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# Relay-Assisted Primary and Secondary Transmissions in Cognitive Radio Networks

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**ABSTRACT** We assume a set of cognitive relay nodes that assists both primary and secondary transmissions in a time-slotted cognitive radio networks. To regulate the channel access of the various nodes in the network, we propose an overlapped spectrum sensing strategy for channel sensing, where the secondary source node senses the channel from the beginning of the time slot and the cognitive relay nodes sense the channel for double the sensing time used by the secondary source node to detect the activities of both the primary and secondary source nodes. Hence, the secondary source node has an intrinsic priority over the relay nodes. The relay nodes help both the primary user and the secondary user to deliver their unsuccessfully decoded packets at their destinations. In a given time slot, the scheduled relay node for data transmission starts its transmission when both the primary and secondary users are sensed to be inactive (i.e. have no data to transmit). We propose two optimization-based formulations with quality-of-service (QoS) constraints involving average queueing delay and average service rate requirements. We investigate both cases of perfect and imperfect spectrum sensing. To further enhance the users' QoS requirements, we propose three packet decoding strategies at the relay nodes and compare their performance. We derive an upper bound on the secondary queue average service rate to determine which decoding strategy can achieve that bound. Our numerical results show the benefits of relaying and its ability to enhance the performance of both the primary and secondary users. Moreover, the performance of the proposed schemes is close to the derived upper bound.

**INDEX TERMS** Cognitive radio, queueing delay, relaying, cooperative communications, stability analysis.

## I. INTRODUCTION

For efficient usage of radio spectrum and to achieve high reliability and high speed wireless transmission, cognitive radio and cooperative communications are utilized as two of the most promising technologies in wireless communications. In cooperative communications [2]–[4], some of the channel resources, e.g., time slots and bandwidth, are assigned to one or a set of relay nodes for cooperation. These relay nodes cooperate with the source nodes to help in forwarding their data packets to a destination node. Cooperation enhances communication reliability, reduces the required transmitted power and achieves spatial diversity. In some scenarios, the use of relay nodes may result in some bandwidth efficiency loss since portion of the channel resources are assigned to the relay nodes to perform their task. To solve this critical problem, cognitive relaying is proposed as a powerful solution to this problem since the cognitive relay nodes can utilize the

channel only when the source nodes are not utilizing it (i.e. when the source nodes have no data packets to transmit).

In [5], Sadek *et al.* considered a cognitive relay that aids multiple nodes in transmitting their data to a common receiver. The proposed schemes exploit the source burstiness to enable cooperation during unutilized time slots by the buffer-aided source nodes in a time-division multiple access (TDMA) network. In [6], the authors proposed to deploy a *dumb* relay node in cognitive radio networks to improve network spectrum efficiency. The relay node helps both the primary and the secondary nodes in their transmissions. The authors analyzed and optimized the proposed scheme for a network model consisting of a pair of primary users (PUs) and a pair of secondary users (SUs). In [7], the authors considered a set of relay nodes that serves multiple PUs when they do not have data to send. The authors proposed two secondary access scenarios. In the first access

scenario, the SUs sense the activity of both the PUs and the relay nodes, thereby remaining silent when any of them is active. In the second access scenario, the relay nodes and the SUs are assumed to perform a random access scheme. Hence, their transmissions may collide.

Relay nodes with data buffers have received great attention in the wireless communications literature recently [8]–[14]. In [10] and [11], the authors proposed a max-max relay selection scheme. In this scheme, the relay node with the best source-relay channel for reception and the best relay-destination channel for transmission are simultaneously selected. The scheme is employed over two time slots where the schedule for the source and relay transmissions is fixed a priori. However, this fixed-assignment limitation has been relaxed in [12] where each slot is allocated dynamically to either the source or relay transmissions according to the instantaneous quality of the links and the buffer state information at the relay nodes. In [13] and [14], the authors investigated the two-hop communication system, where the SU exploits periods of silence of the PU to transmit its packets to a set of relay nodes. Moreover, the relay nodes can transmit even when the PU has data packets to send since they can act together and create a beamformer to suppress or even null the interference at the primary destination. The authors assumed perfect instantaneous channel state information at the relay nodes.

In this paper, we investigate the impact of having a set of buffered relay nodes with cognitive capabilities to enhance both the primary and secondary users quality-of-service (QoS) requirements.<sup>1</sup> The relay nodes accept fractions of the unsuccessfully delivered packets at the primary and secondary destination nodes and store them into their buffers. The relay nodes then forward these packets to the primary and secondary destinations when both the primary and secondary nodes are sensed to be silent. Motivated by the fact that *the perfect channel estimation is impossible in practice and it consumes a great portion of the communication time*,<sup>2</sup> we do not assume instantaneous channel knowledge and, hence, our schemes do not involve relay selection on the basis of instantaneous channel quality.<sup>3</sup>

We can summarize the contributions in this paper as follows.

- We propose an optimized network where a set of relay nodes can assist both the primary and the secondary systems under the priority in transmission assigned to the PUs over the SUs. To coordinate the channel access

<sup>1</sup>As argued in many references in the literature, e.g., [15]–[17] and the references therein, the proposed cognitive cooperation schemes and the theoretical development in this paper can be generalized to cognitive radio networks with more PUs and more SUs, in which the PUs and the SUs are operating under TDMA or frequency-division multiple access (FDMA).

<sup>2</sup>As the number of relay nodes increases, the complexity of channel estimation and channel feedback are greatly increased as well. Hence, the cost of channel estimation makes it impractical, especially at high number of relay nodes. Moreover, the feasibility of channel estimation is questionable.

<sup>3</sup>As shown in the numerical results, although we do not assume channel state information at the transmitting nodes, we can still achieve the upper bound of the nodes' data rates.

among the transmitting nodes, we propose a new efficient overlapped spectrum sensing technique.

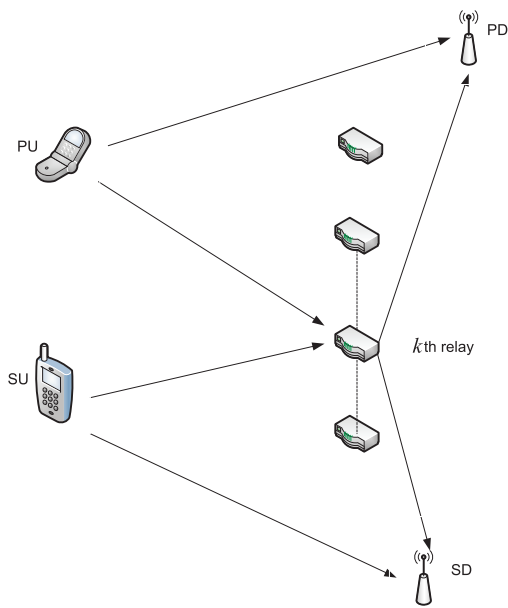
- We propose an ordered acceptance strategy, denoted by  $\mathcal{S}_{OD}$ , in which the relays are ordered in terms of accepting the undelivered packets of the PU and the SU into their queues.
- To simplify the decoding process at the relay nodes, we propose a random assignment decoding scheme, denoted by  $\mathcal{S}_{RD}$ , and a round robin decoding scheme, denoted by  $\mathcal{S}_{RR}$ , in which each relay node is assigned to the decoding role for a fraction of the time slots.
- We propose two optimization-based formulations. In the first formulation, we maximize the secondary average service rate for certain queueing delay requirements at both primary and the secondary users. In the second formulation, we minimize the number of relay nodes deployed in the network to achieve specific levels of QoS requirements at both the primary and secondary users.
- We investigate the case of sensing errors at the relays' spectrum sensors. In contrast with many existing work involving automatic repeat request (ARQ) feedback, we take into our consideration the cost of the feedback durations.
- We show analytically and numerically that  $\mathcal{S}_{OD}$  outperforms both  $\mathcal{S}_{RD}$  and  $\mathcal{S}_{RR}$ , in terms of the queue's service rates, for the case of a negligible feedback duration per relay.

The rest of the paper is organized as follows. In Section II, we describe the system model adopted in this paper. The proposed decoding strategies are presented in Section III. In Section IV, we investigate the average arrival and service rates and the average queueing delays of the nodes. The optimization problems are formulated in Section V. The system with sensing errors is investigated in Section VI. We provide some numerical results in Section VII and conclude the paper in Section VIII.

## II. SYSTEM MODEL

We consider the following wireless network. A primary source node 'p' communicates with its destination node 'pd' in the presence of a secondary source node 's' that wishes to communicate with its destination node 'sd'. A set of  $N$  relay nodes labeled as  $1, 2, 3, \dots, N$ , as shown in Fig. 1, are assumed to help both primary and secondary source nodes in their transmissions. The relay nodes are assumed to be half-duplex, which means that they either transmit or receive but cannot do both at the same time. We consider a wireless collision channel model where concurrent transmissions by two or more nodes are assumed to be lost [7]. Each source node has an infinite data buffer for storing fixed-length packets. We assume that each queueing system operates as discrete-time Geo/Geo/1 [5], [7], [18].<sup>4</sup> The arrived packets at the

<sup>4</sup>The notion of discrete-time Geo/Geo/1 queue is used to describe a queueing system with a Bernoulli arrival process and geometrically distributed service times.



**FIGURE 1.** System model:  $N$  relays assist primary and secondary transmissions from the PU and the SU to the primary destination (PD) and secondary destination (SD), respectively.

nodes' buffers are assumed to be independent and identically distributed (i.i.d.) Bernoulli random variables from one time slot to another with averages  $\lambda_p \in [0, 1]$  and  $\lambda_s \in [0, 1]$  packets per time slot for the primary and secondary queues, respectively. Arrival processes at the primary and secondary buffers are statistically independent of one another. Relay node  $k \in \{1, 2, \dots, N\}$  has two distinct queues: a queue for storing the relaying packets of the PU, denoted by  $Q_{p,k}$ , and a queue for storing the relaying packets of the SU, denoted by  $Q_{s,k}$ . If a terminal transmits during a time slot, it sends exactly one packet to its respective receiver.

