Energy Efficient Switching between Data Transmission and Energy Harvesting for Cooperative Cognitive Relaying Systems

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***Abstract*—A dual-hop cognitive (secondary) relaying system incorporating collaborative spectrum sensing to opportunistically switch between data transmission and energy harvesting is introduced. The secondary relays, first scan the wireless channel for a primary network activity, and then convey their reports to a secondary base station (SBS). Afterwards, the SBS, based on these reports and its own estimation, decides cooperatively the presence of primary transmission or not. In the former scenario, all secondary relays start to harvest energy from the transmission of one or more primary nodes. In the latter scenario, the system initiates secondary communication via a best relay selection policy. The performance of the proposed scheme is thoroughly investigated by assuming realistic channel conditions, i.e., non-identical link-distances and outdated channel estimation, while its overall energy consumption is evaluated, indicating the efficiency of the switching approach.**

***Index Terms*—Cognitive relaying systems, cooperative spectrum sensing, detection probability, energy efficiency, energy harvesting.**

I. Introduction

A principal requirement of cognitive radio (CR) is the effectiveness of spectrum sharing performed by secondary (unlicensed) nodes, which is expected to intelligently mitigate any harmful interference caused to the primary (licensed) network nodes. This requirement is directly related to the accuracy of spectrum sensing/sharing techniques, reflecting the reliable detection of primary transmission. Moreover, to further guarantee a sufficient quality level of primary communication, the transmission power of CR is generally limited, such that its interference onto primary users remains below prescribed tolerable levels. However, this dictated constraint dramatically affects the coverage and/or capacity of the secondary communication. Such a condition can be effectively counteracted with the assistance of wireless relaying transmission. In particular, the rather feasible dual-hop multi-relay communication scheme with best relay selection is of paramount interest due to its enhanced performance gains (e.g., see [1]-[3] and references therein).

Building on the aforementioned system deployment, the spectrum sensing process can also be significantly enhanced. By means of the so-called cooperative sensing [4], each secondary node may sense the channel in fixed time periods and then forward its sensing measurement to a central secondary base station (SBS), which acts as a fusion center. The latter entity is responsible for the final decision on a primary transmission occurrence, benefiting from the spatial diversity of several sensing reports. Such a distributed (cooperative) spectrum sensing was shown to deliver much more accurate decisions than local (standalone) sensing regarding the detection of primary transmissions [4]. On another front, driven by the ever increasing economical and environmental (e.g., carbon footprint) costs associated with the operating expenditure of communication networks, energy efficiency (EE) has become an important design consideration in current and forthcoming wireless cognitive infrastructures [5].

In cooperative CR systems, two different types of relaying protocols have dominated so far, namely, amplify-and-forward (AF) and decode-and-forward (DF). It is noteworthy that AF outperforms the computational-demanding DF in terms of EE and/or power savings. In [6] and [7], the tradeoff between consumed power and performance of the secondary system was investigated. However, in these works, the objective was performance enhancement (in terms of either outage probability [6] or throughput [7]) not EE. In [8], the authors focused on the energy minimization of cognitive relaying networks. Yet, EE and data transmission requirements (e.g., in terms of a data rate and/or error rate target) were not jointly considered in these works. In [5], the latter problem was jointly considered, given a predetermined detection probability on the primary nodes activity (i.e., providing conditional expressions). A recent approach dealing efficiently with power savings and minimization of consumed energy is energy harvesting [9]. From the CR perspective, [10], [11] investigated cognitive systems enabled with energy harvesting equipment, but cooperative spectrum sensing or relayed transmission was not considered.

In this paper, we introduce an opportunistic strategy incorporating energy harvesting for CR cooperative systems.

According to the proposed strategy, secondary nodes switch between data transmission and energy harvesting depending on their sensing decision on the existence of primary nodes activity. More specifically, a dual-hop relaying system with multiple AF relays is adopted for the secondary system, where the end-to-end ($e2e$) communication is facilitated via a best relay selection policy. Cooperative spectrum sensing is performed in a fixed sensing time duration, followed by a reporting of relay sensing measurements to SBS. Upon the aggregate decision at SBS, secondary nodes enter into either the energy harvesting phase (if primary transmission is detected) or the transmission phase (if primary transmission is not detected).

Throughout this paper, the following notations are used: $\mathbb{E}[\cdot]$ stands for the expectation operator and $\Pr[\cdot]$ returns probability. Also, $f_X(\cdot)$ and $F_X(\cdot)$ denote, respectively, probability density function (PDF) and cumulative distribution function (CDF) of random variable (RV) X. Furthermore, $\Gamma(\cdot,\cdot)$ represents the upper incomplete Gamma function [12, Eq. (8.350.2)], $\mathrm{Ei}(\cdot)$ is the exponential integral [12, Eq. (8.211.1)], $J_0(\cdot)$ denotes the zeroth order Bessel function of the first kind [12, Eq. (8.411)], $I_0(\cdot)$ is the zeroth order modified Bessel function of the first kind [12, Eq. (8.431)], and $K_n(\cdot)$ is the nth order modified Bessel function of the second kind [12, Eq. (8.446)].

