Resource Allocation for Two-Way Relay-Assisted Hybrid Cognitive Radio Networks

Farhad Arpanaei[1], Majid Shakeri [2], Nahid Ardalani[3]

[1]*Young Researcher and Elite Club, Central Tehran Branch, Islamic Azad University, Tehran, Iran*
[2]*Young Researcher and Elite Club, Natanz branch, Islamic Azad University, Natanz, Iran*
[3]*Department of Electrical Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran*
majid_shakeri@hotmail.com

Abstract—**In this paper, we focus on the resource allocation (RA) in Orthogonal Frequency Division Multiplexing Access (OFDMA) Two-Way Relay-Assisted (TWR) Cognitive Radio Network (CRN). The spectrum availability in hybrid spectrum sharing was examined based on a sensing-based spectrum sharing. Aggregate Weighted Ergodic Throughput (AWET) of the secondary network was considered as the main objective of the RA. In addition to subcarrier assignment policy, the system design parameters are the transmission power of Secondary Users (SUs), Base Station (BS) and relay nodes, sensing parameters i.e. the sensing time and energy detection threshold. The main contributions of this paper is the proposed novel sensing based RA algorithm and its near optimal solution adopting dual technique coupled with block coordinate descent algorithm for OFDMA TWR-assisted CRNs. Simulation results corroborated the theoretical findings and confirmed the superiority of the hybrid spectrum sharing against overlay and underlay spectrum sharing.**

Index Terms—**Cognitive Radio; Orthogonal Frequency Division Multiplexing Access; Resource Allocation; Spectrum Sensing; Two Way Relay-Assisted**

I. INTRODUCTION

CRNs has been proposed as a promising technology for the mitigation of spectrum scarcity and enhancement of spectral efficiency [1]. Via Opportunistic Spectrum Access (OSA) SUs, also known as cognitive radio users allows for the detection and utilization portion of the primary licensed bands [2]. Conducting spectrum-sensing procedure such as Cyclo-stationary detection permits the SUs to dynamically detect the under-utilized parts of the spectrum [3], which is known as the overlay spectrum access [4]. While the approach seems promising in improving the spectral efficiency, inherent inaccuracy in spectrum sensing limits the potential spectral performance (due mainly to false alarm incidents as the SU finds idle spectrum busy) and may result in causing harm to the primary service (PS) by imposing intolerable interference (because of faulty detection as the SU declares the busy spectrum as idle). Much works have been done to improve the accuracy of spectrum sensing. Nevertheless, stand-alone SUs may not able to ensure a good performance with stringent detection probability imposed by PS due to inherent Receiver Operating Characteristic curve (ROC) [5].

In this context, cooperative spectrum sensing is suggested, considering it can improve the spectrum sensing performance by reducing false alarm and faulty detection probabilities (see, [6] and [7]). Note that miss detection incident may not end up in performance degradation in PS due to fading and predefined Interference Threshold Constraint (ITC).

Relating to the notion of ITC, the SU is able to access the spectrum even when it is busy, provided the ITC is guaranteed, which is referred as underlay spectrum sharing [8]. The PS is actually vulnerable to levels of interference that is greater than ITC. Hence, in overlay spectrum access, lower false alarm probability is reachable with loose detection performance subjected to ITC. The question is, can SU do better than ITC? The answer is 'yes' based on the recognition of the two degrees of freedom in SU action that are the spectrum sensing and the power allocation. In this case, SU accesses with overlay spectrum sharing, whenever the spectrum is declared idle without ITC; thus, transmission with high power is viable, and with underlay whenever the spectrum is busy, although with extra constraint of ITC. This spectrum sharing technique is referred as the Hybrid Spectrum Sharing (HSS) ([9] and [10]) and it is proven to outperform both the overlay and underlay spectrum access. In this paper, the spectrum sharing access strategy is chosen considering the virtues of HSS in improving spectral efficiency and PS protection.

Although HSS is a promising technique, ITC may unfortunately squeeze the allocated power at SUs, which in turn results in reducing the potential spectral efficiency. On the other side, the relay assisted cognitive radio scheme has been recently introduced as an effective and collaborative approach, in which the reliability and Quality of Service (Qos) for secondary services have been significantly improved compared to the traditional CRNs [11] and [12]. These advantages are related to the inherent features of cooperative relay-assisted networks, which provide more diversity gains, energy saving and coverage extensions, accordingly the overall throughput enhancement of secondary network is guaranteed [13]. Moreover, the inflicted interference to Primary Users (PUs) is kept minimal in the relay-assisted CRNs since SUs can communicate with lower transmit power [14]. One of the advantages of cooperative relay-assisted CRNs is that the designers' incentive trend to relay-assisted CRNs. Two main relaying protocols, named as Amplify-and-Forward (AF) and Decode-and-Forward (DF) are massively studied in the literature [15].

In this paper, we consider AF protocol due to its simplicity, although the cost is lower than the spectral performance. Two main approaches exist for the half-duplex systems: the one-way relaying and two-way and the

bidirectional relaying [16]. With the virtue of the latter in improving the spectral efficiency [17], the focus of this paper is on two-way relaying. To the best of the authors' knowledge, the cooperative sensing based radio resource allocation of OFDMA-TWR assisted CRNs in the HSS environment has not been investigated yet. Since, OFDMA technology is the most popular and promising strategy in multiband/ multiuser applications such as WiMAX, LTE [18], an investigation of an efficient, higher throughput and low cost of OFDMA-TWR assisted CRNs in the HSS environment seems vital. In this manner, we assume that the SUs cannot reliably detect the presence of the PUs individually due to the very low SNR of the received signal [19], [20].Thus, we prefer to use cooperative spectrum sensing instead of non-cooperative approaches. Without the loss of generality, unlike the related works, e.g., [11], [21] and [22], we assume the SUs and BS are located in the proper situation in respect of PUs; therefore, SUs and BS can sense the existence of PU's activity and transmit sensing results to fusion center without the help of any relay nodes. Recently, some new works have been investigating the relay-assisted CRNs. With reference to some of the studies e.g.,[11], [22] and [23], the authors considered cooperative spectrum sensing relay-assisted cognitive radio networks without performing power allocation or RA. Other studies, such as [16], [17] and [24] considered only relay-assisted CRNs in non-HSS environment. However, the multiband/multiuser cooperative spectrum sensing OFDMA-TWR assisted CRNs in HSS environment has been remained open in the literature area until now. Different from many related works, such as [25], [26] and [27], we have concurrently considered all assigned powers i.e., SU powers, BS powers and relay node powers, sensing time (ST) and energy detection threshold (ETD).

