Spectrum Leasing Via Cooperative Interference Forwarding

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***Abstract*—A primary (licensed) link communicates in the presence of an interferer. A secondary (unlicensed) link is also active in the same band and can access the channel through a spectrum leasing (SL) mechanism, whereby the primary system grants transmission opportunities to the secondary link. This paper investigates the possibility that the secondary link gains access to the channel, to transmit its own data, by cooperating with the primary link via interference mitigation. Specifically, SL is enabled if the interfering signal is decoded by the secondary link and is forwarded to the primary link to allow for interference mitigation. The SL decision at the primary link hinges on whether the advantage accrued from interference mitigation by allowing secondary transmissions overcome the loss of spectral resources due to SL. This form of primary–secondary cooperation contrasts with previously proposed approaches to SL, whereby the secondary user gains credit by forwarding the primary packet, and not the knowledge of interference to the primary receiver (PR). A SL scheme is proposed that leverages the hybrid automatic repeat request (HARQ) retransmission processes at primary and interfering links. Numerical results demonstrate conditions under which the proposed approach based on interference forwarding outperforms more conventional techniques based on primary packet relaying.**

***Index Terms*—Cognitive radio, cooperative systems, hybrid automatic repeat request (HARQ), interference forwarding, spectrum leasing (SL).**

I. Introduction

Spectrum leasing (SL) via cooperation, which is proposed in [1] (see also [2] and [3] for similar independent work), dictates the local coexistence of primary (licensed) and secondary (unlicensed) users through the following mechanism. Secondary users gain credit to access the channel by cooperating with the primary users, and primary users lease spectrum to the secondary nodes under two conditions: 1) That the advantage on the primary performance accrued from secondary cooperation overcomes the loss of spectral resources for the primary system due to SL; and 2) that secondary nodes are leased with enough spectrum to satisfy their quality-of-service (QoS) constraints (which are made known to the primary system to enable SL decisions). For an introduction to more general approaches to SL, we refer to [5].

Previous work [1], [2] has investigated the principle of SL via cooperation by assuming that secondary-to-primary cooperation takes place, conventionally, by having the secondary users relay packets for the primary nodes. We refer to this conventional approach as *cooperative transmission* (CT), and we refer to [4] for a survey of cooperation. Recent research has demonstrated that, from an information-theoretic standpoint, in interference-limited scenarios, conventional CT can be outperformed by a different form of cooperation, which we refer to as *cooperative interference management* (CIM) [6], [7]. In CIM, the cooperating node forwards information about the interference and not about the useful signal. The rationale of this approach is that boosting the reception of the interference at the receiver can allow the latter to decode the interfering signal jointly with the useful signal, and thus enhance performance via interference mitigation. We emphasize that previous work on CIM [6], [7] focused on relay networks with no SL (NSL), along with static and known channels.

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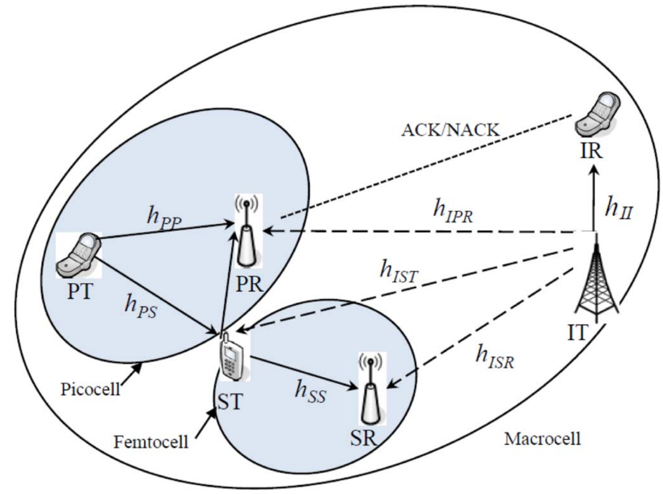

Fig. 1. System model. A primary link, between a PT and a PR, coexists with a secondary link between an ST and an SR. An interfering link between an IT and an IR is also present, which affects both the PR and the SR. We can think of the PR as a picocell base station and the SR as a neighboring femtocell base station with the IT being the base station of the macrocell that encompasses the femtocell and the picocell.

In this paper, we propose to use CIM to enable SL via cooperation. In other words, unlike previous work [1], [2], the secondary user gains credit to access the channel by forwarding *interference* (rather than the *primary signal*) to the primary receiver. Moreover, unlike in [6] and [7], CIM is implemented as a means to enable SL and integrated with hybrid automatic repeat request (HARQ) processes at the primary and interfering links to cope with fading channels unknown to the transmitters. The rest of this paper is organized as follows. In Section II, we describe the system model, whereas Section III presents the proposed SL strategy based on CIM, along with reference techniques. In Section III, we also explain the transmission strategies. Performance analysis is discussed in Section IV. Finally, numerical results and final remarks are provided in Sections V and VI, respectively.

II. System Model

We consider the system in Fig. 1, in which a primary link, between a primary transmitter (PT) and a primary receiver (PR), coexists with a secondary link between a secondary transmitter (ST) and a secondary receiver (SR). An interfering link between an interfering transmitter (IT) and an interfering receiver (IR) is also present, which affects both the PR and the SR. We can think of the PR as a picocell base station and the SR as a neighboring femtocell base station, with the IT being the base station of the macrocell that encompasses the femtocell and the picocell [8]. In this uplink setting, the PT is a picocell user, the ST is a femtocell user, and the IR is a macrocell user. The reason for considering the IT to be a macro base station is that the proposed strategy based on CIM becomes particularly relevant, as we will see when the disturbance caused by the interference sets the main bottleneck in the performance of the PT–PR link.

