Buffered-Relay Selection in an Underlay Cognitive Radio Network

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***Abstract*—We consider an underlay relay-assisted time-slotted cognitive radio network operating on the same band used by a primary link. For implementation simplicity, one relay is selected at any time slot for reception from the secondary source, or for transmission to the secondary destination. Relay selection depends on the instantaneous channel gains and the occupancy status of the relays' buffers. Selection is constrained by a maximum tolerable interference level at the primary receiver. We provide a theoretical framework based on a Markov chain to model the system and obtain the secondary throughput and average queueing delay. We verify our obtained expressions via numerical system simulations and investigate the impact of the various system parameters on performance.**

I. INTRODUCTION

The continual growth in wireless communication has raised the demand for spectrum resources. Cognitive radio technology has been introduced as a solution to spectrum-related problems such as underutilization and inefficiency. The main idea of cognitive radio is to permit the unlicensed (secondary) users to operate as long as the licensed (primary) users are inactive, or as long as the secondary transmission does cause interference to the primary transmission above some specified value. In addition, cognitive radio users are able to tune their transmission parameters according to the primary users' activity states and channel conditions.

In this paper, we study an underlay cognitive radio system in which coexistence of primary and secondary transmissions is allowed under the constraint that the interference induced by the cognitive users on the primary links is kept below a maximum tolerable level. In addition, we focus on the case where the direct link between a cognitive source and its respective receiver cannot support reliable communications due to, for instance, severe shadowing and pathloss. In this case, the cognitive system employs relaying in order to establish a working link between source and destination. Relaying in cognitive systems has received much attention by the wireless communications research community. For example, refer to [1], [2], [3], [4], [5] and the references therein.

We focus in this work on the case where the secondary relays of the cognitive system have buffers in order to support retransmission of undelivered data packets to the secondary destination. Relays with buffers in non-cognitive and cognitive settings are also considered in [6], [7], [8], [9], [10], [11], [12], [13], [14]. The "max-max" relay selection policy is considered in [8] and [9]. Buffered relays enable the selection of the relay with the best source-relay channel for reception and the best relay-destination channel for transmission. The scheme relies on a two-slot protocol where the schedule for the source and relay transmission is fixed a priori. This limitation is relaxed in [10] where the "max-link" relay selection scheme is proposed with each time slot being allocated dynamically to the source or relay transmission according to the instantaneous quality of the links and the state of the buffers.

In [11] and [12], the authors consider a two-hop cognitive setting, where the secondary user exploits periods of silence of the primary user to transmit its packets to a set of relays. Moreover, the relays can transmit even when the primary user is busy because they can act together and create a beamformer to suppress or even null the interference at the primary receiver. The instantaneous channel gains are assumed to be known at the relay stations. In [13] an amplify and forward (AF) relaying network is considered. The primary transmitter is considered as a source of interference at the relaying nodes. The best relay chosen is the one with the highest received signal-to-interference-plus-noise ratio (SINR). A diversity analysis is provided and a closed form expression is derived for the outage probability. A distributed best-relay node selection scheme is proposed in [14] in order to maximize the achievable data rate by cooperative communication in an underlay network while keeping the data rate of the primary transmission at a certain minimum level for a certain portion of time. The authors model the cognitive radio network as a restless bandit process, and the time-varying channel is characterized by a finite-state Markov channel model.

In this paper, we consider the max-link relay selection scheme proposed in [10] for a non-cognitive scenario and investigate its application to an underlay cognitive radio setting. In order to fit this scheme to the cognitive mode of operation, a constraint is imposed on the interference introduced by secondary transmission at primary receiver. This constraint applies to both the secondary source and the secondary relays. Using a Markov chain model for the constrained secondary network, we obtain the secondary throughput and average queueing delay. We compare our proposed scheme with the max-max relay selection scheme in [9], also after adapting it to an underlay cognitive radio setting. Numerical simulations are provided to validate the analysis, compare the relay selection schemes and study the impact of the various system parameters on performance.

The remainder of the paper is organized as follows. In Section II, the system model is introduced. We describe the cognitive max-link relay selection scheme with interference constraint in Section III and provide its mathematical analysis using Markov chains. Finally, in Section IV we provide some numerical results and simulations.