The remainder of this paper is organized as follows: In Section II, the system model is described and we introduce the corresponding framework for cooperative spectrum sensing in OFDMA TWR assisted CRN in HSS environment. After that, in Section III, the problem formulations and the analysis of the proposed solution are established in detail. In this section, the power allocation and subcarrier pairing allocation are developed. We then introduce the RA algorithm based on the previous sections. Furthermore, the simulation results and numerical outcomes are provided in Section IV. Section V concludes the paper. The descriptions of each of the parameters and variables in the following formulation are listed in Table 2.

Table 2
Description of the parameters and variables in the following formulation

Symbol	Description
ξ^n	EDT on subcarrier n
f_s	sampling frequency
T_s	Sensing time (ST)
$W^{l,n}$	Channel power gain between the primary transmitter and the SU's "l" at subcarrier "n"
$P_{(i,j)}^n(\xi^n, T_s)$	Access probability of SS to subcarrier "n"
$P_{c,d}^n(\xi^n, T_s)$	Probability of detection
$P_{c,f}^n(\xi^n, T_s)$	False alarm probability
$X_{RS,(i,j)}^{l,n,m}$	Received signal at mth RS in subcarrier "n" and sensing status pair (i,j),
$X_{SU}^{l,n,m}$	Emitted signal from l^{th} SU with transmission power $p_{su,j}^{l,n,m}$ in subcarrier "n" to relay "m"
$X_{BS}^{n,m}$	Emitted signal from BS
$p_{bs,j}^{n,m}$	Transmission power from BS
$g_{SU-RS}^{l,n,m}$	Channel gain between lth SU and mth RS on nth subcarrier
$h_{BS-RS}^{l,n,m}$	Channel power gain between BS and mth RS
$d_{SU-PU}^{l,n}$	Channel power gain between lth SU and PS on subcarrier n
f_{BS-PU}^n	Channel power gain between BS and PS,
$q_{RS-PU}^{k,m}$	Channel power gain of mth RS and PS on subcarrier k
$Y_{SU,(i,j),(i',j')}^{l,(n,k),m}$	Received signal at lth SU from mth RS with sensing status $(i,j) \epsilon \mathcal{S}$ assuming subcarrier pair (n,k)
$Y_{BS,(i,j),(i',j')}^{l,(n,k),m}$	Received signal at BS from mth RS with sensing status $(i,j) \epsilon \mathcal{S}$ assuming subcarrier pair (n,k)
$\varphi_{j'}^{l,(n,k),m}$	Amplification factor of mth RS on subcarrier pair (n,k).
$\eta^{l,k}$	AWGN at SU l on subcarrier "k"
η^k	AWGN at BS on subcarrier "k"
$\vartheta^{l,k}$	Imposed interference from PS on the SU "l" in subcarrier "k"
ϑ^k	Imposed interference from PS on BS in subcarrier "k"
$p_{RS,(i,j),j'}^{l,(n,k),m}$	Amplified and forwarded by power to BS and lth SU on subcarrier "k" in the sensing pair $(i', j') \forall (i,j), (0,j'), (1,j') \epsilon S$,
ρ^l	$\epsilon[0,1]$as lth SU priority
$\alpha, \beta^m, \lambda^n$ and μ^k	Lagranigian multiplier

II. SYSTEM MODEL

A single cell OFDMA spectrum sensing (SS) co-existing with a PS is considered (see Figure 1). The SS contains a BS, *M* two-way relay stations (RS) indexed by $m \epsilon \mathcal{M} = \{1, ..., M\}$, and *L* SUs indexed by $l \epsilon \mathcal{L} = \{1, ..., L\}$. The total number of subcarriers is N. We consider TWR assisted systems with two-hop communications. The first hop, also known as multiple-access (MAC) hop is designated such that both the SUs and BS simultaneously transmit signals to the RSs. In the second hop, also known as Broadcast (BC) hop, the RSs retransmit the received signals from the SUs(BS) adopting AF relaying to the BS (SUs). More specifically, it is assumed that the relay "*m*" receives the signal transmitted from the SU "*l*" and BS on subcarrier "*n*" on MAC hop. The RS amplifies the received signals and then forwards the outputs on subcarrier "k" in the BC hop. We also introduce the notation $\prod(n) = k$ to emphasize that the subcarrier "*k*" in the BC hop is paired with the subcarrier "*n*" in the MAC hop. In order to prevent multi-

user interference (overlapping subcarrier assignment), the subcarrier pair *(n; k)* is devoted to only one SU in the MAC hop and one RS in the BC hop. Of course, one SU/RS can use more than one subcarrier pairs in both MAC and BC hops [25].

Like [15] and [24], we assume that the SUs and BS can cancel self-interference from the received signal in the BC hop. We also assume that there is no direct link between BS and SUs: Such an assumption is also considered in the literature e.g., [24], [25]. Note that this setting is practically a resemblance of scenarios by which SUs are in cell edge and far from the BS, which are in essence the main concern of cooperation communications.

It is noteworthy to point out that in spectrum sharing environment, one of the main constraints is ITC; thus, removing long-range transmission between BS and SUs is suitable not only the PS protection but also the SS performance. In this system, the relay nodes mainly help for exchanging information between the SU and the BS. Moreover, the SS is performed by secondary networks in the first of each time frame, and these sensing decisions are similarly preserved in both the first and second hops (see Figure. 2). In fact, the time duration time of the signal transmission in the first and second hops is very short so that the situation of sensing results and channels does not change significantly. Accordingly, we can use the same sensing parameters in the first and second hops for each subcarrier. In this study, the HSS environment is considered [28].For SS, we assume cooperative sensing, whereby the status of multiple frequency bands is examined by adopting multi-band joint energy detectors [20], [29]. The SS performance is measured by the probability of detection $P_{c,d}^{n}(\xi^{n}, T_s)$ and false alarm probability $P_{c,f}^{n}(\xi^{n}, T_s)$ respectively, as [20]:

$$p_{c,d} = (\varepsilon^n, T_s) = Q\left(\frac{\left(\varepsilon^n - \left(L\sigma_0^2 + \sum_{l=1}^{L}|W^{l,n}|^2\right)\right)\sqrt{T_s f_s}}{\sqrt{2N\sigma_0^2\sum_{l=1}^{L}\left(\sigma_0^2 + 2|W^{l,n}|^2\right)}}\right) \quad (1)$$

$$p_{c,f}^n = (\varepsilon^n, T_s) = Q\left(\frac{\left(\varepsilon^n - L\sigma_0^2\right)\sqrt{T_s f_s}}{\sqrt{2NL\sigma_0^2}}\right)$$

