda_{L,t}$.

To facilitate the derivation, the Chernoff bound is employed to obtain performance bounds. For a random process $X(t)$, the Chernoff bound can be expressed as

$$P\{X(t) \geq x\} \leq e^{-\theta x} E[e^{\theta X(t)}]$$

where θ is a free parameter, and can be used to optimize the performance bounds for $\theta > 0$. As can be seen from the expression, moment generation functions (MGFs) are indispensable to obtain the bounds [22]. The MGF of a random process $X(t)$ is defined as

$$M_{X(t)}(\theta) = E[e^{\theta X(t)}]. \tag{6}$$

where θ is a free parameter as that in the Chernoff bound. In addition, we can have the Laplace transform for a random process $X(t)$ as

$$\overline{M}_{X(t)}(\theta) = E[e^{-\theta X(t)}]$$

where θ is also a free parameter. These two transformations are crucial for the latter throughput analysis.

4. Analytical model

In this section, the analytical model is presented for the multi-hop transmission of SUs. Specifically, we first describe the arrival process for SUs. Then we introduce an impairment process for the transmission in each hop, based on which the end-to-end service process is constructed.

4.1. Arrival process

Since we focus on the throughput of SUs, the PU arrivals can be ignored and we concentrate on the arrivals of SUs. Due to the assumption of homogeneous secondary network in Section 2, we can suppose the arrival process be identical for transmit-SUs and SUs belonging to contention set, which is denoted as $A^{SU}(t)$. And we further assume that the arrival process is saturated as

$$A^{SU}(t) = \begin{cases} 0, & t = 0, \\ \infty, & t > 0. \end{cases} \tag{7}$$

This saturation condition confirms to the definition of contention set that SUs always have packets stored in queue, and packets can be transmitted immediately once the channel is available to SUs.

The saturated condition for SUs lies in that it enables us to focus on how different impacting factors jointly influence the end-to-end throughput of SUs without being restricted by specific packet arrivals. Accordingly, the results obtained give insight into the multi-hop CRNs.

4.2. Service process of SU

In this section, we conduct the service process of SUs, which is critical to derive the per-user throughput bounds for SUs.

According to the network model in Section 2, the transmission of SUs in each hop follows two phases. The SUs first cooperatively sense the channel to identify the state of channel and then, if the channel is sensed to be idle, the transmit-SU competes for the channel with other SUs belonging to contention set. As a result, the transmit-SU is capable to transmit with a certain probability. During the process, we can observe that a number of issues have impact on the transmission including:

- PU activity determines the period of idle state of channel which provides transmission opportunities to SUs.
- Sensing errors interfere with the transmission of both PU and SUs.
- Media access determines whether time slots can be assigned to SUs for transmission.
- Hop count implies the distance between source and destination.

We next focus on how these issues influence the multi-hop transmission of SUs. To this end, an impairment process $I(s, t)$ is introduced to describe the wasted service that cannot be utilized by SUs, which is defined as follows.

Definition 2. In a time-slotted system, the impairment process $I(s, t)$ for a server with service rate C is a cumulative increment process during period of $(s, t]$, denoted as $I(s,t) = \sum_{i=s}^{t-1} I(i, i+1)$, where

$$I(i, i+1) = \begin{cases} C\delta, & \text{if service is impaired in the} \\ & \quad \text{time slot } (i, i+1], \\ 0, & \text{otherwise}. \end{cases}$$

where s and t represent the index of time slot.

Starting with this definition, we now construct the service process of multi-hop transmission for SUs. We first model the impairment process for a single-hop transmission, denoted with $I_h(s, t)$ $(h = 1, 2, \ldots, H)$, where h represents the hth hop. Based on the impairment process, service process for the hth hop, denoted as $S_h(s, t)$, can be derived. Finally, the end-to-end service process $S(s, t)$ is constructed for the multi-hop transmission.

To model the impairment process for each hop, we take into account the following three aspects, namely PU activity, spectrum sensing errors, and media access scheme.

4.2.1. PU activity

Due to the hierarchical architecture in the overlay CRNs, SUs transmit over the channel only when PU is idle. Therefore, PU activity determines that whether channel can be utilized by SUs or not. If the queue of PU is empty, channel comes into the state of idle. Otherwise, channel is in the state of busy. The stochastic nature of packet arrivals of PU results in a random characteristic of channel state. To describe PU activity, a Poisson process has been employed in Section 2. Let α^{PU} be the average rate for the arrivals. Then, we can have the following probability that channel is idle within a time slot

$$p_{Idle} = e^{-\alpha^{PU}\delta} \tag{8}$$

where δ is slot time. This expression means that, for a time slot, channel is available to SUs with a certain probability. As a complementary event, the probability of busy state during a time slot, denoted with p_{Busy}, can be computed as $p_{Busy} = 1 - p_{Idle}$. This represents a block probability that SUs cannot access to the channel for a time slot.

In addition, we assume that packets of PU arrived within a slot can be transmitted immediately if the channel is idle. Otherwise, the packets will be served in the next slot.

4.2.2. Spectrum sensing errors

SUs sense the channel state persistently to identify a vacant period for transmission. However, sensing errors are inevitable which degrade the performance of SUs. The sensing errors can be categorized into mis-detection (MD) and false alarm (FA) [23]. Mis-detection means that the channel is occupied by PU but the sensing result says it is available to SUs. As a result, SUs transmit over the channel leading to a collision between PU and SUs. Whereas, false alarm occurs in the opposite way, when the spectrum is idle but SUs believe the spectrum is being used by PU, which will

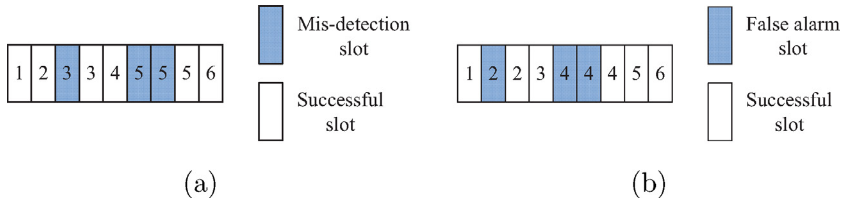


Fig. 3. Spectrum sensing errors interfere with transmission for both PU and SUs, which results in a waste of service for SUs. (a): Mis-detection errors result in retransmission for PU. The 3rd packet is retransmitted one time, and the 5th packet is for twice. (b): False alarm errors lead to a waste of transmission opportunities for SUs. The 2nd packet wastes one slot, and the 4th packet wastes two.

waste transmission opportunities for SUs. Both MD and FA can be viewed as impairment to the service of SUs.