II. System Model

A secondary (cognitive) dual-hop system consisted of a source (S) communicating with a destination (D) via M relay (R_i with $1 \leq i \leq M$) nodes is considered.[1] Direct communication between source and destination is not available due to the long distance and strong propagation attenuation, while keeping in mind that in secondary systems the transmission power must in principle be maintained in quite low levels. The system operates in the vicinity of another licensed primary network, which consists of L primary (P_j with $1 \leq j \leq L$) nodes. In current study, we assume that all the involved signals are subject to independent and non-identical distributed (i.n.i.d.) Rayleigh fading as well as additive white Gaussian noise (AWGN) with a common power N_0. Thus, PDF of the instantaneous signal-to-noise ratio (SNR) is given by

$$f_{\gamma_{i,j}}(x) = \frac{N_0 \exp\left(-\frac{N_0 x}{p_{i,j}\bar{\gamma}_{i,j}}\right)}{p_{i,j}\bar{\gamma}_{i,j}}, \quad x \geq 0 \tag{1}$$

where $\gamma_{i,j}$, $p_{i,j}$ and $\bar{\gamma}_{i,j} \triangleq d_{i,j}^{-\alpha_{i,j}}$ denote the instantaneous SNR, the signal power and the average received channel gain, respectively, from the ith to jth node. Moreover, $d_{i,j}$ and $\alpha_{i,j}$ represent the corresponding distance and path loss factor, respectively. Usually, $\alpha_{i,j} \in \{2,6\}$ denoting free-space loss to dense urban environmental conditions, correspondingly.

A. Protocol Description

The secondary nodes operate in a time division multiple access scheme, where sensing and transmission or harvesting phases are periodically alternating.

1) Sensing Phase: First, the relays and the destination enter into the *sensing phase* where they listen to the presence of primary users' signals over the shared spectrum band within a fixed sensing duration. The received signal at the ith relay or destination can be expressed as $y_{P,\mathcal{X}} = \sum_{j=1}^{L} \theta_j \sqrt{p_p} g_{P_j,\mathcal{X}} s_j + n_{\mathcal{X}},\ 1 \leq i \leq M,\ \mathcal{X} \in \{R_i, D\}$, where $\theta_j = 1$ or 0 when the jth primary signal is present or absent, respectively. Also, p_p, $g_{P_j,\mathcal{X}}$, s_j and $n_{\mathcal{X}}$ denote the transmit power of primary nodes,[2] the instantaneous channel gain from P_j to $\mathcal{X}$, the transmitted data of the jth primary node and AWGN at $\mathcal{X}$, respectively.

2) Reporting Phase: Next, each relay amplifies and forwards its local sensing measurement to the destination on its particular time slot (which is a priori reserved from the system), entering into the *reporting phase*. Hence, the received signal at the destination, forwarded by the ith relay at its allocated time slot, yields as $y_{R_i,D} = \sqrt{p_{R_i,D}^{(\mathcal{R})}} g_{R_i,D} G_{\mathcal{R},i} y_{P,R_i} + n_D$, where $p_{R_i,D}^{(\mathcal{R})}$ and $g_{R_i,D}$ are the transmission power and channel gain from R_i to D, respectively, whereas $G_{\mathcal{R},i}$ denotes the fixed gain of the ith relay, all indicating the reporting phase.

3) Harvesting Phase: Then, the destination determines the presence of a primary transmission or not, according to the received signals' power. In fact, it compares the maximum from $M+1$ signals (from the relays and its own) with a predetermined power threshold value λ. In the case when this signal power is greater than λ, a detection event is declared in a subsequent time slot and all the relays initiate a harvesting phase, collecting energy from the occurring primary transmission(s). To this end, we have that

$$P_d \triangleq \Pr\left[\max\left\{\gamma_{P,D}, \max_i \left\{\gamma_{e2e,i}^{(\mathcal{R})}\right\}_{i=1}^{M}\right\} \geq \lambda\right] \tag{2}$$

where P_d stands for the detection probability, while $\gamma_{e2e,i}^{(\mathcal{R})}$ represents the $e2e$ SNR at the sensing phase from the (potentially active) primary nodes to destination via the ith relay. Moreover, the harvested energy at the ith relay conditioned on a detection event, reads as $E_{H,i} = \eta P_d p_p \sum_{j=1}^{L} \theta_j \bar{\gamma}_{P_j,R_i} \left|g_{P_j,R_i}\right|^2$, where $\eta \in (0,1]$ is the radio frequency-to-direct current (RF-to-DC) conversion efficiency.

4) Transmission Phase: On the other hand, if the power of the signal in (2) is lower than λ, primary transmission is not detected with a probability $1-P_d$. In such a case, capitalizing on the status of channel gains from all the relay-to-destination links (collected from the aforementioned reporting phase), the destination selects the relay with the highest instantaneous SNR (i.e., R_s with s determined by the condition $\gamma_{R_s D} = \max_l \{\gamma_{R_l,D}\}_{l=1}^{M}$) and broadcasts this information in the subsequent time slot. In turn, the selected relay informs the secondary source to enter into the transmission mode of operation.[3] Based on this call, the secondary system enters

[1] Note that the terms D and SBS will be interchangeably used in the rest of this paper.

[2] Without loss of generality and for the sake of clarity, a common power profile for the primary nodes is adopted.

