Spectrum Leasing via Cooperative Opportunistic Routing in Distributed Ad Hoc Networks: Optimal and Heuristic Policies

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***Abstract*—A spectrum leasing strategy is considered for the coexistence of a licensed multihop network and a set of unlicensed nodes. The primary network consists of a source, a destination and a set of additional primary nodes that can act as relays. In addition, the secondary nodes can be used as extra relays and hence potential next hops following the principle of opportunistic routing. Secondary cooperation is guaranteed via the "spectrum leasing via cooperation" mechanism, whereby a cooperating node is granted spectral resources subject to a Quality of Service (QoS) constraint.**

The objective of this work is to find *optimal* as well as efficient *heuristic* routing policies based on the idea outlined above of spectrum leasing via cooperative opportunistic routing. The optimal policy is obtained by casting the problem in the framework of stochastic routing. The optimal performance is then numerically compared with two proposed heuristic routing schemes, which are shown to perform close to optimal solutions and as well being tunable in terms of end-to-end throughput *vs* primary energy consumption.

***Index Terms*—Spectrum leasing, cooperative transmission, opportunistic routing, superposition coding, optimal policies, heuristic routing schemes**

I. Introduction

Routing strategies that exploit the diversity offered by the radio channel by selecting the routes in an opportunistic fashion, based on instantaneous channel conditions, are being studied under the subject of opportunistic routing [1]–[3].

Enabling the coexistence of wireless networks with different priorities through appropriate interference management mechanisms is at the core of the cognitive radio research field. Usual approaches consider that the primary network operates as if the secondary nodes were not present and the latter keep their interference to the primary receivers below an acceptable level [4]. Alternatively, according to a spectrum leasing approach (see, e.g., [5]), the primary network owns the used spectrum and the secondary nodes can access it only if granted transmission by the primary network.

In this work, we consider a routing mechanism based on a combination of the principles of opportunistic routing and of "spectrum leasing via cooperation" [6], [7]. We recall that opportunistic routing refers to routing strategies that exploit the diversity offered by the radio channel by selecting the routes in an opportunistic fashion, based on instantaneous channel conditions [1]–[3]. Following the spectrum leasing via cooperation paradigm, secondary nodes may potentially cooperate with the primary network, acting as extra relays and hence possible next hops for an opportunistic routing scheme, but only in exchange for leasing of spectral resources from the primary network. Secondary nodes enforce Quality of Service (QoS) requirements in terms of rate and/or reliability on the spectral resources offered by the primary network, when deciding whether or not to cooperate. Reference [8] studied the idea outlined above in the context of a simple linear network topology and for given heuristic opportunistic routing schemes.

The objective of this work is to find *optimal* as well as efficient *heuristic* routing policies to route a primary packet through primary and secondary transmitters in an *arbitrary topology*, adopting the spectrum leasing via cooperation principle. Optimal policies are obtained by formulating the problem as an instance of stochastic routing [9]. Moreover, two heuristic policies with low complexity are proposed, that are shown to perform very close to the optimal scheme.

The paper is structured as follows. In Section II we introduce the system model for opportunistic routing. In Section III we formulate opportunistic routing in ad hoc networks with arbitrary topology as a stochastic routing problem [9]. In Section IV we devise distributed heuristic routing schemes, which are thus numerically compared against optimal routing in Section V. Our concluding remarks are given in Section VI.

II. System Model

A packet from a *primary source* P_o is to be routed to a *primary destination* P_d, possibly via multi-hop routing through two sets of relays. The first set $\mathcal{R}_P$ is formed by N_P *primary nodes*, while the second set $\mathcal{R}_S$ consists of N_S *secondary nodes* that coexist with the primary network via spectrum leasing. Specifically, as detailed below, a secondary relay can transmit only if leased a portion of the spectrum by the primary network. The two sets of relays are arbitrarily placed in a square area with normalized side equal to one, where source P_o and destination P_d are positioned in the middle of two opposite sides. The position of each node is static and known by the all nodes in the network. We define the set of all nodes as $\mathcal{T} = \mathcal{R}_P \cup \mathcal{R}_S \cup \{P_o, P_d\}$.

Transmission of the packet is organized in time slots and is composed of ℓ (complex) channel uses each. Nodes work in half-duplex mode and spatial reuse is not allowed, therefore

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only one node is allowed to transmit in each slot. In the first slot, the primary source P_o uses a transmission rate of $\mathrm{R_P}$ bits/s/Hz to transmit the primary packet, which is $\ell\,\mathrm{R_P}$ bits long. In the following slots, retransmissions may be done by the source P_o or by one of the relays, either primary or secondary (depending on the routing policy adopted by the primary network), until the final destination P_d correctly receives the packet. After correct decoding, the process starts again with a transmission of a new packet by the source P_o (i.e., always backlogged).