To improve the performance of spectrum sensing, cooperative sensing is proposed to exploit the spatial diversity of spatially located SUs [24]. The cooperative spectrum sensing is carried out by three steps. First, cooperating SUs sense the channel state independently. Then, each SU reports their results to fusion center. The fusion center may be a CR base station for centralized cooperative sensing, or any sensing SU for distributed cooperative sensing. Finally, the fusion center determines the channel state according to the reports from SUs by using a certain fusion scheme. Though cooperative sensing enhances the sensing performance, it is influenced by several factors which mainly includes sensing techniques, cooperative models, data fusion and user selection etc. Therefore, the probability density function (PDF) of sensing errors is related to these factors. However, from the perspective of our studies, we concentrate on the impact of sensing errors to the multi-hop transmission, specifically, we focus on that how the probability of sensing errors influences the throughput. To this end, we next investigate how mis-detection and false alarm impact the transmission.

As illustrated in Fig. 3, MD and FA errors occur in colored slots, while the blank slots represent successful transmissions. Since the slot time is assumed to be fixed to the duration of one packet transmission, only one time slot is needed for a successful transmission if there is no error happening within the slot. However, if sensing errors occur, additional time slots are required for SUs. (1) MD errors lead to collisions of PU transmission with SUs, therefore additional time slots are required for retransmission of PU. Refer to Fig. 3a, the 3rd packet needs one more time slot for retransmission, while the 5th packet needs two extra slots to account for two consecutive MD errors. These additional time slots result in that SUs have to wait more time slots for transmission opportunities due to the retransmission of PU. (2) FA errors lead to a waste of transmission opportunities for SUs, such as the 2nd and 4th packets in Fig. 3b. Specifically, consecutive FA errors determine a series of wasted time slots, the observation is that the 4th packet requires two more time slots to accomplish the transmission.

As can be seen, MD errors and FA errors have the same impact on the transmission of SUs in that each error ruins one time slot for SUs. Therefore, we can take the two kinds of errors as a whole, whose probability is defined as

$$p_e = P(\text{Sensing error happens in a time slot.}). \tag{9}$$

This probability captures the stochastic nature of sensing errors. We note that sensing errors happen independently in each time slot.

4.2.3. Media access scheme

In each hop, the transmit-SU shares spectrum with SUs belonging to the contention set, we denote the total number of SUs as N_h for the hth hop. The CSMA scheme is introduced for spectrum sharing among these SUs, which is suitable for the non-infrastructure based network. Since the CRN is assumed to be homogeneous, SUs have identical transmission range. In addition, considering the uniform distribution of SUs over the network, the number of SUs is the identical for each hop, i.e.

$$N_h = N \quad \text{for} \quad h = 1, 2, \ldots, H. \tag{10}$$

The CSMA MAC scheme adopts the IEEE802.11 DCF which is briefly described as follows. Each SU has a total B backoff stages. When the channel is sensed to be idle, SU initializes the backoff at stage 0 and chooses a random number, named as back-off counter, in the range [0, CW], where CW is the contention window size and set to W_0 for stage 0. SU counts down at each slot if channel is idle, otherwise, SU freezes its counter. If the channel is sensed to be idle again, SU resumes the counter. When the counter reaches to zero, SU transmits packet if the channel is idle, or doubles the contention window for next backoff stage if the channel is busy again or the packet transmission fails. In special, SU discards current packet if the backoff stage exceeds the maximum B, and starts a new packet transmission.

Therefore, the probability of one successful contention in a slot is related to PU activity, number of SUs, contention window size and back-off stage. Referring to [25,26], we can get that one SU succeeds in accessing to channel with a probability p_{acc} as

$$p_{acc} = \frac{\tau(1-\tau)^{N-1}}{1-(1-\tau)^N}, \tag{11}$$

where τ is the probability that one SU transmits in a randomly chosen backoff slot, and can be obtained by numerical computation [25].

We have addressed the three factors that contribute to the impairment process for SUs in each hop. We can observe that the transmit-SU, in each hop, is capable to access successfully to the channel if and only if the idle state of channel is correctly identified and the SU successfully accesses to the channel. Considering PU activity, spectrum sensing errors and media access, the probability of a successful transmission for a SU in each hop, denoted as p_{TR}, can be expressed as a joint probability

$$\begin{aligned} p_{TR} &= p_{Idle} \cdot (1-p_e) \cdot p_{acc} \\ &= e^{-\alpha^{PU}\delta} \cdot (1-p_e) \cdot \frac{\tau(1-\tau)^{N-1}}{1-(1-\tau)^N}. \end{aligned} \tag{12}$$

This probability accounts for a transmission opportunity for any SU, which implies that each SU is provisioned with service in a time slot at a certain probability of (12). Further, we can get the distribution of the impairment process $I_h^{SU}(i, i+1)$ within a time slot at the hth hop for SUs as follows

$$\begin{cases} P\left(I_h^{SU}(i, i+1) = C\delta\right) = 1 - p_{TR}, \\ P\left(I_h^{SU}(i, i+1) = 0\right) = p_{TR}. \end{cases} \tag{13}$$

As can be seen, the impairment process in each time slot follows a Bernoulli distribution.

