Performance improvement of multiuser cognitive relay networks with full-duplex cooperative sensing and energy harvesting

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Abstract: Energy harvesting cognitive radio has been considered as a promising technology in the fifth generation (5G) of wireless networks to solve the lack of spectrum and energy. In this paper, a novel wireless energy harvesting relay network is proposed for a multiuser cognitive radio to obtain the maximum throughput and decrease the false alarm and misdetection probabilities. The secondary user (SU) can harvest energy from solar sources while utilizing the licensed spectrum of the primary user (PU). Cooperative spectrum sensing is applied to improve the performance of the secondary network and decrease collision and sensing time. In this paper, the SU can carry out the transmitting, harvesting, and sensing using a full-duplex technique at the same time. Furthermore, we analyze the spectrum sensing of the proposed multiuser network under a data fusion scheme to discover the frequency hole. We demonstrate that the optimization problem can convert into a convex problem and achieve the optimal regulated rate of energy harvesting based on the Lagrangian function. This new network provides improved throughput, precise spectrum sensing, and high energy harvesting compared to the existing works studied so far. Finally, we verify the efficiency of the proposed method via simulation results and show that the optimal regulated rate is determined based on the priority of given constraints.

Key words: Cognitive radio, cooperative spectrum sensing, energy harvesting, full-duplex, relay

1. Introduction
In the last few years, energy harvesting cognitive relay systems have received significant attention as an efficient technology to utilize the ambient energy and idle spectrum for unlicensed users. In the process of energy harvesting, the secondary user (SU) extracts energy from the harvestable sources of the environment such as wind, heat, waves, and light. Opportunistic spectrum access has also been a hot topic in cognitive radio, which can improve the bandwidth efficiency and simplify the spectrum reuse. In other words, the SUs can share the frequency band when the primary users (PUs) give up the channel [1–3]. A general summary of radio frequency energy harvesting systems was discussed in [4], including new research, system architecture, useful techniques, and available applications. Additionally, the applications of radio frequency energy harvesting are investigated in different networks, such as wireless sensor networks [5] and wireless charging networks [6]. An optimal cooperation protocol was proposed for an energy harvesting cognitive radio system in [7] to maximize the achievable throughput and provide the optimal decision, which consists of a two-level test. Furthermore, the average throughput was formulated under collision and energy constraints in [8] in order to achieve the optimal sensing time and threshold of the energy detector.

Relay technology was investigated for cognitive radio networks in [9–12]. In [13], the effect of relaying
protocol was analyzed on the throughput and outage probability in energy harvesting cognitive radio systems. A fast spectrum sensing algorithm was proposed in [14] to obtain the optimum decision. Another approach was studied in [15] to maximize the throughput with cooperative sensing, where the optimum number of SUs is achieved by an iterative algorithm for a certain number of iterations. Most works on linear cooperative spectrum sensing are considered as a single objective optimization, whereas in [16, 17] a multiple objective optimization approach was proposed to maximize the throughput and minimize the missed detection probability. Furthermore, one optimal algorithm and two suboptimal algorithms were defined in [18] to optimize the resource allocation of the SU in a cognitive radio system under an interference constraint. This work employs the Lagrange formulation to maximize the downlink capacity of the network. A three-dimensional Markov model was investigated for an energy harvesting system in [19] to maximize the throughput and optimize the harvested energy rate.

The rest of this paper is organized as follows. Section 2 describes the specifications of the proposed multiuser network and the differences from the literature. Section 3 introduces the system model for the proposed multiuser cognitive relay network. The active probability that operates the transmitter of the SU for the hybrid channel is described in Section 4. Cooperative spectrum sensing is studied for the proposed network in Section 5. Section 6 provides the maximum throughput and the optimal regulated rate for cooperative spectrum sensing under the active probability, the average transmit, and interference power constraints. In Section 7, the results and discussion are presented. Finally, our conclusions are stated in Section 8.

2. Related works
Relay cooperation can improve the spectrum efficiency and achievable throughput in energy harvesting cognitive networks [20, 21]. In this paper, we apply the amplify-and-forward (AF) relay protocol to amplify the transmit power of the SU in the proposed multiuser network, where the direct path is blocked due to deep fading and each SU uses only its relay. Cooperative spectrum sensing is another important approach in cognitive radio networks and is greatly studied; hence, we focus on it to enhance the precision of spectrum sensing. The maximum throughput of the secondary network is achieved based on cooperative spectrum sensing in two types, data fusion and decision fusion, in [22], where the SU acts in time slotted mode and harvests energy from the environment. Unlike our proposed multiuser approach, the SU can only do either spectrum sensing, data transmission, or energy harvesting at every time point. We propose an optimal power allocation based on regulated rate of energy harvesting to improve the average throughput. The problem of power allocation was analyzed in [23, 24] to maximize the expected achievable throughput of cognitive relay networks. We develop our proposed multiuser network under a collision constraint in order to protect the PU from damaging interference of the SU. The work in [25] suggested interference aware spectrum sensing to improve the efficiency of the spectrum hole discovery. In this scenario, the optimization problem is formulated to find the detection threshold for a single detector and cooperative detectors. In the majority of the above works, THS occurs in separate time slots, whereas the SU performs these three operations at the same time in our proposed scheme based on full-duplex communications. Additionally, performance improvement is given by optimal power allocation, optimal harvested rate, full-duplex cooperative sensing, and satisfied constraints in this paper. The optimization problem of transmission power was studied in [26] to maximize the sum-throughput of the SU, inspired by recent advancement in full-duplex. Additionally, the authors in [27] investigated the problem of power control in an underlay cognitive radio network where the SU exploits full-duplex transmissions. Wireless full-duplex spectrum sensing schemes were also studied for SUs in multichannel non-time-slotted cognitive radio networks in [28].
The performance improvement of the proposed network can be justified by the fact that the simultaneous THS protocol increases the duration of energy harvesting, data transmitting, and spectrum sensing. The first benefit of it compared to existing works is that the addition of energy harvesting time provides more stored power in the battery of the SU. Also, this addition of the power leads to the increase of the average throughput. The second advantage is that the addition of the spectrum sensing period causes the decrease of false alarms and the misdetection probabilities and the increase of the correct detection probability. It also provides more guarding for the PU from damaging interference of the SU and facilitates the use of a more complex spectrum sensing method that requires more spectrum sensing duration. Thirdly, when the data transmission time is increased the average throughput of the SU network improves and the connection between the transmitted data packets is provided in the proposed multiuser network.

