Cooperative spectrum leasing using parallel communication of secondary users

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Abstract

In this paper, a multi-hop transmission protocol based on parallel communication of secondary users (SUs) is proposed. The primary multi-hop network coexists with a set of SUs by cooperative spectrum sharing. The main optimization target of our protocol is the overall performance of the secondary system with the guarantee of the primary outage performance. The energy consumption of the primary system is reduced by the cooperation of SUs. The aim of the primary source is to communicate with the primary destination via a number of primary relays. SUs may serve as extra decode-and-forward relays for the primary network. When an SU acts as a relay for a primary user (PU), some other SUs that satisfy the condition for parallel communication are selected to simultaneously access the primary spectrum for secondary transmissions. For the proposed protocol, two opportunistic routing strategies are proposed, and a search algorithm to select the SUs for parallel communication is described. The throughput of the SUs and the PU is illustrated. Numerical results demonstrate that the average throughput of the SUs is greatly improved, and the end-to-end throughput of the PU is slightly increased in the proposed protocol when there are more than seven SUs.

Keywords: Cooperative relaying, cooperative spectrum sharing, routing strategies, secondary user selection, parallel transmission

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1. Introduction

With the development of wireless communication and the steadily increasing demands for higher quality of service (QoS), the spectrum scarcity problem has become increasingly serious. The low utilization efficiency of the radio spectrum is the critical factor that leads to this problem. Cognitive radio (CR) [1] has been recently proposed, which is a promising technology for improving the utilization efficiency of the radio spectrum [2]. The main idea of this technology is to allow secondary user (SU) networks to coexist with primary user (PU) networks through spectrum sharing, provided that the secondary spectrum access will not adversely affect the performance of the PU. Based on the type of available network side information along with the regulatory constraints, there are three CR network models [3]: interweave, underlay, and overlay. The interweave model operates by the SUs first sensing the availability of spectrum holes, i.e., spectrum bands not occupied by the PUs. The SUs are then restricted to transmit over these bands. In the underlay model, the SUs simultaneously transmit with the PUs over the same spectrum, provided that the received SUs' signal power levels at all PU receivers are kept below a predefined threshold. Finally, the overlay model is a special dynamic spectrum-sharing model that allows the SUs to simultaneously transmit with the PUs over the same spectrum, provided that the SUs aid the transmission of the PUs using cooperative communication techniques such as the advanced coding techniques and cooperative-relaying techniques. The overlay model has attracted considerable research interest [4]–[8], when spectrum-sharing protocols based on cooperative amplify-and-forward were proposed in [4, 5] and the protocol based on decode-and-forward (DF) was proposed in Ref. [6]. In Refs. [7]–[9], the DF-based spectrum-sharing protocols were generalized for a multi-user scenario in which some methods were adopted in selecting the relay. All these protocols are two-phase protocol, which are only suitable for one-hop or two-hop network cases.

In a multi-hop scenario, relaying is a promising solution to enhance the throughput of the multi-hop networks over the fading channels. In Ref. [10], it was proven that the per-user throughput can be increased substantially by exploiting the channel diversity offered by the availability of multiple possible next hops. In Ref. [11], a primary multi-hop network is considered that coexists with a set of secondary nodes. The coexistence was regulated via a spectrum-leasing mechanism based on cooperation and opportunistic routing. The author mainly illustrated the tradeoff between the throughput and the energy consumption of the PU, but the performance of the SUs was not discussed. In Ref. [12], the secondary system was a multi-hop network, and SUs could access the radio spectrum owned by the PUs. The authors analyzed the end-to-end (e2e) performance gain of the CR networks (CRNs) on the basis of whether relaying was employed or not, and whether the concurrency over the CRN was considered or not. The system performance was discussed in terms of e2e channel utilization, reliability, energy consumption, and transmission delay. A cooperative multi-relay scheme for the secondary system was proposed in Ref. [13], in which the optimization targets for the network model were similar to that of our study except that the method for relays selection depended on a centralized control unit. In addition, mechanisms of artificial self-organization have also been emphasized to address the emerging spectrum scarcity problem in CRNs, different aspects of bio-inspired mechanisms and variant aspects of self-organization paradigms in cognitive radio networks are survey in Ref. [14][15]. This work is also an simply self-organization paradigm in cognitive radio networks.