To proceed, we introduce the MGF and Laplace transform of impairment process $I_h(s, t)$, denoted with $M_{I_h^{SU}(s,t)}(\theta)$ and $\overline{M}_{I_h^{SU}(s,t)}(\theta)$ respectively, as follows,

$$M_{I_h^{SU}(s,t)}(\theta) = E[e^{\theta I_h^{SU}(s,t)}] \tag{14}$$

and

$$\overline{M}_{I_h^{SU}(s,t)}(\theta) = E[e^{-\theta I_h^{SU}(s,t)}] \tag{15}$$

where $\theta > 0$ is a variable used to optimize the performance bounds.

According to Definition 2, we can get the MGF of $I_h^{SU}(s,t)$ as

$$M_{I_h^{SU}(s,t)}(\theta) = E\Big[e^{\theta \sum_{i=s}^{t-1} I_h^{SU}(i,i+1)}\Big] = \prod_{i=s}^{t-1} E\Big[e^{\theta I_h^{SU}(i,i+1)}\Big].$$

Since the impairment process can be viewed as a Bernoulli process according to (13), then we can get

$$M_{I_h^{SU}(s,t)}(\theta) = \prod_{i=s}^{t-1}[(1-p_{TR})e^{\theta C\delta} + p_{TR}] = [(1-p_{TR})e^{\theta C\delta} + p_{TR}]^{t-s}. \tag{16}$$

The first equality comes from the MGF of a Bernoulli distribution for each time slot. The second equality is due to the fact that the impairment process in each time slot follows an independent and identical distribution.

Similarly, we can obtain the Laplace transform of the impairment process as

$$\overline{M}_{I_h^{SU}(s,t)}(\theta) = [(1-p_{TR})e^{-\theta C\delta} + p_{TR}]^{t-s}. \tag{17}$$

Since the service process and impairment process are mutually complementary, we can get the service process of single-hop transmission for a SU as

$$S_h^{SU}(s,t) = C(t-s) - I_h^{SU}(s,t) \tag{18}$$

where C is the service rate of the channel.

Having constructed the service process for the hth hop, we can easily extend this single-hop service to the multi-hop service by using the min–plus convolution. According to Lemma 1, the end-to-end service process $S^{SU}(s,\ t)$ for the multi-hop transmission of SUs can be expressed as

$$S^{SU}(s,t) = S_1^{SU} \otimes S_2^{SU} \otimes \cdots \otimes S_H^{SU}(s,t) = \inf_{s\le u_1\le\cdots\le u_{H-1}\le t}\{S_1^{SU}(s,u_1) + \cdots + S_H^{SU}(u_{H-1},t)\}. \tag{19}$$

This concatenation property of min–plus convolution facilitates the performance analysis of multi-hop transmission, which will be demonstrated in the following section where the throughput bounds will be derived.

5. Throughput bounds analysis

In Section 4, we construct the service process of multi-hop transmission for SUs by introducing an impairment process. In this section, the throughput bounds are derived for SUs in the form of both non-asymptotic and asymptotic ones. We first present the throughput bounds in the following theorem, and then give the proof.

Theorem 1. *Consider a CRN with single PU and multiple SUs, where SUs transmit to destination in a multi-hop way as in Fig. 1. Assume that arrivals from PU follow a Poisson process with average arrival rate of α^{PU}, arrivals of SUs are saturated. Then there exist an upper bound and a lower bound of non-asymptotic throughput for each SU. The upper bound is*

$$\lambda_{U,t}^{SU} = C + \frac{1}{\theta}\log[p_{TR} + (1-p_{TR})e^{-\theta C\delta}] - \frac{1}{\theta t}\log\varepsilon \tag{20}$$

and the lower bound is

$$\lambda_{L,t}^{SU} = C - \frac{1}{\theta}\log[p_{TR} + (1-p_{TR})e^{\theta C\delta}] - \frac{1}{\theta t}\log C_{t-1}^{H-1} + \frac{1}{\theta t}\log\varepsilon \tag{21}$$

where C is service rate, δ is slot time, H is hop count, p_{TR} is the probability as in (12), ε is violation probability and θ is free parameter from the MGF and Laplace transform.

Proof. We first present the proof of upper bound. Deriving from the definition of upper bound of throughput in (4), and the departure process in (1), it follows that

$$P\Big(D^{SU}(t) \ge \lambda_{U,t}^{SU}t\Big) = P\Big(\inf_{0\le s\le t}\{A^{SU}(s) + S^{SU}(t-s)\} \ge \lambda_{U,t}^{SU}t\Big).$$

Since the arrival process of SU is assumed to be saturated, i.e., $A^{SU}(0)=0$ and $A^{SU}(t)=\infty$ for $t > 0$, the min–plus convolution of $\inf_{0\le s\le t}\{A^{SU}(s) + S^{SU}(t-s)\}$ will achieve its infimum value when $s=0$. Inserting this infimum yields

$$P\Big(D^{SU}(t) \ge \lambda_{U,t}^{SU}t\Big) = P\Big(S^{PU}(t) \ge \lambda_{U,t}^{SU}t\Big) = P\Big(\inf_{u_0\le\cdots\le u_H}\sum_{h=1}^{H} S_h^{SU}(u_{h-1},u_h) \ge \lambda_{U,t}^{SU}t\Big)$$

where, we use the equivalent end-to-end service process derived in (19), and we let $u_0=0$ and $u_H=t$. Note that the bivariate service $S(s,\ t)$ comes into the univariate function $S(t)$, if we let $s=0$. Substituting the service process of each hop $S_h^{SU}(t)$ in (18), the above expression follows that

$$P\Big(D^{SU}(t) \ge \lambda_{U,t}^{SU}t\Big) = P\Big(Ct + \inf_{u_0\le\cdots\le u_H}\sum_{h=1}^{H} -I_h^{SU}(u_{h-1},u_h) \ge \lambda_{U,t}^{SU}t\Big) = P\Big(\inf_{u_0\le\cdots\le u_H}\sum_{h=1}^{H} -I_h^{SU}(u_{h-1},u_h) \ge (\lambda_{U,t}^{SU} - C)t\Big). \tag{22}$$