[3] The event of no signal returning from any relay back to the source, at this stage, can be interpreted as a triggering of harvesting phase for the secondary source.

into the *transmission phase*, while the source communicates with the destination via the selected relay (all the other ones stay idle).

In fact, the classical half-duplex dual-hop AF relaying protocol is established at this stage, where the source-to-relay and relay-to-destination links occur in orthogonal transmission phases (e.g., in two consecutive time slots). Hence, the received signals at the relay and destination are, respectively, given by $r_{t,r}=\sqrt{p_{t,r}^{(\mathcal{T})}}h_{t,r}z+n_r$, $t\in\{S,R_S\}$, $r\in\{R_S,D\}$, where z, h_{S,R_s}, $p_{R_s,D}^{(\mathcal{T})}$ and $G_{T,s}$ correspond to the source data, instantaneous channel gain from S to R_s, transmission power from S to R_s, and fixed gain of the sth relay during the transmission phase, respectively. Also, $\hat{h}_{R_s,D}$ denotes the channel estimate of the selected relay to the destination, based on the instantaneous channel status derived from the previous reporting phase. It is noteworthy that $\hat{h}_{R_s,D}$ could vary from the actual $h_{R_s,D}$ due to a possible *outdated* CSI at the destination. This condition is realized when a feedback delay and/or rapidly varying fading channels between the reporting and transmission phases are present. As such, the channel estimate is formed as [13] $\hat{h}_{R_s,D}\triangleq\rho_s h_{R_s,D}+(\sqrt{1-\rho_s^2})w_{R_s,D}$, where $w_{R_s,D}$ is a circularly symmetric complex Gaussian RV with the same variance as $h_{R_s,D}$, while ρ_s denotes the time correlation coefficient between $\hat{h}_{R_s,D}$ and $h_{R_s,D}$. It follows that in the case when the channel instances remain constant between the reporting and transmission phase, then $\rho=1$ and $\hat{h}_{R_s,D}=h_{R_s,D}$.

B. Transmission Power of Secondary Nodes

Although the transmission power of the primary service takes arbitrary values, this condition does not apply for the secondary system. We adopt an average interference constraint for the transmission power of secondary nodes, taking also into consideration the maximum output power, namely, $P_{\max}$. Thereby, for the reporting phase, the following condition should be satisfied

$$p_{R_i,D}^{(\mathcal{R})}=\min\left\{P_{\max},\frac{Q}{\mathbb{E}\left[q_{R_i}\right]}\right\},\quad 1\leq i\leq M \tag{3}$$

where Q represents the received power threshold that should not be exceeded at the primary nodes, and $q_{R_i}\triangleq\max_j\left\{\gamma_{i,P_j}\right\}_{j=1}^{L}$. In the case when the system enters into the transmission phase, we have from [14, Eq. (6)] that

$$p_{t,r}=\min\left\{P_{\max},\frac{Q}{(1-P_d)\mathbb{E}\left[q_t\right]}\right\},t\in\{S,R_s\},r\in\{R_s,D\} \tag{4}$$

where $q_S\triangleq\max_j\left\{\gamma_{S,P_j}\right\}_{j=1}^{L}$, while q_{R_s} is obtained from the aforementioned condition $\gamma_{R_sD}=\max\{\gamma_{R_l,D}\}_{l=1}^{M}$).

III. Performance Analysis

A. SNR Statistics in the Sensing Phase

The received SNR from primary nodes to D involves the sum of i.n.i.d. exponential RVs (with different link distances) and is obtained by[4] $\gamma_{P,D}\triangleq\frac{p_p}{N_0}\sum_{j=1}^{L}\theta_j\gamma_{P_j,D}$. Thus, CDF of $\gamma_{P,D}$ is directly obtained as [15, Eq. (5)]

$$F_{\gamma_{P,D}}(x)=1-\left(\frac{N_0}{p_p}\right)\sum_{k=1}^{L}\prod_{\substack{j=1\\j\neq k}}^{k}\left(\frac{p_p\bar{\gamma}_{P_k,D}}{\bar{\gamma}_{P_k,D}-\bar{\gamma}_{P_j,D}}\right)\times\exp\left(-\frac{N_0x}{p_p\bar{\gamma}_{P_k,D}}\right). \tag{5}$$

B. SNR Statistics in the Reporting Phase

The SNR of $P-R_i-D$ link (with $1\leq i\leq M$) is given by $\gamma_{e2e,i}^{(\mathcal{R})}=\frac{\gamma_{1,i}^{(\mathcal{R})}\gamma_{2,i}^{(\mathcal{R})}}{\gamma_{2,i}^{(\mathcal{R})}+U_i^{(\mathcal{R})}}$, where $\gamma_{1,i}^{(\mathcal{R})}\triangleq\frac{p_p}{N_0}\sum_{j=1}^{L}\theta_j\gamma_{P_j,R_i}^{(\mathcal{R})}$ and $\gamma_{2,i}^{(\mathcal{R})}\triangleq\frac{p_{R_i,D}^{(\mathcal{R})}}{N_0}\gamma_{R_i,D}^{(\mathcal{R})}$. The parameter $U_i^{(\mathcal{R})}=1/\left(G_{\mathcal{R},i}^2N_0\right)$ indicates a constant parameter, which is related to the value of fixed gain of the ith relay for the reporting phase. Among some popular precoding designs for this parameter, there is quite an efficient one [16], yielding

$$U_i^{(\mathcal{R})}\triangleq\left(\mathbb{E}\left[\frac{1}{\gamma_{1,i}^{(\mathcal{R})}+1}\right]\right)^{-1}. \tag{6}$$