Based on Ref. [11], the current paper mainly presents the improvement in the performance of the secondary system. SUs coexist with the primary multi-hop network by cooperative parallel communication. Primary packets are transmitted from the primary source (PS) to the primary destination (PD) via a set of relays. Secondary transmitters may be designated as possible candidates for relaying the primary packets. When the assistance of a secondary transmitter is beneficial for the improvement of the PU performance, the secondary transmitter is selected as the next hop for relaying the primary packets. Meanwhile, the other secondary transmitters that satisfy the condition of parallel communication can communicate with the secondary destination (SD) over the same spectrum as the PU. The main contributions of this work are as follows. 1) A protocol using the parallel communication of multiple SUs is proposed. 2) Two opportunistic routing strategies are proposed with the same routing policy as Ref. [11] for the primary network transmission, and a nearest-neighbor routing (NNR) policy is employed for the secondary network transmission. 3) A search algorithm is proposed and exploited to select the secondary transmitters for parallel communication. The main concept of the algorithm is that the selected secondary transmitters cannot adversely affect the PU performance. 4) The average throughput of the SUs and the e2e throughput of the PU are illustrated. Theoretical analysis and simulation results indicate that the average throughput of the SUs is greatly improved when the number of secondary transmitters is sufficiently large, and the e2e throughput of the PU improves slightly

In the proposed protocol, the PU plays a dominant role in the cooperative spectrum sharing. The protocol may be applied when the transmission of the PU requires the assistance of secondary nodes. This case includes very poor channel conditions of the primary networks, and the primary packet cannot be correctly delivered to the destination using only the primary network, or the energy of the primary system is not sufficient for the successful delivery of all packets to the destination. When the assistance of the SUs is beneficial for the primary transmission, some SUs can coexist in the same spectrum as the PU because of the fairness of the cooperative spectrum sharing.

The rest of this paper is organized as follows. Section 2 presents the system model for cooperative parallel communication. Section 3 investigates the two routing strategies for relaying the primary packets using parallel communication of the SUs. Section 4 analyzes the conditions for parallel communication and the performance of the proposed protocol. Section 5 provides the numerical results to compare the performance of the two multi-hop transmission protocols. One protocol uses parallel communication, and the other uses non-parallel communication. Finally, section 6 summarizes the conclusions.

2. System model for cooperative parallel communication

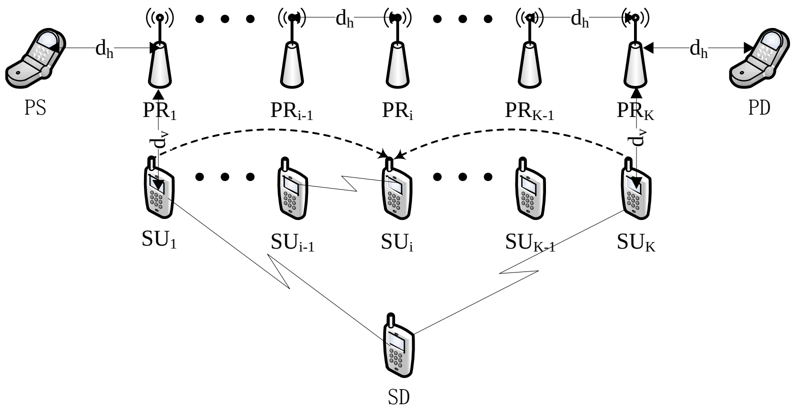

Fig. 1. Primary linear multi-hop network $(PS, PR_1, PR_2, \cdots, PR_K, PD)$ with $k+1$ hops and a secondary network $(SU_1, SU_2, \cdots, SU_K)$ aligned with respect to the primary relay nodes.

Fig. 1 shows that the primary and secondary networks coexist via cooperative spectrum sharing. The curved solid lines represent the transmission of the desired signals, and the dotted lines represent the transmission of the interference signals. The secondary network contains a number of transmitters $SU_i \in S = \{SU_1, SU_2, \cdots, SU_K\}$ and an SD. We assume that the SD is equipped with multiple antennas and can simultaneously decode more than one signal transmitted over the same frequency at the same time from different secondary transmitters. The primary network contains a source-destination pair PS-PD and a number of relay nodes $PR_i \in P = \{PR_1, PR_2, \cdots, PR_K\}$. The purpose of the PUs is to deliver the packets from the PS to the PD successfully, possibly by taking advantage of the multi-hop routing through two sets (P and S) of additional nodes placed along two linear geometries parallel to vertical distance d_v. The PU performs a multi-hop transmission whereas the SU performs a single-hop transmission with a normalized value for the distance between the PS and the PD. The relay nodes of the primary system in set P are arranged in a uniform linear manner whereas the elements in S (as the secondary transmitters) are aligned with respect to the primary relay nodes. Thus, the distance between two adjacent primary nodes or two adjacent secondary transmitter nodes is $d_h = 1/(K+1)$. Just as one secondary transmitter is selected to serve as a DF relay for the primary system, some other nodes in set S that satisfy certain conditions can access the channel to communicate with the SD.

An application scenario in which the SUs are limited to short-range (i.e., single-hop) transmissions is one where the PUs and the SUs belong to the same wireless network, and the SUs have lower priority than the PUs. The PS and the PD may be either mobile terminals or infrastructure nodes, such as femtocell access points. In this case, the energy and the throughput are both equally important performance criteria.