The wireless channel between a pair η of nodes is characterized by a small-scale fading coefficient h_η and by a path loss $d_\eta^{-\gamma}$, where d_η

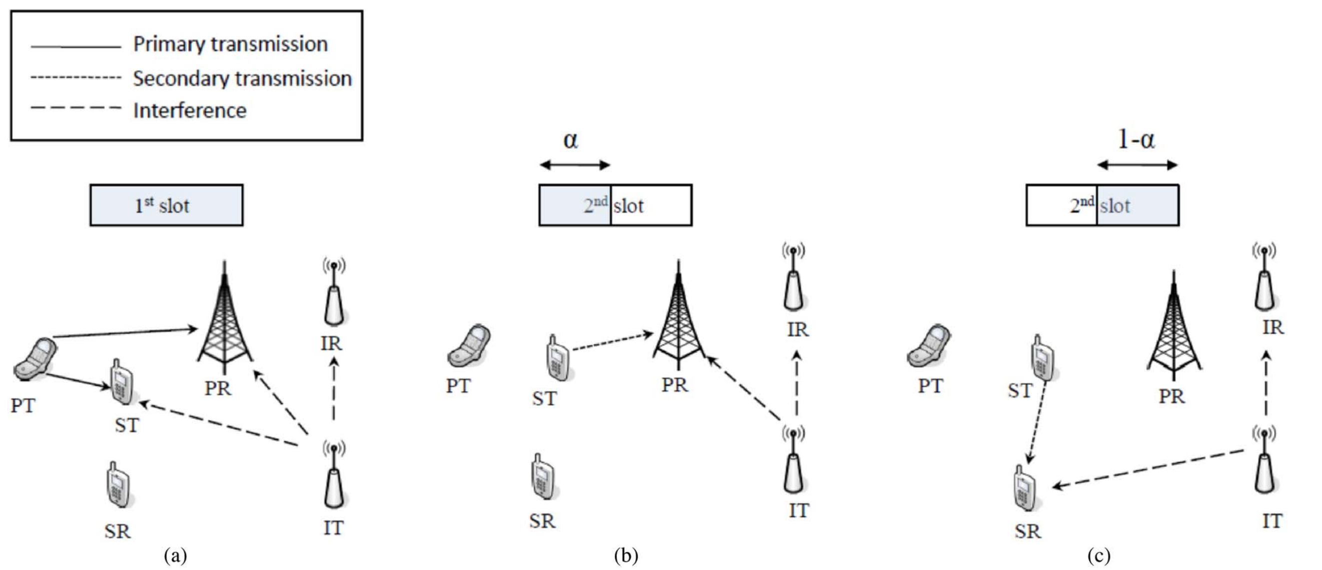

Fig. 2. ST gains access to the spectrum either by cooperating with the primary for transmission of the primary packet (SL-CT) or by forwarding interference information (SL-CIM). (a) Primary transmission. (b) Cooperation slot. (c) Leased slot.

is the distance between the two nodes and γ is the path-loss exponent. The power gain for link η is thus $g_\eta = |h_\eta|^2 d_\eta^{-\gamma}$. For instance, the power gain, the fading coefficient, and the distance for the PT–SR link are g_{PS}, h_{PS}, and d_{PS}, respectively. We refer to Fig. 1 for an illustration of all channel gains. Time is slotted. A block Rayleigh fading model is assumed, in which all fading channels stay constant during each transmission slot but change independently from slot to slot. No channel state information (CSI) is assumed at the transmitters, but full CSI is available at the receivers. A primary packet carries R_P bits/s/Hz, which is referred to as primary rate, whereas the secondary rate is R_S, and the interferer rate is R_I. We assume that the codebook used by the interferer is known at PR and SR when implementing SL-CIM.[1]

III. Transmission Strategies

Both links PT–PR and IT–IR employ type-I HARQ with a maximum number of attempts (original and retransmissions) of $K \geq 2$ and $K_I \geq 2$, respectively. Recall that, with type-I HARQ, the transmitter retransmits a copy of the same packet at every new attempt, and the receiver discards previously received packets and decodes based only on the last received signal. If the packet is unsuccessfully decoded at the last attempt, i.e., the Kth attempt for the primary link and the K_Ith attempt for the interfering link, the packet is dropped, and a new packet is transmitted in the next slot. Type-I HARQ is selected for simplicity of analysis, but the proposed principle can be applied also to more complex forms of HARQ.

We describe the process by following the transmission of a primary packet and by denoting the first transmission slot of a primary packet as slot $i = 1$, the second transmission (or first retransmission) slot as $i = 2$, and so forth until the Kth primary transmission. The state of the HARQ process of the interferer at time slot $i \in \{1, \ldots, K\}$ is described by a variable $U_{I,i} \in \{1, \ldots, K_I\}$, so that we have $U_{I,i} = k$ if in slot i the interferer (re)transmits the current packet for the kth time (i.e., $k = 1$ corresponds to the first transmission, etc.). For simplicity of analysis, we assume that $U_{I,1}$ has a generic distribution $\Pr[U_{I,1} = a_1]$.[2]

In the proposed approach, SL is triggered by errors on the PT–PR link. Specifically, the PT can follow three different policies on how to handle retransmissions. The first option is not to perform SL. In this case, the retransmissions are performed directly by the PT. With the last two options, instead, parts of the retransmission slots, under given conditions to be discussed, are leased to the ST. We detail the three policies in the following.