The primary network selects the routing policy and corresponding parameters (see Section IV). Cooperating secondary node enforce QoS requirements on the amount of spectral resources leased by the primary network. In particular, each secondary requires to be able to transmit its own traffic at rate $\mathrm{R_S}$ to a node at distance d_S with an outage probability of at most ϵ_S. The use of the tuple (d_S, $\mathrm{R_S}$, ϵ_S) is further discussed below. When selected as relay of the primary packet, a secondary node has to multiplex the primary packet with a secondary packet. In this paper, this multiplexing is achieved using superposition coding (SC), see, e.g., [10]: the primary packet is summed to the secondary packet with an appropriate power allocation $0 \leq \psi \leq 1$ and then transmitted. Parameter ψ represents the fraction of power allocated to secondary transmissions with respect to that allocated to the transmission of primary data and is set so as to satisfy the desired secondary QoS requirements in terms of rate and reliability. We remark that SC is known to be optimal for Gaussian broadcast channels [10] and it can be proved to be optimal also for the model studied here by following [11].

Routing decisions are made in an on-line fashion by the node in charge of transmitting the primary packet, which chooses the next hop based on 1) the specific node selection policy adopted by the primary network and 2) the feedback received at the end of the previous time slot from its neighbouring nodes (primary and secondary) that have successfully received the packet. The mechanism used by the relays to send acknowledgements to the primary network is not further analyzed here. A study on the design of feedback signalling can be found in [12], [13] for systems with no secondary nodes.

A. Signal Model and Outage Probabilities

Considering a transmission from node $a \in \mathcal{T} \setminus \{P_d\}$, let $y_{a,n}(b,t)$ denote the discrete-time (complex) baseband sample received by the node $n \in \mathcal{T} \setminus \{P_o\}$ during the b-th time slot at channel use t, $t = 1, \ldots, \ell$. The channel between nodes a and n is denoted as $h_{a,n}(b)$ and assumed to be constant within a time slot (block-fading), Rayleigh distributed with zero mean and unit power. Moreover, notation $x_a(b,t)$ represents the discrete-time (complex) baseband sample transmitted by the scheduled node a with a per-symbol power constraint fixed to $\mathbb{E}\left[|x_a(b,t)|^2\right] \leq E_\mathrm{N}$, where E_N is equal to E_P or E_S when the transmitter is a primary or a secondary node, respectively. The relation between transmitter and receiver is given by $y_{a,n}(b,t) = d_{a,n}^{-\eta/2} h_{a,n}(b) x_a(b,t) + z_{a,n}(b,t)$, where $d_{a,n}$ is the distance between the nodes, η is the power path-loss exponent and $z_{a,n}(b,t)$ represents the complex white Gaussian noise term with zero mean and power $\mathbb{E}[|z_{a,n}(b,t)|^2] = N_0$.

Channel state information $h_{a,n}(b)$ is not known to the transmitter node a, but only to the receiver node n. The average received signal-to-noise ratio (SNR) for primary users is given by $\xi_\mathrm{P} = E_\mathrm{P}/N_0$ denoting the ratio between the maximum average energy directly received by P_d from the source P_o and the noise power N_0. Hence, the term $\xi_\mathrm{P} d^{-\eta}$ represents the average received SNR for a transmission from a primary node that covers a distance d, and $\xi_\mathrm{S} d^{-\eta} = E_\mathrm{S}/N_0 d^{-\eta}$ denotes the average received SNR for a transmission from a secondary node that covers a distance d.

We now detail the outage probabilities and we discuss the secondary QoS requirements, which are parametrized by tuple $\mathcal{Q} = (d_\mathrm{S},\ \mathrm{R_S},\ \epsilon_\mathrm{S})$. First, consider the transmission from a primary node $a \in \mathcal{R}_P \cup \{P_o\}$. Let $P_\text{out,P}(d_{a,n})$ be the outage probability for a packet transmitted by the primary node a to a primary or secondary node $n \in \mathcal{T} \setminus \{P_o\}$ at distance $d_{a,n}$. Assuming that the coding block is long enough, we have (see, e.g., [8], [14]),

$$P_\text{out,P}(d_{a,n}) = 1 - \exp\left(-\frac{2^{\mathrm{R_P}} - 1}{\xi_\mathrm{P} d_{a,n}^{-\eta}}\right). \qquad (1)$$