II. System Model

We consider a secondary network with a source node, a destination node and K relaying nodes, all equipped with single antennas (Fig.1). The direct channel between the secondary source and destination suffers from significant pathloss and, hence, communication between both nodes takes place only through the relays. In addition, we consider the presence of a primary receiver in the range of transmission of both the source and the relaying nodes. This primary receiver is required to be protected from excessive interference. Our model is an adaptation of the non-cognitive formulation studied in [10] such that it is extended to a cognitive setting with an interference constraint in order to protect a licensed primary link. We require that the secondary source or any secondary relay would not transmit if it causes an interference power at the primary receiver exceeding a specified level α.

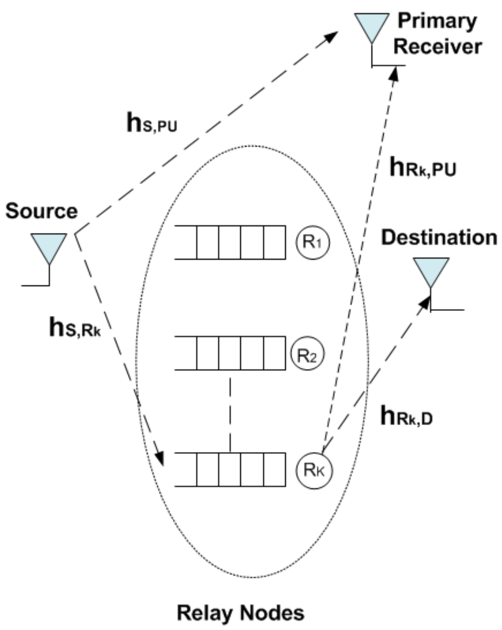

Fig. 1. System Model: A secondary source communicates with its destination via K buffered relays. The channels between the various terminals are explained in the text.

Secondary operation is slotted in time. During each slot transmission may occur from the source to one of the relays, or from one of the relays to the destination. Exactly one packet is transmitted during a time slot. We assume that the relays employ the decode-and-forward (DF) mode of operation. All the relays are assumed to be half duplex, which means that each relay can not send and receive data simultaneously. Each relay R_j holds a data buffer Q_j of size L. The number of packets in the data buffer is denoted by $\Psi(Q_j) \in \{0, 1, ..., L-1, L\}$. The source node does not have a data queue, and it transmits a new packet at the beginning of every time slot. If the packet is not transmitted successfully to one of the relays, it is considered to be lost. We are currently investigating the case of a buffered source for an extended version of this work.

Without loss of generality, we assume that the transmit power of the secondary source and each relay is unity. All channel links suffer from additive white Gaussian noise (AWGN) with zero mean and variance equal to σ^2. The source-relay and relay-destination channels are assumed to be independent and identically distributed (i.i.d) channel links all having the same gain $\Gamma_{\rm s}$. Denoting by h_{S,R_j} the channel between the source and relay R_j, and by $h_{R_j,D}$ the channel between R_j and the destination, Γ_s is given by:

$$\Gamma_{\rm s} = \mathbb{E}|h_{S,R_j}|^2 = \mathbb{E}|h_{R_j,D}|^2, \ \forall j \in \{1, 2, ..., K\} \quad (1)$$

where $\mathbb{E}$ denotes the expectation operator.

Let $h_{S,PU}$ and $h_{R_j,PU}$ be the channels between the secondary source and relay R_j, respectively, and the primary receiver. These channels are assumed to be i.i.d with an average gain $\Gamma_{\rm i}$,

$$\Gamma_{\rm i} = \mathbb{E}|h_{S,PU}|^2 = \mathbb{E}|h_{R_j,PU}|^2, \ \forall j \in \{1, 2, ..., K\} \quad (2)$$

Further, each channel changes independently from one time slot to another. We consider a Rayleigh fading model where each channel is a zero-mean circularly symmetric complex Gaussian random variable. This means that the magnitude squared of each channel is exponentially distributed with a mean equal to either $\Gamma_{\rm s}$ or $\Gamma_{\rm i}$.

The relay selection process is performed at the destination node as in [10], where all channel state information and all states of buffers are available. After the selection process is completed, the destination node sends back the selection result to the source and relays identifying which link to be used for transmission.

At the beginning of the transmission process, all buffers are empty. The number of packets in the buffer can increase by one for a given relay, if this relay is selected to receive data from the source node and the received signal-to-noise ratio (SNR) is higher than a certain threshold β_{SR}. If the received SNR is below this threshold level, the relay will not be able to decode the packet correctly. The packet will then be lost because the source node is not equipped with a data buffer.