3. Multiuser cognitive relay model with energy harvesting

As shown in Figure 1, we consider an energy harvesting cognitive relay system where the SUs are allowed to exploit the frequency band of the PU by spectrum overlay and spectrum underlay techniques. Furthermore, the SUs are capable of harvesting energy from a small solar panel in order to provide the required power for the dynamic spectrum access and data transmission. The energy storage of the SUs can charge and discharge at the same time based on new energy harvesting devices \[29\]. Additionally, the SUs can sense the channel and transmit data if the frequency band is idle at the same time based on full-duplex. The first frame is only dedicated for sensing. If the frequency band is sensed to be idle, sensing and transmitting occur at the same time in the next frames. If the energy detector alarms the presence of the PU, SUs stop data transmission and give up the channel while spectrum sensing is continued during the frame until a frequency hole is discovered. In other words, THS can be performed concurrently at each frame in the proposed model. In order to increase the average throughput of the SUs, it is supposed that the data queue of the SUs is saturated and the SUs always have a stack for data transmission in a buffer.

As depicted in Figure 2, the frame structure of the energy harvesting cognitive relay system for multiple...
SU in most existing works is separately divided into three parts. First, the SU harvests energy for $\tau_1$ s, and then it listens to the channel for $\tau_2$ s. The SU will use the spectrum for the remaining frame, i.e. $T - \tau_1 - \tau_2$ if the spectrum hole is detected or not, and it will harvest energy as long as the next frame. Accordingly, there is a trade-off between the period of THS. When the period of the energy harvesting is increased, the stored energy of the battery is also increased. Similarly, addition to the spectrum sensing period results in higher spectrum exploitation, although the duration increase of energy harvesting and spectrum sensing causes a reduction of data transmission duration, which leads to the decrease of the average throughput of the energy harvesting cognitive relay system.

To solve the trade-off problem, we propose a new frame structure for an energy harvesting cognitive relay system as illustrated in Figure 3, where THS functions are performed at the same time. The energy harvesting time of the previous frame is equal to $\tau_1 < T$, while it is equal to $T$ in the new one, which causes the addition of storage power and leads to the increase of the achievable throughput because of new frame increase active probability (discussed in Section 4). Throughput is multiplied by active probability. Furthermore, the spectrum sensing duration of the previous frame is $\tau_2 < T$, while it is $T$ in the proposed one. The increase of sensing time leads to the increase of the number of data samples ($N = T f_s$, $f_s$ is sampling frequency). When the number of samples of the energy detector is added, the precision of the energy detector to detect the PU is increased. Thus, this results in the decrease of false alarms and missed detection probabilities and the increase of correct detection probability. The data transmission period of the previous frame is $T - \tau_1 - \tau_2 < T$, while it is $T$ in the new frame. The average throughput of the previous frame is multiplied by $((T - \tau_1 - \tau_2)/T) < 1$, which degrades the performance, while the throughput of the proposed system is independent of $T$ (i.e. $((T/T) = 1$). Thus, the new frame improves the average throughput.

As is known, missed detection and false alarm probabilities are two main problems in cognitive radio systems, which decrease the system performance and spectrum utilization. Missed detection take places when the PU is present but the detector declares that the channel is idle, which leads to the collision of the SU with the PU. A false alarm happens when the PU is absent but the detector announces that the channel is busy. Thus, the energy harvesting cognitive relay system should be designed in such a way that the false alarm and missed detection probabilities are decreased as much as possible. Let $P_f$ and $P_d$ be the false alarm and detection probabilities, respectively.
Frame structure of proposed energy harvesting cognitive relay system with multiple SUs.

In order to implement concurrent sensing and transmission, it is supposed that the SU has two antennas where one antenna catches the signal from the surroundings to listen to the frequency band (idle/busy) and another antenna sends data packets at the same time [30]. The sensing/receiving and transmitting antennas are denoted by SU-RX and SU-TX, respectively, as shown in Figure 4. The self-interference at SU-RX is caused by the leakage of the radio frequency signal from SU-TX to SU-RX. The full duplex procedures are applied to eliminate the self-interference such as null-steering beam-forming, digital elimination, antenna polarization diversity, passive radio frequency suppression, and active analog radio frequency cancellation. The factor of self-interference elimination capability is represented by $\alpha$, which is yielded by dividing the remaining self-interference (after applying full duplex methods) by the whole self-interference. If the self-interference suppression is carried out perfectly, $\alpha$ will be equal to zero.

In this proposed energy harvesting cognitive relay system, the frequency band of the PU is considered as a hybrid channel, which consists of two cases: an overlay case and an underlay case. In the overlay case, when the frequency band is idle and the PU is not active, the SU can utilize the channel, called a spectrum hole. If the PU is active and the spectrum is busy, the SU must sense the channel in order to detect the idle spectrum. In the underlay case, the SU and PU can exist in the channel at the same time provided that the power of the SU is below the maximum interference power. Let $H_0$ and $H_1$ denote the channel status for idle and busy spectra with probabilities $P(H_0)$ and $P(H_1)$, respectively.