To bound the probability, we employ the Chernoff bound in (6), the above equation is then transformed into the following inequation

$$P\Big(D^{SU}(t) \ge \lambda_{U,t}^{SU}t\Big) \le e^{-\theta(\lambda_{U,t}^{SU}-C)t}E[e^{\theta \inf_{u_0\le\cdots\le u_H}\sum_{h=1}^{H} -I_h^{SU}(u_{h-1},u_h)}]. \tag{23}$$

Since the infimum can be viewed as the minimum value of a function, we use a sample path to bound the above infimum of summation. Then, we can have

$$P\Big(D^{SU}(t) \ge \lambda_{U,t}^{SU}t\Big) \le e^{-\theta(\lambda_{U,t}^{SU}-C)t}E[e^{\theta\sum_{h=1}^{H} -I_h^{SU}(u_{h-1},u_h)}] = e^{-\theta(\lambda_{U,t}^{SU}-C)t}\prod_{h=1}^{H}E[e^{-\theta I_h^{SU}(u_{h-1},u_h)}]. \tag{24}$$

The last equation lies in that the impairment process of each hop is independent with each other. We next employ the Laplace transform of the impairment process of $I_h^{SU}(s,t)$ as derived in (17), and consider the independency of each hop, we can get

$$P\Big(D^{SU}(t) \ge \lambda_{U,t}^{SU}t\Big) \le e^{-\theta(\lambda_{U,t}^{SU}-C)t}[p_{TR} + (1-p_{TR})e^{-\theta C\delta}]^t$$

where p_{TR} is the probability of a successful transmission over the channel for each SU, given in (12).

Lastly, let the violation probability ε equal to the right hand side of the above inequation, and with a mathematical manipulation, the upper bound of throughput (20) can be obtained.

As to the lower bound of throughput $\lambda_{L,t}^{SU}$, it can be proved in a similar way. Start with departure process (1) as well as service process (19), and consider the service process of each hop (18), we can easily get the following derivation as that of upper bound

$$P\big(D^{SU}(t) \le \lambda_{L,t}^{SU} t\big)$$
$$= P\left(Ct + \inf_{u_0 \le \cdots \le u_H} \sum_{h=1}^{H} -I_h^{SU}(u_{h-1}, u_h) \le \lambda_{L,t}^{SU} t\right)$$
$$= P\left(\sup_{u_0 \le \cdots \le u_H} \sum_{h=1}^{H} I_h^{SU}(u_{h-1}, u_h) \ge (C - \lambda_{L,t}^{SU})t\right),$$

here, we use again the saturated condition of arrival process $A^{SU}(t)$ to obtain the first equality. The last equality lies in that the infimum and supremum have the relationship of $\sup_x\{f(x)\} = -\inf_x\{-f(x)\}$. By applying the Union bound, we can bound the last term in the above by

$$\sum_{u_0 \le \cdots \le u_H} P\left(\sum_{h=1}^{H} I_h^{SU}(u_{h-1}, u_h) \ge (C - \lambda_{L,t}^{SU})t\right),$$

and using again the Chernoff bound, the above expression can be further bounded by

$$\sum_{u_0 \le \cdots \le u_H} e^{-\theta(C-\lambda_{L,t}^{SU})t} E\left[e^{\theta \sum_{h=1}^{H} I_h^{SU}(u_{h-1}, u_h)}\right].$$

Consider the statistical independency of impairment process, we can get that

$$P\big(D^{SU}(t) \le \lambda_{L,t}^{SU} t\big) \le \sum_{u_0 \le \cdots \le u_H} e^{-\theta(C-\lambda_{L,t}^{SU})t} \prod_{h=1}^{H} E\left[e^{\theta I_h^{SU}(u_{h-1}, u_h)}\right]$$
$$= C_{t-1}^{H-1} e^{-\theta(C-\lambda_{L,t}^{SU})t}\left[p_{TR} + (1-p_{TR})e^{\theta C\delta}\right]^t. \tag{25}$$

For the second equation, the MGF of impairment process of (16) is employed. The binomial term C_{t-1}^{H-1} in the last equation is the number of combinations for the summation in the first inequality. Note that the binomial term implies a condition of $t \ge H$ which is always satisfied, since the throughput is observed at the destination for the Hth hop by the time t.

Finally, let the violation probability ε equal to the last expression, the lower bound of throughput $\lambda_{L,t}^{SU}$ can be derived after a simple mathematical transformation. □

The non-asymptotic throughput bounds $\lambda_{U,t}^{SU}$ and $\lambda_{L,t}^{SU}$ are functions of time t, which capture the dynamic nature of the network. On the other hand, if we take the limit as $t \to \infty$, the asymptotic upper bound and lower bound of throughput are obtained as

$$\lambda_U^{SU} = \lim_{t\to\infty} \lambda_{U,t}^{SU} = C + \frac{1}{\theta}\log(p_{TR} + (1-p_{TR})e^{-\theta C\delta}) \tag{26}$$

and

$$\lambda_L^{SU} = \lim_{t\to\infty} \lambda_{L,t}^{SU} = C - \frac{1}{\theta}\log(p_{TR} + (1-p_{TR})e^{\theta C\delta}). \tag{27}$$

The two asymptotic throughput bounds are independent with time t, which represent the steady state of the network. After an optimization with constraint in parameter θ, we can further get the following two optimized bounds as

$$\lambda_{U-opt}^{SU} = \inf_{\theta \ge 0} \lambda_U^{SU} \tag{28}$$

and

$$\lambda_{L-opt}^{SU} = \sup_{\theta \ge 0} \lambda_L^{SU}. \tag{29}$$

These two optimized bounds provide the minimum upper bound λ_{U-opt}^{SU} and maximum lower bound λ_{L-opt}^{SU} from a mathematical perspective based on parameter θ.

In this section, we present the derivation of non-asymptotic and asymptotic throughput bounds for the multi-hop transmission of SUs. The impact from different factors on the throughput will be revealed by the numerical results in the next section.