Where, $Q(x) = \left(\frac{1}{2\pi}\right)\int_{x}^{\infty} exp\left(-\frac{t^2}{2}\right)dt$. We defined the sensing status set $S = \{\{(i,j)|i,j\epsilon\{0,1\}\}$. Index *"i"* shows the PS activity so that *i = 1 (i = 0)* stands for the existence H_1^n (absence H_0^n) of PS on the subcarrier *"n"*, and index *"j"* stands for sensing output; *j = 0 (j = 1)* means idle (busy) detection. We define $P_{(i,j)}^{n}(\xi^{n}, T_s)$ as the access probability of SS to subcarrier *"n"*, which is obtained according to sensing performance and PS activity. Namely, $P_{(0,0)}^{n} = Pr\{H_0^n\}\left(1 - P_{c,f}^{n}(\xi^{n}, T_s)\right), P_{(0,1)}^{n} = Pr\{H_0^n\}P_{c,f}^{n}(\xi^{n}, T_s),$

$P_{(1,0)}^{n} = Pr\{H_1^n\}\left(1 - P_{c,d}^{n}(\xi^{n}, T_s)\right)$ and
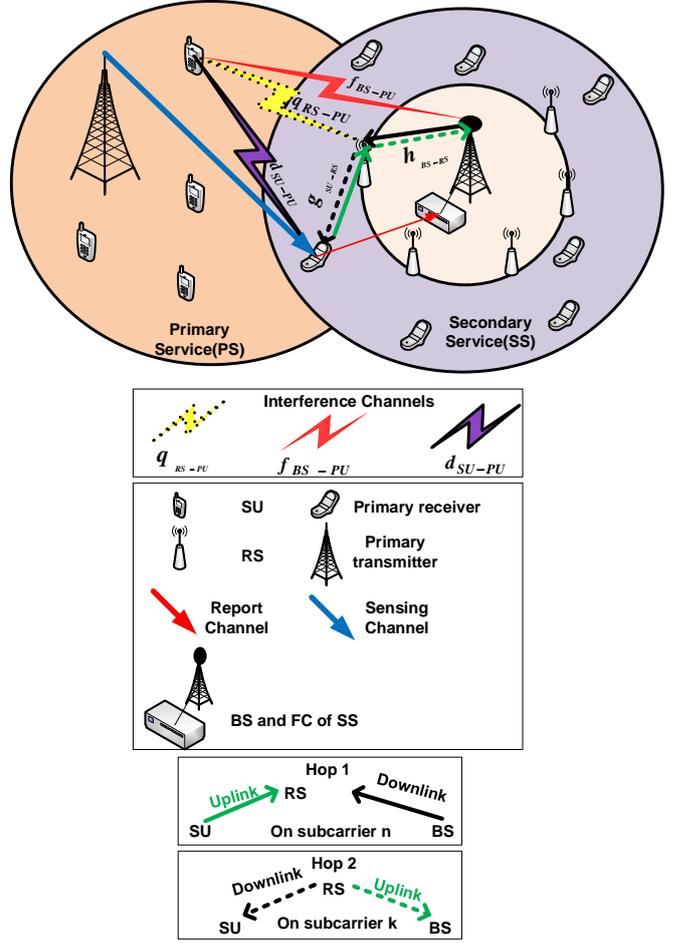
Figure 1: System model

$P_{(1,1)}^{n} = Pr\{H_1^n\}P_{c,d}^{n}(\xi^{n}, T_s)$, we assume that sensing output stays valid during both the MAC and BC hops. Therefore, the corresponding sensing status of subcarrier *"k"* in the second hop is defined by $(i',j') \epsilon S$. In a similar approach, which is defined for subcarrier *"n"*, the access probability of SS to subcarrier *"k"* is referred to $P_{(i',j')}^{n}(\xi^{n}, T_s)$. Assuming subcarrier *"n"* and sensing status pair *(i,j)*, the constituents of the received signal at m^{th} RS i.e., $X_{RS,(i,j)}^{l,n,m}$ are the signal $X_{SU}^{l,n,m}$ emitted from l^{th} SU with the transmission power $p_{su,j}^{l,n,m}$ and signal $X_{BS}^{n,m}$ emitted from BS transmission power $p_{bs,j}^{n,m}$ as:

$$X_{RS,(i,j)}^{l,n,m} = g_{SU-RS}^{l,n,m}\sqrt{P_{SU,j}}X_{SU}^{l,n} + h_{BS-RS}^{n,m}\sqrt{P_{BS,j}}X_{BS}^{l,n} + \eta^{n,m} + iv^{n,m}; \forall(i,j) \in S \quad (2)$$

in which, $g_{SU-RS}^{l,n,m}$ is the channel gain (including fading, shadowing, and distance-dependence path-loss attenuation) between l^{th} SU and m^{th} RS on n^{th} subcarrier and $h_{BS-RS}^{l,n,m}$ is the channel power gain between BS and m^{th} RS. We assume the channel power gains stay constant during MAC and BC hops. Also, $\eta^{n,m}$ is an i.i.d. ambient Additive White Gaussian Noise (AWGN) with zero mean and variance $\sigma_{\eta^{n,m}}^2$. Additionally, the $v^{n,m}$ denotes the interference due to PS transmissions at m^{th} RS on subcarrier *"n"* as $v^{n,m} \epsilon \mathcal{CN}(0, \sigma_{v^{n,m}}^2)$. We assume that the transmitted symbols of SUs and BS are zero mean with variance $\mathbb{E}\left[|X_{SU}^{l,n,m}|^2\right] = \mathbb{E}[|X_{BS}^{n,m}|^2] = 1 \forall l, n, m$, [14].