### A. MEDIUM ACCESS CONTROL (MAC) LAYER

We propose an overlapped spectrum sensing scheme as depicted in Fig. 2. The SU senses the channel up to  $\tau$  seconds relative to the beginning of the time slot, while all the relay nodes sense the channel over the interval  $[0, \tau]$  to detect the PU's activity and over the interval  $[\tau, 2\tau]$  to detect SU's activity. There is a feedback phase at the end of the time slot to indicate the status of packet delivery. The PU transmits the packet at the head of its queue starting from the beginning of the time slot. If the PU is sensed to be idle by the SU, the SU transmits the packet at the head of its queue after  $\tau$  seconds from the beginning of the time slot. A relay node with nonempty queues transmits during a time slot after  $2\tau$  seconds if that relay node is scheduled to transmit and it senses the PU and the SU to be idle. For the relay nodes' channel access, we assume TDMA is used as the multiple-access scheme for the communication between the relay nodes and the destinations where only one relay node is selected for data transmission in a given time slot. The probability that relay node  $k$  is scheduled to transmit

during a time slot is  $\omega_k$ .<sup>5</sup> This means that over a large number of time slots relay node  $k$  is assigned to transmit during a fraction of time slots  $\omega_k$  of the total time slots. It is clear that  $\sum_{k=1}^N \omega_k = 1$ . We define a vector  $\boldsymbol{\omega} = [\omega_1, \omega_2, \dots, \omega_N]$  to indicate the fraction of time slots allocated to each relay for transmission. If relay node  $k$  is scheduled for transmission, which occurs with probability  $\omega_k$ , it chooses a packet from  $Q_{p,k}$  with probability  $\alpha_k$  and from  $Q_{s,k}$  with probability  $1 - \alpha_k$ . We define the  $N$ -dimensional vector  $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \dots, \alpha_N]$ .

If a relay node receives a data packet during a time slot, it distinguishes between the primary and the secondary transmissions through an identifier contained in each transmitted packet.<sup>6</sup> If a relay node correctly receives a data packet, it decides to accept the packet with a certain probability that depends on the packet's source. More specifically, the acceptance probability vector of the undelivered primary packets is  $\mathbf{f}_p$ , where the element  $f_{p,k}$  is the probability that relay node  $k$  admits a correctly received primary packet to  $Q_{p,k}$ . Similarly, the vector  $\mathbf{f}_s$  has  $N$  elements with  $f_{s,k}$  being the probability of admitting a correctly received secondary packet to  $Q_{s,k}$ .

### III. PROPOSED DECODING STRATEGIES

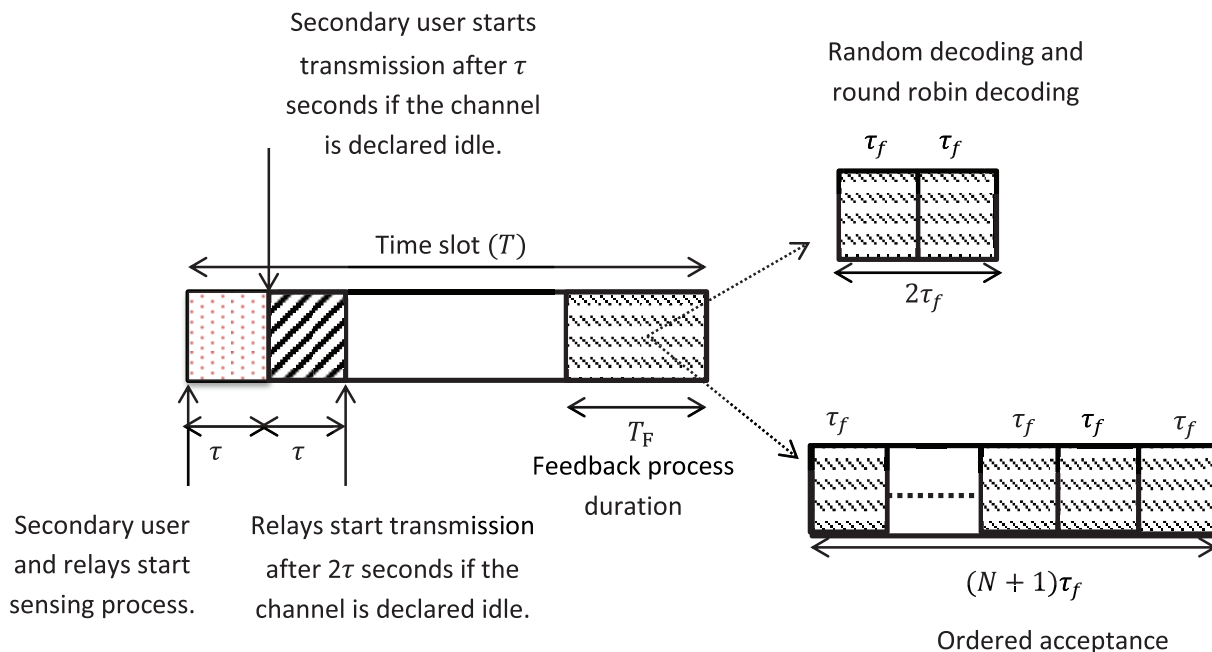
In this section, we propose three decoding strategies that can be adopted at the relay nodes. The proposed strategies differ in terms of complexity and the required feedback duration to implement the feedback phase.

#### A. ORDERED ACCEPTANCE STRATEGY

When the ordered acceptance strategy,  $S_{OD}$ , is utilized, the operation of the relay nodes is described as follows. If a relay node senses either the PU or SU to be busy, it operates in the receiving mode until the data transmission time within the time slot is over. If the primary destination (PD) or secondary destination (SD) acknowledges the correct reception of the transmitted data packet by sending an acknowledgment (ACK) message, the relay nodes discard what they have received from the PU or the SU. If the PD or SD declares its failure to decode the transmitted packet by generating a negative-acknowledgment (NACK) message, the relay nodes attempt to decode the received packet and determine its origin. If the received packet is correctly decoded and, hence, its origin is identified by the first-ranked relay, it decides whether to accept the packet. If the packet is admitted, an ACK is transmitted by the relay node to inform the PU or SU to drop the packet from its queue and to notify the other relay nodes that the packet has already been accepted by the first-ranked relay. If the first-ranked relay fails to decode the packet or does not accept it, that relay remains silent and

<sup>5</sup>Even though a relay may be scheduled for transmission in a particular time slot, it will only transmit in this time slot if the PU and the SU are sensed to be idle.

<sup>6</sup>The reason the origin of a packet is identified by a certain embedded identifier is that spectrum sensing may be erroneous. If sensing were perfect, the relay could identify the origin of transmission depending on whether it has proceeded at the beginning of the time slot or after  $\tau$  seconds. In this paper, although we start with the perfect sensing case, we later address the issue of spectrum sensing errors.



**FIGURE 2.** Time slot structure. The explanation for the feedback process and its duration is provided at the end of Section II.

the second-ranked relay makes the acceptance decision in case it has decoded the packet correctly. Generally speaking, a relay node, depending on its decoding rank, decides whether to accept a correctly decoded packet provided that all the preceding relays (i.e. relays with lower decoding orders) do not admit the packet. We assume perfect decoding of the feedback messages at all nodes [5]. This assumption is reasonable when strong channel codes with low modulation indices are employed for the feedback channel [5].

The relays' acceptance order is the  $N$ -tuple  $\mathbf{m}_n = (m_1, m_2, \dots, m_i, \dots, m_N)$ , where  $m_i \in \{1, 2, \dots, N\}$  and  $m_i \neq m_k, \forall i, k : i \neq k$ . The  $N$ -tuple  $(m_1, m_2, \dots, m_N)$  means that relay node 1 is assigned the  $m_1$ th acceptance rank, relay node 2 is assigned the  $m_2$ th rank and so on. Let  $\Pi$  denote the set of all the permutations over the set  $\{1, 2, \dots, N\}$ . There are  $N!$  such permutations, where  $N!$  indicates the factorial of  $N$ . We define  $\mathbf{m}_n$  as the  $n$ th permutation of  $\Pi$ . In addition, we define the probability  $\rho_n^{(p)}$  as the probability of the  $n$ th permutation of  $\Pi$  resulting in the acceptance order  $(m_1, m_2, \dots, m_N)$  if the received packet comes from the PU. This probability can be also interpreted as the fraction of time slots with ranking order  $(m_1, m_2, \dots, m_N)$ . Similarly, we define the probability  $\rho_n^{(s)}$  if the packet is transmitted by the secondary source node. Finally, we define the two  $N!$ -dimensional vectors  $\boldsymbol{\rho}^{(p)}$  and  $\boldsymbol{\rho}^{(s)}$  that contain the aforementioned probabilities.

The medium access control (MAC) operation can be summarized as follows

- At the beginning of a time slot, the primary source transmits the packet at the head of  $Q_p$  to the PD. The secondary source and the relay nodes can overhear the primary transmission.

- The secondary source senses the spectrum over the first  $\tau$  seconds of the time slot. If it detects the channel to be unoccupied by the primary source, it transmits the packet at the head of  $Q_s$  if the buffer is not empty. The relay nodes overhear the secondary transmission.
- If the primary source is active and its transmitted packet is received correctly by the PD, an ACK message is fed back from the PD. The primary packet is then dropped from the primary queue,  $Q_p$ . In addition, the relay nodes discard what they have received.
- If the primary packet is not received correctly by the PD, a NACK message is fed back from the PD. The relay nodes then attempt to decode the received packet and determine its origin. Based on their primary packet acceptance ranking, the first-ranked relay node decides whether or not to accept the primary packet if it is decoded correctly. If the packet is admitted by the relay node, an ACK message is transmitted, thereby inducing the primary source node to drop the packet from its queue head. If the first-ranked cognitive relay node fails to decode the primary packet or does not accept it, the second-ranked relay node tries to decode it. This relay node issues an ACK message if it decodes the packet correctly and decides to accept it. The operation continues based on the used ranking order in the ongoing time slot until a relay decodes and accepts the source node's packet. If no relay node accepts the packet, the packet will be kept in the primary source node's queue for future retransmissions.
- In the case of a secondary transmission, the relay nodes perform the same operation as described for

primary transmissions. However, the ranking order of the relay nodes to accept the secondary packets differs from the ranking order of accepting the primary packets. The relay nodes should use the appropriate decoding order as explained earlier.