The authors in Ref. [16] proposed two cognitive relaying schemes that exploited the cooperation opportunities inherent in a primary retransmission to improve the secondary throughput. In the present study, we considered that all devices work in half-duplex mode. In each primary packet transmission, only one node is active to relay the packet at the same time, and the PS, primary relays and secondary nodes may perform retransmissions until the packet is correctly decoded by the next-hop node. After the packet is correctly delivered to the destination, the PS transmits a new packet, and the process is repeated.

When transmitter node N_i of the current hop is a primary node, i.e., $N_i \in \{PS, PR_1, \cdots, PR_K\}$, the received signal from N_i at receiver node N_j is written as

$$r_{N_iN_j}^{P(1)}(t) = \sqrt{P_P} d_{N_iN_j}^{-\alpha/2} h_{N_iN_j}(t) x_P(t) + n_{N_j}(t), \tag{1}$$

where $N_j \in \{PR_1, \cdots, PR_K, PD, SU_1, SU_2, \cdots, SU_K\}$ and P_P is the transmitted power on N_i. $x_P(t)$ represents the transmitted signal symbol by N_i with $E\left[|x_P(t)|^2\right] = 1$, making $N_0 = PS, N_{K+1} = PD$. $h_{N_iN_j}(t)$ is the channel coefficient between N_i and N_j, which is assumed to be quasi-static Rayleigh fading, i.e., a complex Gaussian random variable with zero mean and a unit power. α is the path loss exponent. $n_{N_j}(t)$ is the complex white Gaussian noise with zero mean and power N_0. $d_{N_iN_j}$ is the distance between N_i and N_j; thus, $d_{N_iN_j}$ is expressed in the following two forms (see also Fig. 1): if N_j is a primary node, $d_{N_iN_j} = (j-i) d_h$; if N_j is a secondary node, $d_{N_iN_j} = \sqrt{(j-i)^2 d_h^2 + d_v^2}$.

When transmitter node N_i of the current hop is a secondary node, i.e., $N_i \in \{SU_1, SU_2, \cdots, SU_K\}$, $N_j \in \{SU_2, \cdots, SU_K, PD\}$ is the receiver node of the current hop which makes $SU_{K+1} = PD$. The set of SUs for parallel communication is denoted as $\mathrm{I}_i = \{SU_1, SU_2 \cdots, SU_m, SU_n, \cdots, SU_{K-1}, SU_K\}$, where $m < i$ and $j < n$. Considering the transmission between N_i and N_j, the received signal at N_j is written as

$$r_{N_iN_j}^{P(2)}(t) = \sqrt{P_S} d_{N_iN_j}^{-\alpha/2} h_{N_iN_j}(t) x_P(t) + \sum_{N_k \in \mathrm{I}_i} \sqrt{P_S} d_{N_kN_j}^{-\alpha/2} h_{N_kN_j}(t) x_{S_k}(t) + n_{N_j}(t), \tag{2}$$

where P_S represents the transmit power for the secondary nodes, $N_k \in \mathrm{I}_i$, $x_{S_k}(t)$ is the transmitted signal symbol from N_k with $E\left[|x_{S_k}(t)|^2\right] = 1$, $d_{N_kN_j}$ is the distance between N_k and N_j, and $d_{N_iN_j}$ and $d_{N_kN_j}$ are expressed in the following two forms: if N_j is a secondary node, $d_{N_iN_j} = d_h$ and $d_{N_kN_j} = |j-k| d_h$; if N_j is the PD, $d_{N_iN_j} = \sqrt{d_h^2 + d_v^2}$ and $d_{N_kN_j} = \sqrt{(j-k)^2 d_h^2 + d_v^2}$. When $\mathrm{I}_i = \varnothing$, communication between $SU_i, i \in (1, \cdots, K)$ and the SD is interrupted. When $\mathrm{I}_i \neq \varnothing$, parallel communication between $SU_i, i \in \mathrm{I}_i$ and the SD is established, i.e., parallel communication of the SUs is achieved. The received signal at the SD is written as

$$r^S(t) = \omega \left[\sum_{N_k \in \mathrm{I}_i} \sqrt{P_S} d_{N_kSD}^{-\alpha/2} h_{N_kSD}(t) x_{S_k}(t) + n_{SD}(t) \right]. \tag{3}$$

Where ω denotes the reception beam weight, $h_{N_kSD}(t) \in C^{K\times1}$ is the channel coefficient vector between N_k and the SD. And $n_{SD}(t) \in C^{K\times1}$ is the reception noise vector. The elements of the noise vector are complex white Gaussian noise with zero mean and power N_0. After using a multiple antenna technology, all $x_{S_k}(t)$ can be obtained at the SD.

3. Routing Strategies for the Multi-hop Transmission Protocol with Parallel Communication

Here, we have detailed two routing strategies for the primary packets. We note that the two strategies are based on a Type-I hybrid automatic repeat request (ARQ), also known as the traditional ARQ. These strategies allow the primary network to accrue performance benefits with low energy consumption while allowing the SUs to achieve high throughput. The definition of the routing strategies in this work is similar to that in Ref. [11].