Now consider the transmission from a secondary node. As explained above, this combines both primary and secondary data using SC. Moreover, the power allocation parameter ψ must be picked so as to meet the QoS requirements of the secondary users. In order to decode either the primary or the secondary packet, receivers at all nodes employ two parallel decoders so that detection of the desired message is correct if either one of the two decoders correctly decodes. The first decoder decodes the desired packet (primary or secondary) by treating the undesired packet as additive Gaussian noise. The second decoder, instead, estimates and cancels the undesired packet from the received signal and then decodes the desired packet from the interference-free signal. Based on this discussion, the outage probability related to the decoding of a primary packet transmitted from the secondary node $a \in \mathcal{R}_S$ to a primary or secondary node $n \in \mathcal{T} \setminus \{P_o\}$ at distance $d_{a,n}$ is given by (see for details [11])

$$P_\text{out,SP}(d_{a,n}) = 1 - \exp\left[-\min\left(\mathcal{H}_\mathrm{P}^{(1)}, \mathcal{H}_\mathrm{P}^{(2)}\right)\right], \qquad (2)$$

where $\mathcal{H}_\mathrm{P}^{(1)}$ represents the outage threshold for the first decoder, in which the interference (i.e., secondary packet) is treated as noise and is equal to $[2^{\mathrm{R_P}}-1]/[(1-(1-\psi)2^{\mathrm{R_P}})\xi_\mathrm{S} d_{a,n}^{-\eta}]$ if $1-2^{-\mathrm{R_P}} < \psi \leq 1$ or ∞ otherwise. The remaining term $\mathcal{H}_\mathrm{P}^{(2)}$ is the threshold outage of the successive decoding scheme, where the receiver first decodes the secondary packet and then the primary one and is equal to $\max\{[2^{\mathrm{R_S}} - 1]/[(1 - \psi 2^{\mathrm{R_S}})\xi_\mathrm{S} d_{a,n}^{-\eta}], [2^{\mathrm{R_P}} - 1]/[\psi \xi_\mathrm{S} d_{a,n}^{-\eta}]\}$ if $0 < \psi < 2^{-\mathrm{R_S}}$ or ∞ otherwise. To impose the QoS requirements (d_S, $\mathrm{R_S}$, ϵ_S) we need the expression of the outage probability that a secondary packet (superimposed with a primary message) transmitted by a secondary node is not decoded correctly by a secondary node placed at distance d. This term is given by

$$P_{\text{out,SS}}(d) = 1 - \exp\left[-\min\left(\mathcal{H}_{\text{S}}^{(1)}, \mathcal{H}_{\text{S}}^{(2)}\right)\right], \qquad (3)$$

where $\mathcal{H}_{\text{S}}^{(1)}$ and $\mathcal{H}_{\text{S}}^{(2)}$ have a similar form of $\mathcal{H}_{\text{P}}^{(1)}$ and $\mathcal{H}_{\text{P}}^{(2)}$ (for further details see [11]). Imposing the condition on the outage probability as $P_{\text{out,SS}}(d_{\text{S}}) = \epsilon_{\text{S}}$, we can numerically extract the parameter ψ from this equation for any given rate pair $(\text{R}_{\text{P}}, \text{R}_{\text{S}})$.

B. Performance Metrics

Thanks to spectrum leasing, the primary network can gain on two fronts: 1) throughput, because of an improved multiuser diversity in the selection of the next hop, due to the availability of secondary nodes; 2) primary energy consumption, due to the fact that transmissions can be delegated to the secondary network.

We define the *primary end-to-end throughput* $T(k, \text{R}_{\text{P}}, \mathcal{Q})$ as the average number of *successfully* transmitted bits per second per Hz, given the total number of hops k, the primary transmission rate R_{P} and the tuple $\mathcal{Q}$. Using renewal theory, the throughput is given as (see, e.g., [15]):

$$T(k, \text{R}_{\text{P}}, \mathcal{Q}) = \frac{\text{R}_{\text{P}}}{\mathbb{E}[M]}, \qquad (4)$$

where M is the total number of time slots used to correctly forward a given primary packet from the source P_o to the destination P_d, i.e., $M = M_{\text{P}} + M_{\text{S}}$ where M_{P} and M_{S} represent the number of *primary* and *secondary transmissions*, respectively. We also define the primary energy $E(k, \text{R}_{\text{P}}, \mathcal{Q})$ as the average overall energy spent by the primary network to deliver a packet successfully, normalized with respect to the energy expenditure of a single primary transmission. Therefore, this quantity is measured via the number of time slots that involve *primary* transmissions,

$$E(k, \text{R}_{\text{P}}, \mathcal{Q}) = \mathbb{E}[M_{\text{P}}]. \qquad (5)$$