NSL: The primary link does not lease a spectrum to ST at any time. If the reception of the primary packet fails in the first slot, as shown in Fig. 2(a), the PT performs up to $(K-1)$ retransmissions until the packet is successfully received, or the maximum number $K-1$ of retransmissions is carried out.

SL via CT (SL-CT): If the ST decodes the PT's packet in the first slot or any slot during the following $(K-2)$ retransmissions, it informs the PT and/or the PR. Part of the next retransmission slot is then leased to the ST, along with all possible subsequent retransmissions. Specifically, the spectral resources in the slots at hand are divided into two parts, e.g., in time or frequency, as shown in Fig. 2(b). In the first part of the slot, termed *cooperation slot*, of relative size $0 \leq \alpha \leq 1$, ST cooperates with PT in forwarding a fraction α of symbols of the primary packet to the PR. The second part of the slot, termed *leased slot*, of relative size $\bar{\alpha} = 1 - \alpha$, is instead leased to secondary transmission for communication between the ST and the SR, as shown in Fig. 2(c). This scheme is akin to the strategy proposed in [9].

SL via CIM (SL-CIM): If ST decodes IT's packet in the first slot or any slot during the following $(K-2)$ retransmissions, it informs the PT and/or the PR. We assume that PR is able to overhear the acknowledgment (ACK) or no ACK (NACK) messages fed back by the IR regarding the previous transmission of IT. Since these messages are typically transmitted with powerful error-correcting codes, the assumption appears reasonable in practical systems. If a NACK message from IR is observed and the ST has correctly decoded IT's packet, ST signals to the PT its availability for

[1]This only requires the ST to be able to decode the preamble of IT's packet, which typically contains the information regarding the physical-layer mode used in the packet.

[2]This means that the distribution of $U_{I,1}$ can be any distribution.

SL. This way, part of the retransmission slot is leased to the ST, along with all subsequent retransmission slots in which the IT retransmits the same packet. The rationale for this is that, unlike SL-CT, in the cooperation slot shown in Fig. 2(b), the ST forwards a fraction α of the symbols of the IT's packet, rather than the primary packet, to the PR. This way, the ST boosts the reception of the interfering signal with the aim of enabling more effective interference mitigation by joint decoding at the PR.

Note that, in both SL strategies described earlier, ST is always in the receiving mode and begins transmitting its own data only when part of the primary slot is leased to it. Moreover, parameter α is set by the secondary link to satisfy its QoS requirements. Secondary QoS requirements are defined by a maximum probability of outage $P_{\text{out}}^{\max,S}$ that must be supported on the ST–SR link in the case that SL is granted. Note that the ST–SR link does not employ HARQ.

IV. Performance Analysis

Here, we analyze the performance of NSL, SL-CT, and SL-CIM. To this end, the following definitions are useful. Let the Shannon capacity of a Gaussian channel be $C(x) = \log_2(1+x)$ and $(x)^+ = \max\{x, 0\}$. Consider a scenario with two transmitters and one receiver, i.e., a multiple-access channel (MAC), in which the signal from transmitter 1 is received with power ρ_1 and transmitter 2 with power ρ_2. The maximum rate achievable by user 1 if user 2 transmits at rate r_2 is well known to be given by $C_1(\rho_1, \rho_2, r_2) = \max(R_N(\rho_1, \rho_2), R_J(\rho_1, \rho_2, r_2))$, where [10, Lecture note 4]

$$\begin{aligned} R_N(\rho_1, \rho_2) &= C\left(\rho_1(1+\rho_2)^{-1}\right), R_J(\rho_1, \rho_2, r_2) \\ &= \min\left\{C(\rho_1), (C(\rho_1+\rho_2) - r_2)^+\right\}. \end{aligned} \tag{1}$$

Rate $R_N(\rho_1, \rho_2)$ is achieved if the receiver treats the signal of transmitter 2 as noise (subscript "N" stands for "Noise"), whereas rate $R_J(\rho_1, \rho_2, r)$ is achieved if the receiver jointly decodes the two users (subscript "J" stands for "Joint"). By optimally choosing between the two decoders, rate $C_1(\rho_1, \rho_2, r_2)$ is achieved.

By using the definitions given, the primary outage probability $P_{\text{out},P}$ for all (re)transmissions, in which the PT transmits directly to the PR, is given by

$$P_{\text{out},P} = \Pr\left[R_P \geq C_1(g_{\text{PP}} P_P, g_{\text{IP}} P_I, R_I)\right]. \tag{2}$$

where R_P is the primary rate. This is because, when PT transmits, the PR is the receiver in a MAC with the two transmitters being the PT (which plays the role of user 1 in the discussion above) and the IT (which plays the role of user 2). Recall that with type-I HARQ, decoding in different slots takes place independently. Similar calculations apply also for the other links, as explained in the following.