The first strategy is called Only Secondary (Only-S) strategy. This strategy minimizes the primary transmission, i.e., minimize the energy consumption of the primary system. In this strategy, the nodes that are exploited to relay the primary packets are secondary nodes (i.e., without exploiting any primary relay), allowing primary (re)transmissions only from the PS. The basic routing strategy of the primary packet is divided into two types. One is that as the transmitter of the current hop is the PS, SU_i (which has decoded the previous transmission and is the closest to the PD) is selected as the transmitter for the next hop. In this case, the routing strategy is the same as that in Ref. [11]. The other type is that as the transmitter of the current hop is SU_i, the next node SU_{i+1} (which has decoded the previous transmission and is the closest to the PD) is selected as the transmitter for the next hop. Compared with that in Ref. [11], this routing strategy has two different characteristics. One is that superposition coding (SC) is not exploited in the secondary transmitter. The other is that SU_i just relays the primary packet to the next secondary node SU_{i+1}. With SU_i in the relaying phase (if possible), some other secondary transmitters SU_k are selected to access the primary spectrum to communicate with the SD, where SU_k belong to I_i. We note that SU_k must satisfy an interference constraint to ensure that the outage performance of the primary system is not degraded as compared with the case where there is no secondary spectrum access; this interference constraint is discussed in Section IV.

We have known that the Only-S strategy minimizes the primary transmission energy but may let the PU suffer from poor throughput. Once the primary packet has entered the secondary network, the primary packet is simply transmitted to the next secondary node closest to the PD because of the selfishness of the SUs. As a result, the primary packet is successfully delivered from the PS to the PD via a number of hops, and thus, the transmission delay is long.

The second strategy, called Primary to Secondary (P-to-S) strategy, is proposed in this paper, which offers a better tradeoff between the throughput and the energy to the primary system. In contrast to the Only-S strategy, the P-to-S strategy employs a primary relay until a secondary node in a “sufficiently good” position has decoded, as dictated by m. In the P-to-S strategy, the packet is handled by the secondary network is similar to that in the Only-S strategy. When transmitter of the current hop is a primary node, it first determines the type of node closest to the PD that has successfully decoded the current packet. If the closest node is a secondary node, it is selected as the transmitter for the next hop; if it is a primary node, it is selected only if the best secondary node is at least $m+1$ hops behind the closest node in order to minimize the primary energy consumption. The best secondary node is the closest secondary node to the PD that has successfully decoded the current packet. In other words, the next transmitter is selected as either the primary node at hand closest to the PD or the secondary node closest to the PD within a window of m hops from the position of the primary node toward the PS. This window is referred to as a backward window. The main idea of this strategy is shown in Fig. 2 of Ref. [11].

When a primary packet enters the secondary network in the above strategies, it cannot return to the primary network except for the final PD. The two routing strategies have the same transmission mode in the secondary network, termed as the NNR, and this mode does not exploit orthogonal multiplexing (OM) or SC which are used in Ref. [11]. The advantages of the NNR were described in Ref. [12]. Compared with the farthest neighbor routing, NNR results in better channel quality for the same transmit power or consumes less power and incurs less interference for the same QoS. The two strategies have different transmission modes in the primary network. The Only-S strategy minimizes the primary energy consumption but has a poor primary throughput whereas the P-to-S strategy offers a better tradeoff between the throughput and the energy of the primary system compared with the Only-S strategy, and these definitions are the same as that in [11].

4. Transmission Conditions and Performance Analysis for Parallel Communication of Secondary Users

4.1 Secondary User Selection for Parallel Communication

On the basis of the captured model in [17, 19], in order to guarantee a transmit rate that is more than R_T, we consider that a given packet is transmitted successfully if the received signal to interference plus noise ratio (SINR) is above a preset threshold Θ obtained from the equation $R_T = W\log_2(1+\Theta)$, where W denotes the bandwidth. Thus, the probability of successfully receiving a packet transmitted at rate R_T in the Rayleigh fading model is written as in Ref. [19]

$$\mu = \Pr\left\{SINR \ge \Theta\right\} = \underbrace{\exp\left(-\frac{\Theta N_0 d_{S,D}^{-\alpha}}{P_S}\right)}_{\mu_{SNR}} \times \underbrace{\frac{1}{1+\Theta\left(P_I/P_S\right)\left(d_{S,D}/d_{I,D}\right)^{\alpha}}}_{\mu_{SIR}}, \tag{4}$$

where $d_{S,D}$ represents the distance between the desired source and the receiver, $d_{I,D}$ is the distance between the interferer and the receiver, P_S is the transmit power from the desired source, P_I is the transmit power from the interferer, and N_0 is the noise power. In Equation (4), the first term is the probability of successful reception with only the noise and is denoted as μ_{SNR}. The second term is the probability of successful reception with only the interference and is denoted as μ_{SIR}. Note that $0 \le \mu, \mu_{SNR}, \mu_{SIR} \le 1$, where SNR and SIR denote the signal-to-noise ratio and the signal-to-interference ratio, respectively

The primary transmission rate is denoted by R_P, and the primary received SINR is denoted by Θ_P. Transmitter node N_i of the current hop is a primary node, as shown in Equation (1). The received signal includes the desired signal and noise. Thus, the probability of successfully receiving a primary packet at N_j is written as

$$\mu_P^{(1)} = \Pr\left\{SINR_{N_j} \ge \Theta_P\right\} = \exp\left(-\frac{\Theta_P N_0 d_{N_i,N_j}^{\alpha}}{P_P}\right). \tag{5}$$

This equation represents the non-cooperative transmission case, i.e., no secondary data exist in transmission.