III. Optimal Routing Policies

The problem to be solved is to find optimal routing transmission policies for the scenario discussed above. With the term optimal we refer here to policies that minimize, across all the possible evolutions of the system, the expected throughput (*throughput optimal*), the expected total transmission energy expended by primary users (*energy optimal*) or a combination of throughput and primary energy through a weighting factor $\alpha \in [0, 1]$. We show below that the problem can be formulated as an instance of stochastic routing [9].

Time is slotted and a single copy of the packet is transmitted in any slot $k = 0, 1, 2, 3, \ldots$. The system evolution is described through a suitable Markov chain with states $x_k \in \Omega$, where Ω is the set of all states and $x_k \subseteq \mathcal{T}$ identifies the nodes that have correctly decoded the packet up to and including time slot k. Moreover, we define the *starting* state s and the *final* state f.

At time $k = 0$, only the primary source P_o has the packet and the Markov chain is in state s (i.e., $x_0 = s$). In the first transmission slot, $k = 1$, P_o transmits its packet and the system moves to $x_1 \supseteq s$. If $P_d \notin x_1$, a relay node $a \in x_1$ (either primary or secondary) is selected from x_1 to transmit the packet in the next time slot $k = 2$. This process is iterated for the subsequent slots $k = 3, 4, \ldots$, until the destination node P_d correctly receives the packet, i.e., $P_d \in x_k$. At this point, the Markov chain transitions to the final state f with probability one and the cost associated with this transition is zero.

The dynamics of the network are captured by transition probabilities $p_{xy}(a)$, $x, y \in \Omega$, with $y \supseteq x$ and $a \in x$, which return the probability that, starting from state x, the system transitions to state y, that is, nodes in $y \setminus x$ correctly receive the packet, when node (action) a is elected as the relay. For the computation of $p_{xy}(a)$, we define the *outage probability* $p_{\text{out}}(a, n)$ for any node $n \in \mathcal{T}$ when a is the transmitter and $d_{a,n}$ is their distance:

$$p_{\text{out}}(a, n) = \begin{cases} P_{\text{out,P}}(d_{a,n}) & \text{when } a \in \mathcal{R}_P \cup \{P_o\} \\ P_{\text{out,SP}}(d_{a,n}) & \text{when } a \in \mathcal{R}_S\,. \end{cases} \qquad (6)$$

Moreover, for $x \neq f$ with $P_d \notin x$ and $y \neq f$, we define

$$P_{xy}(a) = \prod_{\substack{n \in \mathcal{T} \text{ s.t.} \\ n \in y, n \notin x}} [1 - p_{\text{out}}(a, n)] \prod_{\substack{m \in \mathcal{T} \text{ s.t.} \\ m \notin y}} p_{\text{out}}(a, m)\,. \qquad (7)$$

Thus, it follows that

$$p_{xy}(a) = \begin{cases} 0 & (P_d \in x \text{ or } x = f) \text{ and } y \neq f \\ 1 & (P_d \in x \text{ or } x = f) \text{ and } y = f \\ 0 & P_d \notin x,\ x \neq f \text{ and } y = f \\ P_{xy}(a) & P_d \notin x,\ x \neq f \text{ and } y \neq f \end{cases} \qquad (8)$$

The final state f is absorbing, i.e., $p_{ff}(a) = 1$, $\forall\, a \in f$.

Each transition also has an associated cost $c(x, a, y)$ and the goal is to minimize the total expected discounted cost

$$J(s) \stackrel{\text{def}}{=} \mathbb{E}_\pi\left[\sum_{k=0}^{+\infty} \gamma^k c(x, a, y) \middle| x_0 = s\right], \qquad (9)$$

where $\gamma \in (0, 1)$ is a discount factor and $\mathbb{E}_\pi[\cdot | x_0 = s]$ is the conditional expectation given that routing policy π is employed. The cost $c(x, a, y)$ is incurred when the current state is $x \in \Omega$, action $a \in x$ is selected and the system moves to state $y \in \Omega$. In detail, we have

$$c(x, a, y) = \alpha c_{\text{Thr}}(x, a, y) + (1 - \alpha) c_{\text{E}}(x, a, y)\,, \qquad (10)$$

where $c_{\text{Thr}}(x, a, y)$ accounts for the *throughput cost*, $c_{\text{E}}(x, a, y)$ is the *energy cost* for the primary users involved in the transmission process and $\alpha \in [0, 1]$ is a weighting factor.