We consider the *throughput*, i.e., the average number of primary packets that are successfully delivered per slot, as the performance metric of interest, which can be calculated as

$$T_P = \frac{P_{\text{succ}}^{(K)}}{E[N_P]} \tag{3}$$

where $P_{\text{succ}}^{(K)}$ is the probability of the successful primary packet delivery within the maximum number of transmissions of K slots, and $E[N_P]$ is the average number of time slots used by the primary HARQ process. The random variable $N_P \in \{1, \ldots, K\}$ denotes the (random) number of transmission attempts spent by the primary HARQ process, accounting also for the possibly leased time slots, and its probability distribution is given by

$$\Pr[N_P = k] = \begin{cases} \left(1 - P_{\text{out},P}^{(k)}\right) \prod_{j=1}^{k-1} P_{\text{out},P}^{(j)}, & \text{for } k = 1, \ldots, K-1 \\ \prod_{j=1}^{K-1} P_{\text{out},P}^{(j)}, & \text{for } k = K \end{cases} \tag{4}$$

where $P_{\text{out},P}^{(k)}$ is the probability of outage at the PR in slot k given that all previous transmission attempts up to the $(k-1)$th attempt were unsuccessful. Note that $N_P = K$ only entails that the first $K-1$ transmissions were unsuccessful, which explains the second line in (4). The probability $P_{\text{succ}}^{(K)}$ is then given by

$$P_{\text{succ}}^{(K)} = \sum_{k=1}^{K-1} \Pr[N_P = k] + \Pr[N_P = K]\left(1 - P_{\text{out},P}^{(K)}\right) \tag{5}$$

whereas the average number of retransmissions is evaluated as $E[N_P] = \sum_{k=1}^{K} k \Pr[N_P = k]$. We now detail the evaluation of $P_{\text{out},P}^{(k)}$ for the different schemes.

A. NSL

With NSL, the probability of outage at the kth retransmission is simply given by $P_{\text{out},P}^{(k)} = (P_{\text{out},P})^k$ since, with HARQ type-I, all transmission attempts are independent. Note that the HARQ processes of the PT–PR and IT–IR links evolve independently with NSL.

B. SL-CT

Here, we derive the performance of SL-CT. The derivation does not follow from [9] due to the presence of the interferer. Consider first the calculation of the SL parameter α based on the secondary QoS, as defined by outage probability $P_{S,\text{out}}^{\max}$. Assuming for simplicity that SR decodes based only on the signal received in the leased slot, the SL parameter α is calculated by imposing the following condition:

$$\Pr\left[R_S \geq \bar{\alpha} C_1(g_{\text{SS}} P_S, g_{\text{ISR}} P_I, R_I \bar{\alpha}^{-1})\right] \leq P_{S,\text{out}}^{\max} \tag{6}$$

where R_S and R_I is the secondary and interferer rates, respectively, and the left-hand side of (6) is the secondary outage probability. This is because, in the leased slot, the SR acts as the receiver in a MAC with the two transmitters being ST and IT [recall the discussion around (1)]. Note that the effective interferer's rate observed by the SR in the leased part of the slot is $R_I \bar{\alpha}^{-1}$ due to the fraction $\bar{\alpha}$ of channel uses allocated to the leased slot. If (6), taken with equality, has a solution in $0 \leq \alpha \leq 1$, this choice of α guarantees the secondary QoS constraint. If it does not have a solution, then we say that *SL is not feasible* for the given secondary QoS constraints.

Assuming that SL is feasible, the primary outage probability $P_{\text{out},P}^{(k)}$ in the kth slot given that all previous transmissions were unsuccessful can be calculated by definition as

$$P_{\text{out},P}^{(k)} = \Pr[\mathcal{O}_k | \mathcal{O}_1, \ldots, \mathcal{O}_{k-1}] = \frac{\Pr[\mathcal{O}_1, \ldots, \mathcal{O}_k]}{\Pr[\mathcal{O}_1, \ldots, \mathcal{O}_{k-1}]} \tag{7}$$

where $\mathcal{O}_j$ is the outage event at the PR in time slot j. The joint probability $\Pr[\mathcal{O}_1, \ldots, \mathcal{O}_k]$ can be calculated using the law of total probability as

$$\begin{aligned} \Pr[\mathcal{O}_1, \ldots, \mathcal{O}_k] = &\sum_{j=1}^{k-1} \Pr[N_{\text{PS}} = j](P_{\text{out},P})^j \left(P_{\text{out},P}^{SL-CT}\right)^{k-j} \\ &+ \left(1 - \sum_{j=1}^{k-1} \Pr[N_{\text{PS}} = j]\right)(P_{\text{out},P})^k \end{aligned} \tag{8}$$

where the random variable N_{PS} measures the number of primary transmission attempts needed for ST to decode the primary packet. Specifically, we have $N_{\mathrm{PS}} = j$ if ST decodes PT's packet at the jth slot (i.e., at the jth primary transmission attempt). Moreover, $P_{\mathrm{out},P}^{\mathrm{SL-CT}}$ is the probability of outage at the PR given that the ST transmits the primary packet in the cooperation slot, which is given by

$$P_{\mathrm{out},P}^{SL-CT} = \Pr\left[R_P \geq \alpha C_1\left(\left|h_{\mathrm{PP}}\sqrt{d_{\mathrm{PP}}^{-\gamma}P_P} + h_{\mathrm{SP}}\sqrt{d_{\mathrm{SP}}^{-\gamma}P_S}\right|^2, g_{\mathrm{IP}}P_I, R_I\alpha^{-1}\right)\right]. \quad (9)$$