Transmitter N_i and receiver N_j of the current hop are secondary nodes, as shown in Equation (2), and the received signal includes the desired signal, interference, and noise. The number of SUs for parallel communication may be more than one and so is the number of interferers. Similar to Eq. (39) in Ref. [12], the probability of successfully receiving the primary packet at N_j is written as

$$\mu_P^{(2)} = \Pr\left\{SINR_{N_j} \geq \Theta_P\right\} = \exp\left(-\frac{\Theta_P N_0 d_{N_i,N_j}^{\alpha}}{P_S}\right) \times \frac{1}{1+\Theta_P \sum_{SU_k \in \mathrm{I}_i} \left(\frac{1}{|j-k|}\left(d_{N_i,N_j} / d_h\right)\right)^{\alpha}}. \quad (6)$$

When transmitter of the current hop is SU_i, the next node SU_{i+1} (which has decoded the previous transmission and is the closest to the PD) is selected as the transmitter for the next hop.The PD is selected only if secondary node SU_j does not exist. In Equation (6), if the selected node is a secondary node, $d_{N_i,N_j} / d_h = 1$; if the selected node is the PD, $d_{N_i,N_j} / d_h = \sqrt{\left(d_h^2 + d_v^2\right)/d_h^2}$.

To guarantee the QoS of the PU, the probability obtained from Equations (5) and (6) must exceed a target ε_P. The conditions to be met by the user for parallel communication are written as

$$\mu_P^{(2)} = \exp\left(-\frac{\Theta_P N_0 d_{N_i,N_j}^{\alpha}}{P_S}\right) \times \frac{1}{1+\Theta_P \sum_{SU_k \in \mathrm{I}_i} \left(\frac{1}{|j-k|}\left(d_{N_i,N_j} / d_h\right)\right)^{\alpha}} \geq \varepsilon_P. \quad (7)$$

Simplifying Inequality (7) yields,

$$\sum_{SU_k \in \mathrm{I}_i} \left(\frac{1}{|j-k|}\left(d_{N_i,N_j} / d_h\right)\right)^{\alpha} \leq \frac{1}{\Theta_P \varepsilon_P} \exp\left(-\frac{\Theta_P N_0 d_{N_i,N_j}^{\alpha}}{P_S}\right) - \frac{1}{\Theta_P} = f_0. \quad (8)$$

Set I_i of SUs for parallel communication is obtained from Inequation (8). For a given system, I_i depends on the position of the secondary nodes, and a larger number of secondary transmitters mean that I_i contains more elements. The parallel communication factor is defined as $l = |j-k|$, which represents the distance between the current receiver node N_j and an element SU_k of I_i, where SU_k is the nearest element to N_j. Because obtaining I_i from a direct solution of Inequality (8) is difficult, a search algorithm is proposed, as summarized in Table.1.

Table 1. SU selection algorithm for parallel communication

1) Initially, set $S' = \{SU_1, SU_2, \cdots, SU_K, SU_{K+1}\}$ includes all secondary transmitters and the PD, i.e., $SU_{K+1} = PD$. SU_{j-1} and SU_j denote the transmitter and the receiver of the current hop of

the multi-hop transmission, respectively. Let $I_{j0}=\varnothing$. I_j is a set of SUs for parallel communication. $\overline{\overline{I}}_{j,k}$ represents the number of elements in set $I_{j,k}$.	