Lemma 1: A closed-form expression for the CDF of $\gamma_{e2e,i}^{(\mathcal{R})}$ under i.n.i.d. Rayleigh fading channels reads as

$$F_{\gamma_{e2e,i}^{(\mathcal{R})}}(x)=1-\sum_{k=1}^{L}\frac{2\bar{\gamma}_{P_k,R_i}^{\frac{3}{2}}\sqrt{U_i^{(\mathcal{R})}x}}{\left(\frac{p_p}{N_0}\right)^{\frac{5}{2}-k}\sqrt{\frac{p_{R_i,D}^{(\mathcal{R})}\bar{\gamma}_{R_i,D}}{N_0}}}\times\prod_{\substack{j=1\\j\neq k}}^{k}\left(\frac{1}{\bar{\gamma}_{P_k,D}-\bar{\gamma}_{P_j,D}}\right)K_1\left(2N_0\sqrt{\frac{U_i^{(\mathcal{R})}x}{p_p p_{R_i,D}^{(\mathcal{R})}\bar{\gamma}_{P_k,R_i}\bar{\gamma}_{R_i,D}}}\right) \tag{7}$$

with

$$U_i^{(\mathcal{R})}=\left(\sum_{k=1}^{L}\prod_{\substack{j=1\\j\neq k}}^{k}\left(\frac{(N_0/p_p)}{\bar{\gamma}_{P_k,D}-\bar{\gamma}_{P_j,D}}\right)\frac{\Gamma\left(0,\frac{N_0}{p_p\bar{\gamma}_{P_k,R_i}}\right)}{\exp\left(-\frac{N_0}{p_p\bar{\gamma}_{P_k,R_i}}\right)}\right)^{-1} \tag{8}$$

$$p_{R_i,D}^{(\mathcal{R})}=\left(\frac{1}{P_{\max}}+\frac{\mathbb{E}[q_{R_i}]}{Q}\right)^{-1} \tag{9}$$

and

$$\mathbb{E}[q_{R_i}]=\sum_{l=1}^{L}\sum_{k=0}^{L}\sum_{n_k}\frac{(-1)^k}{k!\bar{\gamma}_{R_i,P_l}\left(\frac{1}{\bar{\gamma}_{R_i,P_l}}+\sum_{t=1}^{k}\frac{1}{\bar{\gamma}_{R_i,P_{n_t}}}\right)^2} \tag{10}$$

where $\sum_{n_k}\triangleq\underbrace{\sum_{n_1=1}^{L}\cdots\sum_{n_k=1}^{L}}_{n_1\neq\cdots\neq n_k\neq k}$.

Proof: The proof is relegated in Appendix A. ■

[4]Since we model the signals as RVs with known transmission power, energy detector is adopted at the receiver, as being the optimal technique to detect the primary transmission(s) [4].

C. Detection Probability

Proposition 1: Detection probability for a given power threshold λ, $P_d(\lambda)$, is given by $P_d(\lambda) = 1 - \prod_{i=1}^{M} F_{\gamma_{e2e,i}^{(\mathcal{R})}}(\lambda) F_{\gamma_{P,D}}(\lambda)$.

Proof: Let $Y \triangleq \max\{y_i\}_{i=1}^{W}$. Then, the complementary CDF of Y, $\bar{F}_Y(x) \triangleq \Pr[Y > x] = 1 - F_Y(x)$, becomes $\bar{F}_Y(x) = 1 - \prod_{i=1}^{W} F_{y_i}(x)$. Hence, according to (2), while using (5) and (7), the desired result is derived in a closed formulation. ■

D. Average Harvested Energy

Proposition 2: The average harvested energy of the ith relay, defined as $\overline{E}_{H,i}$, which is collected upon a detection of the primary system's transmission, is given by[5]

$$\overline{E}_{H,i} = \eta P_d(\lambda) p_p \sum_{k=1}^{L} \prod_{\substack{j=1 \\ j \neq k}}^{k} \left(\frac{\bar{\gamma}_{P_k,R_i}^2}{\bar{\gamma}_{P_k,R_i} - \bar{\gamma}_{P_j,R_i}} \right). \tag{11}$$

Proof: It holds that $\overline{E}_{H,i} \triangleq \mathbb{E}[E_{H,i}] = \int_0^\infty x f_{E_{H,i}}(x) dx$, yielding $f_{E_{H,i}}(x) = \sum_{k=1}^{L} \prod_{\substack{j=1 \\ j \neq k}}^{k} \frac{\exp(-\frac{x}{\eta P_d p_p \bar{\gamma}_{P_k,R_i}})}{\eta P_d(\lambda) p_p (\bar{\gamma}_{P_k,R_i} - \bar{\gamma}_{P_j,R_i})}$. Then, after some simple manipulations, (11) is obtained. ■