We assume that transmission is over Rayleigh flat fading channels and additive white Gaussian noise.
is distributed as a circularly symmetric complex with zero-mean and variance $\sigma_z^2$. Also, $\sqrt{\beta}$ denotes the AF amplification factor of the relay. Each frame includes two equal time slots, i.e. $T_1 = T_2 = \frac{T}{2}$, where $T_1$ is the transmission duration from SU1 to the relay and $T_2$ is transmission duration from relay to SU2, as shown in Figure 4. In the total frames after the first frame, the SU can concurrently sense the channel for detection of the spectrum hole, receive data packets from peer nodes, harvest energy from the environment, and transmit data packets to the relay, whereas the relay amplifies and sends the signal to the peer node of the SU.

The key notations used for the proposed multiuser network are summarized in Table 1.

<table>
<thead>
<tr>
<th>Notation</th>
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<tr>
<td>$P_d$</td>
<td>Detection probability</td>
<td>$P_f$</td>
<td>False alarm probability</td>
</tr>
<tr>
<td>$T$</td>
<td>Duration of frame structure</td>
<td>$N$</td>
<td>Total number of samples</td>
</tr>
<tr>
<td>$\sqrt{\beta}$</td>
<td>Amplification factor of the relay</td>
<td>$\alpha_m$</td>
<td>Factor of self-interference elimination</td>
</tr>
<tr>
<td>$p_sT$</td>
<td>Energy needed for spectrum sensing</td>
<td>$p_tT$</td>
<td>Energy needed for data transmission</td>
</tr>
<tr>
<td>$P(H_0)$</td>
<td>Idle spectrum probability</td>
<td>$P(H_1)$</td>
<td>Busy spectrum probability</td>
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<tr>
<td>$\lambda_m$</td>
<td>Regulated rate of energy harvesting</td>
<td>$w_m$</td>
<td>Contribution weight</td>
</tr>
<tr>
<td>$h_{ss}^m$</td>
<td>Channel coefficient from SU-TX to SU-RX</td>
<td>$h_{rp}^m$</td>
<td>Channel coefficient from relay to PU</td>
</tr>
<tr>
<td>$h_{sp}^m$</td>
<td>Channel coefficient from SU-TX to PU</td>
<td>$h_{ps}^m$</td>
<td>Channel coefficient from PU to SU-RX</td>
</tr>
<tr>
<td>$h_{sr}^m$</td>
<td>Channel coefficient from SU-TX to relay</td>
<td>$h_{rs}^m$</td>
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</tr>
<tr>
<td>$\Gamma_m$</td>
<td>Maximum interference power</td>
<td>$P_{total_m}$</td>
<td>Total allowed transmission power</td>
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4. Active operation of the SU’s transmitter by harvested energy in hybrid channel

In this section, we analyze the active probability of the SU’s transmitter based on harvested energy rate. The SU uses the harvested energy to sense the spectrum and transmit data. Let $p_s$ and $p_t$ be the power required for spectrum sensing and data transmission, respectively. The energy needed for spectrum sensing and data transmission is given by $p_sT$ and $p_tT$ in the proposed multiuser network. Suppose $E_n$ and $E_n^{ch}$ denote the remaining harvested energy at the start of frame $n$ and the harvested energy during frame $n$, respectively. The harvested energy is stacked in the battery with finite capacity. Also, it is assumed that there is no power storage except for the harvested energy capacitor for the SU.

In this setup, the transmitter of the SU works in two decision modes: active mode and nonactive mode. In the active mode ($\theta_n = 1$), the remaining harvested energy is equal to or more than the energy needed for spectrum sensing and data transmission so data transmission can occur in the overlay case if the PU is not present in the frequency spectrum and in the underlay case if the channel is busy. In the nonactive mode ($\theta_n = 0$), $E_n$ is less than $p_sT + p_tT$. Thus, the transmitter is turned off and does not consume energy until the next frame. Accordingly, a spectrum access decision for activation of the SU is given by:

$$
\theta_n = \begin{cases} 
0 & E_n < p_sT + p_tT \\
1 & E_n \geq p_sT + p_tT 
\end{cases}
$$

(1)

In the active mode, the average harvested energy at each frame should not be less than the average
consumed energy. Therefore, the average consumed energy in the active mode can be written as:

$$E_n^c = p_s T + p_t T \left(P(H_0) (1 - P_f) + P(H_1) (1 - P_d)\right)$$ (2)

The remaining energy at the start of the next frame is obtained by:

$$E_{n+1} = E_n + E_n^{ch} - E_n^c$$ (3)

Accordingly, the ratio of mean harvested energy to mean consumed energy for the $m$th SU in overlay and underlay cases can be respectively calculated by:

$$\psi^o_m = \frac{E_{n}^{ch}}{E_n^c} = \frac{E_{n}^{ch} \lambda^o_m T}{p_s T + p_t T \left(P(H_0) (1 - P_f) + P(H_1) (1 - P_d)\right)}, m = 1, 2, ..., 2M$$ (4)

$$\psi^u_m = \frac{E_{n}^{ch}}{E_n^c} = \frac{E_{n}^{ch} \lambda^u_m T}{p_s T + p_t T \left(P(H_0) P_f + P(H_1) P_d\right)}, m = 1, 2, ..., 2M$$ (5)

Here, $\lambda^o_m$ and $\lambda^u_m$ indicate the harvested energy rates in overlay and underlay cases, respectively, with integer numbers, i.e. 1, 2, 3, ..., and $E_n^{ch}$ denotes energy amount of each harvested energy unit. We consider $E_n^{ch}$ as a very minor value, for example 0.0001 J, where the harvested energy ($E_{n}^{ch} \lambda^o_m$ and $E_{n}^{ch} \lambda^u_m$) approximately consists of all possible values. The active probabilities in overlay and underlay cases is given by $P_m^o = \min(1, \psi^o_m)$ and $P_m^u = \min(1, \psi^u_m)$, respectively. Since we assumed that the capacity of energy storage is limited and finite, we always consider $P_m^o = \psi^o_m \leq 1$ and $P_m^u = \psi^u_m \leq 1$, unlike previous literature assuming infinite capacity. On the other hand, we suppose that the average harvested energy cannot be more than the mean consumed energy because of the capacity constraint of the battery.