2) If $\lvert K-j\rvert>\lvert j-1\rvert$
a)For $k=1:K-2j+1$
Let $f(k)=\left(\frac{1}{\lvert K-(k-1)-j\rvert}\left(d_{SU_{i-1},SU_i}/d_h\right)\right)^{\alpha}$
If $\sum_{n=1}^{k}f(n)>f_0$
The selected user set $I_{j,k}=I_{j,k-1}$. Break.
else
The selected user set $I_{j,k}=I_{j,k-1}+\{SU_{K-k+1}\}$.
b)If $\overline{\overline{I}}_{j,k}<K-2j+1$
The selected user set $I_j=I_{j,k}$.
Algorithm terminated.
else
Let $k_0=K-2j+1$, $f_1=\sum_{n=1}^{k_0}f(n)$
For $k=k_0+1:K-j$
If $f_1+\sum_{n=k_0+1}^{k-1}2f(n)+f(k)>f_0$
The selected user set $I_{j,k}=I_{j,k-1}$.Break.
else if $f_1+\sum_{n=k_0+1}^{k-1}2f(n)+f(k)<f_0$ and
$f_1+\sum_{n=k_0+1}^{k}2f(n)>f_0$
The selected user set $I_{j,k}=I_{j,k-1}+\{SU_{K-k+1}\}$
or $I_{j,k}=I_{j,k-1}+\{SU_{k-k_0}\}$.
else
The selected user set
$I_{j,k}=I_{j,k-1}+\{SU_{K-k+1}\}+\{SU_{k-k_0}\}$.
	Else
	a)For $k=1:2j-K-1$
	Let $f(k)=\left(\frac{1}{\lvert j-k\rvert}\left(d_{SU_{i-1},SU_i}/d_h\right)\right)^{\alpha}$
	If $\sum_{n=1}^{k}f(n)>f_0$
	The selected user set $I_{j,k}=I_{j,k-1}$.Break.
	else
	The selected user set $I_{j,k}=I_{j,k-1}+\{SU_k\}$.
	b)If $\overline{\overline{I}}_{j,k}<2j-K-1$
	The selected user set $I_j=I_{j,k}$.
	Algorithm terminated.
	else
	Let $k_0=2j-K-1$, $f_1=\sum_{n=1}^{k_0}f(n)$
	For $k=k_0+1:j-2$
	If $f_1+\sum_{n=k_0+1}^{k-1}2f(n)+f(k)>f_0$
	The selected user set $I_{j,k}=I_{j,k-1}$.Break.
	else if $f_1+\sum_{n=k_0+1}^{k-1}2f(n)+f(k)<f_0$ and
	$f_1+\sum_{n=k_0+1}^{k}2f(n)>f_0$
	The selected user set $I_{j,k}=I_{j,k-1}+\{SU_k\}$
	or $I_{j,k}=I_{j,k-1}+\{SU_{K-(k-k_0)+1}\}$.
	else
	The selected user set
	$I_{j,k}=I_{j,k-1}+\{SU_k\}+\{SU_{K-(k-k_0)+1}\}$.

3) The final set I_j of SUs for parallel communication is obtained.	

4.2 Throughput Analysis

A secondary node is denoted by $SU_o, o\in\{1,2,\cdots,K\}$, which is the first selected secondary node to relay a primary packet. As described in Section 3, the multi-hop transmission of a PU can be divided into two parts: the primary and the secondary network transmissions. The primary network transmission of our proposed protocol is the same as that of the protocol in Ref. [11], but the secondary network transmission is quite different from these two protocols. When a secondary node is selected as a relay, OM or SC is used to multiplex the primary and secondary traffic [11], but the multiplexing technology is not employed in the proposed protocol that conducts parallel communication of the SUs. To facilitate the comparison, the throughput of the PU and SUs in Ref. [11] is described as the follows. The elements in set J are the selected secondary transmitters for relaying a primary packet, the number of which is denoted by M , where $1 \le M \le K - o + 1$. The average throughput of the SUs is written as

$$T_{S_0} = \frac{\sum_{SU_k \in J} \log\left(1 + d_{SU_k SD}^{-\alpha}\left(1-\beta\right) P_S / N_0\right)}{M} \text{ bit/s/user,} \tag{9}$$

where SC is used to multiplex the primary and secondary traffic and β is the power distribution factor. The bandwidth of the transmission channel is normalized as 1 Hz. Secondary transmission can be achieved over the primary spectrum only when an SU relays the primary packets cooperatively. During a primary packet transmission, the performance of the SUs is expressed by Equations (9) and (11), which are both achieved by each cooperative SU. The e2e throughput of the PU is written as

$$T_{P_0} = \frac{E\left[N\right] \cdot R_P + \left(K - o + 1\right) \cdot \log\left(1 + d_h^{-\alpha} \beta P_S / N_0\right)}{\left(E\left[N\right] + K - o + 1\right)^2} \text{ bit/s.} \tag{10}$$

$E\left[N\right]$ denotes the number of hops for the packet transmission in the primary network. In Equations (10) and (12), the transmission delay can be represented by the number of transmission hops.