This is because the ST does not know the channel to the SR; thus, cooperation with the PT takes place by forwarding the PT's packet noncoherently. The probability of $N_{\mathrm{PS}} = j$ is given by $\Pr[N_{\mathrm{PS}} = j] = (P_{\mathrm{out},S}^{\mathrm{SL-CT}})^{j-1}(1 - P_{\mathrm{out},S}^{\mathrm{SL-CT}})$, where $P_{\mathrm{out},S}^{\mathrm{SL-CT}}$ is the probability that the ST is not able to decode the PT's packet in a slot, which is easily seen to be given by $P_{\mathrm{out},S}^{\mathrm{SL-CT}} = \Pr[R_P \geq C_1(g_{\mathrm{PS}}P_P, g_{\mathrm{IS}}P_I, R_I)]$. We remark that (8) reflects the fact that, upon decoding at the jth retransmission, all the following possible primary retransmissions are leased to ST. Furthermore, probability (8) is calculated using the fact that, when conditioned on the event $\{N_{\mathrm{PS}} = j\}$ for $j = 1, \ldots, k-1$ or on the complement of event $\cup_{j=1}^{k-1}\{N_{\mathrm{PS}} = j\}$ (i.e., on the event the ST does not decode PT's packet during the first $k-1$ transmissions), the decoding attempts at different slots by PR are independent.

C. SL-CIM

With SL-CIM, calculation of parameter α is done in the same way as for SL-CT, i.e., through condition (6). We now assume that SL is feasible, i.e., that (6), taken with equality, has a solution. Calculation of the outage probability $P_{\mathrm{out},P}^{(k)}$ of the PT in the kth slot with SL-CIM is complicated by the fact that $P_{\mathrm{out},P}^{(k)}$ depends not only on whether ST successfully decoded the IT's packet in some previous slot but also on the current state of the IT's HARQ process. This is because, as described earlier, SL is performed only if IT retransmits a previously transmitted packet in the current slot to enable interference boosting at PR. Note that, based on the above, SL-CIM not only depends on the channels between the ST and the IT but also on the channels between the IT and the IR.

To elaborate, for each $k = 1, \ldots K$, we define two random vectors, namely $U_I^k = [U_{I,1}, \ldots, U_{I,k}]$ and $U_{\mathrm{IS}}^k = [U_{\mathrm{IS},1}, \ldots, U_{\mathrm{IS},k}]$, where we recall that $U_{I,j} \in \{1, \ldots, K_I\}$ is the index of the IT's transmission attempt during the jth transmission slot of the PT, whereas random variable $U_{\mathrm{IS},j} \in \{0, 1\}$ indicates whether the ST has decoded in some prior slot the packet currently being transmitted by the IT ($U_{\mathrm{IS},j} = 1$) or not ($U_{\mathrm{IS},j} = 0$). Therefore, we have $U_{\mathrm{IS},j} = 1$ if, at the beginning of slot j, the ST has made available the packet that the IT transmits in slot j, and we have $U_{\mathrm{IS},j} = 0$ if otherwise. With these definitions, probability $P_{\mathrm{out},P}^{(k)}$ can be calculated as follows:

$$P_{\mathrm{out},P}^{(k)} = \sum_{a\in\{1,\ldots,K_I\}^k, b\in\{0,1\}^k} \Pr\left[U_I^k = a, U_{\mathrm{IS}}^k = b\right] \times (P_{\mathrm{out},P})^{N_I(a,b)}\left(P_{\mathrm{out},P}^{\mathrm{SL-CIM}}\right)^{k-N_I(a,b)} \quad (10)$$

where the sum in (10) is taken with respect to all possible pairs of sequences U_I^k and U_{IS}^k. Moreover, for given sequences $U_I^k = a$ and $U_{\mathrm{IS}}^k = b$, $N_I(a, b)$ is the number of slots j at which the ST does not have available the currently transmitted IT packet, i.e., at which either IT starts a new transmission (i.e., $U_{I,j} = 1$), or the IT retransmits, but the ST was not able to decode the IT's packet in any of the previous slots (i.e., $U_{I,j} \neq 1$, and $U_{\mathrm{IS},j} = 0$). Finally, $P_{\mathrm{out},P}^{\mathrm{SL-CIM}}$ is the probability of outage at the PR, given that ST forwards interference in the cooperation slot. This is given by

$$P_{\mathrm{out},P}^{\mathrm{SL-CIM}} = \Pr\left[R_P \geq \alpha C_1\left(g_{\mathrm{PP}}P_P, \left|h_{\mathrm{IP}}\sqrt{d_{\mathrm{IP}}^{-\gamma}P_I} + h_{\mathrm{SP}}\sqrt{d_{\mathrm{SP}}^{-\gamma}P_S}\right|^2, R_I\alpha^{-1}\right)\right] \quad (11)$$

since, for a fraction α of the time (the cooperation slot), the IT's signal is received by the PR boosted by the transmission of ST. Notice that the signals from the IT and the ST add incoherently at the PR due to the lack of CSI. Probability (11) follows since the PR in the cooperation slot acts as the receiver in a MAC with the transmission to be decoded being the PT's packet in the presence of the IT's transmission. We finally remark that (10) reflects the fact that, when conditioned on sequences $(U_I^k, U_{\mathrm{IS}}^k)$, the decoding error events at PR in each slot are independent.