5. Cooperative spectrum sensing with $\alpha$ factor

Spectrum sensing is an important technique for cognitive radio networks to detect frequency holes and support the PU in avoiding adverse collision with the SU. Shadowing and multipath fading are the most common problems in the spectrum detection process. Cooperative spectrum sensing can solve these issues using spatial diversity. As illustrated in Figure 1, $2M$ SUs participate to find unoccupied channels. In this paper, we apply an energy detection scheme based on data fusion because of simple computation and low complexity. SUs transmit local observations to the fusion center (FC) for finding the PU through a common control channel, where the final decision is concluded by gathering all received signals from the cooperative SUs; see Figure 5. A fusion center is a centralized processor in which each SU sends a weighted squared received signal. Then the fusion center sums the information of SUs, compares it to a given threshold, and makes a final decision on PU presence/absence. Finally, the fusion center feeds back the result of the comparison to the SUs to transmit data if the channel is idle.

After self-interference elimination, the received signal at the SU-RX antenna of the $m$th SU can be given by:

$$x_m(n) = \begin{cases} \alpha_m s_m(n) h_{ss}^m + z_m(n), & H_0 \\ p(n) h_{ps}^m + \alpha_m s_m(n) h_{ss}^m + z_m(n), & H_1 \end{cases}$$ (6)

Here, $\alpha_m$ is the factor of self-interference elimination and $s_m(n)$ is the self-interference SU signal. $h_{ss}^m$ denotes the channel coefficient from the SU-TX antenna to the SU-RX antenna. $z_m(n)$ is additive white Gaussian noise.
with zero-mean and variance $\sigma^2_m$ and $p(n)$ is the PU signal at the $n$th sample of $N$ samples for each frame. $h_{pm}^n$ denotes the channel coefficient from the PU to SU-RX antenna. The self-interference signal is the leakage and unwanted emission of the radio frequency signal from SU-TX to SU-RX. This phenomenon is a specific kind of noise, which reduces the signal to noise ratio at SU-RX. After applying self-interference cancellation techniques, the residual signal at the SU-RX antenna, denoted $\Delta s_m(n)$, is divided by the transmitted signal from the SU-TX antenna ($s_m(n)$). The result of this fraction is interpreted as a factor of self-interference cancellation, which is obtained by $\alpha_m = \Delta s_m(n)/s_m(n)$. The physical meaning of $\alpha_m$ is the ratio of the remainder signal to the total signal of SU at SU-RX and indicates the ability of self-interference cancellation technique for suppression.

To discover the frequency hole and compare with the threshold, the energy detector needs to know the energy of signals (i.e. the sum of squared signals). The local sensing outcomes are accumulated for each SU as follows:

$$v_m = \sum_{n=0}^{N-1} |x_m(n)|^2, \quad m = 1, 2, \ldots, 2M \quad (7)$$

Here, $2M$ is the number of SUs. Based on the central limit theorem [31], if the number of samples is sufficiently large ($N \geq 10$), then the local sensing outcomes have Gaussian distribution. The received signals at the FC are written by:

$$r_c = \sum_{m=1}^{2M} w_m(v_m + u_m), \quad m = 1, 2, \ldots, 2M \quad (8)$$

Here, $u_m$ indicates the noise of the common control channel with zero-mean and variance $\gamma^2_m$. $w_m$ denotes the contribution weight of the $m$th SU for the final decision, $0 \leq w_m \leq 1$ and $\sum_{m=1}^{2M} w_m = 1$. When deep fading and shadowing occur, the weight of the SUs can be changed in order to decrease the negative effects. $r_c$ is compared to a threshold, $\delta_c$, and then the FC makes its own decision. If $r_c$ is smaller than $\delta_c$, the channel will
be assumed idle. For \( r_c \geq \delta_c \), the channel will be considered busy. \( v_m \) is a normal random variable and the linear fusion \((r_c)\) is normal. According to the data fusion technique, first the local sensing results of each SU \((v_m)\) are added by noise of the common control channel, and then the weighted coefficients of each SU \((w_m)\) are accumulated in the fusion center to compare with the threshold \( \delta_c \). On the other hand, \( w_m \) indicates the contribution share of each SU for the final decision. \( r_c \) has means under \( H_0 \) and \( H_1 \) hypotheses as follows:

\[
E(r_c \mid H_0) = \sum_{m=1}^{2M} \left( N \sigma_m^2 + \alpha_m^2 E_s^m h_{ss}^m \right) w_m
\]  

(9)

\[
E(r_c \mid H_1) = \sum_{m=1}^{2M} \left( N \sigma_m^2 + \alpha_m^2 E_s^m h_{ss}^m \right) w_m
\]