In case of relay transmission, the number of packets in the data buffer is decreased by one when the relay is chosen to transmit to the destination node and the received SNR is higher than a certain threshold β_{RD}. If the received SNR is below this level, the destination will not be able to decode the received packet properly. It will signal back to the relay this decoding failure, thereby inducing the relay to retain the packet in its buffer for retransmission during a later time slot. That is, we assume that the links between the relays and the destination employ automatic repeat request (ARQ) feedback where the destination sends an acknowledgment (ACK) or negative acknowledgment (NACK) to indicate the status of packet decoding. The ARQ protocol is assumed to be infinite-persistent, which means that the erroneous packets stay in their buffer till they are delivered successfully to the destination. We assume that the ARQ packets are very short compared to the duration of a time slot. Moreover, they are always received correctly due to the use of a strong channel code.

III. Cognitive max-link Relay Selection with Interference Constraint

Max-link relay selection was introduced in [10]. It dynamically allocates a time slot either to relay reception if the best link is a source-relay link, or relay transmission if the best link is a relay-destination link. A source-relay link is considered available if the relay buffer is not full. On the other hand, a relay-destination link is considered available if the relay buffer is not empty. The selection policy can then be written as

$$R^* = \underset{j \in 1 \ldots K}{\text{argmax}} \left\{ \bigcup_{\Psi(Q_j) \neq L} \{|h_{S,R_j}|^2\} \bigcup_{\Psi(Q_j) \neq 0} \{|h_{R_j,D}|^2\} \right\} \tag{3}$$

Since we have a primary receiver that should be protected from interference, we modify the above rule to inhibit source or relay transmission if it produces an interference level at the primary receiver exceeding α. Hence, the chosen relay is given by:

$$\begin{aligned} R^* = \underset{j \in 1 \ldots K}{\text{argmax}} \Bigg\{ & \bigcup_{\Psi(Q_j) \neq L, |h_{S,PU}|^2 \leq \alpha} \{|h_{S,R_j}|^2\} \\ & \bigcup_{\Psi(Q_j) \neq 0, |h_{R_j,PU}|^2 \leq \alpha} \{|h_{R_j,D}|^2\} \Bigg\} \end{aligned} \tag{4}$$

Note that no relay acts as a receiver if the source node violates the interference constraint.

We model the cognitive radio system using a Markov chain with states describing the number of packets in each of the relays' buffers. Since each buffer can be empty or has up to L data packets, the number of states is $(L+1)^K$. In the next subsection, we find the state transition probabilities between all different buffer states.

A. State Transition Probabilities

The state transition matrix, A, is a square matrix of size $(L+1)^K \times (L+1)^K$. Element A_{uv} denotes the transition from state v to state u. The numbering of states is related to the occupancy of buffers such that state v corresponding to a particular $(\Psi(Q_1), ..., \Psi(Q_K))$ is given by:

$$v = 1 + \sum_{i=1}^{K} \Psi(Q_i)(L+1)^{i-1} \tag{5}$$

Thus, the first state ($v = 1$) corresponds to the case where all buffers are empty. The second state pertains to the situation where the buffer of R_1 has one packet and all the other buffers are empty, and so forth.

In order to compute the transition probabilities, we introduce $S_N \in \{0, 1\}$ that denotes whether the interference constraint is satisfied, where $N \in \{0, 1, ..., K\}$. Parameter $S_0 = 1$ if the secondary source node satisfies the interference constraint, and is equal to zero otherwise. On the other hand, parameter S_N for $N \neq 0$ is equal to unity when relay R_N can transmit while obeying the interference constraint and zero otherwise.

We also introduce the quantity $\Lambda^{(v)}(S_0, S_1, ..., S_K)$ which indicates the number of links available for transmission during a time slot when the buffers are in state v. Note that ignoring the buffer states and the interference constraint, each relay contributes two links to the total number of links, one over which it can receive from the source node, and one from which it can transmit to the destination. Nevertheless, a source-relay link is excluded from the possible links if the source node violates the interference constraint or the relay's buffer is full. A relay-destination link is unusable if the relay's buffer is empty or the relay does not satisfy the interference constraint. Therefore,

$$\begin{aligned} &\Lambda^{(v)}(S_0, S_1, ..., S_K) = \\ &\sum_{j=1}^{K} \Bigg\{ 2 - \Big[\mathbb{1}\{\Psi(Q_j) = L\} + \mathbb{1}\{S_0 = 0\} - \mathbb{1}\{\Psi(Q_j) = L\}\mathbb{1}\{S_0 = 0\} \Big] \\ &- \Big[\mathbb{1}\{\Psi(Q_j) = 0\} + \mathbb{1}\{S_j = 0\} - \mathbb{1}\{\Psi(Q_j) = 0\}\mathbb{1}\{S_j = 0\} \Big] \Bigg\} \end{aligned} \tag{6}$$