6. Numerical results and simulations

We illustrate the upper bound and lower bound of the throughput by numerical examples and simulations in this section. According to the CRN model described in Section 2, we assume that packets from SUs traverse H hops to the destination. In each hop, there exists N SUs sharing the channel, whose service rate is C. Packet size is fixed to L. Correspondingly, slot time is of fixed length of $\delta = \frac{L}{C}$. Without loss of generality, we normalize the service rate as $C = 1$, and let the packet length be $L = 1$, therefore, slot time becomes a unit length $\delta = 1$. In addition, the arrival rate of PU is restricted to $\alpha^{PU} \in (0, C)$. As to SUs, the arrivals is assumed to be saturated that is, the queue of each SU is always nonempty, the packets will be transmitted as long as SU obtains an transmission opportunity. As a result, the arrival rate of SUs can be ignored.

For the parameters in simulation, the service rate is set as $C = 54$Mbps, packet length as $L = 256$kbits. As to the DCF, we set the total backoff stage as $B = 3$, and the initial contention window as $CW0 = 32$. The other parameters are configured with different values for various simulations, which will be presented in the following section.

6.1. Non-asymptotic throughput bounds

We first present the non-asymptotic throughput bounds under different conditions. Since the arrival of SUs is assumed to be saturated, it has no impact on the throughput. The influence on the throughput bounds of SUs stem from four parameters, namely average arrival rate of PU α^{PU}, sensing error probability p_e, number of SUs N in each hop, and hop count H.

Comparing the numerical and simulation results, we can observe that the throughput based on simulations generally locates between the upper and lower bounds, which validates the theoretical results. Referring to the numerical results, the upper bound decreases dramatically and lower bound increases sharply at the beginning, and then, they converge to be stable. Correspondingly, the gap between upper and lower bounds is large at the beginning, and then it shrinks until arrives at a steady value. The variation of this gap implies that the end-to-end throughput fluctuates severely first and becomes steady. According to the simulation results, the throughput is zero at first, then it increases with fluctuation and finally tends to a constant. The variation of the throughput can be explained as follows. For the value of zero, the reason lies in that it takes time for the first packet to be transmitted through H hops, before which the throughput is zero. After that, the throughput increases with consecution packet arrivals. However, the inter arrival of packets at the last hop varies due to the influence of impacting factors, which results in that the queue maybe empty occasionally. Therefore, the throughput fluctuates. Later on, the cumulative packet arrivals lead to a backlogged queue in every relay-SU, then the last relay-SU transmits one packet for each transmission opportunity. Considering that the contention process of DCF scheme comes into a steady state as time t increases, the relay-SU successfully access to the channel with a steady state probability. As a result, the throughput finally becomes a constant.

In details, we perform the analysis following four scenarios.

In Fig. 4a, we show the throughput bounds as functions of average arrival rate of PU, which captures the influence caused by PU activity. During the simulation, we fix the number of SUs as $N = 10$, sensing error probability as $p_e = 0.01$ and hop count as $H = 10$. The normalized arrival rate of PU α^{PU} varies among

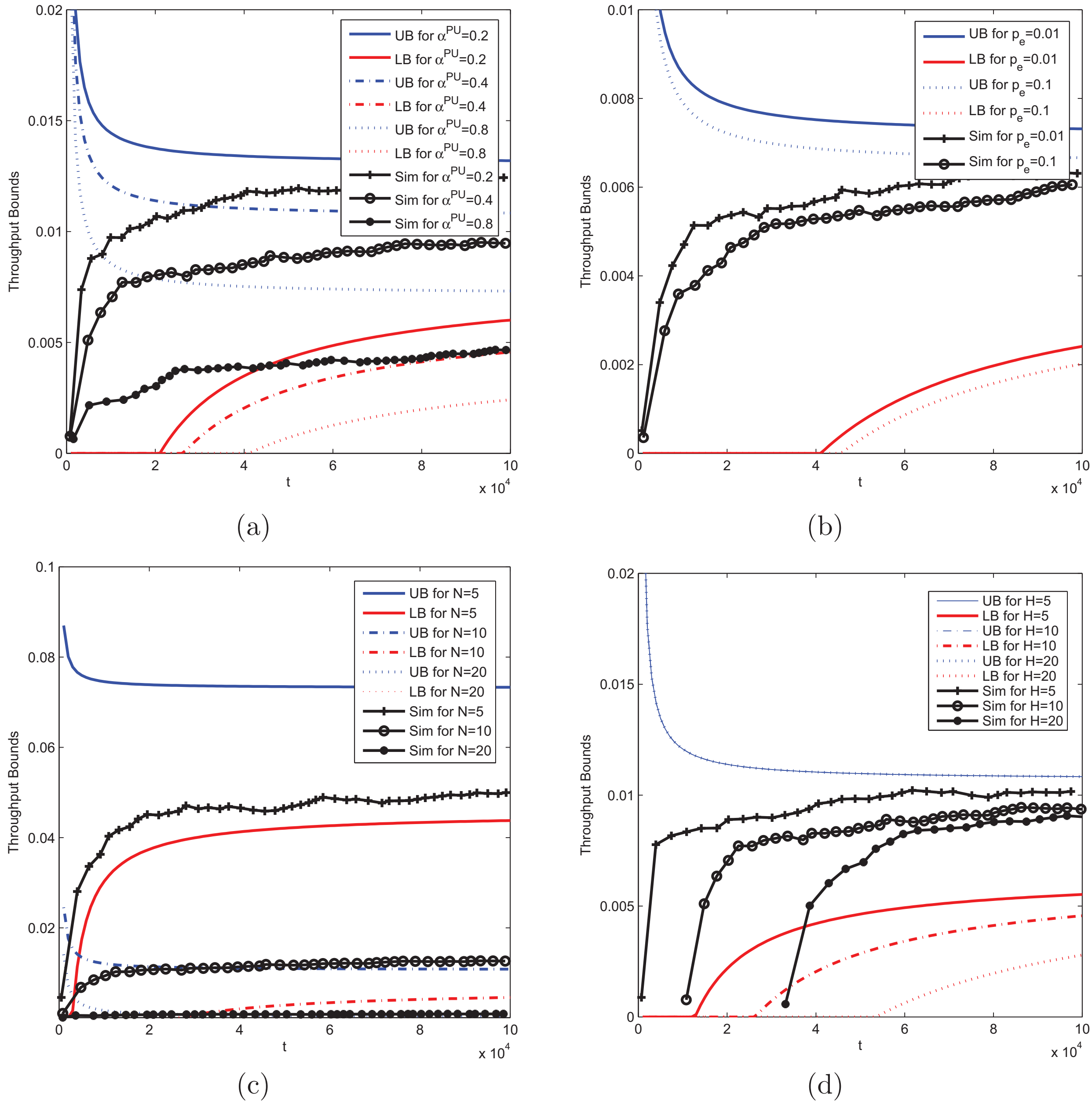
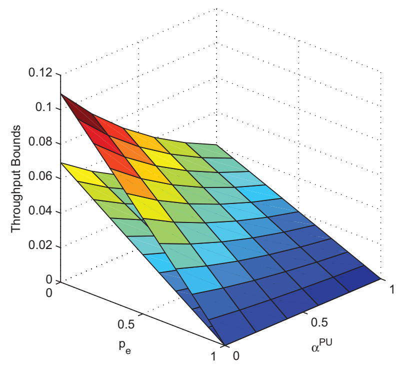