The cost functions in (10) are defined as follows. For the throughput cost we set $c_{\text{Thr}}(x, a, y) = 1$, $\forall\, x, y \in \Omega$, $a \in x$ so that the total accumulated throughput cost equals the number of transmissions performed to correctly deliver a data packet from P_o to P_d. Due to (4), minimizing c_{Thr} is equivalent to maximizing the end-to-end throughput.

For the energy cost we have,

$$c_{\mathrm{E}}(x,a,y)=\begin{cases}1 & \text{when } a\in\mathcal{R}_P\cup\{P_o\}\\ 0 & \text{when } a\in\mathcal{R}_S\,.\end{cases}\tag{11}$$

Thus, $c_{\mathrm{E}}(x,a,y)$ accounts for the number of primary transmissions associated with the transition from x to y, so that the accumulated energy cost represents the total number of primary transmissions M_{P} incurred in correctly delivering a packet from P_o to P_d. Hence, due to (5) minimizing the energy cost $c_{\mathrm{E}}(x,a,y)$ amounts to minimizing the total primary energy expenditure to correctly deliver a packet from the source P_o to the destination P_d.

Using the definitions above, the problem is an instance of the stochastic routing problem defined in [9]. Thus, an optimal policy in the form of an index policy for the considered problem is guaranteed to exist and can be found using the algorithms provided in [9]. In [9], both a centralized and a distributed implementation are provided. The centralized implementation has a complexity of $O(|\mathcal{T}|^2)$, requires full knowledge of the network topology and can be used to obtain offline, optimal index policies. In particular, the centralized algorithm determines a global ranking of the nodes of the network that can be used at each hop to determine the best relay node. The distributed implementation computes the optimal index policies in a distributed fashion through the repeated exchange of local information among neighboring nodes. The convergence time of the distributed implementation depends on the particular network topology and thus cannot be inferred a priori.

IV. Heuristic Routing Policies

In this section, we detail two low-complexity heuristic policies that adopt the spectrum leasing via opportunistic routing technique and are suitable for a distributed implementation. With these policies the relay selection is made on the fly by the current transmitter at each hop, only based on local interactions. The optimal policies of Section III, instead, are determined either through a centralized solver that requires full knowledge of the network topology and are then used in an offline manner, or through a distributed computation which requires an iterative exchange of messages among neighboring nodes in order to converge to the optimal solution.

We introduce a *primary energy budget* K which permits to control the trade-off between the primary energy consumption and the end-to-end throughput. In particular, K represents the maximum number of primary relays that can be used to route any given primary packet from P_o to P_d (note that K does not take into account the retransmissions performed by these nodes). We considered this definition of K for analytical simplicity and to reduce complexity.

The primary energy budget K is stored within the packet header and decremented by one unit each time a new primary relay is selected. At each time slot $k=0,1,\dots,$ we have $K=K_{\mathrm{used}}+K_{\mathrm{res}}$, where K_{used} is the number of primary relays already used in the current routing path. If the residual energy budget $K_{\mathrm{res}}>0$ then the next relay can either be a primary or a secondary node. Otherwise, if $K_{\mathrm{res}}=0$, the current primary transmitter is the last primary node that can be used along the routing path from P_o to P_d. Subsequent relays must all be secondary nodes.

Observe that using the energy budget K has the potential drawback of limiting the available multiuser diversity, as fewer receivers will be available to act as relay, and thus reducing the achievable end-to-end throughput. Moreover, secondary users only allocate a portion ψ of the total power for their primary transmissions, so that they can cover a shorter distance with respect to primary transmissions for the same outage probability (assuming they use the same transmitting power). We now detail two heuristic routing policies for primary packets.

A. K-Closer

The K-Closer policy aims at minimizing the overall number of network transmissions while controlling the energy consumption of primary users through the budget parameter K. Let us consider a generic transmitter at time slot k, which broadcasts a copy of the primary packet. All nodes that correctly receive it are ranked by the transmitter according to their distance from the destination P_d so that closer nodes have a higher rank.[1] Now, if $K_{\mathrm{res}}>0$, the transmitter elects as the relay the receiver with the highest rank; if this receiver is a primary node, K_{res} is decremented by one while it is left unchanged otherwise. On the other hand, if $K_{\mathrm{res}}=0$, the transmitter elects as the relay the secondary node having the highest rank. This process is iterated until the primary packet is correctly received by P_d.