where $\mathbb{1}\{\cdot\}$ is the indicator function, which is equal to one if its argument is true and zero otherwise. The first square bracket is zero only if the relay's buffer is non-full and, hence, the relay can receive and the source can send a packet because its transmission satisfies the interference constraint. The second square bracket is zero if the relay can transmit a packet because its buffer is nonempty and its transmission does not violate the interference constraint.

We focus now on the state transitions where the length of one of the buffers is increased by one. To have such an increase in the number of packets in a given buffer, four conditions must be satisfied. The first condition is that the chosen relay for reception from the source node has the strongest link among all available links. The second is that the buffer of that relay is not full else it is not eligible for reception. The third condition is that the interference caused by this relay when it transmits does not exceed the maximum tolerable interference level at the primary receiver. Finally, the received SNR at the relay node must exceed the detection threshold for the packet to be decoded correctly and accepted into the buffer.

Based on this, we can write the following expression for the transition probability from a state v to another state where the ith buffer is incremented by one.

$$\begin{aligned} P_{v,i}^{\text{inc}} = \mathbb{1}\{\Psi(Q_i) \neq L\} \sum_{S_0,..,S_K} \Bigg\{ & P(S_0, S_1, ..S_K) \mathbb{1}\{S_0 = 1\} \times \\ & \mathbb{1}\{\Lambda^{(v)}(S_0, .., S_K) > 0\} \frac{1}{\Lambda^{(v)}(S_0, .., S_K)} P_{S,R_i}^{(c)} \Bigg\} \end{aligned} \tag{7}$$

This expression is a summation over all the possible combinations of S_N, $N \in \{0,1,...,K\}$. Probability $P(S_0,S_1,..S_K)$ is the probability of a certain combination of S_N values and is given by:

$$P(S_0,S_1,..S_K) = q^{\Sigma_{i=0}^{k} S_i}(1-q)^{K+1-\Sigma_{i=0}^{k} S_i} \tag{8}$$

where q is the probability of the channel gain to the primary receiver being below α. Given our Rayleigh channel model,

$$q = \exp\left(-\frac{\alpha}{\Gamma_i}\right) \tag{9}$$

Probability $P^{(c)}_{S,R_i}$ is the probability of correct reception between the source node and the ith relay node. In the case of Rayleigh fading, and since transmission occurs over the link with maximum gain among $\Lambda^{(v)}(S_0,...,S_K)$ channels, this probability is given by:

$$P^{(c)}_{S,R_i} = 1 - \left[1-\exp\left(-\frac{\beta_{SR}\sigma^2}{\Gamma_s}\right)\right]^{\Lambda^{(v)}(S_0,...,S_K)} \tag{10}$$

where, as mentioned in Section II, Γ_s is the average secondary channel gain and β_{SR} is the SNR detection threshold needed between the source node and any relay node. Recall that the transmit power is assumed to be unity. As is evident from (5), an increment of $\Psi(Q_i)$ by one means that a transition occurs from some state v to state $u = v + (L+1)^{i-1}$. Therefore,

$$A_{uv} = P^{\text{inc}}_{v,i} \text{ for } u = v + (L+1)^{i-1} \tag{11}$$

In a similar vein, we can obtain the probability of state transition from state v with the length of the buffer of relay R_i decreasing by one. In this case, the relay must transmit successfully to the destination. The transition probability is given by:

$$P^{\text{dec}}_{v,i} = \mathbb{1}\{\Psi(Q_i) \neq 0\} \sum_{S_0,..,S_K} \Bigg\{ P(S_0,S_1,...,S_K)\mathbb{1}\{S_i = 1\} \times \mathbb{1}\{\Lambda^{(v)}(S_0,..,S_K) > 0\} \frac{1}{\Lambda^{(v)}(S_0,..,S_K)} P^{(c)}_{R_i,D} \Bigg\} \tag{12}$$

where $P^{(c)}_{R_i,D}$ is the probability of correct reception at the destination when it receives from relay R_i and is given by:

$$P^{(c)}_{R_i,D} = 1 - \left[1-\exp\left(-\frac{\beta_{RD}\sigma^2}{\Gamma_s}\right)\right]^{\Lambda^{(v)}(S_0,...,S_K)} \tag{13}$$