Fig. 4. These figures illustrate the influence of four parameters on the non-asymptotic throughput bounds of SUs by means of numerical computations and simulations. The increase of these parameters results in decrease of both bounds $\lambda^{SU}_{L,t}$ and $\lambda^{SU}_{U,t}$. However, the upper bound $\lambda^{SU}_{U,t}$ is independent with the hop count. (a): Throughput bounds vary with average arrival rate of PU α^{PU}. (b): Throughput bounds vary with sensing error probability p_e. (c): Throughput bounds vary with number of SUs N. (d): Throughput bounds vary with hop count H.

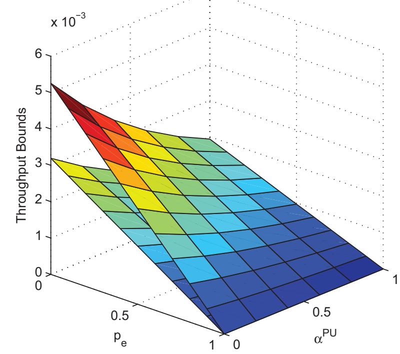
{0.2, 0.4, 0.8}. As expected, both upper bound and lower bound of throughput deteriorate when the arrival rate of PU increases. The intuition is as follows. A larger arrival rate α^{PU} implies more packets arriving at the queue of PU which requires more service, as a result, less service can be left for SUs. From the perspective of transmission opportunities, a larger α^{PU} is equivalent to a smaller average inter-arrival time $\frac{1}{\alpha^{PU}}$ which corresponds to less period of idle state of PU, then less opportunities are provided for SUs. Consequently, it takes more time for SUs to accomplish the transmission, which results in a decrease of throughput.

In Fig. 4b, we evaluate the throughput bounds with varying sensing error probabilities, where we deploy the normalized arrival rate of PU as $\alpha^{PU} = 0.4$, number of SUs as $N = 10$, hop count as $H = 10$ and sensing error probability p_e varies between 0.01 and 0.1. The figure depicts a decrease of throughput bounds with increasing of p_e. Comparing the throughput bounds under $p_e = 0.01$ and $p_e = 0.1$, we can find that p_e increases tenfold, both upper and lower bounds decrease almost by 10 percents. This is due to the fact that more sensing errors result in more collisions between PU and SUs and more wasted transmission opportunities for SUs. Even though the spectrum sensing errors have influence on both PU and SUs, the sensing error probability is usually very small. Therefore, the impact from sensing errors on the throughput bounds is not very prominent.

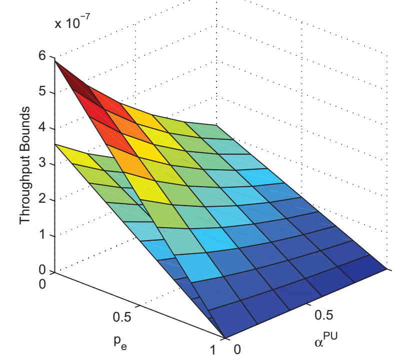
Fig. 4c shows the throughput bounds with different number of SUs N, whose value is chosen from {5, 10, 20}. And the other parameters are set as $\alpha^{PU} = 0.4$, $p_e = 0.01$ and $H = 10$. According to the figure, we can observe that the throughput bounds decrease dramatically with the increase of N. This sharp decrease arises from that SUs compete for transmission opportunities, and each SU



(a) $N = 5$



(b) $N = 10$



(c) $N = 20$

Fig. 5. These figures illustrate the influence of three parameters (namely the arrival rate of PU α^{PU}, sensing error probability p_e and number of SUs N in each hop) on the asymptotic throughput bounds of SUs. The increase of these three parameters results in decrease of both bounds λ_L^{SU} and λ_U^{SU}. And among the three parameters, the arrival rate of PU α^{PU} has dominant impact on the throughput bounds.

succeeds in the contention process with a probability of $\frac{\tau(1-\tau)^{N-1}}{1-(1-\tau)^N}$. Therefore, a larger N implies a smaller probability, which results in that each SU may fail to access to the channel in a large number of consecutive time slots, and finally the throughput declines. However, the trend of decrease becomes gentle along with the increase of N, which can be observed according to the asymptotic throughput bounds that will be presented in the latter section.