Here, \( E_s^m = \sum_{n=0}^{N-1} |s_m(n)|^2 \) and \( E_p = \sum_{n=0}^{N-1} |p(n)|^2 \). Also, the variances of \( r_c \) under \( H_0 \) and \( H_1 \) hypotheses are derived by:

\[
\text{Var}(r_c \mid H_0) = \sum_{m=1}^{2M} \left( 2N \sigma_m^4 + 4\alpha_m^2 E_s^m h_{ss}^m \sigma_m^2 + \gamma_m^2 \right) w_m^2
\]  

(10)

\[
\text{Var}(r_c \mid H_1) = \sum_{m=1}^{2M} \left( 2N \sigma_m^4 + 4\alpha_m^2 E_s^m h_{ss}^m \sigma_m^2 + \gamma_m^2 \right) w_m^2
\]

(11)

Then the false alarm and detection probabilities of the proposed multiuser network are respectively calculated by:

\[
P_f = \Pr (r_c \geq \delta_c \mid H_0) = Q \left( \frac{\delta_c - E(r_c \mid H_0)}{\sqrt{\text{Var}(r_c \mid H_0)}} \right)
\]  

(13)

\[
P_d = \Pr (r_c \geq \delta_c \mid H_1) = Q \left( \frac{\delta_c - E(r_c \mid H_1)}{\sqrt{\text{Var}(r_c \mid H_1)}} \right)
\]  

(14)

Here, \( Q \) indicates the complementary Gaussian distribution function defined as \( Q(x) = \int_x^\infty e^{-t^2/2} \, dt \).

6. Maximum throughput and optimal regulated rate

In this section, we formulate the maximum average throughput of the SU according to cooperative spectrum sensing versus optimal regulated rate of energy harvesting, implemented in the hybrid model. As depicted in Figure 1, the proposed multiuser network consists of \( M \) transmitter-receiver pairs of SUs. \( m \) and \( \hat{m} \) denote the peer nodes of link \( m \). We first acquire the transmission power from the \( m \)th SU node to the \( \hat{m} \)th SU node in overlay and underlay cases as follows, respectively:

\[
p_s^o_{\text{sum}} = \left( S/T + E_{u}^{ch} \lambda_{m}^o - p_s \right), \ m = 1, 2, \ldots, 2M
\]  

(15)

\[
p_s^u_{\text{sum}} = \left( S/T + E_{u}^{ch} \lambda_{m}^u - p_s \right), \ m = 1, 2, \ldots, 2M
\]

(16)

Here, \( S \) is the remaining energy in the storage battery at the start of the frame. In order to control the harvested energy rates for maximizing throughput, a buffer equipped with a regulator is placed at the gate of the SU storage. Let \( \Lambda_m \) indicate the harvested energy during one frame in the buffer. \( \Lambda_m \) varies at each frame because of the environmental circumstances, which specify the value of the harvested energy. It is clear that the constraints \( E_{u}^{ch} \lambda_{m}^o T \leq \Lambda_m \) and \( E_{u}^{ch} \lambda_{m}^u T \leq \Lambda_m \) should be satisfied in our network. Furthermore, in order
to simplify the optimization problem in a hybrid cognitive radio network, let the maximum possible value of $\lambda^u_m$ in the underlay case be the minimum amount satisfying three conditions, $p^u_m \leq \beta PT_{\text{Threshold}}$, $P^o_m \leq 1$, and $E_{u}^{ch}\lambda_m^u T \leq \Lambda_m$, as:

$$
\lambda_m^u = \min \left\{ \frac{(p_s T + p_t T (P (H_0) P_f + P (H_1) P_d))}{(E_{u}^{ch} T)} \frac{(\beta PT_{\text{Threshold}} - S/T + p_s)}{E_{u}^{ch} T} \right. \frac{\Lambda_m}{E_{u}^{ch} T} \right\}
$$

(17)

Here, $PT_{\text{Threshold}}$ is the maximum allowed interference power in the underlay case. On the other hand, when the frequency band is occupied by the PU, the transmission power of the relay should not exceed $p$. Consequently, in order to maximize the average throughput, the problem optimization is only derived with regard to $\lambda^o_m$. The harvested energy rate of the SU should be regulated to support the PU in avoiding damaging interference. Therefore, the interference power constraint of the $m$th SU and related relay is given by:

$$
(p^o_{su_m} P (H_1) (1 - P_d) + p^u_{su_m} P (H_1) P_d) (|h_{sp}|^2 + \beta |h_{rp}|^2) \leq \Gamma_m
$$

(18)

Here, $h^m_{sp}$ and $h^m_{rp}$ are the channel coefficients from node $m$ and its relay to PU receiver, respectively. $\Gamma_m$ indicates the maximum interference power tolerated by the PU in the hybrid channel. Furthermore, the total energy budget constraint of node $m$ after relay is derived by:

$$
(p^o_{su_m} (P (H_0) (1 - P_f) + P (H_1) (1 - P_d)) + p^u_{su_m} (P (H_0) P_f + P (H_1) P_d)) \beta |h_{sr}|^2 |h_{rs}|^2 \leq P_{total_m}
$$

(19)

Here, $h^m_{sr}$ is the channel coefficient from node $m$ to its relay, and $h^m_{rs}$ is the channel coefficient from relay to node $\hat{m}$. $P_{total_m}$ denotes the total allowed transmission power for node $m$. Thus, the throughput optimization problem of the secondary network is formulated with respect to $\lambda^o_m$ as follows:

$$
\text{maximize } R_{su} (\lambda^o_m) = \sum_{m=1}^{2M} \frac{E_{u}^{ch} \lambda^o_m T}{p_s T + p_t T (P (H_0) (1 - P_f) + P (H_1) (1 - P_d)) (P (H_0) (1 - P_f) r_{00}^m + (P (H_1) (1 - P_d) r_{10}^m)} + (P (H_1) (1 - P_d) r_{10}^m) + \frac{E_{u}^{ch} \lambda^o_m T}{p_s T + p_t T (P (H_0) P_f + P (H_1) P_d)} (P (H_0) (P_f) r_{01}^m + (P (H_1) (P_d) r_{11}^m)
$$