- If both the primary source node and the secondary source node are found to be inactive, the relay nodes start transmitting the packets at the heads of their queues based on the TDMA scheme. The  $k$ th relay node is scheduled for data transmission in a given time slot with probability  $\omega_k$ .

**B. RANDOM ASSIGNMENT DECODING STRATEGY**

The basic difference between random assignment decoding,  $\mathcal{S}_{RD}$ , and  $\mathcal{S}_{OD}$  is that in  $\mathcal{S}_{RD}$  only one relay is scheduled to decode, and possibly accept, the undelivered primary or secondary packet in a given time slot. Hence, the ordered decoding, where all relays attempt to decode the source's packet, has better probability of decoding the ongoing transmission by at least one of the  $N$  relay nodes. In the  $\mathcal{S}_{RD}$  scheme, the probability that relay node  $k$  is assigned the decoding role in a time slot is denoted as  $\beta_k$ . We define the vector  $\beta = [\beta_1, \beta_2, \dots, \beta_N]$  with the constraint  $\sum_{k=1}^N \beta_k = 1$ . The vectors  $\alpha$ ,  $\omega$ ,  $f_p$  and  $f_s$  are similar to those in  $\mathcal{S}_{OD}$ . The operation of the relay nodes can be summarized as follows

- At the beginning of each time slot, the index,  $k$ , of the randomly selected relay node for data decoding role is generated according to the discrete distribution  $\beta$ .
- If the primary packet is not decoded correctly at the PD, a NACK message is fed back from the PD. The relay node which is assigned the packet decoding role tries to decode the unsuccessfully decoded primary packet at the PD. If the packet is decoded correctly at the relay node, the relay node accepts it with probability  $f_{p,k}$  and an ACK message is transmitted, thereby inducing the primary source to drop the packet. If the cognitive relay node assigned the packet decoding role fails to decode the primary packet or does not accept it, the packet will be kept in the primary queue  $Q_p$  for future retransmissions.
- If the primary source is sensed by the secondary source to be inactive, the secondary source, if its queue is not empty, starts its transmission and the relays repeat the same operation as described earlier for the PU's relaying scenario. Note that the origin of the received packets at the assigned relay can be known from the packet's identifier. Based on the identifier, the relay node  $k$  assigned the packet decoding role accepts the packet into  $Q_{p,k}$  with probability  $f_{p,k}$ , or into  $Q_{s,k}$  with probability  $f_{s,k}$ .

**1) ROUND ROBIN DECODING STRATEGY**

In this scheme, each relay node is selected to decode the data packets in a round robin manner. More specifically, if the relay node  $k$  is selected for relaying the PU's packet in

time slot  $t$ , it will be selected again for relaying in time slot  $t + N$ . Hence, the random round robin decoding,  $\mathcal{S}_{RR}$ , is a simplification of  $\mathcal{S}_{RD}$  in which the decoding assignment probability is equal for all relay nodes. In particular, the  $k$ th relay node is selected for data decoding with probability  $\beta_k = 1/N$ , where  $k \in \{1, 2, \dots, N\}$ .

We conclude this section by investigating the outage probability of the links under each of the proposed decoding schemes. The channel outage event for the relay and the SU transmissions can be calculated as follows. The transmitters adjust their transmission rates depending on when they start transmission during the time slot. Assuming that the number of bits in a packet is  $b$  and the time slot duration is  $T$ , the transmission rate is

$$r_i = \frac{b}{T \left(1 - \frac{T_{SF}}{T}\right)} \tag{1}$$

where  $T_{SF} = i\tau + T_F < T$  with  $T_F$  denoting the time spent to perform the feedback process. The parameter  $i = 0$  if the transmitter is the primary source node since its transmission proceeds at the very beginning of the time slot,  $i = 1$  for the secondary source node since its transmission is preceded by a spectrum sensing duration of  $\tau$  seconds, and  $i = 2$  for all the relay nodes since their transmissions are preceded by a spectrum sensing duration of  $2\tau$  seconds. Channel outage occurs when the data transmission rate is greater than the channel capacity. Hence, the channel outage probability of the link connecting Node  $j$  and Node  $k$  is given by [5]

$$P_{j,k} = \Pr \left\{ r_i > W \log_2 (1 + \gamma_{j,k} h_{j,k}) \right\} \tag{2}$$

where  $W$  represents the channel bandwidth,  $\gamma_{j,k}$  represents the received signal to noise ratio (SNR) when  $h_{j,k} = 1$ , and  $h_{j,k}$  represents the channel gain (i.e. norm square of the channel coefficient), which is an exponentially-distributed random variable in the case of Rayleigh fading channel. The channel gain  $h_{j,k}$  is assumed to be independent from one time slot to another and from one link to another. The outage probability can be expressed as

$$P_{j,k} = \Pr \left\{ h_{j,k} < \frac{2^{\frac{r_i}{W}} - 1}{\gamma_{j,k}} \right\} \tag{3}$$

Assuming that the average value of  $h_{j,k}$  is  $\sigma_{j,k}^2$ ,

$$P_{j,k} = 1 - \exp \left( - \frac{2^{\frac{r_i}{W}} - 1}{\gamma_{j,k} \sigma_{j,k}^2} \right). \tag{4}$$

Let  $\bar{P}_{j,k} = 1 - P_{j,k}$  be the probability of correct reception. It is therefore given by

$$\bar{P}_{j,k} = \exp \left( - \frac{2^{\frac{r_i}{W} \left(1 - \frac{T_{SF}}{T}\right)} - 1}{\gamma_{j,k} \sigma_{j,k}^2} \right). \tag{5}$$

The duration of the feedback process,  $T_F$ , varies according to the decoding strategy adopted by the relay nodes. In the

TABLE 1. List of key variables.

Symbol	Description
$T$ and $W$	Slot duration and channel bandwidth
$\tau$	One duration of channel sensing
$\tau_f$	Duration of feedback process from one node
$\omega_k$	Probability that relay node $k$ is scheduled to transmit during a time slot is $\omega_k$
$\alpha_k$	Probability of choosing a packet from $Q_{p,k}$ for transmission
$f_{\ell,k}$	Probability that relay node $k$ admits a correctly received packet from Node $\ell \in \{p, s\}$ to $Q_{\ell,k}$
$\rho_n^{(\ell)}$	Probability of the $n$ th permutation of $\Pi$ resulting in the acceptance order $(m_1, m_2, \dots, m_N)$ if the received packet comes from Node $\ell \in \{p, s\}$
$\beta_k$	Probability that relay node $k$ is assigned the decoding role in a time slot
$P_{j,k}$	Outage probability of the link between Node $j$ and Node $k$
$\lambda_\ell$ and $\lambda_{\ell,k}$	Average arrival rate to $Q_\ell$ and $Q_{\ell,k}$ , $\ell \in \{p, r\}$
$\mu_\ell$ and $\mu_{\ell,k}$	Average service rate of $Q_\ell$ and $Q_{\ell,k}$ , $\ell \in \{p, r, s\}$
$Q_{\ell,k}$	Relaying buffer at relay node $k$ to store the packets of Node $\ell$
$Q_\ell$	Queue (buffer) of source Node $\ell$

case of  $S_{OD}$ , the relay nodes are ordered in terms of sending the ACK messages if they accept a correctly received packet. If each relay node spends  $\tau_f$  seconds for employing the feedback process, then the overall feedback duration is  $T_F = (N + 1)\tau_f$  given that the PD also needs  $\tau_f$  seconds to acknowledge the reception of a data packet. On the other hand,  $S_{RD}$  and  $S_{RR}$  need only  $T_F = 2\tau_f$  for the feedback process to be realized. From (5), as the feedback duration increases, the outage probabilities of the channels increase. The decoding process, taking into account the duration of the feedback process, will result in a reduction in the allowable data transmission time of both the primary and secondary source nodes. That is, the total data transmission time will be reduced to  $T - T_{SF}$ . A list of the used variables is given in Table 1.

**IV. QUEUES' MEAN ARRIVAL AND SERVICE RATES AND MEAN QUEUEING DELAYS**

We first analyze the different decoding schemes for the perfect spectrum sensing scenario. Then, we consider spectrum sensing errors in the next section.

**A. AVERAGE ARRIVAL AND SERVICE RATES**

1) ORDERED ACCEPTANCE

Consider the primary queue first. A packet can be served in either one of the following events: the channel between PU and PD is not in outage; or the primary channel is in outage and one of the relay nodes can decode the packet correctly and accepts it. For relay node  $k$  to admit the primary packet in its buffer, all the relays having a higher priority in accepting the packet should either fail to receive the packet correctly due to channel outage, or reject the packet. Hereinafter, we adopt the notation  $\bar{x} = 1 - x$ . The average service rate of the primary queue is given by

$$\mu_p = \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \left[ \bar{P}_{p,k} f_{p,k} \sum_{\Pi} \rho_n^{(p)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \bar{P}_{p,v} f_{p,v} \right]. \tag{6}$$

The secondary queue can be analyzed in a similar fashion. The probability of the primary queue being empty is given by [5], [19], [20]

$$\pi_{p,o} = 1 - \frac{\lambda_p}{\mu_p}. \tag{7}$$

When the queue of the primary source node, denoted by  $Q_p$ , is empty, the packet at the queue head of the secondary source data queue,  $Q_s$ , is served in either one of the following two events: 1) the channel between the SU and SD is not in outage; or 2) the channel between the SU and the SD is in outage and one of the relay nodes decodes and decides to accept the packet. The average service rate of the secondary queue,  $Q_s$ , is thus given by

$$\begin{aligned} \mu_s &= \pi_{p,o} \left[ \bar{P}_{s,sd} + P_{s,sd} \sum_{k=1}^N \left( \bar{P}_{s,k} f_{s,k} \sum_{\Pi} \rho_n^{(s)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \bar{P}_{s,v} f_{s,v} \right) \right]. \end{aligned} \tag{8}$$