Fig. 4d indicates the impact of hop count on the throughput bounds. The simulation parameters are as follows, $\alpha^{PU} = 0.4$, $p_e = 0.01$, $N = 10$ and hop count H varies among {5, 10, 20}. It is illustrated that different values of H have identical upper bound of throughput. This can be also observed in (20) that hop count H is not implied in the expression. The reason is that, to derive the upper bound, we employ a sample path in (24) to bound the infimum of the MGF in (23). Since we focus on the end-to-end throughput, it is essential that the last hop is accomplished by the time t. Consequently, the time index t contains the hop count H implicitly. However, the lower bound of throughput varies with hop count. Therefore, we concentrate on the lower bound, where the increase of hop count deteriorates the lower bound. The reason is that each transmit-SU has to compete with the SUs within contention set to transmit over the channel in each hop, which implies that the packets must wait in the queue until a transmission opportunity is obtained. This contention procedure prolongs the service time of packets in each hop, and finally the total time for the end-to-end transmission is extended, which results in the decrease of end-to-end throughput. In addition, we can observe that the lower bound becomes independent with hop count when it comes into an asymptotic one, which will be illustrated in the latter section.

According to the figures, we can find that the non-asymptotic throughput bounds decline with the increase of average arrival rate of PU α^{PU}, sensing error probability p_e, number of SUs N in each hop and hop count H.

6.2. Asymptotic throughput bounds

Based on Fig. 4, we give an insight into the non-asymptotic throughput bounds of how they are influenced by different parameters. Moreover, we can observe that no matter how the parameters change, all bounds converge to asymptotic ones. Therefore, we present analysis of the asymptotic bounds to get more in-depth understanding of the throughput according to (26) and (27).

From the two equations, we can see that the asymptotic throughput bounds are independent with the hop count H. This can be explained in twofold. First, from the perspective of QoS guarantees provided by the CRNs, when time t goes to infinity, the throughput can be assured no matter how many hops packets traverse. Therefore, the throughput is independent with hop count. Second, when time t increases, the cumulative packet arrivals make the queue of the relay-SUs be backlogged, then, for each transmission opportunity, one packet can be transmitted. In addition, the DCF scheme makes the contention process for each hop be in a steady state, which results in that each SU successfully competes for the channel with a steady state probability. As a result, the throughput keeps unchanged as soon as the last relay-SU is backlogged, and no matter how much the hop count H is.

Now, we can concentrate on the other three parameters. From Fig. 5, we can observe that among the three variables, number of SUs has a dominant impact on the throughput bounds. Comparing the three figures, it is illustrated that doubling N leads to a decrease of throughput bound by nearly 50% which implies an inverse relationship between throughput and number of SUs. This inverse relationship lies in that all SUs fairly share the spectrum to get a service of $\frac{C}{N}$ (where C is normalized as $C = 1$ in this section). In fact, based on the contention-based CSMA scheme, collisions may happen among SUs which results in a service less than $\frac{C}{N}$ provisioned to SUs. Moreover, the increase of p_e declines the throughput, which is intuitive in that large p_e implies more sensing errors. Consider an extreme case of $p_e = 1$, this results in that a sensing error happens in each slot, then, the service cannot be provided to neither PU nor SUs, consequently, both the upper bound and lower bound of throughput come into the value of zero. Furthermore, the increment of α^{PU} gives rise to the decrease of throughput, because more service is needed for large α^{PU}. However, we can find that even when $\alpha^{PU} = 1$, SUs can obtain service except for the case of $p_e = 1$. This is due to the fact that even though $\alpha^{PU} = 1$, SUs can successfully access to the channel with a certain probability according to (12). Therefore, the throughput is not equal to zero.

In this section, we analyze the asymptotic throughput bounds. It is demonstrated that the hop count does not have influence on the throughput bounds. The number of SUs in each hop has a prominent impact on the throughput bounds than the other two, i.e., average arrival rate of PU and sensing error probability.

7. Conclusion

In this paper, we carried out throughput analysis for multi-hop cognitive radio networks. Specifically, we derived upper bound and lower bound of throughput for SUs. We resorted to a stochastic network calculus approach and modeled transmission as service process by using moment generation functions, based on which the multi-hop transmission was transformed into an equivalent single-hop transmission. We investigated the impact on the throughput bounds caused by PU activity, spectrum sensing errors, media access and hop count.

Numerical results and analysis reveal that the non-asymptotic throughput bounds decrease with the increase of average arrival rate of PU, spectrum sensing error probability, number of SUs in each hop and hop count. For the asymptotic bounds, they also decline with the increment of these parameters, while the bounds are independent with hop count. Furthermore, the media access scheme, implied by number of SUs in each hop, has a dominant impact on the throughput bounds than other factors, such as PU activity and spectrum sensing errors.

Acknowledgment

This work was supported in part by the Key project of National Natural Science Foundation of China (NSFC) (Grant no. 61231010), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant no. 20120142110015), the 863 project (Grant nos. 2014AA01A701 and 2015AA011303) and National Natural Science Foundation of China (NSFC) (Grant no. 61471408). This is an extended version of a paper that appeared in the proceedings of WCSP2014.