B. K-One Step Look Ahead (K-OSLA)

The potential drawback of K-Closer is to choose, due to the limited amount of information that it uses, a relay with a small number of neighbors in its proximity. Notably, this leads to an increase in the average number of retransmissions that are necessary to reach the next relay. In what follows, we extend the K-Closer heuristic to avoid this situation.

For any node $a\in\mathcal{R}_P\cup\mathcal{R}_S$ let $\delta_a=d_{a,P_d}$, denote the proximity of a to the destination P_d. We assume that each node a can collect this proximity metric from all nodes (both primary and secondary) that are closer to the destination with respect to itself. After that, a builds an ordered set $\mathcal{B}(a)$ as follows: $\mathcal{B}(a)=\{n_1,n_2,\dots,n_{|\mathcal{B}(a)|}\}$, where $n_i\in\mathcal{T}\setminus\{P_o\}$ and $\delta_a\geq\delta_{n_i}\geq\delta_{n_{i+1}}$, $i=1,\dots,|\mathcal{B}(a)|-1$. At the same time, node a determines the ordered subset $\mathcal{B}^S(a)\subseteq\mathcal{B}(a)$, with $\mathcal{B}^S(a)=\{m_1,m_2,\dots,m_{|\mathcal{B}^S(a)|}\}$, which only contains the secondary nodes in $\mathcal{B}(a)$. This procedure is carried out for each node $a\in\mathcal{R}_P\cup\mathcal{R}_S$, except the destination P_d.

Also, let $g_{a,n}=\delta_a-\delta_n$ denote the geographical advancement of a toward P_d provided by a relay node n. Moreover, we define the expected geographical advancement toward

[1] This implies a feedback mechanism from the receivers to the transmitter, whose design is out of the scope of this work.

the destination provided by node a when both primary and secondary nodes can act as relay as:

$$g_a = \sum_{i=1}^{|\mathcal{B}(a)|} g_{a,n_i}[1 - p_{\text{out}}(a, n_i)] \prod_{j=i+1}^{|\mathcal{B}(a)|} p_{\text{out}}(a, n_j) \ . \quad (12)$$

Similarly, we define g_a^S as the expected geographical advancement toward the destination given by node a when only secondary nodes can be selected as relay, i.e.,

$$g_a^S = \sum_{i=1}^{|\mathcal{B}^S(a)|} g_{a,m_i}[1 - p_{\text{out}}(a, m_i)] \prod_{j=i+1}^{|\mathcal{B}^S(a)|} p_{\text{out}}(a, m_j) \ . \quad (13)$$

Finally, we introduce $G_{a,n} = g_{a,n} + g_n$ that represents the overall expected advancement, with respect to a, provided in the next two transmission hops by the selection of node n. Similarly defined is $G^S_{a,n} = g_{a,n} + g^S_n$.

K-OSLA works as follows. Let a be the node that sends the primary packet and $\{r_1, \dots, r_M\}$ be the M nodes that successfully decoded it. If $K_{\text{res}} > 1$, the transmitter a rearranges this set according to the metrics $\{G_{a,r_1}, \dots, G_{a,r_M}\}$ and selects as the relay the receiver node $r^* \in \{r_1, \dots, r_M\}$ with the highest metric G_{a,r^*} (i.e., $G_{a,r^*} \geq G_{a,r_i}\ \forall\ i = 1, \dots, M$). If r^* is a primary user, K_{res} is decremented by one. When $K_{\text{res}} = 1$, the transmitter a orders the set $\{r_1, \dots, r_M\}$ using the metric G^S_{a,r_i} or G_{a,r_i} in case that r_i is a primary or a secondary node, respectively, with $i = 1, \dots, M$. Afterwards, the transmitter a selects as relay the receiver node with the highest metric, and if it is a primary user, K_{res} is decremented by one. Finally, if $K_{\text{res}} = 0$, only secondary nodes of the set $\{r_1, \dots, r_M\}$ are ranked according to the metric $G^S_{a,n}$ and the secondary node having the highest metric is selected by the transmitter as the next relay. This procedure is iterated until the packet is correctly received by P_d.