(20)

This is subject to Eq. (18), Eq. (19), $P^o_m \leq 1$, $E_{u}^{ch} \lambda_m^u T \leq \Lambda_m$, and $\lambda^o_m \in \mathbb{Z}^+$. For simplicity, we assume that the peer nodes $(m,\hat{m})$ have the same conditions, transmitting and receiving equal power at each link $m$. Accordingly, we define:

$$
\begin{align*}
\lambda^m_{00} &= \log \left( 1 + \frac{\beta p^o_{su_m} |h_{sr}|^2 |h_{rs}|^2}{\alpha_m^2 p^u_{su_m} |h_{rs}|^2 + \sigma^2_m} \right) \\
\lambda^m_{10} &= \log \left( 1 + \frac{\beta p^o_{su_m} |h_{sr}|^2 |h_{rs}|^2}{\alpha_m^2 p^u_{su_m} |h_{rs}|^2 + \sigma^2_m + \nu^2_m |h_{ps}|^2} \right) \\
\lambda^m_{01} &= \log \left( 1 + \frac{\beta p^o_{su_m} |h_{sr}|^2 |h_{rs}|^2}{\alpha_m^2 p^u_{su_m} |h_{rs}|^2 + \sigma^2_m} \right) \\
\lambda^m_{11} &= \log \left( 1 + \frac{\beta p^o_{su_m} |h_{sr}|^2 |h_{rs}|^2}{\alpha_m^2 p^u_{su_m} |h_{rs}|^2 + \sigma^2_m + \nu^2_m |h_{ps}|^2} \right)
\end{align*}
$$

(21)
Here, $\nu^2_m$ is the variance of PU at the $m$th SU node. The problem of Eq. (20) can be converted to a convex problem with the transformation of variable $\lambda^o_m = \sqrt{z}$ and reformulated as follows:

$$\maximize \quad r_{su}(z) = R_{su}(\sqrt{z}) \quad (22)$$

**Proof** From convex optimization principles, the two problems of Eq. (20) and Eq. (22) are distinctly similar. If $\lambda^o_m$ solves the problem of Eq. (20), then $z = (\lambda^o_m)^2$ can solve the problem of Eq. (22), and if $z$ solves the problem of Eq. (22), then $\lambda^o_m = \sqrt{z}$ can solve the problem of Eq. (20). Furthermore, for maximizing, if the objective function is concave and the inequality constraints are convex, then the problem of Eq. (22) will be convex. Since the inequality constraints are linear with regard to $z$, the constraints are convex. In order to facilitate the proof, it is enough to demonstrate the concavity of the following function:

$$y(z) = \sqrt{\log \left( \frac{1}{2} + \frac{\beta (S/T + E_u^v \sqrt{z} - p_s) |h_m^{s}|^2 |h_m^{r}|^2}{|\alpha_m|^2 |S/T + E_u^v \sqrt{z} - p_s| |h_m^{ss}|^2 + |\sigma_m^2|^2} \right)} = \sqrt{\log \left( \frac{a_1 + a_3 + (a_2 + a_4) \sqrt{z}}{a_3 + a_4 \sqrt{z}} \right)},$$

Here $a_1 = \beta (S/T - p_s) |h_m^{s}|^2 |h_m^{r}|^2$, $a_2 = \beta E_u^v |h_m^{s}|^2 |h_m^{r}|^2$, $a_3 = |\alpha_m|^2 (S/T - p_s) |h_m^{ss}|^2 + |\sigma_m^2|^2$, $a_4 = |\alpha_m|^2 E_u^v |h_m^{ss}|^2$. The first derivative of $y(z)$ is given by:

$$\frac{\partial y(z)}{\partial z} = \frac{1}{2\sqrt{z}} \log \left( \frac{a_1 + a_3 + (a_2 + a_4) \sqrt{z}}{a_3 + a_4 \sqrt{z}} \right) + \frac{a_2a_3 - a_1a_4}{2(a_3 + a_4 \sqrt{z})(a_1 + a_3 + (a_2 + a_4) \sqrt{z}) \ln^2},$$

and the second derivative is written as:

$$\frac{\partial^2 y(z)}{\partial^2 z} = \frac{a_4(a_2a_4 - a_1a_4)}{4\sqrt{z}(a_3 + a_4 \sqrt{z})^2(a_1 + a_3 + (a_2 + a_4) \sqrt{z}) \ln^2} - \frac{a_2a_3 - a_1a_4}{4\sqrt{z}(a_3 + a_4 \sqrt{z})(a_1 + a_3 + (a_2 + a_4) \sqrt{z}) \ln^2} - \frac{a_2a_3 - a_1a_4}{4\sqrt{z}(a_3 + a_4 \sqrt{z})(a_1 + a_3 + (a_2 + a_4) \sqrt{z}) \ln^2} \leq 0$$

since $a_2a_3 - a_1a_4 \geq 0$, which results in $\frac{\partial^2 y(z)}{\partial^2 z} \leq 0$ for total values $z \in \mathbb{Z}^+$. Finally, $y(z)$ is concave and the convexity of Eq. (22) is proved.