For the proposed protocol, the average throughput of the SUs and the e2e throughput of the PU are respectively written as

$$T_S = \frac{\sum_{i=o}^{K} \sum_{SU_k \in \mathrm{I}_i} \log\left(1 + d_{SU_k SD}^{-\alpha} P_S / N_0\right)}{K - o + 1} \text{ bit/s/user, and} \tag{11}$$

$$T_P = \frac{E\left[N\right] \cdot R_P + \left(K - o + 1\right) \cdot \log\left(1 + d_h^{-\alpha} P_S / N_0\right)}{\left(E\left[N\right] + K - o + 1\right)^2} \text{ bit/s.} \tag{12}$$

Equations (9) and (11) represent the throughputs of the SUs corresponding to each cooperative SU. These throughputs mainly depend on the number of SUs that perform the secondary transmission corresponding to each cooperative SU. According to the protocol in Ref. [11], one SU always performs the secondary transmission corresponding to each cooperative SU. In our proposed protocol, when K has a small value, the number of elements in set I_i (which is selected by the search algorithm inTable 1) is very small or equal to zero, which might result in less than one SU performing the secondary transmission corresponding to each cooperative SU; thus, $T_S < T_{S_0}$. As K increases, the number of elements in set I_i also increases. Thus, more than one SU performs the secondary transmission corresponding to each cooperative SU; consequently, $T_S \ge T_{S_0}$. As K continues to increase, the number of SUs that perform the secondary transmission corresponding to each cooperative SU is much greater than one; therefore, $T_S >> T_{S_0}$. In addition, SC was used to multiplex the primary and secondary traffic in Ref. [11]. As a result, the performance of the proposed protocol for the PU is slightly improved, and the performance for the SUs is significantly improved.

5. Numerical Results

Our simulations mainly compare the performance of the two multi-hop transmission protocols. One protocol is conducted with parallel communication whereas the other is conducted with non-parallel communication, which is considered a special situation in Ref. [11], where the largest number of cooperative SUs and the highest throughput of the SUs are achieved. The simulation parameters are as follows: $R_P = 3.5$ bit/s/Hz (the minimum achievable rate for primary nodes), $\Theta_P = 2^{R_P} - 1$, $\alpha = 3$, $1-\varepsilon_P = 0.1$ (the minimum outage probability of primary nodes), and $\beta = 0.6$ (the power allocation index for a PU based on SC).

Fig. 2 shows the average throughput of the SUs versus SNR at the SUs for the two protocols and for the Only-S and P-to-S strategies. The multi-hop transmission protocol using parallel communication curves are calculated using Equation (11), and the multi-hop transmission protocol using non-parallel communication curves are calculated using Equation (9). The special parameters are as follows: $K = 10$ is the number of SUs, $d_h = d_v = 1/(K+1)$ is defined in Section 2, and $d_S = 3/(K+1)$ denotes the distance between the secondary transmitter and the receiver. Fig. 2 shows that the average throughput of the SUs in the proposed protocol is equal to zero when the SNR of the SUs is less than or equal to -6 dB, which is caused by the fact that the right-hand side of Inequation (8) is less than 0.0025. Very few SUs can meet the requirement of Inequation (8), i.e., $\mathrm{I}_i = \varnothing$, and Equation (9) is equal to zero. The average throughput of the SUs in the protocol using non-parallel communication logarithmically changes with the SNR. In this SNR region, the secondary throughput in the protocol using non-parallel communication is larger than that in the proposed protocol. When the SNR of the SUs is more than -6 dB, the average throughput of the SUs in the proposed protocol grows rapidly, particularly when the SNR is more than 1 dB. The secondary throughput of the proposed protocol is greater than that of the protocol that uses non-parallel communication not only in the Only-S routing strategy but also in the P-to-S routing strategy. Thus, the proposed transmission protocol has a better performance in this SNR region. In addition, we find that the throughput of the SUs of the Only-S routing strategy is higher than that of the P-to-S routing strategy. These results agree with those in Ref. [11].

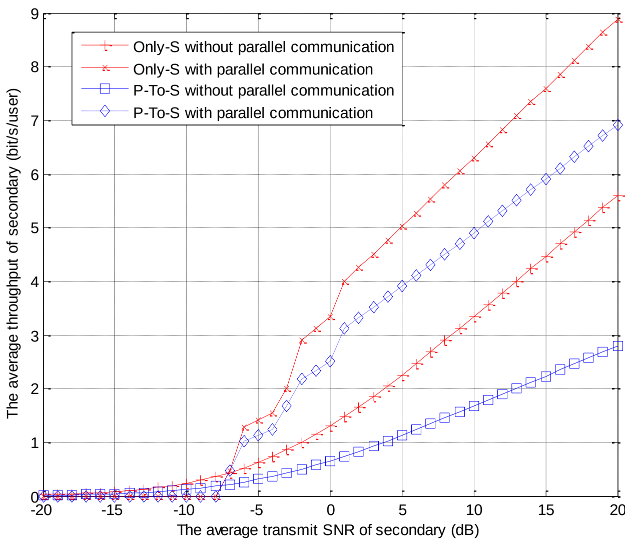

Fig. 2. Average throughput of the SUs for the different transmission protocols

The chart in **Fig. 3** is generated using the same parameters as those in Fig. 2, which shows the e2e throughput of the PU versus SNR of the SU of the two protocols and of the Only-S and P-to-S strategies. The curves of the protocol with parallel communication are calculated using Equation (12), and the curves of the protocol without parallel communication are calculated using Equation (10). Fig. 3 shows that the primary throughput of the P-to-S strategy is significantly greater than that of the Only-S strategy, and this result agrees with that in Ref. [11]. Compared with the Only-S strategy, the P-to-S strategy offers a better tradeoff between the primary and secondary throughputs. In addition, under the same routing strategy, the e2e throughput of the PU of the proposed protocol is higher than that of the protocol using non-parallel communication. The reason for this result is illustrated as follows: once an SU is selected as a relay for the PU in the proposed protocol, it employs all its transmitter power to relay the primary packet and will only be used for relaying the primary packets. In the protocol using non-parallel communication, the selected SU is used to not only relay the primary packet but also transmit the secondary packets. In this case, the transmitter power for the SU is correspondingly divided into two parts to achieve these two transmissions.