V. Numerical Results

We consider a random network with one source P_o, one destination P_d, $N_P = 8$ primary nodes, an equal transmitting power for primary and secondary users, i.e. $E_{\text{P}} = E_{\text{S}}$, which yields $\xi_{\text{P}} = \xi_{\text{S}} = \xi$, where we set $\xi = -5$ dB. Relay nodes are uniformly placed at random in a square area with normalized side equal to one, where source P_o and destination P_d are positioned in the middle of two opposite sides. Optimal policies are obtained setting $\gamma = 0.99$, which is adequate for static networks. The fraction of power allocated to primary transmissions ψ is computed by obtaining the largest ψ that satisfy $P_{\text{out,SS}}(d_{\text{S}}) = \epsilon_{\text{S}}$ for $\epsilon_{\text{S}} = 0.1$ and a distance $d_{\text{S}} = 0.1$ (see (3)). We plot the performance of the considered routing schemes in terms of primary end-to-end throughput (4) *vs* primary energy consumption (expressed in dB, i.e., $10 \log_{10} E(k, \text{R}_{\text{P}}, \mathcal{Q})$, see (5)).

In Fig. 1 we set $\text{R}_{\text{P}} = 3$ bits/s/Hz, $\text{R}_{\text{S}} = 1$ bits/s/Hz and $N_S = 8$. The points in this figure have been obtained by varying α in $[0, 1]$ for the optimal policy (Optimal) and K in $\{0, \dots, N_S\}$ for the heuristic policies (K-Closer and K-OSLA). The performance of optimal and heuristic policies when spectrum leasing is not used (indicated in the figure as "No SL") is also shown for comparison. We observe that cooperation via spectrum leasing allows for improved performance in terms of throughput and energy. Both K-Closer and K-OSLA for increasing K provide better throughput performance at the cost of a slightly increased primary energy consumption. This is due to the fact that larger values of K enable the selection of a large number of primary relay nodes. As expected, K-OSLA improves over K-Closer in terms of throughput performance, especially for high values of K ($K \geq 3$ in the figure). In fact, for increasing K the multiuser diversity is higher as more primary nodes can be selected along the path from P_o to P_d. Notably, we found that

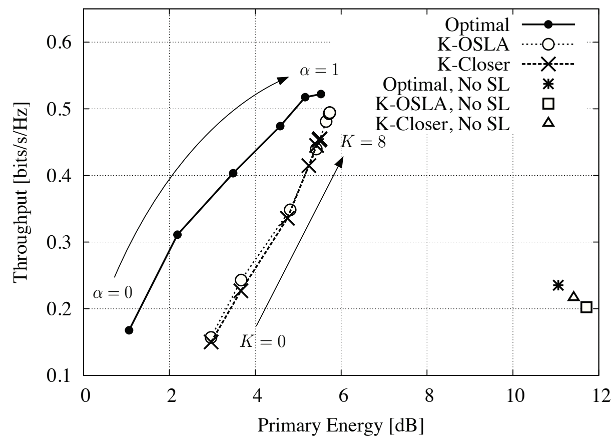

Fig. 1. End-to-end throughput *vs* overall primary energy plotted varying $\alpha \in [0, 1]$ for the optimal policy (solid line) and $K \in \{0, \dots, N_S\}$ for the heuristic policies (dotted lines). The results are obtained for $N_P = N_S = 8$, $\xi = -5$ dB, $\text{R}_{\text{P}} = 3$ bits/s/Hz and $\text{R}_{\text{S}} = 1$ bits/s/Hz.

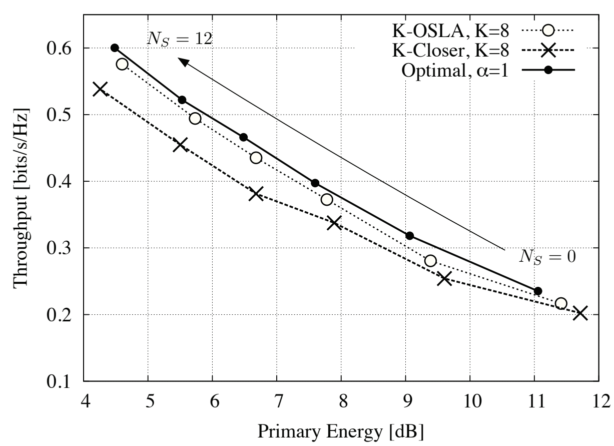

Fig. 2. End-to-end throughput *vs* overall primary energy: comparison of optimal throughput policy ($\alpha = 1$) and the two heuristic policies with $K = 8$. Each point in the graph represents the pair end-to-end throughput and overall primary energy plotted varying the number of secondary nodes deployed $N_S \in \{0, 2, 4, 6, 8, 12\}$, with $N_P = 8$, $\xi = -5$ dB, $\text{R}_{\text{P}} = 3$ bits/s/Hz and $\text{R}_{\text{S}} = 1$ bits/s/Hz. $N_S = 0$ represents the case where spectrum leasing is not used.