In the BC hop, signals $Y_{SU,(i,j),(i',j')}^{l,(n,k),m}$ and $Y_{BS,(i,j),(i',j')}^{l,(n,k),m}$ are respectively received at l^{th} SU and BS from m^{th} RS with sensing status $(i,j) \in S$ assuming subcarrier pair *(n,k)* as:

$$Y_{SU,(i,j),(i',j')}^{l,(n,k),m} = X_{RS,(i,j)}^{l,n,m} \phi_{j'}^{l,(n,k),m} g_{SU-RS}^{l,k,m} + \eta^{l,k}$$
$$+ i' \vartheta^{l,k}; \forall (i,j), (i',j') \in S \quad (3)$$

$$Y_{BS,(i,j),(i',j')}^{l,(n,k),m} = X_{RS,(i,j)}^{l,n,m} \phi_{j'}^{l,(n,k),m} h_{BS-RS}^{k,m} + \eta^{k}$$
$$+ i' \vartheta^{k}; \forall (i,j), (i',j') \in S. \quad (4)$$
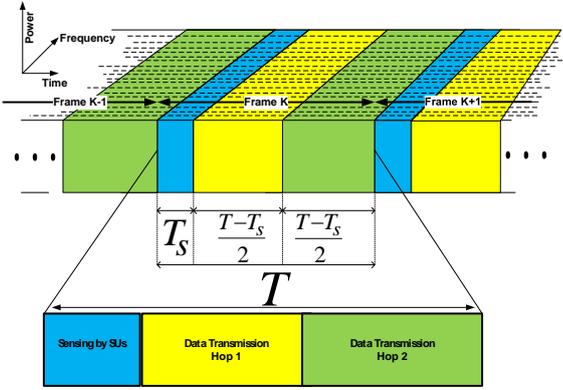
Figure 2: Time frame structure

Here, $\varphi_{j'}^{l,(n,k),m}$ is the amplification factor of mth RS on subcarrier pair *(n,k)*.

$\eta^{l,k} \in \mathcal{CN}(0, \sigma_{\eta^{l,k}}^2)$ and $\eta^{k} \in \mathcal{CN}(0, \sigma_{\eta^{k}}^2)$ are AWGN at SU l and BS, respectively. Further, the $\vartheta^{l,k} \in \mathcal{CN}(0, \sigma_{\vartheta^{l,k}}^2)$ and $\vartheta^{k} \in \mathcal{CN}(0, \sigma_{\vartheta^{k}}^2)$ are the imposed interference from PS on the l SU and BS, respectively.

We assume the reciprocity between the channel power gains between SUs and RSs as well as between BS and RSs [15]. By removing the self-interference in the BC hop by the SUs and BS, we can derive the joint Signal to Interference Plus Noise Ratio (SINR) at l^{th} SU and BS for each sensing pair *(i,j)* with the subcarrier pair *(n,k)*, respectively, as follows:

$$\Gamma_{SU,(i,j),(i',j')}^{l,(n,k),m} =$$
$$\frac{P_{BS,j}^{l,n,m} |\phi_{j'}^{l,(n,k),m}|^2 |h_{BS-RS}^{n,m}|^2 |g_{SU-RS}^{l,k,m}|^2}{\sigma_{\eta^{l,k}}^2 + i' \sigma_{\vartheta^{l,k}}^2 + i |g_{SU-RS}^{l,k,m}|^2 |\phi_{j'}^{l,(n,k),m}|^2 \sigma_{\vartheta^{n,m}}^2 + |g_{SU-RS}^{l,k,m}|^2 |\phi_{j'}^{l,(n,k),m}|^2 \sigma_{\eta^{n,m}}^2}$$
$$; \forall (i,j), (i',j') \in S \quad (5)$$

And

$$\Gamma_{BS,(i,j),(i',j')}^{l,(n,k),m} =$$
$$\frac{P_{SU,j}^{l,n,m} |\phi_{j'}^{l,(n,k),m}|^2 |h_{BS-RS}^{k,m}|^2 |g_{SU-RS}^{l,k,m}|^2}{\sigma_{\eta^{k}}^2 + i' \sigma_{\vartheta^{k}}^2 + i |h_{BS-RS}^{k,m}|^2 |\phi_{j'}^{l,(n,k),m}|^2 \sigma_{\vartheta^{n,m}}^2 + |h_{BS-RS}^{k,m}|^2 |\phi_{j'}^{l,(n,k),m}|^2 \sigma_{\eta^{n,m}}^2} \quad (6)$$
$$; \forall (i,j), (i',j') \in S$$

Note that the received signal at m^{th} RS from l^{th} SU and BS on subcarrier "*n*" assuming sensing pair *(i,j)* is amplified and forwarded by power $p_{RS,(i,j),j'}^{l,(n,k),m}$ to BS and l^{th} SU on subcarrier k in the sensing pair $(i',j') \forall (i,j), (0,j'), (1,j') \in S$, as follows:

$$P_{RS,(i,j),j'}^{l,(n,k),m} = E\left[\left|X_{j'}^{l,n,m} \phi_{j'}^{l,(n,k),m}\right|^2\right]$$
$$= G_{j'}^{l,(n,k),m} \left(P_{BS,j}^{l,n,m} |h_{BS-RS}^{n,m}|^2\right.$$
$$+ P_{SU,j}^{l,n,m} |g_{SU-RS}^{l,n,m}|^2 + \sigma_{\eta^{n,m}}^2 \quad (7)$$
$$\left. + i \sigma_{\vartheta^{n,m}}^2\right); \forall (i,j), (i',j') \in S$$

Where $G_{j'}^{l,(n,k),m} = |\varphi_{j'}^{l,(n,k),m}|^2$. We correspondingly denote $G_{j'}^{l,(n,k),m} = \left[G_{j'}^{1,(1,1),1}, ..., G_{j'}^{l,(n,k),m}\right] \forall j' \in (0,1)$.

