# A Cooperative Spectrum Leasing Scheme with Guaranteed Secrecy Rate for Primary Link

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***Abstract*—In this paper, we consider a cooperative cognitive radio network in which there is an OFDM primary link and multiple single carrier secondary links. The primary link is required to maintain its secrecy rate above a predefined threshold. If the secrecy rate requirement is not satisfied, the secondary system help primary link to maintain its secrecy rate requirement. In doing so, the secondary transmitters work as decode and forward (DF) relays and hence, as a reward, gains access to network resources to transmit its own information. Our objective is to maximize the data rate of secondary system while satisfying the primary secrecy rate constraint and individual transmit power constraints for primary link and secondary system. We solve our proposed optimization problem using dual Lagrange approach to find the set of cooperating secondary link, subcarrier assignments, and transmit power over each subcarrier. Using simulations, we evaluate our proposed scheme in various situations.**

***Index Terms*– Secure communications, cognitive radio network, cooperative communications, OFDM, resource allocation, dual approach.**

## I. Introduction

Cognitive radio [1] is an important concept for improving the efficiency of using the available bandwidth, in which, the primary network is licensed to use the bandwidth. In such a case, as an strategy, the secondary network can cooperate with primary network to improve its transmission performance and as a reward, gains access to network resources to transmit its own information.

Cooperative cognitive radio network has been attracted many interests recently [2]–[11]. In [2], the authors propose a three phase cooperation scheme for cognitive radio networks. In their scheme, secondary users cooperate with primary user in the first two phases to increase its transmission rate and as a reward, cooperating SUs gain access to network resources to perform their transmission in the third phase. In [3], the authors propose a cooperating scheme in which secondary user works as an amplify and forward relay for primary user by allocating a fraction of available subcarriers to primary user's transmission. At the same time, secondary user can transmit its information on the remaining subcarriers. In [4], the authors consider a cognitive radio network in which the secondary base station relays the information transmitted by primary base station to cell-edged primary users. At the same time, secondary base station transmits its own information to secondary users.

The authors in [5], consider a cooperative scenario in which the frequency band is divided into two separate band. In one band, the secondary user help primary user by relaying its information while the other secondary user uses another band to transmit its information. In [6], the authors consider a cooperative communication scenario where secondary user assigns a fraction of its transmit power budget for primary transmission to compensate the effect of its induced interference on primary user. The secondary user then applies superposition coding to eliminate the primary user's interference. The authors in [7], propose a cooperative scheme in which the transmission time is divided into two part. In the first part, secondary users help primary system as relays and as a reward gain access to network resources in the second part for its own transmission. The authors in [8], propose a full duplex cooperative communication in which a secondary user works as a relay for primary user to help information transmission is improved. In doing so, primary information is sent over some of available subcarriers. As a reward, the cooperating secondary user can send its own information over the remaining subcarriers.

The authors in [10] consider an spectrum sharing scenario where there are multiple primary users and multiple secondary users which may act as DF relay for primary users. The authors formulate the resource allocation problem in an optimization framework where the relay selection, the secondary transmit powers, and the cooperative relaying power splitting parameters is optimized. In [11], the authors consider dynamic spectrum leasing where there are uncertainty in the network parameters. The authors use the stochastic Cournot game theory and variational inequality theory to model the behavior of users and maximize the long-term utility.

An important characteristic of wireless channel is its broadcast nature meaning that any information which is sent over it can be eavesdropped by unauthorized users. Physical layer security [12] can be seen as an effective approach which makes secure communications feasible. In [13], the authors consider secure communications in presence of multiple eavesdroppers using a set of decode and forward (DF) relays. The authors in [14] consider the problem of relay selection for secrecy ca-

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pacity maximization using amplify and forward (AF) and DF relaying schemes. Cooperative jamming to enhance security in cooperative networks is considered in [15]. Although many works have been done in cooperative communications and spectrum leasing in cognitive radio networks, secure communications in such schemes achieved less attention.

In [16], the authors propose a spectrum leasing scheme in which secondary user help primary user to improve its secrecy rate and instead gains access to the network. In their scheme, secondary user produce interference to eavesdropper via a propose design of beamformer. Their objective is to maximize the secrecy rate of primary network while maintaining secondary network's data rate requirement. In [9], two cooperation scheme is proposed for spectrum access in cognitive radio networks. In the first scheme, the primary user cooperative with two secondary users where one secondary users works as relay and the other works as friendly jammer. At the expense of cooperation, the primary user allocate a fraction of time to secondary users for their own transmission. In the second scheme, a set of secondary users help primary user improve its secrecy rate via beamforming and as a reward, gain access to the network for a fraction of time to transmit their own information. In [17], the authors propose a new spectrum leasing technique where the secondary user acts as amplify-and-forward (AF) relay for primary user. In this regard, the secondary user can simultaneously sends it information over the same spectrum via power allocation to primary signal and its own signal. However, the primary user act as an eavesdropper for secondary users and hence, the secondary secure communication measured by the secrecy rate should be taken into account. In [18], the authors consider the problem of secure communications in the spectrum sharing cognitive radio networks in a game theoretical framework. The time is divided into three part. In the first part the primary user sends while in the second part secondary user act as a trusted relay. In the third part, the secondary user sends its own information. The authors formulate the resource allocation of each part as an optimized problem and the cooperation is modeled using the multi-level Stackelberg game.