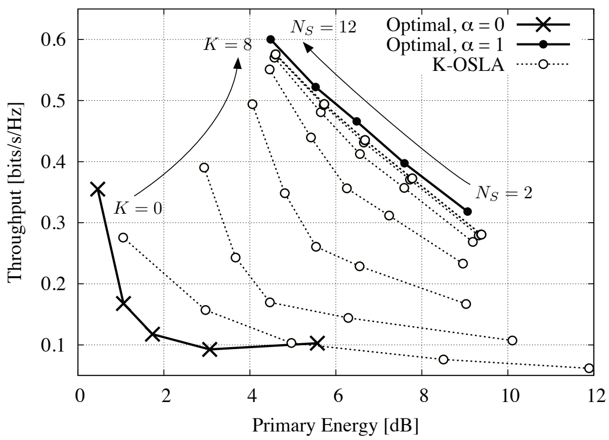

Fig. 3. Impact of K on the heuristic policy K-OSLA by varying the number of secondary nodes deployed $N_S \in \{2, 4, 6, 8, 12\}$, with $N_P = 8$, $\xi = -5$ dB, $\mathrm{R_P} = 3$ bits/s/Hz and $\mathrm{R_S} = 1$ bits/s/Hz. The performance of the optimal routing policy is also shown by varying $N_S \in \{2, 4, 6, 8, 12\}$ for $\alpha = 0$ (energy optimal) and $\alpha = 1$ (throughput optimal).

the throughput increase of K-OSLA can even be much larger than the one obtained in Fig. 1 if we increase $\mathrm{R_S}$ (i.e., the secondary QoS requirements); these results are not shown here due to space constraints. For the primary energy consumption, as expected, for $K = 0$ (i.e., the relays are all secondary nodes) the energy expenditure of the two schemes is the same. Instead, for $K \geq 1$, K-OSLA has a slightly higher energy consumption with respect to K-Closer and this is due to the fact that the expected advancement metric slightly favors primary nodes. In fact, these nodes provide higher expected advancements due to the higher transmission power they use for the transmission of primary packets.

With Fig. 2 we investigate how close heuristic policies can get to the optimal throughput performance ($\alpha = 1$). The curves in this figure have been obtained setting $K = 8$ and varying the number of secondary nodes $N_S \in \{0, 2, 4, 6, 8, 12\}$. The main observations from this plot are that: 1) the usage of spectrum leasing allows for a substantial increase in the throughput (twofold increase) and primary energy performance (gains as high as 6 dB) with respect to the case where only primary transmissions are allowed (i.e., $N_S = 0$) and 2) K-OSLA approaches the optimal throughput performance for nearly all values of N_S.

In Fig. 3, we focus on the throughput *vs* energy performance of K-OSLA for varying K. In this graph, solid lines represent the performance of optimal energy and throughput policies, which are respectively indicated as "Optimal, $\alpha = 0$" and "Optimal, $\alpha = 1$". The remaining curves show the performance of K-OSLA where N_S is varied as the independent parameter, whereas K is kept constant for each curve but varied from 0 to 8 across them. From this plot we can say that K can be conveniently used as a tunable parameter to obtain suitable trade-offs in terms of throughput *vs* primary energy. This is especially important for the implementation of practical routing protocols. The same plot has also been obtained for K-Closer, which showed similar behavior (e.g., see the performance in Fig. 2), except for the fact that this scheme has lower throughput performance with respect to K-OSLA. Nevertheless, K-Closer may also be a good candidate scheme for implementation due to its low complexity.

VI. Conclusions

In this paper, a spectrum leasing solution to the problem of coexistence of primary and secondary nodes is proposed, wherein secondary nodes are granted the possibility to transmit by the primary network in exchange for forwarding primary packets. Routing decisions are made by the primary network in an on-line fashion according to the principle of opportunistic routing based on the secondary QoS requirements. We refer to this strategy as spectrum leasing via cooperative opportunistic routing. Optimization of the strategy is tackled by framing the routing design as a stochastic routing problem. Two heuristic policies with lower complexity are also proposed, showing performance close to the optimal policy. Moreover, numerical results lend evidence to the throughput and energy gains that can be attained by the proposed spectrum leasing approach by the primary network, all the while allowing also the secondary nodes to transmit.

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