A decrement of $\Psi(Q_i)$ by one means that a transition occurs from state v to state $u = v - (L+1)^{i-1}$. Hence,

$$A_{uv} = P^{\text{dec}}_{v,i} \text{ for } u = v - (L+1)^{i-1} \tag{14}$$

Note that since all columns of A sum to unity,

$$A_{vv} = 1 - \sum_{\substack{u=1 \\ u\neq v}}^{(L+1)^K} A_{uv} \tag{15}$$

It can be shown as in [10] that the Markov chain modeling our proposed system has a steady state distribution. Consider vector π of the steady state probabilities $\pi_1, \pi_2, ..., \pi_{(L+1)^K}$. Vector π is the eigenvector of matrix A corresponding to the unity eigenvalue, i.e., $A\pi = \pi$. Defining vector b as a vector of ones of length $(L+1)^K$ and matrix B of size $(L+1)^K \times (L+1)^K$ whose elements are all unity, it is clear that $B\pi = b$ because the state probabilities sum to one. It can be shown that matrix $A - I + B$, where I is the identity matrix, is invertible [10]. Therefore, both equations $A\pi = \pi$ and $B\pi = b$ can be combined to obtain π using the following expression:

$$\pi = (A - I + B)^{-1} b \tag{16}$$

B. Secondary Throughput and Average Queueing Delay

We define the throughput, T, in the cognitive setting under investigation as the fraction of packets correctly transmitted from the source node to the destination. Since a relay transmits and retransmits a packet till it is delivered to the destination, a packet is lost when the source, which has a new packet at each time slot, fails to deliver it to any of the relays. This occurs when the source node is not chosen for transmission, or when it transmits but the receiving relay does not decode the packet successfully. Using the Markov chain model of the system, the throughput is therefore given by:

$$T = \sum_{v=1}^{(L+1)^K} \sum_{i=1}^{K} \pi_v P^{\text{inc}}_{v,i} \tag{17}$$

Now we turn our attention to the average queueing delay, D. Due to secondary network link symmetry, the average queueing delay of a packet is identical for all buffers. Note that each buffer has an arrival rate equal to the secondary throughput divided by the number of relays. Given this arrival rate, the average delay can be obtained using Little's law. Delay D is given by:

$$D = 1 + \frac{1}{T/K} \sum_{v=1}^{(L+1)^K} \pi_v \Big[(v-1) \bmod (L+1)\Big] \tag{18}$$

where $x \bmod y$ is the remainder of the division of x by y. The explanation of the sum is as follows. Because of the symmetry, we can compute the average number of packets in a buffer using any buffer. We use here the buffer of relay R_1. From expression (5), it is clear that the number of packets in R_1's buffer, $\Psi(Q_1)$, is equal to $v-1$ modulo $L+1$. The added one in expression (18) for the delay is due to the fact that one time slot is needed to transfer a packet from the source node to one of the buffers.

IV. Numerical Results

We provide here some numerical results for the scheme described in this paper. We compare first between the results obtained from expressions (17) and (18) and those obtained from simulating the system. Fig. 2 shows the throughput variation with α, while Fig. 3 provides the average queueing delay variation with α. The parameters used to generate the

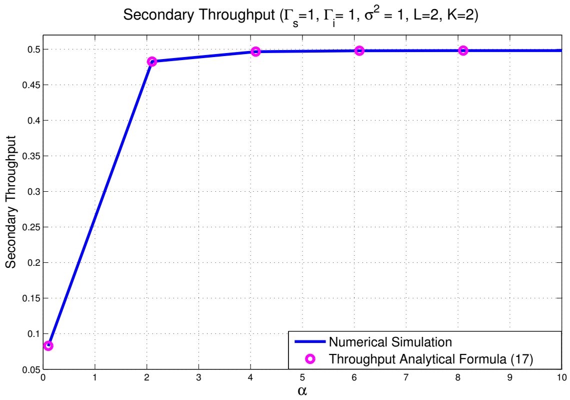

Fig. 2. Comparison between expression (17) for the secondary throughput and a system simulation. The parameters used to generate the figures are: $K = 2$, $L = 2$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$.