E. Outage Probability in the Transmission Phase

Following similar lines of reasoning as in the reporting phase, the corresponding $e2e$ SNR of the $S - R_s - D$ link is given by $\gamma_{e2e,s}^{(\mathcal{T})} = \frac{\gamma_{1,s}^{(\mathcal{T})} \gamma_{2,s}^{(\mathcal{T})}}{\gamma_{2,s}^{(\mathcal{T})} + U_s^{(\mathcal{T})}}$, where $\gamma_{1,s}^{(\mathcal{T})} \triangleq \frac{p_{S,R_s}}{N_0} |h_{S,R_s}|^2$ and $\gamma_{2,s}^{(\mathcal{T})} \triangleq \frac{p_{R_s,D}^{(\mathcal{T})}}{N_0} \left| \hat{h}_{R_s,D} \right|^2$. Also, $U_s^{(\mathcal{T})}$ is explicitly defined in (6), by substituting the superscript $(\cdot)^{\mathcal{R}}$ with $(\cdot)^{\mathcal{T}}$, denoting the transmission phase this time.

In what follows, we investigate the scenario of symmetric channels (i.i.d. statistics), i.e., when the distances between the source-to-relay and relay-to-destination links are equal for each relay.

Outage probability, P_{out}, is defined as the probability that the SNR of the $e2e$ $S - R_s - D$ link falls below a certain threshold value, γ_{th}, such that $P_{\text{out}}(\gamma_{\text{th}}) = \Pr\left[\gamma_{e2e,s}^{(\mathcal{T})} \leq \gamma_{\text{th}}\right]$.

Lemma 2: CDF of the $e2e$ SNR for the $S - R_s - D$ link over Rayleigh fading channels is expressed as

$$F_{\gamma_{e2e,s}^{(\mathcal{T})}}(x) = 1 - 2\,\Xi_M \exp\left(-\frac{N_0 x}{p_{S,R_s}\bar{\gamma}_{S,R_s}}\right) \times \sqrt{\frac{N_0 U_s^{(\mathcal{T})} x}{Z_M p_{S,R_s}\bar{\gamma}_{S,R_s}}} K_1\left(2\sqrt{\frac{N_0 U_s^{(\mathcal{T})} Z_M x}{p_{S,R_s}\bar{\gamma}_{S,R_s}}}\right) \tag{12}$$

where

$$\Xi_M \triangleq \frac{\Psi_M}{(1-\rho_l^2) p_{R_l,D}^{(\mathcal{T})} \bar{\gamma}_{R_l,D} \left(\Phi_M + \frac{\rho_l^2}{(1-\rho_l^2) p_{R_l,D}^{(\mathcal{T})} \bar{\gamma}_{R_l,D}}\right)}$$

$$Z_M \triangleq \frac{1}{(1-\rho_l^2) p_{R_l,D}^{(\mathcal{T})} \bar{\gamma}_{R_l,D}} - \frac{\rho_l^2}{(1-\rho_l^2)^2 (p_{R_l,D}^{(\mathcal{T})} \bar{\gamma}_{R_l,D})^2 \left(\Phi_M + \frac{\rho_l^2}{(1-\rho_l^2) p_{R_l,D}^{(\mathcal{T})} \bar{\gamma}_{R_l,D}}\right)}$$

with

$$\Psi_M \triangleq \sum_{l=0}^{M-1} \frac{\binom{M-1}{l} (-1)^l M}{p_{R,D}^{(\mathcal{T})} \bar{\gamma}_{R,D}}, \quad \Phi_M \triangleq \frac{(l+1)}{p_{R,D} \bar{\gamma}_{R,D}^{(\mathcal{T})}}$$

$$p_{t,j} = \left(\frac{1}{P_{\max}} + \frac{(1-P_d)\mathbb{E}[q_t]}{Q}\right)^{-1}, t \in \{S, R_l\}, j \in \{R_s, D\} \tag{13}$$

and

$$U_i^{(\mathcal{T})} = \left(\left(\frac{N_0}{p_{S,R_s}\bar{\gamma}_{S,R_s}}\right) \frac{\Gamma\left(0, \frac{N_0}{p_{S,R_s}\bar{\gamma}_{S,R_s}}\right)}{\exp\left(-\frac{N_0}{p_{S,R_s}\bar{\gamma}_{S,R_s}}\right)}\right)^{-1}. \tag{14}$$

Proof: The proof is provided in Appendix B. ■

Proposition 3: Outage probability of the $e2e$ SNR for the secondary system, during its transmission phase, is presented as $P_{\text{out}}^{(\text{i.i.d.})}(\gamma_{\text{th}}) = F_{\gamma_{e2e}^{(\mathcal{T})}}(\gamma_{\text{th}})$.

IV. Average Energy Consumption

Motivated by the general interests towards green communications in emerging and future wireless systems, we deploy the results of the previous sections to analyze the average energy required per node in the proposed CR cooperative system.