In this paper, we propose a new cooperating scheme for cognitive radio network. We assume that the exists an OFDM primary user, a set of malicious user, and a set of secondary links in the network. We assume that each secondary link can transmit information on each of available subcarrier, but at the same time it only performs transmission over one of available subcarriers, i.e., single carrier transmission. We set the number of secondary link equal to the number of available subcarriers. The malicious users want to eavesdrop the information transmission by primary user while the primary user is required to maintain its secrecy rate limit. When the secrecy rate requirement of primary user is not satisfied, the secondary links help primary user to satisfy its secrecy rate requirement. In doing so, each secondary link works as a DF relay for primary user. In turn, as reward for cooperation, the remaining links, if any, can transmit their own information over the remaining frequency bands.

We formulate our proposed cooperative scheme as an optimization problem in which we aim at maximizing the data rate of secondary system while maintaining the secrecy rate requirement of the primary users. We solve the optimization problem using dual Lagrange approach where we determine each secondary link should transmit over which of the available frequency bands (subcarriers), transmit power of primary user over each of subcarriers, and the transmit power of each secondary link. We evaluate the efficiency of our proposed scheme using simulations in various situations.

This paper is organized as follows. In Section II, we introduce our system model and formulate the resource allocation problem. We solve our optimization problem in Section III. Simulations are presented in Section IV, and conclusions are in Section V.

## II. System Model And Problem Formulation

We consider the downlink of a cognitive radio network in which there exist one primary transmitter-receiver link and $U^{\text{s}}$ active secondary transmitter-receiver pairs. We assume that, the primary link uses OFDM technology in which the available bandwidth $B$ is divided into $N$ orthogonal subcarriers. For the secondary system, we assume that each secondary link is able to transmit over each subcarrier. However, at each transmission instance, each secondary link can only transmit over one of available frequency bands, i.e., it adopts single carrier transmission like the uplink channel of LTE [**?**].

We assume that there exists $E$ malicious users in the network which want to eavesdrop the ongoing information transmission of primary link. The existing primary link aim is to maintain its secrecy rate above a predefined threshold. However, due to time variations of the channels, it is possible for some channel realizations that the target secrecy rate of primary link is not satisfied. Therefore, primary link asks the secondary system for cooperation by working as a DF relay to help primary link to achieve its target secrecy rate. The reward for secondary system is to gain access to network resources for its own transmission.

We assume that cooperation is performed under a central network controller (CNC) who has access to all channel information including the channel power gains. In case of cooperation, the CNC decides which secondary link should work as DF relay and on which subcarrier. After determination of cooperating secondary links, the remaining secondary links, if any, gain access to network resources to transmit their own information. Note that, CNC also controls the transmission of secondary link in this case and decides which link should transmit on which of available subcarriers.

We assume that each transmission frame is divided into to time slots of equal duration. In the first time slot, primary transmitter transmits information while secondary transmitters and the malicious users listen. The selected secondary transmitters decode the received signals, re-encode them, and transmit them to primary receiver.If not all secondary links involve in the cooperation, the remaining secondary links perform their on transmission.

We denote the primary transmitter by $\mathrm{T_p}$, the primary receiver by $\mathrm{R_p}$, the $u_{\mathrm{s}}^{\mathrm{th}}$ secondary transmitter by $\mathrm{T}_{u_{\mathrm{s}}}$, the $u_{\mathrm{s}}^{\mathrm{th}}$ secondary receiver by $\mathrm{R}_{u_{\mathrm{s}}}$, the set of active secondary links by $\mathcal{U}^{\mathrm{s}} = \{1, \ldots, U^{\mathrm{s}}\}$, the set of eavesdroppers by $\mathcal{E} = \{1, \ldots, E\}$, and that of subcarriers by $\mathcal{N} = \{1, \ldots, N\}$. We assume that the number of active secondary links $U^{\mathrm{s}}$ is equal to the number of subcarriers $N$ such that we can make a one to one correspondence between secondary links and subcarriers. Let, $g_{\mathrm{T_p T}_{u_{\mathrm{s}}} m}$ be the noise power normalized channel gain between primary transmitter and secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ over subcarrier $m$, $g_{\mathrm{T_p}em}$ be the noise power normalized channel gain between primary transmitter and the malicious user $e$ over subcarrier $m$, $g_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R_p}n}$ be the noise power normalized channel gain between secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ and primary receiver $\mathrm{R_p}$ over subcarrier $n$, and $g_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R}_{u_{\mathrm{s}}}k}$ be the noise power normalized channel gain between secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ and secondary receiver $\mathrm{R}_{u_{\mathrm{s}}}$ over subcarrier $k$.