Consequently, the joint transmission rate of the SU l on subcarrier pair *(n,k)* is:

$$R_{(i,j),(i',j')}^{l,(n,k),m} = \frac{T-T_s}{T}\left[r_{BS,(i,j),(i',j')}^{l,(n,k),m} + r_{SU,(i,j),(i',j')}^{l,(n,k),m}\right] \quad (8)$$

Where $r_{BS,(i,j),(i',j')}^{l,(n,k),m}$ and $r_{SU,(i,j),(i',j')}^{l,(n,k),m}$ respectively are $r_{BS,(i,j),(i',j')}^{l,(n,k),m} = 0.5 \log_2\left(1 + \Gamma_{BS,(i,j),(i',j')}^{l,(n,k),m}\right)$ and $r_{SU,(i,j),(i',j')}^{l,(n,k),m} = 0.5 \log_2(1 + \Gamma_{SU,(i,j),(i',j')}^{l,(n,k),m})$.

III. JOINT COOPERATIVE SPECTRUM SENSING BASED RESOURCE ALLOCATION ALGORITHM

A. Problem Formulation

The SS desires to maximize its long-term transmission rate. Nevertheless, spectrum sharing constraints as well as power budget constraints at the BS, RSs, and SUs should be incorporated for valid spectrum access, scheduling and power allocation strategies. Introducing the set as:

$$\sum = \left\{P_{BS,j}, P_{SU,j}, G_{j'} \geq 0, T_s, \zeta^n \geq 0, \varrho_{(n,k)}^{l,m} \in \{0,1\}; \forall l \right.$$
$$\left. \in L, n, k \in N, m \in M, j, j' \in \{0,1\}\right\}$$

The following optimization problem is written as the RA problem in cooperative SS jointed with TWR-assisted cooperative signaling:

$$Problem\ O_1: \max_{\Sigma} \sum_{l,n,k,m} \sum_{(i,j) \in S} \sum_{(i',j') \in S} \left\{\rho^l \varrho^{l,(n,k),m} P_{(i,j),(i',j')}^{(n,k)} \varepsilon_{gh}\left[R_{(i,j),(i',j')}^{l,(n,k),m}\right]\right\}$$

$$s.t.\ C_1: \sum_{l,n,k,m} \sum_{(i,j) \in S} \sum_{(i',j') \in S} \left\{\varrho^{l,(n,k),m} P_{(i,j),(i',j')}^{(n,k)} \varepsilon_{gh}\left[P_{SU,j}^{l,n,m} + P_{BS,j}^{l,n,m}\right]\right\} \leq P_S^{av},$$

$$C_2: \sum_{l,n,k} \sum_{(i,j) \in S} \sum_{(i',j') \in S} \left\{\varrho^{l,(n,k),m} P_{(i,j),(i',j')}^{(n,k)} \varepsilon_{gh}\left[P_{RS,(i,j),j'}^{l,(n,k),m}\right]\right\} \leq P_{RS}^{m,av}; \forall m,$$

$$C_3: \sum_{l,k,m} \sum_{(i,j) \in S} \sum_{(i',j') \in S} \left\{P_{(i,j),(i',j')}^{(n,k)} \varrho^{l,(n,k),m} \varepsilon_{df}\left[I_{BS,j}^{l,n,m} + I_{SU,j}^{l,n,m}\right]\right\} \leq Q_{PU}^{av,n}; \forall n, \quad (9)$$

$$C_4: \sum_{l,n,m} \sum_{(i,j) \in S} \sum_{(1,j') \in S} \left\{P_{(i,j),(i',j')}^{(n,k)} \varrho^{l,(n,k),m} \varepsilon_{ghq}\left[I_{RS,(i,j),j'}^{l,(n,k),m} + I_{SU,j}^{l,n,m}\right]\right\} \leq Q_{PU}^{av,n}; \forall k,$$

$$C_5: \sum_{l,n,m} \varrho^{l,(n,k),m} \leq 1; \forall k, C_6: \sum_{l,k,m} \varrho^{l,(n,k),m} \leq 1; \forall n, C_7: \varrho^{l,(n,k),m} \in \{0,1\}; \forall l, n, k, m$$

$$C_8: 0.5 \leq P_{c,d}^n(\xi^n, T_s) < 1, \quad 0 < P_{c,f}^n(\xi^n, T_s) \leq 0.5; \forall n$$

We introduce $\rho^l \in [0,1]$ as l^{th} SU priority with $\sum_l \rho^l = 1$. $\mathcal{E}$ is expectation operation. Denoting $d_{SU-PU}^{l,n}$ as the channel power gain between l^{th} SU and PS on subcarrier n, f_{BS-PU}^n as the channel power gain between BS and PS, and $q_{RS-PU}^{k,m}$ as

the channel power gain of mth RS and PS on subcarrier k, when it transmits to SU l, then, we have $\mathcal{E}_{gh} \triangleq \mathbb{E}_{g_{SU-RS}^{l,n,m}}[.]\mathbb{E}_{h_{BS-RS}^{n,m}}[.]$, $\mathcal{E}_{df} \triangleq \mathbb{E}_{d_{SU-PU}^{l,n}}[.]\mathbb{E}_{f_{BS-PU}^{n}}[.]$, and $\mathcal{E}_{ghq} \triangleq \mathbb{E}_{d_{SU-PU}^{l,n}}[.]\mathbb{E}_{f_{BS-PU}^{n}}[.]\mathbb{E}_{f_{RS-PU}^{k,m}}[.]$. Note the independency of channel power gains.

Here, $\varrho^{l,(n,k),m}$ is the subcarrier pair allocation indicator. If $\varrho^{l,(n,k),m} = 1$ in the MAC hop, then RS m and BS have access on the subcarrier n. In addition, SU l and RS m have access on this. Moreover, in the BC hop RS m and SU l have access to the subcarrier k, in addition to the access of RS, subcarrier m and BS on this subcarrier.

To avoid multiuser interference, OFDMA assumption is applied across SUs that transmit in MAC hop. This stays valid among RS in the BC hop too. This explicitly implies that SUs and RSs are able to send their data over more than one subcarrier pairs. However, each subcarrier pair (n,k) is designated to only one SU or one RS in the MAC and BC hop. This notion is incorporated in constraints C_5, C_6 and C_7. In $\mathcal{O}_1$ we define the common sensing probability as $P_{(i,j),(i',j')}^{(n,k)}$. As we have assumed in the previous discussion, the sensing status of subcarrier n in the MAC hop and the sensing status of subcarrier k in the BC hop are independent, therefore, we can claim that $P_{(i,j),(i',j')}^{(n,k)} = P_{(i,j)}^{n} P_{(i',j')}^{k}$.