The Lagrangian function of Eq. (22) with respect to $z$ is obtained by:

$$L(z, \eta_1, \eta_2, \eta_3, \eta_4) = r_{su}(z) - \eta_1((S/T + E_u^v \sqrt{z} - p_s)(P(H_0)(1 - P_f) + P(H_1)(1 - P_d)) \beta |h_m^{s}|^2 |h_m^{r}|^2$$

$$+ (S/T + E_u^v \lambda_m^{u} - p_s)(P(H_0)(P_f) + P(H_1)(P_d)) \beta |h_m^{p}|^2 |h_m^{r}|^2 - P_{total,m})$$

$$- \eta_2)((S/T + E_u^v \sqrt{z} - p_s)(P(H_1)(1 - P_d) + (S/T + E_u^v \lambda_m^{u} - p_s)(P(H_1)P_d)(|h_m^{p}|^2$$

$$+ \beta |h_m^{p}|^2 - \Gamma_m) - \eta_3((E_u^v \sqrt{z}T / (p_sT + p_dT)(P(H_0)(1 - P_f) + P(H_1)(1 - P_d)) - 1]$$

$$- \eta_4[E_u^v \sqrt{z}T - \Lambda_m]$$

(23)

Then the Lagrange dual problem is given by:

$$\minimize \quad g(\eta_1, \eta_2, \eta_3, \eta_4), \quad \eta_1, \eta_2, \eta_3, \eta_4 \geq 0 \quad (24)$$

Here, $g(\eta_1, \eta_2, \eta_3, \eta_4)$ denotes the Lagrange dual function as

$$g(\eta_1, \eta_2, \eta_3, \eta_4) = \sup L(z, \eta_1, \eta_2, \eta_3, \eta_4) \quad (25)$$

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For convex problem with linear inequality constraints, the gap between the optimal value of the objective function and dual function is zero. Thus, the Lagrange dual problem of Eq. (24) can be calculated instead of the primary problem of Eq. (22). To solve the problem of Eq. (24), we should first derive the supremum of Lagrangian \( L(z, \eta_1, \eta_2, \eta_3, \eta_4) \). The nonlinear problem of Eq. (24) cannot be solved directly using Karush–Kuhn–Tucker (KKT) conditions. Therefore, we apply Newton’s method to solve the KKT equation set and find the optimum \( z \).

7. Results and discussion

In this section, we discuss the simulation results for the proposed scheme. We compare our full-duplex protocol with existing half-duplex systems versus different, the detection probability, the channel utilization, and signal to noise ratio (SNR) of the PU. Unless stated otherwise, we use the specified values for related parameters in Table 2.

| Parameter   | Value | \( P_d \) | \( P(H_0) \) | \( \beta \) | \( T(\text{ms}) \) | \( 2M \) | \( N \) | \( p_s(w) \) | \( p_t(w) \) | \( \alpha_m \) | \( \Gamma_m(w) \) | \( P_{\text{total}}_m(w) \) | \( \Lambda_m(j) \) |
|-------------|-------|------------|--------------|-------------|----------------|---------|-------|-------------|-------------|-------------|--------------|----------------|----------------|-------|
| Value       | 0.9   | 0.5        | 4            | 100         | 4             | 100     | 1     | 5           | 0.1         | 1.5         | 10           | 0.4            |                  |        |

In Figure 6a and Figure 6b, the optimal transmit energy rate \( (\lambda_m E_{\text{th}}^u) \) and the maximum throughput of the SUs are presented respectively versus the sensing time for various values of the self-interference suppression \( \alpha_m \). The transmit rate in half-duplex is increased by increasing the sensing time, while it does not change in the proposed scheme. Also, the average throughput of the proposed scheme is decreased by an increase in the self-interference factor. As is seen, the proposed multiuser network based on the frame structure of Figure 3 has constant rate and throughput and does not depend on the sensing duration. Furthermore, the concurrent network notably has higher rate and throughput than the half-duplex network based on the frame structure of Figure 2. The maximum throughput of the half-duplex is 3.98 for 40 ms of sensing time. The reason for this efficiency improvement is that the whole frame period is used for THS at the same time, whereas only a section of the frame is applied for these operations in the half-duplex network. Some results are not seen in Figure 6a, such as the better use of the spectrum hole and higher storage of the harvested energy for the proposed multiuser network. Furthermore, the false alarm probability of the half-duplex network is higher than the false alarm probability of the proposed multiuser network for identical detection probability and the same amplification factor.

Figure 7a and Figure 7b illustrate the optimal energy rate and performance versus the power required for data transmission, respectively. As shown, the optimal rate of the proposed scheme is increased by increasing \( p_t \) until a certain point (7, 3.86) and fixed after that, since the constraints of Eq. (18) and \( E_{\text{th}}^u \lambda_m T \leq \Lambda_m \) are dominated, where the harvested rate is not allowed to grow. This occurs because the active probability in overlay (i.e. \( P_m^u \)) is decreased and has a negative effect on the average throughput in part b. Furthermore, the increase of \( p_t \) reduced the active probability in underlay (i.e. \( P_m^u \)) since the harvested rate in underlay does not change from Eq. (17) according to our simulation parameters. Therefore, the utility is decreased by increase of \( p_t \). Similar to Figure 6b, the proposed scheme has a higher efficiency than the half-duplex for different values of \( \alpha \).

We study the effect of the total power budget constraint in Figure 8a and Figure 8b for different values of detection probability. As \( P_{\text{total}}_m \) is increased, the optimal rate and the average throughput are increased until
Figure 6. The effect of sensing time on the proposed and existing schemes versus $\alpha$: (a) optimal harvested energy rate, (b) average throughput.

Figure 7. The result of $p_t$ on the proposed and existing schemes versus $\alpha$: (a) optimal harvested energy rate, (b) average throughput.

specified points. At these points of $(10, 2.89)$, $(11, 3.31)$, $(12, 3.86)$, $(10, 15.19)$, and $(12, 19.98)$, the interference constraint, the active probability constraint, and the total energy constraint of the buffer are overcome and prevent the increase in rate and throughput. It is obviously seen that the full-duplex protocol has much higher performance than the existing method.