We now explain how to calculate the probability $\Pr[U_I^k = a, U_{\mathrm{IS}}^k = b]$ in (10). Recalling that the state $U_{I,1}$ of the HARQ process of the IT–IR link at slot $j = 1$ is assumed to have a uniform probability distribution on the set $\{1, \ldots, K_I\}$ and that $U_{\mathrm{IS},1} = 0$ with probability 1, using the chain rule for probability distributions, we have

$$\begin{aligned}\Pr&\left[U_I^k = a, U_{\mathrm{IS}}^k = b\right] \\ &= \Pr[U_{I,1} = a_1]\delta(b_1)\prod_{j=1}^{k-1}\Pr \\ &\quad\times\left[U_{\mathrm{IS},j+1} = b_{j+1}|U_{I,j} = a_j, U_{\mathrm{IS},j} = b_j\right]\Pr \\ &\quad\times\left[U_{I,j+1} = a_{j+1}|U_{I,j} = a_j, U_{\mathrm{IS},j} = b_j, U_{\mathrm{IS},j+1} = b_{j+1}\right] \quad (12)\end{aligned}$$

where $\delta(\cdot)$ is the Kronecker delta function, i.e., $\delta(x) = 1$ if $x = 0$, and $\delta(x) = 0$ if otherwise. Equation (12) follows since the joint process $(U_I^k, U_{\mathrm{IS}}^k)$ is easily seen to be Markovian. The probability terms in (12) are obtained by evaluating the transition probabilities of this Markov chain, which is shown in Fig. 3. From the description of the system model, it is not difficult to see that the probability $\Pr[U_{\mathrm{IS},j+1} = b_{j+1}|U_{I,j} = a_j, U_{\mathrm{IS},j} = b_j]$ is equal to (13), shown at the bottom of the page, where $P_{\mathrm{out},I}^{\mathrm{SL-CIM}}$ is the probability of outage at the IR in a leased slot, whereas $P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}}$ is the probability that the ST does not successfully decode the IT's packet, which are calculated in the following: To interpret (13), note that the first line reflects the fact that, if the previous slot, i.e., the jth slot, contained the last transmission of an IT packet (i.e., $U_{I,j} = K_I$), then necessarily, the IT sends a new packet in the current slot, i.e., the $(j+1)$th slot; therefore, this packet is not available at the ST (i.e., $U_{\mathrm{IS},j+1} = 0$). The following lines account for the cases in which the previous slot was not the last transmission of an IT packet. Specifically, the second line follow since,

$$\begin{cases}\delta(b_{j+1}) & \text{if } a_j = K_I \\ P_{\mathrm{out},I}^{\mathrm{SL-CIM}} & \text{if } a_j \neq K_I, b_j = 1, b_{j+1} = 1 \\ \dfrac{\left(1-P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}}\right)P_{\mathrm{out},I}}{\left(1-P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}}\right)P_{\mathrm{out},I}+P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}}P_{\mathrm{out},I}+(1-P_{\mathrm{out},I})} & \text{if } a_j \neq K_I, b_j = 0, b_{j+1} = 1\end{cases} \quad (13)$$

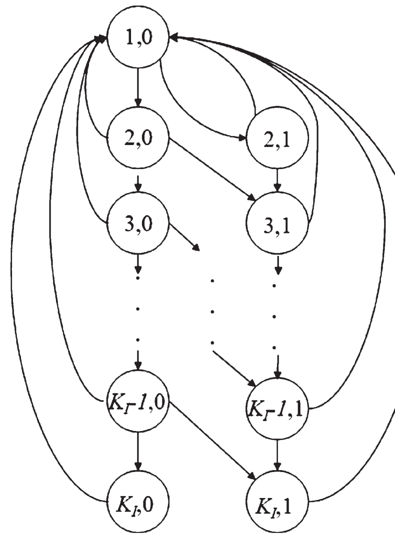

Fig. 3. State transition diagram of the Markov chain $(U_I^k, U_{\mathrm{IS}}^k)$, where $U_I^k = (U_{I,1}, \ldots, U_{I,k})$, with $U_{I,j}$ being the index of IT's transmission attempt during the jth transmission slot of PT, and $U_{\mathrm{IS}}^k = (U_{IS,1}, \ldots, U_{IS,k})$, with $U_{\mathrm{IS},j}$, indicating whether ST has decoded in some prior slot the packet currently being transmitted by the IT or not. States are represented by $(U_{I,j} = a, U_{\mathrm{IS},j} = b)$ with $a \in \{1, \ldots, K_I\}$ and $b \in \{0, 1\}$. Only nonzero transition probabilities are illustrated as edges.

when the ST had the IT's packet available in the previous slot (i.e., $U_{\mathrm{IS},j} = 1$), then in the current slot $j+1$, we have that $U_{\mathrm{IS},j+1} = 1$ if the IT's transmission was in outage in the previous slot. Finally, the third line reflect the fact that, if ST does not have the current IT packet in slot j (i.e., $U_{\mathrm{IS},j} = 0$), it will have it in the next slot if the IT suffers outage and, at the same time, the ST successfully decodes the IT's packet in the jth slot. The probability that the link IT–IR is in outage in a leased slot can be calculated as

$$P_{\mathrm{out},I}^{\mathrm{SL-CIM}} = \Pr\left[R_I \geq \alpha C\left(\left|h_{\mathrm{II}}\sqrt{d_{\mathrm{II}}^{-\gamma} P_I} + h_{\mathrm{SI}}\sqrt{d_{\mathrm{SI}}^{-\gamma} P_S}\right|^2\right) + \bar{\alpha} R_N(g_{\mathrm{II}} P_I, g_{\mathrm{SI}} P_S)\right]. \quad (14)$$

This follows from simple information-theoretical considerations since, for a fraction α of the time (the cooperation slot), the IT's signal is received by the IR boosted by the transmission of ST [first term in (14)], whereas for the remaining fraction of time, the ST transmits the secondary packet, which we treat for simplicity as noise [second term in (14)]. Instead, the probability that the ST does not successfully decode the IT's packet is given by $P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}} = \Pr[R_I \geq C_1(g_{\mathrm{IST}} P_I, g_{\mathrm{PST}} P_P, R_P)]$ since ST acts as the receiver in a MAC with two transmitters being the IT and the PT.