Constraint C_1 represents the transmission power constraint summed up over all SUs and BS. This is relevant since all consumed power at the SUs and BS can indicate some insights on how green the resource allocation is and how large the interference at other cells and other services might be. Further, we consider this constraint to reduce the size of our resource allocation problem. We extend the results to the case, in which the imposed individual power allocation budget of SUs is straightforward due to the space limit is ignored. Here, we set P_S^{av} as the maximum allowable power consumed at SUs and BS. Feasible power allocation vectors associated with SUs and BS respectively is $\mathbf{P}_{SU,j} = [p_{SU,j}^{1,1,1}, ..., p_{SU,j}^{L,N,M}]$ and $\mathbf{P}_{BS,j} = [p_{BS,j}^{1,1,1}, ..., p_{BS,j}^{L,N,M}] \; \forall j \; \epsilon \; \{0,1\}$.

Constraints C_2 addresses RS's individual power budgets where $P_{RS}^{m,av}$ indicates the maximum transmission power of RS m. To protect PS, we also considered interference threshold constraints for the MAC hop in C_3. The allowable interference conflicted at PS on subcarrier n is denoted by $Q_{PU}^{av,n}$, that is the same for the BC hope in C_4. Here, we set $I_{SU,j}^{l,n,m} = p_{SU,j}^{l,n,m}|d_{SU-PU}^{l,n}|^2$ and $I_{BS,j}^{l,n,m} = p_{BS,j}^{l,n,m}|f_{BS-PU}^{n}|^2 \; \forall (1,j) \; \epsilon \; \mathcal{S}$ associated with the MAC hop and $I_{RS,(i,j),j'}^{l,(n,k),m} = p_{RS,(i,j),j'}^{l,(n,k),m}|q_{RS-PU}^{k,m}|^2$ associated with the BC hop. In C_8, the spectrum sensing constraints are considered. Similarly to [20], [29], we enforce the detection probability higher than 0.5 and false alarm probability lower than 0.5.

B. Solution

The outline of the developed solution referred as Sensing based Resource Allocation (SRA) is presented in Table 2. With reference to SRA algorithm, we note that: in *Step 1*, firstly, one needs to interpret the constraints on the acceptable miss detection and false alarm probabilities as acceptable C_8. In *Step 2*, let $\varrho_{(n,k)}^{l,m}$, , T_s and ξ^n are given and fixed. In this step, a near optimal power allocation solution is proposed for SUs, BS and RSs. Since $\mathcal{O}_1$ is a multi-variable non-convex optimization problem, we present an

iterative algorithm to find the near optimal solution using the *Lagrangian* method [30] and Block Coordinate Descent Algorithm (BCDA). For this, we first form the Lagrange dual optimization problem of $\mathcal{O}_1$. After that, we develop an iterative algorithm based on BCDA to solve the *Lagrange* dual optimization problem. In this method, the variables are partitioned into a number of blocks (equal to the number of Variables) and, in each iteration, the *Lagrange* function is maximized with respect to one of the selected variables, while the others are maintained fixed [31],[32]. The *Lagrangian* function associated with $\mathcal{O}_1$ when the subcarrier indicators ST and EDTs are fixed, is

$$
\begin{aligned}
\mathcal{L}(P_{BS,j}, & P_{SU,j}, G_{j'}, \alpha, \beta, \lambda, \mu) \\
& = \sum_{l,n,k,m} r^{l,(n,k),m} + \alpha P_S^{av} \\
& + \sum_{m=1}^{M} \beta^m P_{RS}^{m,av} \\
& + \sum_{n=1}^{N} \lambda^n Q_{PU}^{av,n} + \sum_{k=1}^{N} \mu^k Q_{PU}^{av,k}
\end{aligned}
\tag{10}
$$

where α is the *Lagrangian* multiplier associated with C_1, and $\beta = [\beta^1 ... , \beta^M]$, $\lambda = [\lambda^1 ... , \lambda^N]$ and $\mu = [\mu^1 ... , \mu^N]$ are

Table 3
SRA algorithm.

Step No	Function
Step 1	For given ST and EDT when supporting C_8
Step 2	Initialize α, β^m, λ^n and μ^k and fix arbitrary $\varrho^{l,(n,k),m}$
Step 3	Find $\mathbf{P}_{BS,j}^*, \mathbf{P}_{SU,j}^*, \mathbf{G}_{j'}^*$ by applying Karush-Kuhn-Tucker (KKT) conditions [28].
Step 4	The subcarrier assignment ϱ^* is obtained from Table 2. $\varrho^{*l*,(n,k),m*} = 1_{k=\Pi(n)}$ where $k = \Pi(n) = max_k \Upsilon^{*1*,(n,k),m*} \forall n \in N$.
Step 5	Update α, λ^n, β^m and μ^k until the convergence.
Step 6	If stop criteria is satisfied go to *Step 8*, otherwise go to *Step3*.
Step 7	Find T_s^* and ξ^* such that: (T_s^*, ξ^*) $= \arg\max T_s, \xi \sum_{l,n,k,m} \sum_{(i,j)\in S} \sum_{(i',j')\in S} P^{l*}\varrho^{*l*,(n,k),m*} P_{(i,j)}^n P_{(i',j')}^k R'$

The *Lagrangian* vectors are associated with C_2, C_3, and C_4 respectively. Further, $\Upsilon^{l,(n,k),m}$ is defined as follows:

$$
\begin{aligned}
\Upsilon^{l,(n,k),m} &= \sum_{(i,j)\in S} \sum_{(i',j')\in S} \left(\rho^l \varrho^{l,(n,k),m} P_{(i,j)}^n P_{(i',j')}^k \mathcal{E}_{gh}\left[\mathcal{R}_{(i,j),(i',j')}^{l,(n,k),m}\right] \right) \\
& - \alpha \left\{ \sum_{(i,j)\in S} \sum_{(i',j')\in S} \left(\varrho^{l,(n,k),m} P_{(i,j)}^n P_{(i',j')}^k \mathcal{E}_{gh}[P_{SU,j}^{l,n,m} + P_{BS,j}^{l,n,m}] - P_S^{av} \right) \right\} \\
& - \beta^m \left\{ \sum_{l,n,k} \sum_{(i,j)\in S} \sum_{(i',j')\in S} \left\{ \varrho^{l,(n,k),m} P_{(i,j)}^n P_{(i',j')}^k \mathcal{E}_{gh}\left[P_{RS,(i,j),j'}^{l,(n,k),m}\right] - P_{RS}^{m,av} \right\} \right\} \\
& - \lambda^n \left\{ \sum_{(1,j)\in S} \sum_{(i',j')\in S} \left\{ \varrho^{l,(n,k),m} P_{(1,j)}^n P_{(i',j')}^k \mathcal{E}_{df}[I_{BS,j}^{l,n,m} + I_{SU,j}^{l,n,m}] \right\} - Q_{PU}^{av,n} \right\}
\end{aligned}
\tag{11}
$$