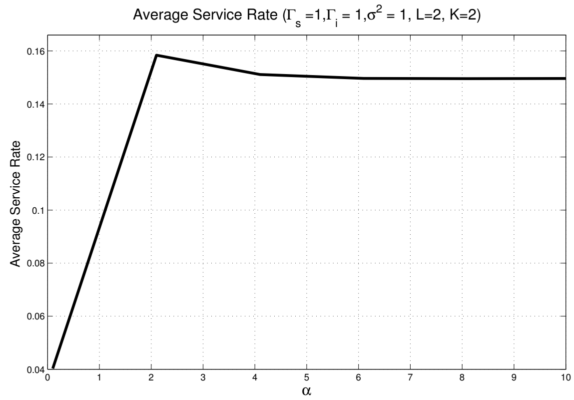

Fig. 4. Variation of average service rate with α. The parameters used to generate the figures are: $K = 2$, $L = 2$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$.

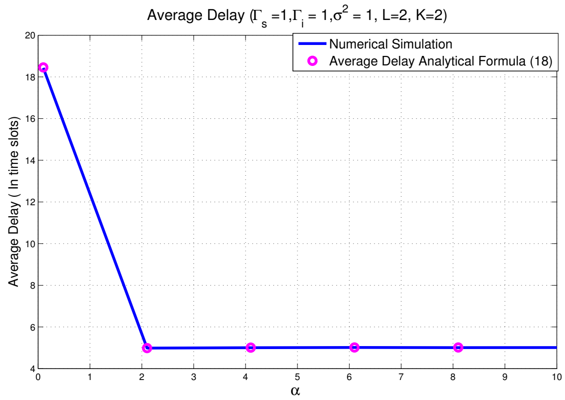

Fig. 3. Comparison between expression (18) for the secondary queueing delay and a system simulation. The parameters used to generate the figures are: $K = 2$, $L = 2$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$.

figures are: $K = 2$, $L = 2$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$. Both figures show a match between Markov chain analysis and the results from system simulation.

To fully explain the queueing delay results in Fig. 3, we calculate the average buffer service rate which we define as the total service rate, i.e., the fraction of packets correctly transmitted from relaying nodes to the destination node, divided by the number of relays participating in the relay transmission. The total service rate can be derived by a methodology that is similar to that adopted in deriving the throughput and is given by,

$$S = \sum_{v=1}^{(L+1)^K} \sum_{i=1}^{K} \pi_v P_{v,i}^{\rm dec}. \tag{19}$$

Fig. 4 shows the variation of the average service rate with α. It can be noticed that the average buffer service rate decreases beyond a certain value of α. The reason behind this is that as α is increased, it becomes very likely that all the relays satisfy the interference constraint. Hence, it is almost the case that all relays are permitted to transmit. This may reduce the average departure or service rate per buffer. This in turn may cause an increase in the queueing delay with increases in α.

In order to judge the performance of the proposed system, it is compared with the max-max relay selection proposed in [9] and adapted to an underlay cognitive radio setting as well. This was done by modifying the rule of relay selection to hinder source or relay transmission if it produces an interference level at the primary receiver exceeding α. In Fig. 5 the throughput obtained when using the max-link scheme in relay selection is compared with that obtained when using the max-max scheme. The parameters used to generate this figure are: $K = 2$, $L = 2$, $\Gamma_{\rm s} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$. The comparison is repeated for $\Gamma_{\rm i} = 1$ and $\Gamma_{\rm i} = 10$. The figure shows the superiority of the proposed scheme on the max-max scheme in addition it shows the effect of $\Gamma_{\rm i}$ on the throughput. As the value of $\Gamma_{\rm i}$ increases this will lead to increased interference level at the primary receiver which will hinder further transmissions, in return to that the secondary throughput will decrease.

Moreover, in order to explore the effect of changing $\Gamma_{\rm s}$ on the throughput we are going to repeat both schemes' simulations for $\Gamma_{\rm s} = 0.1$ and $\Gamma_{\rm s} = 1$ while keeping all other parameters unchangeable. The result is shown in Fig. 6 demonstrating the superiority of the max-link selection over the max-max selection as well as clarifying that the increase in the value of $\Gamma_{\rm s}$ leads to better channel conditions between the source and the relaying nodes which will be translated to an increase in the achieved throughput.