The probability that the secondary queue is empty is

$$\pi_{s,o} = 1 - \frac{\lambda_s}{\mu_s}. \tag{9}$$

Let  $\lambda_{p,k}$  and  $\lambda_{s,k}$  be the arrival rates at the queues  $Q_{p,k}$  and  $Q_{s,k}$  of relay node  $k$ , respectively. For a packet arrival at  $Q_{p,k}$  to occur, the primary queue should be nonempty. For a packet arrival at  $Q_{s,k}$  to occur, the primary queue must be empty to preclude primary transmission and the secondary queue should be nonempty. The expressions for the arrival rates follow directly from (6) and (8) and are given by

$$\lambda_{p,k} = \bar{\pi}_{p,o} P_{p,pd} \left[ \bar{P}_{p,k} f_{p,k} \sum_{\Pi} \rho_n^{(p)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \bar{P}_{p,v} f_{p,v} \right] \tag{10}$$

and

$$\lambda_{s,k} = \bar{\pi}_{s,o} \pi_{p,o} P_{s,sd} \left[ \bar{P}_{s,k} f_{s,k} \sum_{\Pi} \rho_n^{(s)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \bar{P}_{s,v} f_{s,v} \right]. \quad (11)$$

For a relay node to transmit a data packet, both the primary and secondary queues should be empty. Relay node  $k$  transmits from  $Q_{p,k}$  with probability  $\alpha_k$  and from  $Q_{s,k}$  with probability  $1 - \alpha_k$ . The average service rates,  $\mu_{p,k}$  and  $\mu_{s,k}$ , of  $Q_{p,k}$  and  $Q_{s,k}$  at relay node  $k$ , respectively, are given by

$$\begin{aligned} \mu_{p,k} &= \omega_k \pi_{p,o} \pi_{s,o} \alpha_k \bar{P}_{k,pd}, \\ \mu_{s,k} &= \omega_k \pi_{p,o} \pi_{s,o} (1 - \alpha_k) \bar{P}_{k,sd}. \end{aligned} \quad (12)$$

We can upper bound the average service rate of the primary queue as follows. The maximum service rate occurs when all relays decide to accept the primary packet each time slot, i.e.,  $f_{p,k} = 1 \forall k$ , regardless of the decoding order distribution.<sup>7</sup> In this case, the average service rate of the primary node becomes the probability that one of the receiving nodes' channels is not in outage. Therefore, the maximum average service rate of the primary queue under Strategy  $\mathcal{S}_{OD}$  is

$$\mu_p^{\max} = 1 - P_{p,pd} \prod_{v=1}^N P_{p,v} \quad (13)$$

where  $1 - P_{p,pd} \prod_{v=1}^N P_{p,v}$  is the probability that either the PD or one of the relay nodes can decode the primary packet correctly. Similarly, the maximum average secondary service rate under Strategy  $\mathcal{S}_{OD}$  is

$$\begin{aligned} \mu_s^{\max} &= \left[ 1 - P_{s,sd} \prod_{v=1}^N P_{s,v} \right] \tilde{\pi}_{p,o} \\ &= \left[ 1 - P_{s,sd} \prod_{v=1}^N P_{s,v} \right] \left[ 1 - \frac{\lambda_p}{1 - P_{p,pd} \prod_{v=1}^N P_{p,v}} \right] \end{aligned} \quad (14)$$

where  $\tilde{\pi}_{p,o} = 1 - \frac{\lambda_p}{1 - P_{p,pd} \prod_{v=1}^N P_{p,v}}$  is the probability of the primary queue being empty when  $\mu_p = \mu_p^{\max}$  which upper bounds  $\pi_{p,o}$ .

## 2) RANDOM ASSIGNMENT DECODING

In  $\mathcal{S}_{RD}$ , the  $k$ th relay is scheduled to decode the transmitted packet with probability  $\beta_k$ . Hence, the average service rates of the PU and the SU are given by

$$\begin{aligned} \mu_p &= \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \bar{P}_{p,k} f_{p,k} \beta_k, \\ \mu_s &= \pi_{p,o} \left( \bar{P}_{s,sd} + P_{s,sd} \sum_{k=1}^N \bar{P}_{s,k} f_{s,k} \beta_k \right). \end{aligned} \quad (15)$$

The average arrival rates to the relaying queues are

$$\begin{aligned} \lambda_{p,k} &= P_{p,pd} \bar{P}_{p,k} f_{p,k} \beta_k \bar{\pi}_{p,o}, \\ \lambda_{s,k} &= P_{s,sd} \bar{P}_{s,k} f_{s,k} \beta_k \bar{\pi}_{s,o} \pi_{p,o}. \end{aligned} \quad (16)$$

<sup>7</sup>This is because, in any arbitrary slot, each relay, whatever its decoding rank, will attempt to decode the primary packet and admit it, if the lower ranked relays fail in decoding it due to channels outage.

The average service rates of the relaying queues are the same as in the ordered acceptance case. The average service rate of the primary queue is upper bounded as follows. The average service rates of the primary queue under Strategy  $\mathcal{S}_{RD}$  can be upper bounded as follows

$$\begin{aligned} \mu_p &= \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \bar{P}_{p,k} f_{p,k} \beta_k \\ &\leq \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \bar{P}_{p,k} \beta_k, \end{aligned} \quad (17)$$

where the inequality  $\mathcal{E}$  becomes an equality when  $f_{p,k} = 1$  for all  $k$ . Since  $\bar{P}_{p,k}$  belongs to the convex set  $[0, 1]$  and  $\beta_k \in [0, 1]$  is a convex set with  $\sum_{k=1}^N \beta_k = 1$ , then  $\sum_{k=1}^N \bar{P}_{p,k} \beta_k$  is a convex hull with maximum value located at the edges, i.e., at  $\beta_k \in \{0, 1\}$ . Accordingly  $\sum_{k=1}^N \bar{P}_{p,k} \beta_k \leq \max \left\{ \bar{P}_{p,1}, \bar{P}_{p,2}, \dots, \bar{P}_{p,N} \right\}$ , and

$$\begin{aligned} \mu_p &\leq \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \bar{P}_{p,k} \beta_k \\ &\leq \bar{P}_{p,pd} + P_{p,pd} \max \left\{ \bar{P}_{p,1}, \bar{P}_{p,2}, \dots, \bar{P}_{p,N} \right\} \\ &= 1 - P_{p,pd} \min \left\{ P_{p,1}, P_{p,2}, \dots, P_{p,N} \right\} = \mu_p^{\max} \end{aligned} \quad (18)$$

where  $\max\{\cdot\}$  and  $\min\{\cdot\}$  return the maximum and the minimum of all the values in brackets, respectively. The maximum average primary and secondary service rates are

$$\mu_p^{\max} = 1 - P_{p,pd} \min \left\{ P_{p,1}, P_{p,2}, \dots, P_{p,N} \right\} \quad (19)$$

and

$$\begin{aligned} \mu_s^{\max} &= \left[ 1 - P_{s,sd} \min \left\{ P_{s,1}, P_{s,2}, \dots, P_{s,N} \right\} \right] \\ &\times \left[ 1 - \frac{\lambda_p}{1 - P_{p,pd} \min \left\{ P_{p,1}, P_{p,2}, \dots, P_{p,N} \right\}} \right]. \end{aligned} \quad (20)$$

## 3) ROUND ROBIN DECODING

In round robin decoding,  $\mathcal{S}_{RR}$ , each relay node is assigned the decoding role with equal probability, i.e.,  $1/N$ , in a cyclic manner. Hence, the expressions of the data and arrival rates of the queues are similar to those of the random decoding strategy,  $\mathcal{S}_{RD}$ , with the substitution with  $\beta_k = 1/N$ . As in the previous subsection and with setting  $\beta_k = 1/N$ , we can obtain the maximum average service rates of the primary and secondary queues under Strategy  $\mathcal{S}_{RR}$ . The maximum average primary and secondary service rates are thus given by

$$\mu_p^{\max} = 1 - P_{p,pd} \left( 1 - \frac{\sum_{v=1}^N \bar{P}_{p,v}}{N} \right) \quad (21)$$

and

$$\mu_s^{\max} = \left[ 1 - P_{s,sd} \left( 1 - \frac{\sum_{v=1}^N \bar{P}_{s,v}}{N} \right) \right] \times \left[ 1 - \frac{\lambda_p}{1 - P_{p,pd} \left( 1 - \frac{\sum_{v=1}^N \bar{P}_{p,v}}{N} \right)} \right]. \quad (22)$$

*Theorem 1:* The queue service rates of  $\mathcal{S}_{OD}$  always outperform the queue service rates of  $\mathcal{S}_{RD}$  and  $\mathcal{S}_{RR}$  for a network with  $N$  relays if the feedback duration per relay is negligible.

*Proof:* The proof for this theorem under perfect sensing and imperfect sensing (sensing errors) is presented in Appendix A.  $\square$

*Proposition 1:* The SU's maximum average service rate,  $\mu_s^*$ , for an arbitrary decoding strategy is given by

$$\mu_s^* = 1 - \lambda_p. \quad (23)$$

*Proof:* Regardless of the adopted decoding strategy at the relay nodes, the secondary average service rate can always be upper bounded by the probability of the PU's queue,  $Q_p$ , being empty assuming that the SU can successfully transmit its packet with probability one, which means that there is no secondary transmission outage. This can be expressed as  $\mu_s \leq \pi_{p,\circ}$ . Since the probability of the PU being empty is  $\pi_{p,\circ} = 1 - \frac{\lambda_p}{\mu_p} \leq 1 - \lambda_p$  where  $0 \leq \mu_p \leq 1$ , then  $\mu_s \leq 1 - \lambda_p = \mu_s^*$ .  $\square$

*Remark 1:* We emphasize that the derived upper bound is a general bound in the sense that it is also valid for the scenarios where the relay nodes are selected using the instantaneous channel state information at the transmitting nodes. Hence, by showing that the performance of our proposed schemes is close to that upper bound, we demonstrate the gains of our proposed schemes.