$$-\mu^k \left\{ \sum_{(i,j)\epsilon S} \sum_{(1,j)\epsilon S} \left\{ \varrho^{l,(n,k),m} P^n_{(i,j)} P^k_{(1,j')} \varepsilon_{ghq} \left[I^{l,(n,k),m}_{RS,(i,j),j'} \right] - Q^{av,k}_{PU} \right\} \right\}$$

Note that the dual *Lagrangian* function of $\mathcal{O}_1$ with respect to each allocation power or amplification factor is a concave, while the other variables are fixed. To do this, we assume that all variables are fixed except $p^{l,n,m}_{BS,j}$; hence, the corresponding *Lagrangian* function has the general form $f(x) = \sum_{i=1}^{i} A_i \, log \, (1 + a_i x) - \sum_{i=1}^{I} B_i x$, in which x is a positive real variable, e.g., $x = p^{l,n,m}_{BS,j}$. It can easily be shown that the second derivative of $f(x)$ is negative, where $\frac{\partial^2 f(x)}{\partial x^2} = -\sum_{i=1}^{1} A_i \frac{a_i^2}{[1+a_ix]2} \forall x, a \in \mathbb{R}$. Further, when SUs and BSs powers are considered fixed, the *Lagrangian* function with respect to each $G^{l,(n,k),m}_{j'} \forall \, j' , \in \{0,1\}$ has the general form $g(x) = \sum_{i=1}^{I} \log \frac{a_i x}{b_i x + c_i} - \sum_{i=1}^{I} B_i x$. It can be verified that the second order derivation of this function is negative, i.e., $\frac{\partial^2 g(x)}{\partial x^2} = -\sum_{i=1}^{I} A_i \frac{a_i b_i [2c_i(a_i+c_i)x + 2b_i c_i + a_i b_i]}{[c_i(a_i+c_i)x^2 + b_i(a_i+c_i+b_i c_i)x + b_i^2]^2}$, $\forall \, x, A_i, a_i, b_i, c_i \geq 0 \in \mathbb{R}$. Consequently, the iterative BCDA converges to a local optimal solution independent of the initial condition.

The Lagrange dual optimization problem is $min_\Omega \Theta(\alpha,\beta,\lambda,\mu)$, where $\Omega = \{\alpha \geq 0, \beta \leq 0, \boldsymbol{\lambda} \leq 0, \boldsymbol{\mu} \leq 0\}$.

$$\Theta \, (\alpha,\beta,\lambda,\mu) \triangleq \max_{\Sigma,\varrho \, \in \mathcal{A}} \mathcal{L}(\boldsymbol{P}_{BS,j}, \boldsymbol{P}_{SU,j}, \boldsymbol{G}_{j'}, \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\lambda}, \mu). \quad \text{The}$$
corresponding equations for finding power al-location vectors can be solved easily. Computational complexity of SRA algorithm grows as $O(\chi(1 + M + 2N)^2 N^2 (L + M))$ that is fairly high. To alleviate this high computational burden in [25], a sub-optimal algorithm is proposed with lower computational complexity.

IV. SIMULATION RESULTS

In this section, we present the simulation results to evaluate the performance of the proposed primal problem, i.e., $\mathcal{O}_1$(OFDMA TWR assisted CRN in HSS environment or HSSE) and suboptimal RA algorithm, i.e., FSPA[25]. The path-loss exponent α is fixed at 3.5 and the standard deviation of lognormal shadowing is 5.8 db. The small-scale fading is modeled by multipath Rayleigh fading process for the channel gains between the SUs and RSs and interference channels. We assume the Rician random variables with κ = 6 dB for channel gains between BS and RSs, where the power delay profile is exponentially decaying with maximum delay spread of 5 μsec and maximum Doppler spread of 5 Hz. Moreover, for simplicity we assume that $\vartheta^{l,k}, \eta^{l,k}, \vartheta^{l,n}, \eta^{l,n}, \vartheta^{n,m}, \eta^{n,m}, \vartheta^{k,m}, \eta^{k,m}, \vartheta^{k}, \eta^{k}, \vartheta^{n}, \eta^{n} \epsilon \mathcal{CN}(0,1)$.

In addition, we assume a single cell that has two rings. The outer circle boundary has a radius of 1 km and the inner circle a radius of 500 m. The RSs are equally distributed happed boundary regions centered at the BS of SS (see, Figure 1). The outer circle boundary has a radius of 1 km and the inner circle a radius of 500 m. The RSs are equally distributed on the cell boundary of inner circle for assisting the transmission and SUs uniformly distributed in the space between the inner and the outer ring. In addition, in each

channel, SNR between SUs are all assumed to have a mean 20 dB and the channel SNR value from the PU to a SU (either the transmitter or the receiver) is with mean −15dB. Firstly, the sensing parameters are examined and secondly, our proposed schemes are compared with conventional schemes for OFDMA TWR CRNs in opportunistic spectrum sharing environment (or Overlay Environment(OE)), which is discussed in [12],[14], and underlay environment (UE). The optimal EDT, detection and false alarm probability are calculated.

A. AWET versus ST and verification of proposed algorithm

The AWET of versus ST is illustrated in Figure 3 by using the proposed SRA algorithm in terms of two values for $Q^{av,k}_{PU}$ i.e., −5 dB, −10 dB. As it is presented in Figure 3, (System parameters are: $N = 64, L = 6, M = 4, P^{av}_S = 25$ dBm, $P^m_{RS} = 10 \, dBm \, \forall m \in M.$), the AWET is climbing by increasing of $Q^{av,k}_{PU}$. In addition, from Figure 3 we can conclude that when the threshold tolerable interference of PS is climbing, the optimal sensing time is decreased. In fact, the detection probability is increased and the false alarm probability is decreased; consequently, the throughput of SS reasonably is increased.