Finally, following similar reasoning as for (13), the probability $\Pr[U_{I,j+1} = a_{j+1} | U_{I,j} = a_j, U_{\mathrm{IS},j} = b_j, U_{\mathrm{IS},j+1} = b_{j+1}]$ is equal to (15), shown at the bottom of the page, where $P_{\mathrm{out},I}$ is the probability of outage at the IT in a slot in which the ST does not transmit (i.e., a slot that is not leased) given by $P_{\mathrm{out},I} = \Pr[R_I \geq R_N(g_{\mathrm{II}} P_I, g_{\mathrm{PI}} P_P)]$, where we assume, for simplicity, that the PT's signal is treated as noise at the IR.

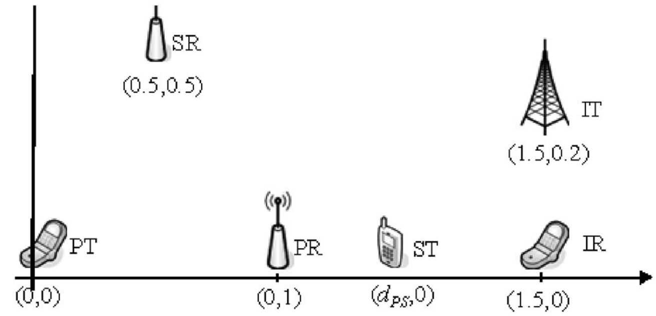

Fig. 4. Geometry of nodes on the xy plane considered in Section V.

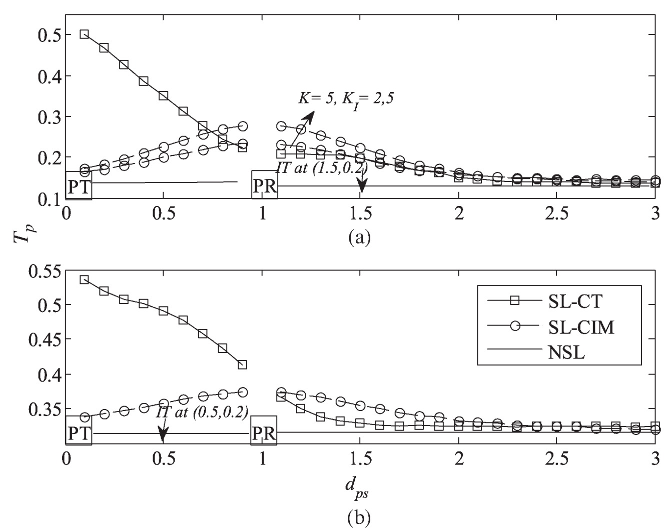

Fig. 5. Primary throughput T_P versus PT–ST distance d_{PS} for NSL, SL-CT, and SL-CIM for $K = 5$ and IT locations. (a) $x = 1.5$, and $y = 0.2$. (b) $x = 0.5$ and $y = 0.2$. ($P_P = P_S = 4$, $P_I = 10$, $R_P = R_S = 1$, $R_I = 4$).

V. Numerical Results

Here, we provide some insights into the performance comparison of NSL, SL-CT, and SL-CIM. We assume that the PT, the PR, and the SR are located at the positions $(x = 0, y = 0)$, $(x = 1, y = 0)$, and $(x = 0.5, y = 0.5)$ of the xy plane, respectively, as shown in Fig. 4. The ST is located on the x-axis aligned with the PT and the PR at a PT–ST distance d_{PS} [4]. Nodes communicate over Rayleigh fading channels. The primary, secondary, and interferer transmit power values are $P_P = P_S = 4$ and $P_I = 10$, respectively, and the path-loss exponent is $\gamma = 3$. The larger power sent by the interferer is typical of scenarios, such as the scenario discussed in Section II, in which the IT is a high-power node such as a macro base station.

Fig. 5 plots the primary throughput T_P versus the PT–ST distance d_{PS} for NSL, SL-CT, and SL-CIM with interference rate

$$\begin{cases} \delta(a_{j+1} - 1) & \text{if } a_j = K_I \text{ or } a_j \neq K_I, b_j = 1, b_{j+1} = 0 \\ \delta\left(a_{j+1} - (a_j + 1)\right) & \text{if } a_j \neq K_I, b_{j+1} = 1 \\ (1 - P_{\mathrm{out},I})\left(P_{\mathrm{out},I} P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}} + (1 - P_{\mathrm{out},I})\right)^{-1} & \text{if } a_j \neq K_I, b_j = 0, b_{j+1} = 0, a_{j+1} = 1 \\ P_{\mathrm{out},I} P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}}\left(P_{\mathrm{out},I} P_{\mathrm{out,IS}}^{\mathrm{SL-CIM}} + (1 - P_{\mathrm{out},I})\right)^{-1} & \text{if } a_j \neq K_I, b_j = 0, b_{j+1} = 0, a_{j+1} = a_j + 1 \end{cases} \quad (15)$$