### B. AVERAGE QUEUEING DELAY ANALYSIS

In our scenario, we have two different formulas for the average queueing delay based on the dynamics of the Markov chains that model the available data queues. The average queueing delays of source nodes' queues when they are stable are given by [5], [21]

$$D_\ell = \frac{1 - \lambda_\ell}{\mu_\ell - \lambda_\ell} \quad (24)$$

where  $\ell \in \{p, s\}$  and  $\mu_\ell > \lambda_\ell$ . On the other hand, the average queueing delay of the  $k$ th relaying queue that maintains the data packets of User  $\ell \in \{p, s\}$ , denoted by queue  $Q_{\ell,k}$ , can be shown to be

$$D_{\ell,k} = \frac{1}{\mu_{\ell,k} - \lambda_{\ell,k}} \quad (25)$$

with  $\mu_{\ell,k} > \lambda_{\ell,k}$ .

The end-to-end average queueing delay of a source node packets is equal to the average queueing delay that any packet experiences from its arrival at the source node's queue until it arrives to the relevant destination node. In our considered system, each packet arriving at  $Q_\ell$  experiences on the average

a delay of  $D_\ell$  time slots, where  $\ell \in \{p, s\}$ . Furthermore, a data packet has an additional average queueing delay of  $D_{\ell,k}$  time slots if it reaches the destination node through relay node  $k$ . Since on the average the probability that a packet that has been served from queue  $Q_\ell$  is buffered at the  $k$ th relay before reaching its destination is  $\frac{\lambda_{\ell,k}}{\lambda_\ell}$ , the average queueing delays of the primary and secondary packets are, respectively, given by

$$D_p^{(T)} = D_p + \frac{\sum_{k=1}^N \lambda_{p,k} D_{p,k}}{\lambda_p},$$

$$D_s^{(T)} = D_s + \frac{\sum_{k=1}^N \lambda_{s,k} D_{s,k}}{\lambda_s}. \quad (26)$$

A similar approach for computing the end-to-end average queueing delay is found in [15], [22], and [23].

## V. OPTIMIZATION PROBLEMS

### A. SECONDARY THROUGHPUT MAXIMIZATION

In this subsection, we state our first proposed optimization formulation which maximizes the secondary average service rate given  $\lambda_p$ ,  $\lambda_s$  and  $N$  subject to predefined tolerable end-to-end average queueing delay constraints for the primary and secondary packets. Under the ordered acceptance strategy,  $\mathcal{S}_{OD}$ , the maximum secondary average service rate can be obtained by solving the following problem:

$$\begin{aligned} & \max_{\alpha, \mathbf{f}_p, \mathbf{f}_s, \boldsymbol{\omega}, \boldsymbol{\rho}^{(p)}, \boldsymbol{\rho}^{(s)}} \mu_s \\ & \text{s.t. } D_s^{(T)} \leq \mathcal{D}_s^{(T)}, \quad D_p^{(T)} \leq \mathcal{D}_p^{(T)}, \\ & \lambda_s < \mu_s, \lambda_p < \mu_p, \\ & \lambda_{p,k} < \mu_{p,k}, \lambda_{s,k} < \mu_{s,k}, \\ & 0 \leq \alpha, \mathbf{f}_p, \mathbf{f}_s \leq 1, \\ & 0 \leq \boldsymbol{\omega}, \boldsymbol{\rho}^{(p)}, \boldsymbol{\rho}^{(s)}, \\ & \|\boldsymbol{\omega}\|_1 = 1, \quad \|\boldsymbol{\rho}^{(p)}\|_1 = 1, \quad \|\boldsymbol{\rho}^{(s)}\|_1 = 1 \end{aligned} \quad (27)$$

where  $\mathcal{D}_p^{(T)} < \infty$  is the maximum allowable end-to-end average queueing delay for the primary packets,  $\mathcal{D}_s^{(T)} < \infty$  is the maximum allowable end-to-end average queueing delay of the secondary packets, the notation  $a \leq \mathbf{z}$  is an element wise condition on vector  $\mathbf{z}$  implying that  $a \leq z_k$  and  $\|\mathbf{z}\|_1$  is the  $\ell_1$ -norm of the vector  $\mathbf{z}$  defined as  $\|\mathbf{z}\|_1 = \sum_k |z_k|$ . The total number of optimization variables in the case of ordered acceptance decoding is  $2N! + 4N$ .

*Remark 2:* The optimization problems are solved at a central unit (e.g. one of the relay nodes) which then supplies the required information to the relay nodes. The optimal parameters are functions of many parameters such as the channels outage between all nodes in the network (based on the expression in (3), the channel outage between any two nodes is a function of the packet length, channel bandwidth, SNR, time slot duration, and many other parameters), primary and secondary arrivals rate, delay constraints, number of relays, misdetection probability, and false alarm probability at each relay. Thus, for a given system's parameters,



the optimal parameters are fixed as far as these parameters remain constant. Once the optimal parameters are obtained, the central unit generates a long sequence of decoding orders and time slot accessing distribution over time slots to be supplied to the relay nodes during the whole operational time of the system. This occurs all at once before the actual operation of the system. The optimal acceptance probabilities of users' packets at the relay nodes and the probability of selecting one of the relaying queues over the other for a given time slot are all generated locally at each relay station. However, the values of the probabilities are also supplied to the relay nodes by the central unit all at once before the actual operation of the system. The optimization problems presented in this work are solved numerically. Specifically, we use Matlab's *fmincon* as in [24]–[28] and the references therein.

For  $\mathcal{S}_{RD}$ , the maximum secondary average service rate can be obtained by solving the following optimization problem:

$$\begin{aligned} & \max_{\alpha, \mathbf{f}_p, \mathbf{f}_s, \omega, \beta} \mu_s \\ \text{s.t. } & D_s^{(T)} \leq \mathcal{D}_s^{(T)}, \quad D_p^{(T)} \leq \mathcal{D}_p^{(T)}, \\ & \lambda_s < \mu_s, \lambda_p < \mu_p, \\ & \lambda_{p,k} < \mu_{p,k}, \lambda_{s,k} < \mu_{s,k}, \\ & 0 \leq \alpha, \mathbf{f}_p, \mathbf{f}_s \leq 1, \\ & 0 \leq \omega, \beta, \quad \|\omega\|_1 = 1, \quad \|\beta\|_1 = 1. \end{aligned} \quad (28)$$

The total number of optimization parameters in the case of random decoding is  $5N$ .

For  $\mathcal{S}_{RR}$ , the maximum secondary average service rate can be obtained by solving an optimization problem similar to (28) with all elements of  $\beta$  equal to  $1/N$ . The optimization problem is stated as follows

$$\begin{aligned} & \max_{\alpha, \mathbf{f}_p, \mathbf{f}_s, \omega} \mu_s \\ \text{s.t. } & D_s^{(T)} \leq \mathcal{D}_s^{(T)}, \quad D_p^{(T)} \leq \mathcal{D}_p^{(T)}, \\ & \lambda_s < \mu_s, \lambda_p < \mu_p, \quad \lambda_{p,k} < \mu_{p,k}, \lambda_{s,k} < \mu_{s,k}, \\ & 0 \leq \alpha, \mathbf{f}_p, \mathbf{f}_s \leq 1, \\ & 0 \leq \omega, \|\omega\|_1 = 1. \end{aligned} \quad (29)$$

The total number of optimization variables is equal to  $4N$ .

*Remark 3:* It should be noticed that the total number of optimization parameters is a reflection of both the degrees of freedom and the degree of complexity of the system. Therefore, the ordered acceptance is considered as the strategy with the highest degrees of freedom and the highest complexity among the proposed strategies in this paper. On the other hand, round robin is the simplest strategy among the proposed strategies and it needs less cooperation between the relays than other strategies; it is a cyclic switching operation shared among relays.

### B. NUMBER OF RELAYS MINIMIZATION

In this subsection, we give our second formulation which minimizes the number of deployed relay nodes in the net-

work,  $N$ , needed to achieve certain average queueing delay and service rate requirements for the primary and secondary users. Given  $\lambda_p$  and  $\lambda_s$  and under the ordered acceptance strategy,  $\mathcal{S}_{OD}$ , the optimization problem is stated as follows

$$\begin{aligned} & \min_{\alpha, \mathbf{f}_p, \mathbf{f}_s, \omega, \rho^{(p)}, \rho^{(s)}} N \\ \text{s.t. } & D_s^{(T)} \leq \mathcal{D}_s^{(T)}, \quad D_p^{(T)} \leq \mathcal{D}_p^{(T)}, \\ & \lambda_s < \mu_s, \lambda_p < \mu_p, \\ & \lambda_{p,k} < \mu_{p,k}, \lambda_{s,k} < \mu_{s,k}, \\ & 0 \leq \alpha, \mathbf{f}_p, \mathbf{f}_s \leq 1, \\ & 0 \leq \omega, \rho^{(p)}, \rho^{(s)}, \\ & \|\omega\|_1 = 1, \|\rho^{(p)}\|_1 = 1, \quad \|\rho^{(s)}\|_1 = 1. \end{aligned} \quad (30)$$

In case of  $\mathcal{S}_{RD}$ , the minimum number of relays required in the network is given by the following optimization problem:

$$\begin{aligned} & \min_{\alpha, \mathbf{f}_p, \mathbf{f}_s, \omega, \beta} N \\ \text{s.t. } & D_s^{(T)} \leq \mathcal{D}_s^{(T)}, \quad D_p^{(T)} \leq \mathcal{D}_p^{(T)}, \\ & \lambda_s < \mu_s, \lambda_p < \mu_p, \\ & \lambda_{p,k} < \mu_{p,k}, \lambda_{s,k} < \mu_{s,k}, \\ & 0 \leq \alpha, \mathbf{f}_p, \mathbf{f}_s \leq 1, \\ & 0 \leq \omega, \beta, \\ & \|\omega\|_1 = 1, \|\beta\|_1 = 1. \end{aligned} \quad (31)$$

For  $\mathcal{S}_{RR}$ , we construct an optimization problem similar to (31) with all elements in  $\beta$  being set to  $1/N$ .