The average energy consumed at the ith relay in each frame is given by $\overline{E}_{\text{total}}^{(i)} \triangleq \overline{E}_{S,i} T_S + \overline{E}_{R,i} T_R + \frac{(1-P_d(\lambda))\overline{E}_{T,i} T_D}{M} - \overline{E}_{H,i} T_D$, where $\overline{E}_{S,i}$, $\overline{E}_{R,i}$ and $\overline{E}_{T,i}$ are the average energy consumed at the sensing, reporting and transmission phase, respectively. In addition, T_S, T_R and T_D denote the duration of the latter phases, correspondingly. Notice that a transmission event occurs with a probability $1 - P_d(\lambda)$, whereas $1/M$ denotes the probability that the ith relay is selected for transmission. On the other hand, as previously stated, all the relays enter into the harvesting phase with a probability $P_d(\lambda)$ during T_D, when a primary transmission is sensed. Notice that $P_d(\lambda)$ is already included within $\overline{E}_{H,i}$, by referring back to (11).

The sensing energy can be considered identical for all the secondary nodes and, thus, it holds that

$$\overline{E}_{\text{total}}^{(i)} \triangleq \overline{E}_S T_S + \overline{E}_{R,i} T_R + \left(\frac{(1-P_d(\lambda))\overline{E}_{T,i}}{M} - \overline{E}_{H,i}\right) T_D. \tag{15}$$

Regarding $\overline{E}_S$, it holds that $\overline{E}_S = P_{R_x}$, where P_{R_x} is the circuit power used to capture the received signal(s) power. Moreover, for $\overline{E}_{R,i}$, we have that [17] $\overline{E}_{R,i} = p_{R_i,D}^{(\mathcal{R})} + P_{T_x}$, where P_{T_x} is the circuit power used for signal transmission and $p_{R_i,D}^{(\mathcal{R})}$ is given by (3). In general, both P_{T_x} and P_{R_x} are quite

[5] It is noteworthy that the corresponding average harvested energy of the secondary source is directly obtained by substituting subscript R_i with S into (11), denoting the corresponding node.

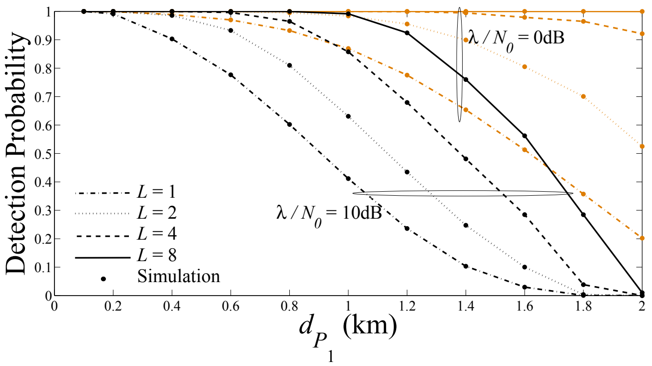

Fig. 1. $P_d(\lambda)$ vs. d_{P_1}. Also, $M = 1$, $d_{R,D} = 0.1$km, $\frac{Q}{N_0} = 2$dB, and $\{\frac{P_{\max}}{N_0}, \frac{p_p}{N_0}\} = 10$dB.

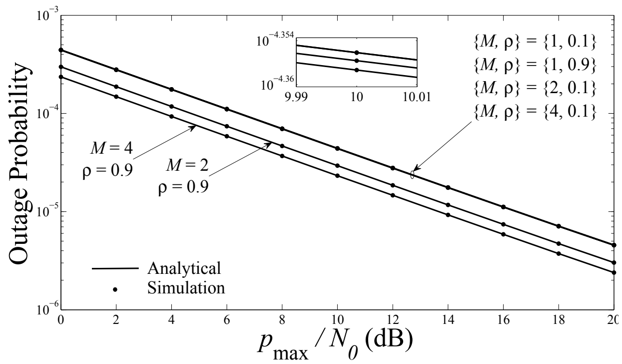

Fig. 2. $P_{\text{out}}(\gamma_{\text{th}})$ vs. $p_{\max}/N_0$. Also, $L = 2$, $d_{S,R} = d_{R,D} = 0.1$km, $d_{P_1,R} = 0.3$km, $d_{P_1,D} = 0.4$km, $\{\frac{\lambda}{N_0}, \frac{\gamma_{\text{th}}}{N_0}\} = 3$dB, $\frac{Q}{N_0} = 6$dB, and $\frac{p_p}{N_0} = 10$dB.

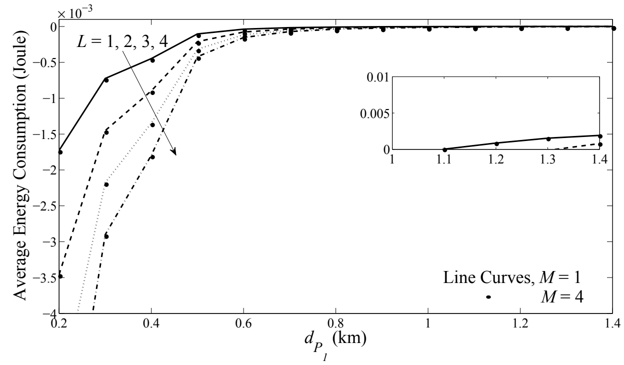

Fig. 3. $\overline{E}_{\text{total}}$ vs. various distances of the primary node-1 and the secondary system (i.e., d_{P_1}). Also, i.i.d. statistics between the $S - R$ and $R - D$ links are considered with $d_{R,D} = 0.1$km and four relays (i.e., $M = 4$). Other parameters are fixed as: $N_0 = -131$dBm, $P_{\max} = p_p = 20$dBm, $\lambda = Q = 17$dBm, $P_{T_x} = 10$dBm, $P_{R_x} = 9$dBm, $\eta = 0.35$, $T_{\text{total}} = 100$msec, $T_R = 1$msec, and $T_S = 20$msec (thus $T_D = 79$msec).