By changing the parameters used to generate the figure to be $K = 4$, $L = 5$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$. We will first compare between the results obtained in expressions (17) and (18) and those obtained from system simulation. Fig. 7 shows the variation of the throughput with α while Fig. 8 shows the queueing delay variation with α. Both figures show a match between Markov chain analysis

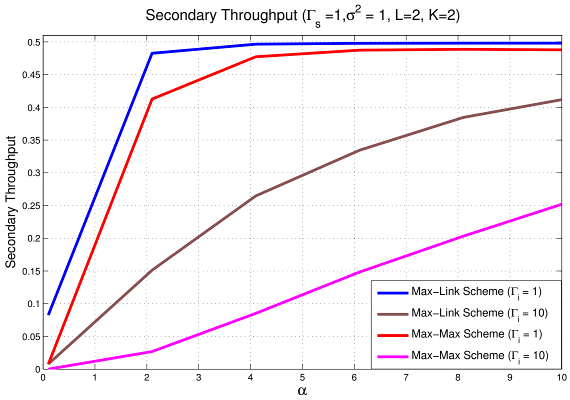

Fig. 5. Comparison between the max-link scheme and the max-max scheme with respect to achieved throughput and the effect of changing $\Gamma_{\rm i}$ on the secondary throughput. The parameters used to generate the figures are: $K = 2$, $L = 2$, $\Gamma_{\rm s} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$, $\beta_{RD} = 0.1$, for $\Gamma_{\rm i} = 1$ and $\Gamma_{\rm i} = 10$.

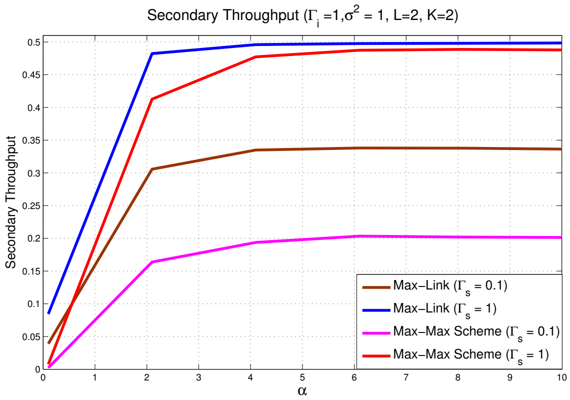

Fig. 6. Comparison between the max-link scheme and the max-max scheme with respect to achieved throughput and the effect of changing $\Gamma_{\rm s}$ on the secondary throughput. The parameters used to generate the figures are: $K = 2$, $L = 2$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$, $\beta_{RD} = 0.1$, for $\Gamma_{\rm s} = 0.1$ and $\Gamma_{\rm s} = 1$.

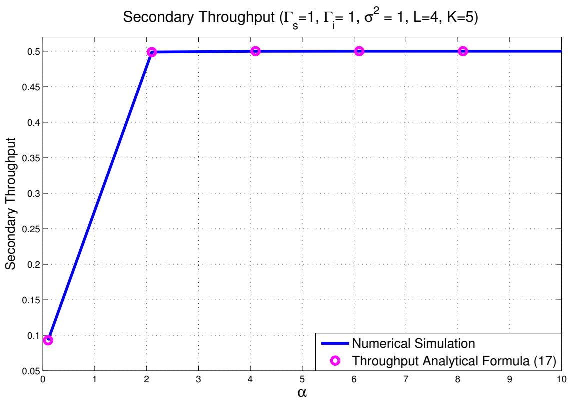

Fig. 7. Comparison between expression (17) for the secondary throughput and a system simulation. The parameters used to generate the figures are: $K = 4$, $L = 5$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$.

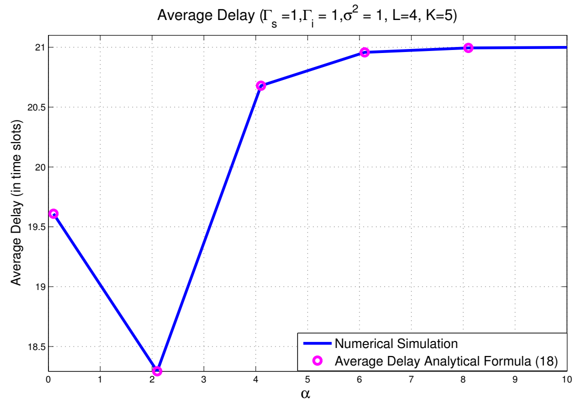

Fig. 8. Comparison between expression (18) for the secondary queueing delay and a system simulation. The parameters used to generate the figures are: $K = 4$, $L = 5$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$.