### VI. THE CASE OF SENSING ERRORS

We address here the specific scenario of a strong sensing channel between the PU and the SU and consider sensing errors at the relay nodes. In other words, we assume that the sensing errors at the SU are negligible, whereas spectrum sensing at the relays may generate erroneous sensing results that should be accounted for. To render the problem tractable and avoid the difficulty of queue interaction due to sensing errors, we impose the assumption that  $Q_{s,k}$  and  $Q_{p,k}$  are never empty. Specifically, when either  $Q_{s,k}$  or  $Q_{p,k}$  is empty, the  $k$ th relay sends dummy packets.<sup>8</sup> The dummy packets do not contribute to the service rates of  $Q_{s,k}$  and  $Q_{p,k}$  but cause interference during concurrent transmission with the primary and secondary terminals. Based on this assumption, the relay scheduled for transmission could cause interference with the primary and secondary transmissions, when it misdetects their transmissions, even if it is empty in the original system. Accordingly, the service rates of the primary and secondary queues are reduced, and the probability of having any of them empty is reduced as well. Consequently, the service rates of the relays are reduced. Therefore, our results provide lower bounds on the primary, secondary and relays service rates.

<sup>8</sup>The assumption of a node sending dummy packets when it is empty has been considered in many works (see, for example, [5], [7], [20], [29], and references therein).

The  $k$ th relay scheduled for transmission at a slot misdetects the SU's transmission with probability  $P_{MD}^{(s,k)}$  and misdetects the PU's transmission with probability  $P_{MD}^{(p,k)}$ . Sensing false alarms have probability  $P_{FA}^k$ . All relays are adjusted on the receiving mode and attempt to decode the transmitter's data packet. The relay node scheduled for transmission is the only relay that decides after  $2\tau$  seconds the state of the time slot: busy or free. If the slot is sensed to be free, that relay switches to the transmission mode and starts retransmission of one of the packets in its relaying queues. If the channel is sensed to be busy over either interval, the relay continues in the receiving mode. Upon data packet decoding, the relay will be able to identify the packet's origin from the identifier attached to the packet and will use the appropriate decoding order in case of order decoding. In case of random decoding or round robin decoding, only one of the relay nodes is assigned the decoding task in each time slot. Based on the above, the service rates of the users' queues and the arrival rates of the relaying queues under sensing errors are only affected by the activity of the relay node scheduled for transmission. The reduction of the average service and arrival rates is equal to  $\sum_r \omega_r \mathcal{B}^{(\ell,r)}$ , where  $\mathcal{B}^{(\ell,r)}$  denotes the complement of the probability that relay node  $r$ , scheduled for transmission, erroneously finds the time slot free given there is an active transmission from User  $\ell$ .

Next, we compute  $\mathcal{B}^{(\ell,r)}$  for both users. The relay node  $r$  scheduled for transmission disrupts the primary if it fails to detect the activity of the PU during both sensing intervals. That is, the probability that the  $r$ th relay detects the time slot as a busy slot due to activity of PU is  $\mathcal{B}^{(p,r)} = (1 - P_{MD}^{(p,r)} P_{MD}^{(p,r)})$ .<sup>9</sup> The probability that the relay node  $r$  scheduled for transmission does not disrupt the secondary activity is equal to the probability that the relay either detects the secondary transmission, or falsely finds the PU to be active while it is not. In either case, it will abstain from transmission, thereby avoiding collision with the secondary transmission. Thus, the probability is given by  $\mathcal{B}^{(s,r)} = (1 - P_{MD}^{(s,r)} [1 - P_{FA}^r])$ . Accordingly, we have the following set of arrival and service rates:

$$\begin{aligned} \mu_\ell^{(SE)} &= \mu_\ell \sum_{r=1}^N \omega_r \mathcal{B}^{(\ell,r)}, \quad \ell \in \{p, s\}, \\ \lambda_{\ell,k}^{(SE)} &= \lambda_{\ell,k} \sum_{r=1}^N \omega_r \mathcal{B}^{(\ell,r)}, \quad \ell \in \{p, s\}, \\ \mu_{\ell,k}^{(SE)} &= \mu_{\ell,k} (1 - P_{FA}^k)^2, \quad \ell \in \{p, s\} \end{aligned} \quad (32)$$

where  $\mu_\ell^{(SE)}$ ,  $\lambda_{\ell,k}^{(SE)}$ , and  $\mu_{\ell,k}^{(SE)}$  are the rates of primary and secondary users and relay nodes in the case of sensing errors and  $\mu_\ell$ ,  $\lambda_{\ell,k}$  and  $\mu_{\ell,k}$  are the rates of users and relays in the case of perfect sensing.<sup>10</sup> We note that the term  $(1 - P_{FA}^k)^2$

<sup>9</sup>As mentioned in Section II, we assume in this paper that if two terminals transmit simultaneously, their packets cannot be decoded correctly at the respective receivers.

<sup>10</sup>These values depend on the decoding strategy used as explained earlier.

TABLE 2. Relays' channel outage probabilities where  $N = 5$  and  $\tau_f = 0$ .

Relay-SD	Relay-PD	SU-relay	PU-relay
$P_{1,sd} = 0.1$	$P_{1,pd} = 0.1$	$P_{s,1} = 0.1$	$P_{p,1} = 0.1$
$P_{2,sd} = 0.1$	$P_{2,pd} = 0.1$	$P_{s,2} = 0.1$	$P_{p,2} = 0.02$
$P_{3,sd} = 0.2$	$P_{3,pd} = 0.2$	$P_{s,3} = 0.02$	$P_{p,3} = 0.2$
$P_{4,sd} = 0.1$	$P_{4,pd} = 0.01$	$P_{s,4} = 0.1$	$P_{p,4} = 0.1$
$P_{5,sd} = 0.01$	$P_{5,pd} = 0.01$	$P_{s,5} = 0.01$	$P_{p,5} = 0.01$

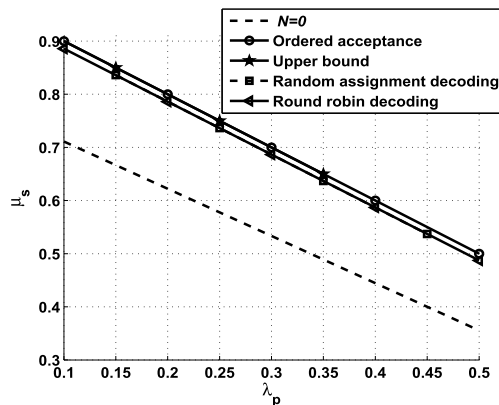


FIGURE 3. Optimal secondary average service rate versus the primary average arrival rate,  $\lambda_p$ .

in (32) represents the probability that the  $k$ th relay finds the time slot free from transmissions. This equals the probability that the sensor of relay node  $k$  does not generate false alarm over both sensing intervals.

To obtain the optimal secondary average service rate in the case of sensing errors at the relay nodes, we construct an optimization problem similar to (27) and (28). For the minimum number of relay nodes needed to achieve certain QoS constraints, we construct an optimization problem similar to (30) and (31).

### VII. NUMERICAL RESULTS

In this section, we simulate our network and present the solutions of the optimization problems considered in this paper. Fig. 3 demonstrates the case of negligible feedback duration, i.e.,  $\tau_f = 0$ , and low outage probabilities for the PU-PD and the SU-SD direct links:  $P_{s,sd} = 0.2$  and  $P_{p,pd} = 0.1$ . The figure is generated using  $N = 2$ ,  $\lambda_s = 0.1$  packets per time slot,  $D_p^{(T)} \leq 1.6$  time slots,  $D_s^{(T)} \leq 3$  time slots,  $\lambda_s = 0.2$  packets per time slot, and the outage probabilities given in the first two lines of Table 2. As shown in Fig. 3, the ordered acceptance strategy with two relays almost achieves the upper bound on the secondary average service rate, which is equal to  $1 - \lambda_p$ . Random assignment and round robin decoding give almost the same performance for the parameters used in the simulation. The primary average service rate for the used parameters are 0.999, 0.998 and 0.94 packets/slot for  $\mathcal{S}_{OD}$ ,  $\mathcal{S}_{RD}$ , and  $\mathcal{S}_{RR}$ , respectively. Without relaying,  $\mu_p = 1 - P_{p,pd} = 0.9$ .

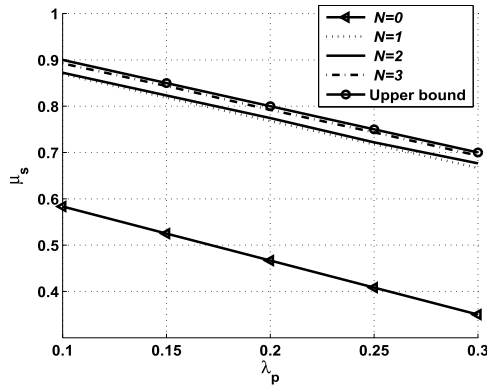


FIGURE 4. Impact of increasing the number of relays on the optimal secondary average service rate for  $S_{RD}$ .

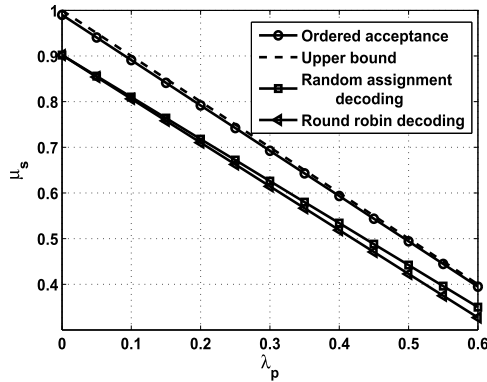


FIGURE 5. Optimal secondary average service rate versus  $\lambda_p$  for the case of no direct links between the PU and the SU and their respective receivers.

Fig. 4 reveals the impact of increasing the number of relays on the optimal secondary average service rate for  $S_{RD}$  with  $\tau_f = 0$ . This figure is generated using  $P_{s,sd} = 0.3$  and  $P_{p,pd} = 0.4$ ,  $\lambda_s = 0.2$  packets per time slot,  $D_p^{(T)} \leq 5$  time slots,  $D_s^{(T)} \leq 10$  time slots, and the outage probabilities given in Table 2. As shown in the figure, when the number of relays,  $N$ , increases, the average service rate of the SU (maximum  $\mu_s$ ) approaches the upper bound.