The challenge of the constraints of the problem in Eq. (20) is illustrated in Figure 9a and Figure 9b versus the maximum power interference for various values of $P(H_0)$. For $P(H_0) = 0.6$, the growth of the harvested rate is not stopped with $\Gamma_m$. This can be easily explained by the fact that other constraints are satisfied, for which the rate is allowed to increase. However, after points $(0.9, 3.26)$, $(1.3, 3.61)$, $(1.4, 2.64)$, $(0.9, 17.86)$, and $(1.3, 19.28)$, the rate and throughput are fixed because the active probability constraint does not allow those to
grow. In Figure 10a and Figure 10b, the result of the total harvested energy in the buffer is shown for different values of the energy of PU. As seen, the harvested rate and the maximum throughput are increased by increase of the energy of the PU. This result is supported by the fact that the energy detector can discover the presence of the PU more precisely by increase of the energy of the PU, and then the effect of $\alpha$ becomes lower, the false alarm probability is reduced, and the detection probability is increased. However, after points (0.5, 2.64), (0.6, 3.86), (0.5, 13.99), and (0.6, 19.98), the performance is not changed because of overcoming constraints defined in Eq. (20).

Figure 8. The result of $P_{\text{total}_m}$ on the proposed and existing schemes versus $P_d$: (a) optimal harvested energy rate, (b) average throughput.

Figure 9. The result of $\Gamma_m$ on the proposed and existing schemes versus $P(H_0)$: (a) optimal harvested energy rate, (b) average throughput.

In Figure 11a and Figure 11b, the optimal energy rate and performance are illustrated versus $\beta$ for different fading channels between the SU and the relay. At $\beta = 4$, the best performance is achieved for the full-duplex method. For values smaller than 4, $\beta$ amplifies the transmit power more than the interference power;
The result of $\lambda_m$ on the proposed and existing schemes versus $E_p$: (a) optimal harvested energy rate, (b) average throughput.

Figure 10. The result of $\lambda_m$ on the proposed and existing schemes versus $E_p$: (a) optimal harvested energy rate, (b) average throughput.

thus, the average throughput is increased by the growth of it. After this point, the throughput is decreased because the amplification factor influences the interference power more than the transmit power. Additionally, the defined constraints in Eq. (20) do not allow the optimal rate to increase so it is fixed until point 4. When the fading channel between the SU and relay becomes more intense, the efficiency of the network is more degraded.

We compare the maximum throughput and the harvested energy rate of our full-duplex method with the existing half-duplex scheme for various parameters in Table 3. As is obviously seen, the proposed performance has higher values than the existing works (half-duplex scheme as in [22]) and the effect of simultaneous THS is outstanding in simulation results.

Figure 11. The result of $\beta$ on the proposed and existing schemes versus $E_p$: (a) optimal harvested energy rate, (b) average throughput.

We compare the maximum throughput and the harvested energy rate of our full-duplex method with the existing half-duplex scheme for various parameters in Table 3. As is obviously seen, the proposed performance has higher values than the existing works (half-duplex scheme as in [22]) and the effect of simultaneous THS is outstanding in simulation results.
Table 3. Performance comparison of the proposed scheme with the existing protocol versus different parameters.

<table>
<thead>
<tr>
<th></th>
<th>$P_d = 0.95$</th>
<th>$P(H_0) = 0.75$</th>
<th>$p_t = 7$</th>
<th>$\alpha_m = 0.2$</th>
<th>$\Gamma_m = 1.3$</th>
<th>$P_{total_m} = 8$</th>
<th>$\Lambda_m = 0.3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{su}\text{ (full-duplex)}$</td>
<td>17.17</td>
<td>18.57</td>
<td>15.54</td>
<td>15.95</td>
<td>15.05</td>
<td>16.52</td>
<td>15.56</td>
</tr>
<tr>
<td>$R_{su}\text{ (half-duplex)}$</td>
<td>2.66</td>
<td>4.73</td>
<td>3.95</td>
<td>3.98</td>
<td>3.89</td>
<td>3.98</td>
<td>3.93</td>
</tr>
<tr>
<td>$\lambda_m^o E^{ch}_{u}\text{ (full-duplex)}$</td>
<td>3.42</td>
<td>3.43</td>
<td>3.86</td>
<td>3.83</td>
<td>2.89</td>
<td>3.18</td>
<td>2.99</td>
</tr>
<tr>
<td>$\lambda_m^o E^{ch}_{u}\text{ (half-duplex)}$</td>
<td>2.05</td>
<td>2.9</td>
<td>3.23</td>
<td>2.62</td>
<td>2.55</td>
<td>2.62</td>
<td>2.58</td>
</tr>
</tbody>
</table>

8. Conclusions

This study introduces a new energy harvesting cognitive relay system with multiple SUs to maximize the average throughput based on cooperative spectrum sensing. In the proposed scheme, each SU sends its local sensing results to the FC and the final decision is obtained according to the channel status. To improve the performance and decrease the false alarm and detection probabilities, data transmitting, energy harvesting, and spectrum sensing are implemented at the same time in a multiuser relay network. Additionally, the self-interference elimination technique is used to solve the trade-off among data transmitting, energy harvesting, and spectrum sensing. Ultimately, the optimal harvested energy rate and power allocation are achieved to optimize the proposed relay network. Simulation results show that the proposed full-duplex network has notably better performance than the half-duplex network. In future studies, the proposed scheme will be generalized for multichannel energy harvesting cognitive relay systems.

References