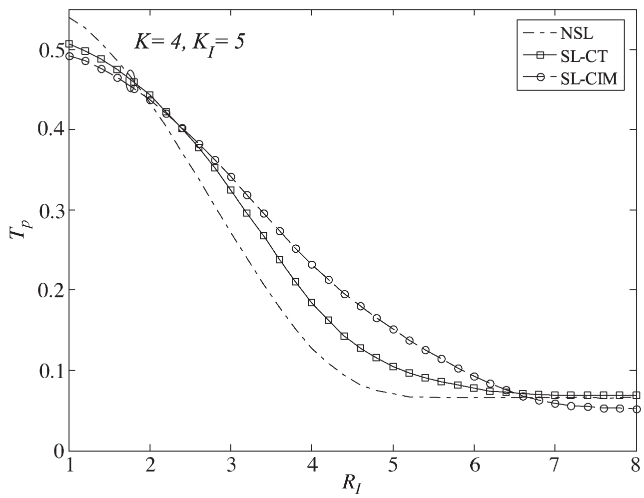

Fig. 6. Primary throughput T_p versus the interferer's rate R_I for NSL, SL-CT, and SL-CIM for fixed IT location $(x = 1.5, y = 0.2)$ $(P_P = P_S = 4, P_I = 10, R_P = R_S = 1, R_I = 4)$.

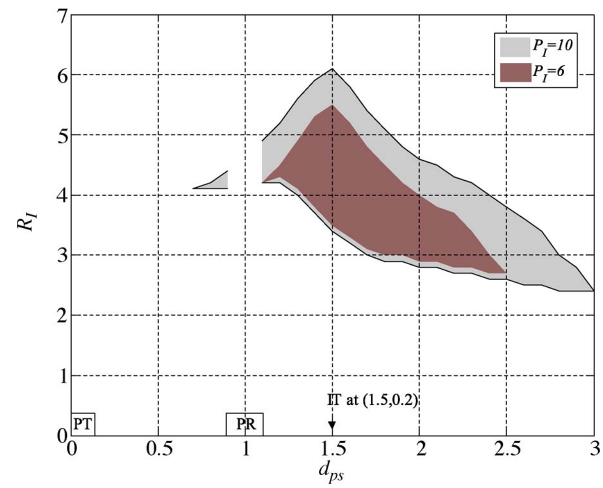

Fig. 7. Region of pairs of interferer's rate R_I and ST position d_{PS} for which SL-CIM is feasible and advantageous over SL-CT. $(P_P = P_S = 4, P_I = 10, 6, R_P = R_S = 1)$.

$R_I = 4$ bits/s/Hz and for different interferer locations, namely $(x = 0.5, y = 0.2)$ and $(x = 1.5, y = 0.2)$. We introduce exclusion zones (boxes on the x-axis) around the points where the PT and the PR are located to avoid divergence of the received power. Note that the performance of SL-CT does not depend on K_I. A first observation is that SL techniques can widely outperform NSL, while allowing both primary and secondary transmissions, as also pointed out in [1] and [2]. In this regard, it is noted that the primary throughput of SL-CT and SL-CIM reduces to the corresponding NSL throughput only as the ST moves sufficiently far away from the PT and the IT, respectively. This is because the ST cannot decode data packets from the PT or the IT.

Regarding the performance comparison of SL-CT and SL-CIM, it is seen that SL-CIM outperforms SL-CT whenever the ST is in the vicinity of IT so that it is more capable of decoding the interference rather than the primary signal. Such performance gains increase as the maximum number of interferer retransmissions K_I is increased since a larger K_I implies that IT's packets are dropped due to exceeding the maximum number of retransmissions; hence, more opportunities for SL arise. It is also seen that moving IT closer to the primary link, i.e., to position $(x = 0.5, y = 0.2)$, reduces the primary throughput gain of SL-CIM, as compared with SL-CT since the PR has a better observation of IT's transmission and can thus perform effective interference management even without the help of the ST.

Fig. 6 plots the primary throughput T_P versus the IT's rate R_I for a fixed position $d_{\text{PS}} = 1.5$, $K_I = 5$, and $K = 4$. It is shown that SL-CIM is the best-performing strategy unless the rate R_I is either too small, in which case interference forwarding is not necessary for effective interference management, or is too large, in which case SL-CIM is not feasible.

Fig. 7 shows as a shaded area the pair of interferer rate R_I and ST position d_{PS} for $P_I = 10, 6$ for which SL-CIM is feasible and advantageous over SL-CT. As it can be seen from the figure, the range of interferer rates R_I, for which SL-CIM is advantageous, is largest when the ST is close to the IT; as in this case, decoding the interfering signal is possible also at larger rates. The figure also shows the effect of a reduced interfering power P_I. As P_I decreases, the range of rates R_I for which SL-CIM is advantageous decreases due to the fact that the interfering signal becomes more difficult to decode at ST.

VI. Concluding Remarks

In this paper, we have investigated the possibility that the secondary link gains access to the channel by forwarding information about the interference rather than the primary signal. We have shown that choosing between SL-CIM and SL-CT, depending on the ST location and interference rate and power, provides substantial performance gains in terms of primary throughput with respect to relying only on the conventional SL-CT (i.e., primary packet relaying). We have also shown that the performance gains depend on the interferer's rate and on the quality of the IT–IR link, and increase as the increase number of allowed retransmission K_I increases (see Fig. 7 for an illustration).

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