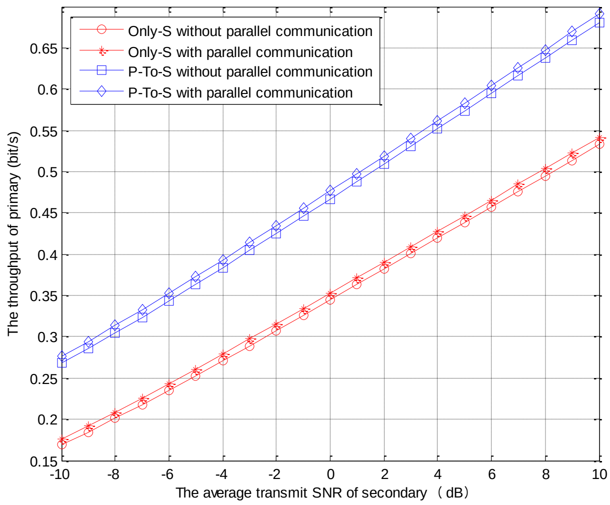

Fig. 3. The e2e throughput of the PU of the different transmission protocols

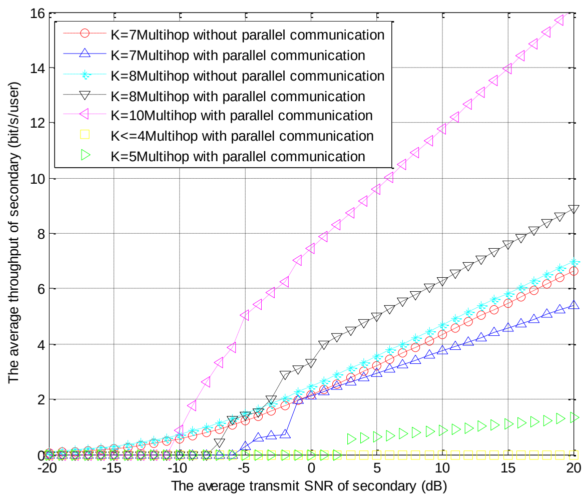

Fig. 4. Average throughput of the SUs with different number of SUs

Fig. 4 shows the average throughput of the SUs versus SNR of SUs with different numbers of SUs, i.e., the number of SUs is fixed at $K = 4,7,8,10$ for the proposed protocol and at $K = 7,8$ for the protocol using non-parallel communication. All other parameters are the same as those shown in Fig.2. The parallel communication factor is obtained by the SU selection algorithm in Table 1, i.e., $l = 5$, which means that when the number of SUs is less than five, parallel communication for the SUs cannot be achieved. Fig. 4 shows that the throughput of the SUs in the proposed protocol is always equal to zero when $K \le 4$. We also find that the average throughput of the SUs in the protocol using non-parallel communication is higher than that in the proposed protocol for $K \le 7$. For $K \ge 8$, the average throughput of the SUs in the protocol using non-parallel communication is always smaller than that in the proposed protocol. When there are more than seven SUs, the proposed transmission protocol shows a better performance than the multi-hop transmission protocol using non-parallel communication. For an increasing number of SUs, the secondary performance of the proposed transmission protocol is significantly improved.

6. Concluding remarks

We have proposed a multi-hop transmission protocol based on parallel communication of SUs, which is achieved by cooperative spectrum sharing. The primary packets are transmitted by multiple hops whereas the secondary packets are transmitted through a single hop. Two proposed opportunistic routing strategies are employed for the multi-hop transmission. A search algorithm is proposed to select the SUs for parallel communication. The performance of the SUs and the PU is interpreted by the throughput. The simulations illustrate the different performance between the Only-S and the P-to-S strategies and between multi-hop transmission using non-parallel communication and parallel communication. The numerical results demonstrate that the proposed protocol can improve the performance of the SUs and the PU under certain conditions. Thus, the research reported in this paper has an important significance. Our work is based on the geometrical simplifying assumptions with the objective of achieving both a solvable theoretical model and an insightful analysis of the cooperative spectrum sharing between the PU and the SUs. More general network topologies will be considered in our future work.

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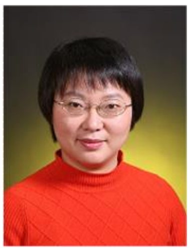

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