References

[1] J. Mitola, G.Q. Maguire Jr, Cognitive radio: making software radios more personal, Pers. Commun. IEEE 6 (4) (1999) 13–18.
[2] FCC, Report of the spectrum efficiency working group, Spectrum Policy Task Force, 2002.
[3] I.F. Akyildiz, W.-Y. Lee, K.R. Chowdhury, Crahns: Cognitive radio ad hoc networks, Ad Hoc Netw. 7 (5) (2009) 810–836.
[4] K.R. Chowdhury, I.F. Akyildiz, Cognitive wireless mesh networks with dynamic spectrum access, IEEE J. Sel. Areas Commun. 26 (1) (2008) 168–181.
[5] Q. Chen, W.-C. Wong, M. Motani, Y.-C. Liang, Mac protocol design and performance analysis for random access cognitive radio networks, IEEE J. Sel. Areas Commun. 31 (11) (2013) 2289–2300.
[6] S. Wang, J. Zhang, L. Tong, A characterization of delay performance of cognitive medium access, IEEE Trans. Wirel. Commun. 11 (2) (2012) 800–809.
[7] Z. Liang, S. Feng, D. Zhao, X. Shen, Delay performance analysis for supporting real-time traffic in a cognitive radio sensor network, IEEE Trans. Wirel. Commun. 10 (1) (2011) 325–335.
[8] K.J. Kim, K.S. Kwak, B.D. Choi, Performance analysis of opportunistic spectrum access protocol for multi-channel cognitive radio networks, J. Commun. Netw. 15 (1) (2013) 77–86.
[9] H.A. Suraweera, P.J. Smith, M. Shafi, Capacity limits and performance analysis of cognitive radio with imperfect channel knowledge, IEEE Trans. Veh. Technol. 59 (4) (2010) 1811–1822.
[10] V.N. Mui, S.H. Choong, B.L. Long, Cross-layer cognitive mac design for multi-hop wireless ad-hoc networks with stochastic primary protection, in: Proceedings of the 2013 IEEE Wireless Communications and Networking Conference (WCNC), Shanghai, 2013, pp. 1802–1807.
[11] Z. Yuchi, F. Zhiyong, L. Huidi, Z. Qixun, Y. Xiao, Y. Jian, Scaling law of multi-hop cognitive network with a novel hybrid access scheme, in: Proceedings of the 2013 IEEE Eightieth Vehicular Technology Conference (VTC Fall), Vancouver, BC, 2014, pp. 1–5.
[12] W.C. Ao, S.-M. Cheng, A lower bound on multi-hop transmission delay in cognitive radio ad hoc networks, in: Proceedings of the 2013 IEEE Twenty Fourth International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), London, United Kingdom, 2013, pp. 3323–3327.
[13] D. Xue, E. Ekici, Guaranteed opportunistic scheduling in multi-hop cognitive radio networks, in: Proceedings of the 2011 Thirtieth IEEE International Conference on Computer Communication INFOCOM, Shanghai, 2011, pp. 2984–2992.
[14] Y. Wu, G. Min, A.Y. Al-Dubai, A new analytical model for multi-hop cognitive radio networks, IEEE Trans. Wirel. Commun. 11 (5) (2012) 1643–1648.
[15] Y. Jiang, Y. Liu, Stochastic Network Calculus, vol. 1, Springer, 2008.
[16] F. Ciucu, O. Hohlfeld, P. Hui, Non-asymptotic throughput and delay distributions in multi-hop wireless networks, in: Proceedings of the Forty Eighth Annual Allerton Conference on Communication, Control, and Computing (Allerton), IEEE, 2010, pp. 662–669.
[17] F. Ciucu, J. Schmitt, On the catalyzing effect of randomness on the per-flow throughput in wireless networks, in: Proceedings of the 2014 IEEE International Conference on Computer Communication, Toronto, 2014, pp. 2616–2624.
[18] G. Yuehong, J. Yuming, Performance analysis of a cognitive radio network with imperfect spectrum sensing, in: Proceedings of the 2010 IEEE Conference on Computer Communications Workshops, INFOCOM, San Diego, CA, 2010, pp. 1–6.
[19] Y. Gao, W. Jiang, J. Yuming, Guaranteed service and delay-constrained capacity of a multi-channel cognitive secondary network, in: Proceedings of the 2012 Seventh International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Stockholm, 2012, pp. 83–88.
[20] P. Gupta, P.R. Kumar, The capacity of wireless networks, IEEE Trans. Inf. Theory 46 (2) (2000) 388–404.
[21] C.-S. Chang, Performance Guarantees in Communication Networks, Springer Science & Business Media, 2000.
[22] M. Fidler, An end-to-end probabilistic network calculus with moment generating functions, in: Proceedings of the Fourteenth IEEE International Workshop on Quality of Service, IWQoS 2006, IEEE, 2006, pp. 261–270.
[23] S. Tang, B.L. Mark, Modeling and analysis of opportunistic spectrum sharing with unreliable spectrum sensing, IEEE Trans. Wirel. Commun. 8 (4) (2009) 1934–1943.
[24] I.F. Akyildiz, B.F. Lo, R. Balakrishnan, Cooperative spectrum sensing in cognitive radio networks: A survey, Phys. Commun. 4 (1) (2011) 40–62.
[25] O.K. Tae, A.S. Alfa, D.C. Bong, Performance analysis of a csma/ca based mac protocol for cognitive radio networks, in: Proceedings of the Seventy Second IEEE Vehicular Technology Conference Fall (VTC 2010-Fall), in: Vehicular Technology Conference Fall (VTC 2010-Fall), Ottawa, ON, 2010, pp. 1–5.
[26] G. B, Performance analysis of the IEEE 802.11 distributed coordination function, IEEE J. Sel. Areas Commun. 3 (18) (2000) 535–547.

Jun Zheng received the B.S. and M.S. degrees from the College of Physical Science and Technology, Huazhong Normal University, Wuhan, China, in 2002 and 2006, respectively, and is currently pursuing the Ph.D. degree in the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China. His current research interests include performance evaluation and modeling of cognitive radio networks.

Peng Yang received the B.S. degrees from the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China in 2013, and is currently pursuing the Ph.D. degree in the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China. His current research interests include capacity scaling law and performance analysis of wireless sensor networks.

Jingjing Luo received the B.S. degrees from the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China in 2010, and is currently pursuing the Ph.D. degree in the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China. Her current research interests include capacity scaling law and mobility models in wireless networks.

Qiuming Liu received the B.S. and M.S. degrees, in 2007 and 2010 respectively, from the Department of Electronics and Information Engineering, Nanchang University, Nanchang, China, and is currently pursuing the Ph.D. degree in the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China. His current research interests include network security and capacity scaling law in wireless networks.

Li Yu received the B.S. degree and Ph.D. degree both from the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China, in 1992 and 1999, respectively. Currently, she is a professor and serves as the director of Multimedia and Communication Network Center, in the School of Electronic Information and Communications, Huazhong University of Science and Technology, China.