Fig. 5 also shows the case of  $\tau_f = 0$ , but this time there are no direct links between the PU and the SU and their respective receivers. That is,  $P_{s,sd} = 1$  and  $P_{p,pd} = 1$ . The parameters used to generate Fig. 5 are:  $\tau_f = 0$ ,  $N = 2$ ,  $\lambda_s = 0.1$  packets per time slot,  $D_p^{(T)} \leq 25$ ,  $D_s^{(T)} \leq 25$ , and the outage probabilities given in the first three lines of Table 2. The primary average service rate for the used parameters are 0.999, 0.98 and 0.94 packets/slot for  $S_{OD}$ ,  $S_{RD}$ , and  $S_{RR}$ , respectively. We emphasize that in this case of no direct links, cooperative relaying is essential since without cooperation, the average service rate of the PU's queue is equal to  $1 - P_{p,pd} = 0$  and both the primary and secondary queues are always backlogged with data packets and unstable. Hence, their packets are never being served. Consequently, the average queuing delay of each user is infinity.

Fig. 6 represents the solution of the optimization problems expressed in (30) and (31), which is the number of relay nodes

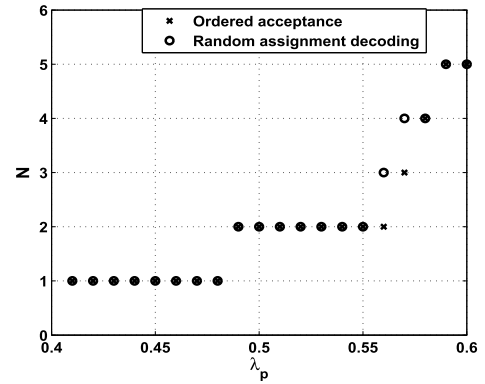


FIGURE 6. Number of relays required to achieve the QoS requirements:  $D_p^{(T)} \leq 2$  time slots, and  $D_s^{(T)} \leq 15$  time slots.

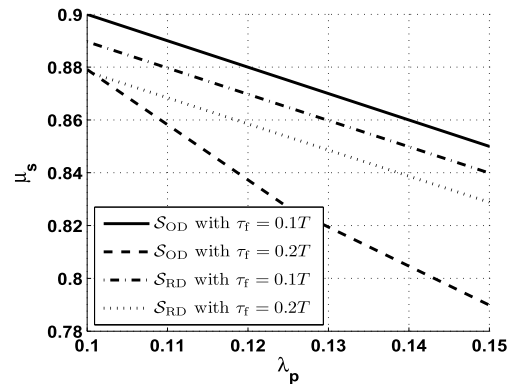


FIGURE 7. Impact of non-zero feedback duration on the maximum secondary average service rate.

required to achieve specific QoS requirements for the PU and the SU. The parameters used to generate the figure are:  $P_{s,sd} = 0.8$ ,  $P_{p,pd} = 0.2$ ,  $\lambda_s = 0.1$  packets per time slot, and channel outage probabilities provided in Table 2.

Fig. 7 shows the impact of feedback duration on the maximum SU's average service rate. As  $\tau_f$  increases, the ordered acceptance strategy loses its edge and is outperformed by the random assignment strategy. The figure is generated using  $N = 2$ ,  $\lambda_s = 0.4$  packets per time slot,  $D_p^{(T)} \leq 5$  time slots,  $D_s^{(T)} \leq 5$  time slots, the channel parameters of relay node 1 and relay node 2 provided in Table 3, and  $\sigma_{s,sd}^2 = 0.4$ .

Fig. 8 represents the secondary average service rate for the case  $N = 3$ ,  $\sigma_{s,sd}^2 = 0.8$ , and  $\tau_f = 0.05T$  in the presence of sensing errors at the relays' spectrum sensors. The figure is for parameters  $N = 3$ ,  $\lambda_s = 0.2$  packets per time slot,  $D_p^{(T)} \leq 3$  time slots, and  $D_s^{(T)} \leq 120$  time slots. The sensing error probabilities are:  $P_{MD}^{(p,1)} = 0.1$ ,  $P_{MD}^{(p,2)} = 0.09$ ,  $P_{MD}^{(p,3)} = 0.12$ ,  $P_{MD}^{(s,1)} = 0.1$ ,  $P_{MD}^{(s,2)} = 0.068$ ,  $P_{MD}^{(s,3)} = 0.09$ ,  $P_{FA}^1 = 0.05$ ,  $P_{FA}^2 = 0.04$ , and  $P_{FA}^3 = 0.03$ . The probabilities of correct reception over the channels between the sources and relays, and the relays and destinations can be computed using the parameters in Table 3 and expression (5). Note that because  $\tau_f$  is nonzero, the outage probabilities differ for the different strategies due to the difference in the feedback duration  $T_F$  as explained in Section II.

TABLE 3. Channel parameters for three relays.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$b$	1000 bits	$W$	10 MHz	$T$	$10^{-3}$ seconds	$\sigma_{1,sd}^2$	0.8
$\sigma_{2,sd}^2$	0.75	$\sigma_{3,sd}^2$	0.9	$\sigma_{1,pd}^2$	0.88	$\sigma_{2,pd}^2$	0.95
$\sigma_{3,pd}^2$	0.85	$\sigma_{s,1}^2$	0.83	$\sigma_{s,2}^2$	0.92	$\sigma_{s,3}^2$	0.79
$\sigma_{p,1}^2$	0.82	$\sigma_{p,2}^2$	0.935	$\sigma_{p,3}^2$	0.815	$\tau$	0.1 T
$\gamma_{s,sd}$	2	$\gamma_{p,pd}$	3	$\gamma_{p,1}$	3	$\gamma_{p,2}$	2.5
$\gamma_{p,3}$	2	$\gamma_{s,1}$	3	$\gamma_{s,2}$	2.5	$\gamma_{s,3}$	2
$\sigma_{p,pd}^2$	1						

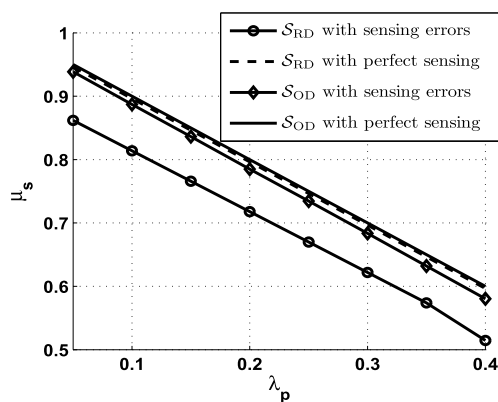


FIGURE 8. Impact of spectrum sensing errors on the maximum secondary average service rate under relatively small feedback duration  $\tau_f = 0.05T$ .

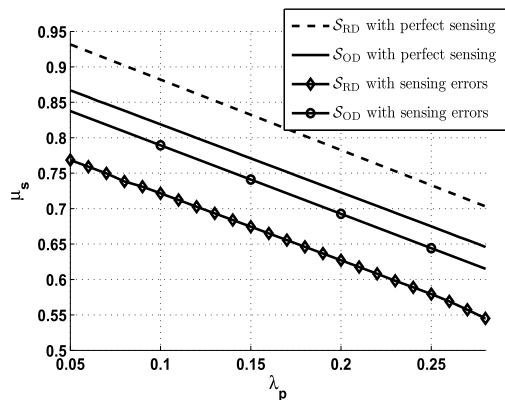


FIGURE 9. Impact of spectrum sensing errors on the maximum secondary average service rate under relatively large feedback duration  $\tau_f = 0.24T$ .

Fig. 9 shows the average service rate of the SU in the case of sensing errors and considerable feedback duration per relay. The parameters used to generate the figure are exactly those of Fig. 8 with  $N = 2$  and  $\tau_f = 0.24T$ . It is noted that  $S_{RD}$  outperforms  $S_{OD}$  in the case of perfect sensing and sensing errors. This is because of the high transmission time losses due to the time consumed in channel feedback coordination in the case of ordered acceptance. In particular, for  $S_{OD}$ , the overall feedback duration is

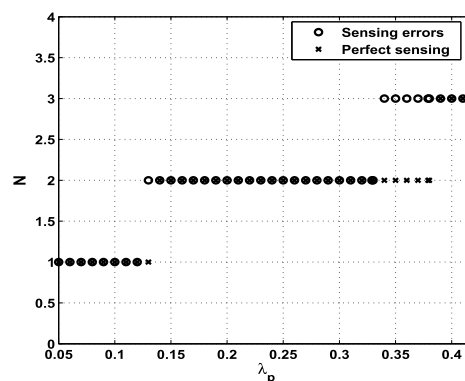


FIGURE 10. Minimum number of relays in the case of ordered acceptance with and without sensing errors. The feedback process duration per relay node is  $\tau_f = 0.05T$ ,  $D_p^{(T)} \leq 10$  time slots, and  $D_s^{(T)} \leq 20$  time slots.

$T_F = (N + 1)\tau_f = 3 \times 0.24T = 0.72T$ , whereas for  $S_{RD}$ ,  $T_F = 2\tau_f = 0.48T$ .

Fig. 10 shows the minimum number of relays in the case of ordered acceptance with and without sensing errors. The parameters used to obtain this figure are the same as those of Fig. 8. From the figure, spectrum sensing errors may cause an increase in the minimum number of relay nodes required to satisfy the primary and secondary queuing delay constraints.

VIII. CONCLUSION

In this paper, we have investigated the use of multiple relays to satisfy pre-specified average queuing delay constraints on the primary and secondary transmissions. We have proposed and investigated three relay decoding strategies; and have seen that the ordered acceptance strategy maintains the best performance under negligible feedback duration. Our work has assumed knowledge of channel statistics, but not the instantaneous values of the channel gains. Two interesting extensions of this work would be the incorporation of the knowledge of the instantaneous values of the channels, in addition to the queue state information, into the relay scheduling decisions and the investigation of the possibility of cooperation among the relays by forming a virtual antenna array.

**APPENDIX A  
PROOF OF THEOREM 1**

In this section, we prove the advantage of decoding strategy  $\mathcal{S}_{OD}$  over  $\mathcal{S}_{RD}$  and  $\mathcal{S}_{RR}$  for a negligible feedback duration per relay, i.e., when  $\tau_f \approx \kappa \ll T$  and  $\kappa \rightarrow 0$ . We first focus on the perfect sensing case assuming that  $\tau$  is large enough to render negligible the probabilities of misdetection and false alarm. Then, we directly prove the case of sensing errors. We compare the nodes' service rates of the queues in the proposed strategies with each other.