small, since each AF relay does not perform decoding, which is usually a more power-consuming operation. Similarly, $\overline{E}_{T,i}$ is obtained as [17] $\overline{E}_{T,i} = p^{(\mathcal{T})}_{R_i,D} + P_{T_x}$. Finally, $\overline{E}_{H,i}$ is presented in (11) and, hence, the average energy consumption is obtained in a closed-form.

V. Numerical Results and Discussion

In this section, numerical results are presented and cross-compared with Monte-Carlo (MC) simulations to assess our theoretical findings. Henceforth, for notational simplicity and without loss of generality, we assume a common time correlation coefficient, defined as ρ. Unless otherwise stated, $N_0 = 1$. Also, the path-loss exponent is assumed fixed as $\alpha = 4$, corresponding to a classical macro-cell urban environment. All the included link distances are normalized with a reference distance equal to 1km. In addition, for clarity reasons, we assume that the distance between the lth primary node and secondary source equals the distance between the lth primary node and ith relay and the distance between the lth primary node and destination, i.e., $d_{P_l,S} = d_{P_l,R_i} = d_{P_l,D} \triangleq d_{P_l}$ $\forall\, l, i$. In what follows (owing to the non-identical statistics of the included nodes), we consider the following link-distance scenarios for the primary nodes; for $L = 1$ let $d_{P_1} \in \mathbb{R}^+$ (in km), while for $L > 1$ it is assumed that $d_{P_{l+1}} \triangleq d_{P_l} + 0.01$ $\forall l \in \{1, L-1\}$. Following similar lines of reasoning, when the link distances per hop for the secondary nodes are non-identical, it is assumed that $d_{S,R_{i+1}} \triangleq d_{S,R_i} + 0.005$ and $d_{R_{i+1},D} \triangleq d_{R_i,D} + 0.005$ $\forall i \in \{1, M-1\}$.

Figure 1 illustrates the detection probability for various distances between primary and secondary nodes. Its performance is worse for higher λ threshold values and/or the existence of fewer primary nodes, as expected. This occurs due to the fact that when more primary nodes are placed in the vicinity of the secondary nodes, transmitting using a relatively high power, their active presence is more likely to be detected and vice versa.

In Fig. 2, outage performance of the secondary system is depicted for various $P_{\max}$ values. It is worth noting that the diversity order is always one regardless of the number of relays, which is in agreement with [2]. Moreover, when very rapidly varying fading channels are present (e.g., $\rho = 0.1$), adding more relays does not alter the coding gain either (in fact, there is quite a marginal performance difference, which can be considered as negligible). Hence, the overall outage performance, i.e., both the coding and diversity gains, cannot be enhanced by maximizing M in such environments. On the other hand, coding gain is improved by adding more relays into the system, when semi-constant channel fading conditions are realized (e.g., $\rho = 0.9$).

Figure 3 is devoted to the average energy consumed by using the proposed opportunistic strategy, from a green communications perspective. To this end, $\overline{E}_{\text{total}}$ is numerically evaluated using (15) under different distances d_{P_1} in Fig. 3. Obviously, there is an emphatic energy gain (on average) for each secondary node as this distance is relatively small (e.g., when $d_{P_1} < 0.4$km). Also, EE is greatly enhanced for higher L values (i.e., more primary nodes). This is a reasonable outcome since the overall average harvested energy is increased in such a scenario. In general, it can be seen that the average harvested energy is higher than the corresponding energy that is consumed for sensing, reporting and (potential) transmitting. This beneficial phenomenon stops holding only for the case when primary nodes are rather far-distant (e.g., when $d_{P_1} > 1.1$km). An insightful observation obtained from Fig. 3 is the fact that the presence of more or less relays at the secondary system does not dramatically affect the average energy consumption. This occurs because when the system enters into the harvesting phase, upon the detection of primary transmission(s), all the included relays switch to the harvesting mode.

APPENDIX

A. Derivation of (7), (8), (9), and (10)

CDF of the $e2e$ SNR for the ith secondary relay reads as [18, Eq. (15)]

$$F^{(i)}_{\gamma^{(\mathcal{R})}_{e2e,i}}(x) = \int_0^\infty F_{\gamma^{(\mathcal{R})}_{1,i}}\left(x + \frac{U^{(\mathcal{R})}x}{y}\right) f_{\gamma^{(\mathcal{R})}_{2,i}}(y)dy. \quad \text{(A.1)}$$

$F_{\gamma^{(\mathcal{R})}_{1,i}}(x)$ can be directly obtained from (5), by substituting D with R_i. Additionally, $f_{\gamma^{(\mathcal{R})}_{2,i}}(x)$ stems as in (1) by substituting $p_{i,j}$ and $\bar{\gamma}_{i,j}$ with $p^{(\mathcal{R})}_{R_i,D}$ and $\bar{\gamma}_{R_i,D}$, respectively. Therefore, utilizing [12, Eq. (3.471.9)] into (A.1), (7) can be easily extracted.