Table 4
Optimal EDTs, Detection Probability, False Alarm Probability (N = 8, L = 6, M = 4)

Parameter	ε^{*n}	$P^n_{c,d}(\varepsilon^{*n}, T^*_s)$	$P^n_{c,f}(\varepsilon^{*n}, T^*_s)$
n=1	3.9826	0.7285	0.3381
n=2	2.6328	0.82371	0.3819
n=3	4.7956	0.6492	0.2584
n=4	2.3769	0.8691	0.4163
n=5	1.8748	0.9361	0.4582
n=6	4.9238	0.5926	0.1949
n=7	5.1389	0.5346	0.1257
n=8	2.01781	0.9026	0.4083
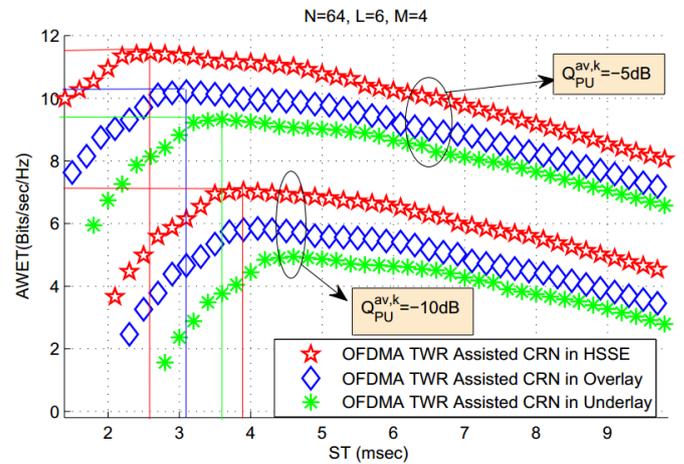
Figure 3: AWET vs. sensing time.

Moreover, as illustrated in Figure 3, the optimal sensing time for overlay and underlay scenario are larger than HSSE scenario. In other words, the SU in the HSSE can be received to the optimal mode in the lower time compared

with the traditional spectrum sharing scenario (see, [12] and [14]). As can be seen in Figure 3 since AWET is monotonically increasing in $Ts = [0,Ts]$, we can say the maximum of AWET in $Ts = [0,Ts]$ is the only local maximum in the entire range of $Ts = [0,Ts]$ (see, [33]).

B. AWET VS P_s^{av} and number of relays

The investigation of our proposed algorithm, i.e., OFDMA TWR assisted CRN in HSSE and other conventional algorithm of CRN in overlay environment (OFDMA TWR CRN in OE) [12] are illustrated in Figure 4 (System parameters are: $L = 6$, $N = 64$, $P_{RS}^m = 10$ dBm $\forall m \in M$ and $Q_{PU}^{av,n} = -10$ dB $\forall n \in N$). According to Figure 4, we can conclude that the OFDMA TWR CRN in HSSE introduces more AWET compared to overlay scenario. Further, the FSPA algorithm is examined in Figure 4 and as shown in Figure 4, the FSPA introduces the near reasonable result compared to the primal optimization problem (SRA), whereas the AWET is larger than OE. Moreover, it is observed from Figure 4 that by increasing the power threshold of secondary network, the AWET is increased. In addition, it can be clearly seen from Figure 4 by increasing the RS's number AWET is increased.
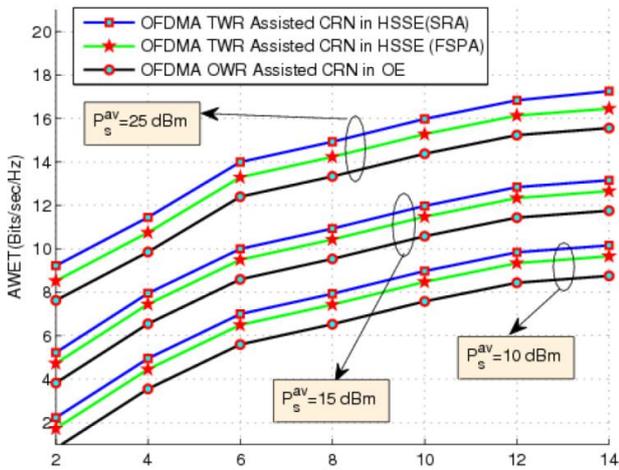
Figure 4: AWET vs. the Number of RS, *M*, for different values of the PS.

V. CONCLUSION

In this paper, both an initial algorithm to dynamically adapt cooperative sensing performance, opportunistically allocate resources in the both uplink, and downlink channels for OFDMA TWR assisted CRN in the HSS environment is proposed. In this study, to the author's best knowledge the RA for cooperative sensing based OFDMA-TWR assisted CRN in HSS environment is introduced for the first time. Different from related works such as [12],[14] and [34], in which the authors only focused on underlay or overlay scenario, the new framework of cooperative sensing based scenario in HSS environment is introduced.

The proposed scenario introduces higher AWET compared to related works. In comparison to the previous works related to RA of OFDMA-TWR networks (see, [17], [24] and [25]) the RA of OFDM-TWR assisted CRNs in HSS environment is considered. Different from the introduced scenario in [35], we consider the sensing parameters i.e., ST and EDT in our study. Further, the

sensing based OFDMA-TWR assisted CRNs in the HSS environment leads to extreme complexity because we deal with five types of optimization variables related to power transmission and sensing performance. In addition, different from the previous works (see, [12] and [25]), we consider all optimization variables. In fact, here we introduce a comprehensive scenario including RA, subcarrier pairing allocation and optimized sensing parameters i.e., assigned near optimal ST and EDT of OFDMA TWR assisted CRN in HSS environment are introduced for the first time. Simulations are also conducted to study the impact of the different system parameters, such as maximum transmission power of secondary transmitter network, maximum acceptable interference that inflicted on primary network and the number of relays on the performance of the radio RA. We also compare our formulation with the conventional methods, in which the TWR assisted CRNs in HSS environment is assumed. It is also observed that without considering the sensing based scheme the AWET is decreased; however, the complexity might be significantly increased.

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