**A. THE CASE OF PERFECT SENSING**

For Strategy  $\mathcal{S}_{OD}$ , we define  $\epsilon_{m_k k}^{(\ell)}$  as the probability of assigning the  $m_k$ th decoding rank to the  $k$ th relay. If the received packet comes from the PU,  $\ell = p$ , whereas if the received packet comes from the SU,  $\ell = s$ . The summation over these probabilities satisfies the constraints

$$\sum_{m_k=1}^N \epsilon_{m_k k}^{(\ell)} = 1, \quad \forall k \in \{1, 2, \dots, N\},$$

$$\sum_{k=1}^N \epsilon_{m_k k}^{(\ell)} = 1, \quad \forall m_k \in \{1, 2, \dots, N\} \quad (33)$$

where  $\ell \in \{p, s\}$ . It should be noted that  $\epsilon_{m_k k}^{(\ell)}$ , the probability that rank  $m_k$  is assigned to relay node  $k$ , relates to the  $q^{(\ell)}$ 's as follows

$$\epsilon_{m_k k}^{(\ell)} = \sum_{\sim m_k} q^{(\ell)}(m_1, m_2, \dots, m_N), \quad \forall k, m_k \in \{1, 2, \dots, N\} \quad (34)$$

where the sum is over all indices except  $m_k$ . Hereinafter, we add superscripts to the average service rates to indicate the strategies to which those rates belong.

The average service rate of the primary queue in Strategy  $\mathcal{S}_{OD}$  is

$$\mu_p^{(\mathcal{S}_{OD})} = \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \left[ \bar{P}_{p,kf_{p,k}} \sum_{\Pi} \rho_n^{(p)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \overline{\bar{P}_{p,vf_{p,v}}} \right]. \quad (35)$$

Using (34), and noting that  $\prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \overline{\bar{P}_{p,vf_{p,v}}} = 1$ , we have

$$\sum_{\Pi} \rho_n^{(p)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \overline{\bar{P}_{p,vf_{p,v}}} = \epsilon_{1k}^{(p)} + \sum_{m_k \neq 1} \left[ \rho_n^{(p)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \overline{\bar{P}_{p,vf_{p,v}}} \right]. \quad (36)$$

Substituting (36) into (35), we get

$$\mu_p^{(\mathcal{S}_{OD})} = \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \bar{P}_{p,kf_{p,k}} (\epsilon_{1k}^{(p)} + \zeta_p) \quad (37)$$

where

$$\zeta_p = \sum_{\substack{\Pi \\ m_k \neq 1}} \rho_n^{(p)} \prod_{\substack{v=1 \\ v \neq k \\ m_v < m_k}}^N \overline{\bar{P}_{p,vf_{p,v}}} \geq 0. \quad (38)$$

Recall that for Strategy  $\mathcal{S}_{RD}$ , the primary and secondary average service rates are given by

$$\mu_p^{(\mathcal{S}_{RD})} = \bar{P}_{p,pd} + P_{p,pd} \sum_{k=1}^N \bar{P}_{p,kf_{p,k}} \beta_k,$$

$$\mu_s^{(\mathcal{S}_{RD})} = \pi_{p,o}^{(\mathcal{S}_{RD})} \left( \bar{P}_{s,sd} + P_{s,sd} \sum_{k=1}^N \bar{P}_{s,kf_{s,k}} \beta_k \right). \quad (39)$$

Subtracting  $\mu_p^{(\mathcal{S}_{RD})}$  from  $\mu_p^{(\mathcal{S}_{OD})}$ , we obtain

$$\mu_p^{(\mathcal{S}_{OD})} - \mu_p^{(\mathcal{S}_{RD})} = P_{p,pd} \sum_{k=1}^N \bar{P}_{p,kf_{p,k}} (\epsilon_{1k} - \beta_k)$$

$$+ P_{p,pd} \sum_{k=1}^N \bar{P}_{p,kf_{p,k}} \zeta_p. \quad (40)$$

Since  $0 \leq \epsilon_{1k}^{(p)}, \epsilon_{1k}^{(s)}, \beta_k \leq 1$ ,  $\sum_{k=1}^N \beta_k = 1$  and  $\sum_{k=1}^N \epsilon_{1k}^{(\ell)} = 1$ , therefore, we can set  $\epsilon_{1k}^{(p)} = \epsilon_{1k}^{(s)} = \beta_k$ . Accordingly, the first term on the right-hand side (RHS) of (40) is equal to zero, and we have

$$\mu_p^{(\mathcal{S}_{OD})} = P_{p,pd} \sum_{k=1}^N \bar{P}_{p,kf_{p,k}} \zeta_p \geq \mu_p^{(\mathcal{S}_{RD})}. \quad (41)$$

The probability that a queue,  $Q_\ell$ , belonging to a system operating under Strategy  $\mathcal{S}_{\mathcal{J}}$  is empty is given by  $\pi_{\ell,o}^{(\mathcal{S}_{\mathcal{J}})} = 1 - \frac{\lambda_\ell}{\mu_\ell^{(\mathcal{S}_{\mathcal{J}})}}$  where  $\mathcal{J} \in \{OD, RD\}$  and  $\ell \in \{p, s\}$ .

Since  $\mu_p^{(\mathcal{S}_{OD})} \geq \mu_p^{(\mathcal{S}_{RD})}$ , therefore,  $\pi_{p,o}^{(\mathcal{S}_{OD})} \geq \pi_{p,o}^{(\mathcal{S}_{RD})}$ . In a similar fashion, the average service rate of the secondary queue can be lower bounded as

$$\mu_s^{(\mathcal{S}_{OD})} \geq \left( \bar{P}_{s,sd} + P_{s,sd} \sum_{k=1}^N \bar{P}_{s,kf_{s,k}} \beta_k \right) \pi_{p,o}^{(\mathcal{S}_{OD})}$$

$$\geq \left( \bar{P}_{s,sd} + P_{s,sd} \sum_{k=1}^N \bar{P}_{s,kf_{s,k}} \beta_k \right) \pi_{p,o}^{(\mathcal{S}_{RD})} = \mu_s^{(\mathcal{S}_{RD})}. \quad (42)$$

From (41) and (42), we have  $\mu_p^{(\mathcal{S}_{OD})} \geq \mu_p^{(\mathcal{S}_{RD})}$  and  $\mu_s^{(\mathcal{S}_{OD})} \geq \mu_s^{(\mathcal{S}_{RD})}$ , and consequently,  $\pi_{p,o}^{(\mathcal{S}_{OD})} \geq \pi_{p,o}^{(\mathcal{S}_{RD})}$  and  $\pi_{s,o}^{(\mathcal{S}_{OD})} \geq \pi_{s,o}^{(\mathcal{S}_{RD})}$ . The average service rates of the relaying queues in  $\mathcal{S}_{OD}$  are lower bounded as

$$\mu_{p,k}^{(\mathcal{S}_{OD})} = \omega_k \pi_{p,o}^{(\mathcal{S}_{OD})} \pi_{s,o}^{(\mathcal{S}_{OD})} \alpha_k \bar{P}_{k,pd}$$

$$\geq \omega_k \pi_{p,o}^{(\mathcal{S}_{RD})} \pi_{s,o}^{(\mathcal{S}_{RD})} \alpha_k \bar{P}_{k,pd} = \mu_{p,k}^{(\mathcal{S}_{RD})} \quad (43)$$

$$\mu_{s,k}^{(\mathcal{S}_{OD})} = \omega_k \pi_{p,o}^{(\mathcal{S}_{OD})} \pi_{s,o}^{(\mathcal{S}_{OD})} (1 - \alpha_k) \bar{P}_{k,sd}$$

$$\geq \omega_k \pi_{p,o}^{(\mathcal{S}_{RD})} \pi_{s,o}^{(\mathcal{S}_{RD})} (1 - \alpha_k) \bar{P}_{k,sd} = \mu_{s,k}^{(\mathcal{S}_{RD})}. \quad (44)$$

Since all of the average service rates of the queues in  $\mathcal{S}_{OD}$  are greater than or equal to the average service rates of the queues in  $\mathcal{S}_{RD}$ , Strategy  $\mathcal{S}_{OD}$  outperforms  $\mathcal{S}_{RD}$ . Based on the above proof, setting  $\epsilon_{1k}^{(p)} = \epsilon_{1k}^{(s)} = \beta_k$  makes  $\mathcal{S}_{OD}$  outperform  $\mathcal{S}_{RD}$ . Therefore, if we optimize over  $\epsilon_{1k}^{(p)}, \epsilon_{1k}^{(s)}$  and the remaining parameters of Strategy  $\mathcal{S}_{OD}$ , of course, we can get much higher performance than setting  $\epsilon_{1k}^{(p)} = \epsilon_{1k}^{(s)} = \beta_k$ . As a corollary to this proof, Strategy  $\mathcal{S}_{OD}$  outperforms  $\mathcal{S}_{RR}$ .

### B. THE CASE OF SENSING ERRORS

As mentioned in Section VI, the service rate of User  $\ell$  and the arrival rate of the relaying queue of that user are reduced, on the average, by a factor  $\sum_r \omega_r \mathcal{B}^{(\ell,r)}$  relative to the case of perfect sensing. In addition, the service rate of the  $k$ th relaying queue of User  $\ell$  is reduced by a factor  $(1 - P_{FA}^k)^2$  relative to the case of perfect channel sensing. Therefore, following the same steps as in the proof in the previous subsection, the service rates of the queues under  $\mathcal{S}_{RD}$  cannot exceed those in  $\mathcal{S}_{OD}$  in the imperfect channel sensing scenario. Furthermore, the arrival rates of the relaying queues in  $\mathcal{S}_{RD}$  cannot be smaller than those in  $\mathcal{S}_{OD}$ . Consequently,  $\mathcal{S}_{OD}$  outperforms  $\mathcal{S}_{RD}$ . A direct result of this proof is that Strategy  $\mathcal{S}_{OD}$  outperforms  $\mathcal{S}_{RR}$ .

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