Further, (6) can be rewritten as $U^{(\mathcal{R})}_i = (\int_0^\infty (x+1)^{-1} f_{\gamma^{(\mathcal{R})}_{1,i}}(x)dx)^{-1}$. Hence, utilizing [19, vol. 1, Eq. (2.3.4.2)], (8) is obtained.

Regarding the derivation of (9), referring back to (3), we have that $f_{\gamma^{(\mathcal{R})}_{2,i}}(x) = \frac{N_0 \exp(-\frac{N_0 x}{P_{\max}\bar{\gamma}_{R_i,D}})}{P_{\max}\bar{\gamma}_{R_i,D}}$ when $\mathbb{E}[q_{R_i}] < \frac{Q}{P_{\max}}$, or $f_{\gamma^{(\mathcal{R})}_{2,i}}(x) = \frac{N_0 \mathbb{E}[q_{R_i}] \exp(-\frac{N_0 \mathbb{E}[q_{R_i}] x}{Q\bar{\gamma}_{R_i,D}})}{Q\bar{\gamma}_{R_i,D}}$ when $\mathbb{E}[q_{R_i}] > \frac{Q}{P_{\max}}$. Hence, it yields that

$$F_{\gamma^{(\mathcal{R})}_{2,i}}(x) = 1 - \exp\left(-\frac{N_0\left(\frac{1}{P_{\max}} + \frac{\mathbb{E}[q_{R_i}]}{Q}\right)x}{\bar{\gamma}_{R_i,D}}\right). \quad \text{(A.2)}$$

By differentiating (A.2), the corresponding (unconditional) PDF of $\gamma^{(\mathcal{R})}_{2,i}$ is formed as in (1) with the yielded transmission power $p^{(\mathcal{R})}_{R_i,D}$ defined in (9).

Finally, since $\mathbb{E}[q_{R_i}] \triangleq \int_0^\infty x f_{q_{R_i}}(x)dx$, while based on [1, Eq. (15)], it holds that $f_{q_{R_i}}(x) = \sum_{l=1}^{L}\sum_{k=0}^{L}\sum_{n_k}\frac{(-1)^k}{k!\bar{\gamma}_{R_i,P_l}} \exp(-(\frac{1}{\bar{\gamma}_{R_i,P_l}} + \sum_{t=1}^{k}\frac{1}{\bar{\gamma}_{R_i,P_{n_t}}})x)$. Thus, after some simple algebra, (10) arises.

B. Derivation of (12)

The $S-R$ link follows a conditional (given the selected relay R_s) exponential distribution yielding $F^{(\mathcal{T})}_{\gamma_{1,s}}(x) = 1 - \exp(-\frac{N_0 x}{p_{S,R_s}\bar{\gamma}_{S,R_s}})$. Regarding the second-hop of the transmission phase, recall that $\gamma^{(\mathcal{T})}_{R_s,D}$ and $\hat{\gamma}^{(\mathcal{T})}_{R_s,D}$ have correlated exponential distributions with a corresponding conditional PDF given by [13, Eq. (31)] $f_{\gamma^{(\mathcal{T})}_{R_s,D}|\hat{\gamma}^{(\mathcal{T})}_{R_s,D}}(x|y) = \frac{\exp(-\frac{x+\rho_s^2 y}{(1-\rho_s^2)p_{R_s,D}\gamma_{R_s,D}})}{(1-\rho_s^2)p_{R_s,D}\gamma_{R_s,D}} I_0\left(\frac{2\rho_s\sqrt{xy}}{(1-\rho_s^2)p_{R_s,D}\gamma_{R_s,D}}\right)$. From the theory of concomitants of ordered statistics, it holds that $f_{\gamma^{(\mathcal{T})}_{R_s,D}}(x) = \int_0^\infty f_{\gamma^{(\mathcal{T})}_{R_s,D}|\hat{\gamma}^{(\mathcal{T})}_{R_s,D}}(x|y) f_{\hat{\gamma}^{(\mathcal{T})}_{R_s,D}}(y)dy$. Thus, since R_s is selected based on maximizing the SNR of the relay-to-destination link, $f_{\hat{\gamma}^{(\mathcal{T})}_{R_s,D}}(\cdot)$ becomes $f_{\hat{\gamma}^{(\mathcal{T})}_{R_s,D}}(y) = \Psi_M \exp(-\Phi_M y)$. Recall that Ψ_M and Φ_M are defined in (12). Utilizing [19, vol. 2, Eq. (2.15.5.4)], it holds that $f_{\gamma^{(\mathcal{T})}_{R_s,D}}(x) = \Xi_M \exp(-Z_M x)$. Further, using the integral in (A.1), (12) can be extracted. Finally, $U^{(\mathcal{T})}_i = \int_0^\infty (x+1)^{-1} f^{(\mathcal{T})}_{\gamma_{1,s}}(x)dx$ with $f^{(\mathcal{T})}_{\gamma_{1,s}}(\cdot)$ being the exponential PDF, yielding (14).

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