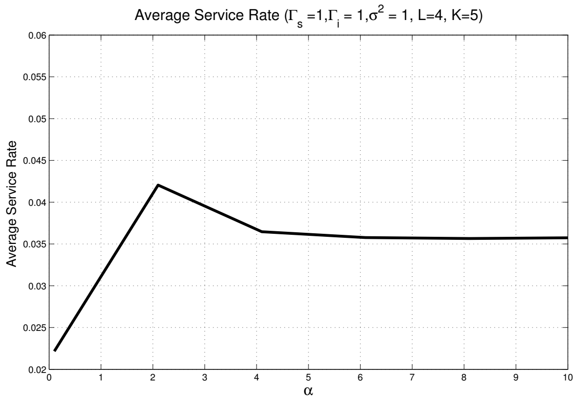

Fig. 9. Variation of average service rate with α. The parameters used to generate the figures are: $K = 4$, $L = 5$, $\Gamma_{\rm s} = 1$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$ and $\beta_{RD} = 0.1$.

and the system simulation result. Fig. 9 shows the variation of the average service rate with α which explains the variation of the queueing delay shown in Fig. 8. At small values of α the average service rate starts to increase which leads to a decrease in the value of the queueing delay, but after that the average service rate starts to decrease which will increase the queueing delay in return.

Fig. 10 and Fig. 11 show the effect of $\Gamma_{\rm i}$ and $\Gamma_{\rm s}$ on the throughput respectively for both the proposed scheme and the max-max scheme. The results obtained indicate the superiority of the proposed scheme over the max-max scheme. In addition they attest the effects of $\Gamma_{\rm i}$ and $\Gamma_{\rm s}$ explained before.

V. CONCLUSION

In this paper, we proposed a buffered relay selection algorithm for an underlay cognitive radio network. The selection is based on the instantaneous channel gains and the occupancy of the relays' buffers. It is also constrained by the maximum interference level that can be tolerated at the primary receiver. We presented a theoretical framework based on a Markov

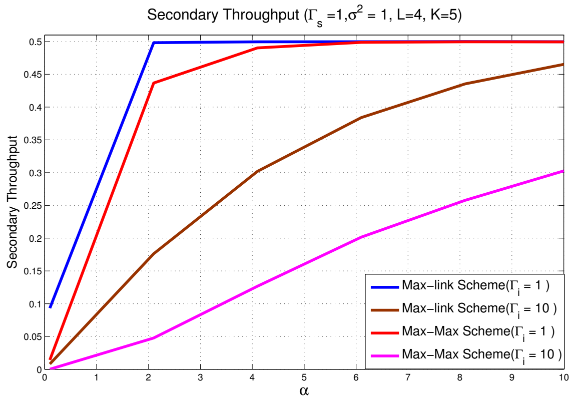

Fig. 10. Comparison between the max-link scheme and the max-max scheme with respect to achieved throughput and the effect of changing $\Gamma_{\rm i}$ on the secondary throughput. The parameters used to generate the figures are: $K = 4$, $L = 5$, $\Gamma_{\rm s} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$, $\beta_{RD} = 0.1$, for $\Gamma_{\rm i} = 1$ and $\Gamma_{\rm i} = 10$.

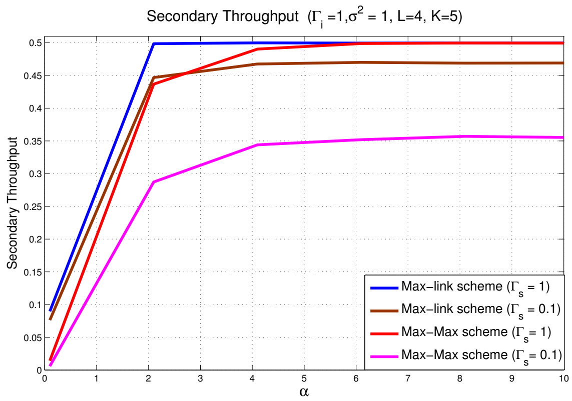

Fig. 11. Comparison between the max-link scheme and the max-max scheme with respect to achieved throughput and the effect of changing $\Gamma_{\rm s}$ on the secondary throughput. The parameters used to generate the figures are: $K = 4$, $L = 5$, $\Gamma_{\rm i} = 1$, $\sigma^2 = 1$, $\beta_{SR} = 0.1$, $\beta_{RD} = 0.1$, for $\Gamma_{\rm s} = 0.1$ and $\Gamma_{\rm s} = 1$.

chain to model the system and obtain the secondary throughput and average queueing delay. We are currently investigating the same system with a buffer at the secondary source and studying how this will impact the system performance.

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