Note that the physical layer security provides security of the communications based on the eavesdropper ambiguity of the transmitted message. In this context, it is assumed that the transmitter uses a code rate $R$ to transmit confidential messages at the rate $R^{\mathrm{SEC}}$. The equivocation rate of the eavesdropper which is a measure of the eavesdropper ambiguity is denoted by $R^{\mathrm{e}}$. According to [12], these rates are related by $R^{\mathrm{SEC}} = R - R^{\mathrm{e}}$. Now, in Gaussian Channels, $R$ is the capacity of the AWGN channel from the transmitter to the receiver and $R^{\mathrm{e}}$ is the capacity of the AWGN channel from the transmitter to the eavesdropper.

In addition, let $p_{T_{\mathrm{p}}\mathrm{T}_{u_{\mathrm{s}}}m}$, $p_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R_p}n}$, and $p_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R}_{u_{\mathrm{s}}}k}$ denote the transmit power level assigned by primary transmitter on subcarrier $m$ to secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ in the first time slot, the transmit power level assigned by secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ to primary receiver $\mathrm{R_p}$ on subcarrier $n$ in the second slot, and the transmit power level assigned by secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ for its transmission to secondary receiver $\mathrm{R}_{u_{\mathrm{s}}}$ on subcarrier $k$, respectively. Suppose that primary transmitter wants to transmit information to primary receiver with the help of secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ over subcarrier pair $(m, n)$ where subcarrier pair $(m, n)$ means that subcarrier $m$ is used in the first time slot and subcarrier $n$ is used in the second time slot meaning that secondary link can work on different subcarriers in each time slot. In this case, the instantaneous secrecy rate of primary transmitter is given by

$$R^{\mathrm{S}}_{\mathrm{T_p},\mathrm{T}_{u_{\mathrm{s}}},m} = \left[ \min(R^m_{\mathrm{T_p},\mathrm{T}_{u_{\mathrm{s}}}}, R^m_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R_p}}) - \max_{e\in\mathcal{E}} R^m_{\mathrm{T_p},e} \right]^+, \quad (1)$$

where

$$R^m_{\mathrm{T_p},\mathrm{T}_{u_{\mathrm{s}}}} = \frac{1}{2}\log(1 + g_{T_{\mathrm{p}}\mathrm{T}_{u_{\mathrm{s}}}m} p_{T_{\mathrm{p}}\mathrm{T}_{u_{\mathrm{s}}}m}), \quad (2)$$

$$R^m_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R_p}} = \frac{1}{2}\log(1 + g_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R_p}m} p_{\mathrm{T}_{u_{\mathrm{s}}}\mathrm{R_p}m}), \quad (3)$$

$$R^m_{\mathrm{T_p},e} = \frac{1}{2}\log(1 + g_{T_{\mathrm{p}}em} p_{T_{\mathrm{p}}\mathrm{T}_{u_{\mathrm{s}}}m}). \quad (4)$$

On the other hand, the secondary transmitter $\mathrm{T}_{u'_{\mathrm{s}}}$, which is not involved in cooperation, is allowed by CNC to transmit its information to its receiver $\mathrm{R}_{u'_{\mathrm{s}}}$ over the subcarrier pair $(m', n')$ in the first and second time slot. Since the secrecy is not an issue for secondary information transmission, the instantaneous data rate of primary link $u_{\mathrm{s}}$ over subcarrier pair $(m', n')$ is given by

$$\begin{aligned} R_{\mathrm{T}_{u'_{\mathrm{s}}},\mathrm{R}_{u'_{\mathrm{s}}},m'} = {} & \frac{1}{2}\log(1 + g_{\mathrm{T}_{u'_{\mathrm{s}}}\mathrm{R}_{u'_{\mathrm{s}}}m'} p^1_{\mathrm{T}_{u'_{\mathrm{s}}}\mathrm{R}_{u'_{\mathrm{s}}}m'}) \\ & + \frac{1}{2}\log(1 + g_{\mathrm{T}_{u'_{\mathrm{s}}}\mathrm{R}_{u'_{\mathrm{s}}}m'} p^2_{\mathrm{T}_{u'_{\mathrm{s}}}\mathrm{R}_{u'_{\mathrm{s}}}m'}), \end{aligned} \quad (5)$$

where $p^1_{\mathrm{T}_{u'_{\mathrm{s}}}\mathrm{R}_{u'_{\mathrm{s}}}m'}$ and $p^2_{\mathrm{T}_{u'_{\mathrm{s}}}\mathrm{R}_{u'_{\mathrm{s}}}n'}$ are, respectively, the transmit power of secondary transmitter $\mathrm{T}_{u^{\mathrm{s}}}$ over subcarriers $m'$ and $n'$ in the first and second time slot, respectively.

Let $\rho_{\mathrm{T_p},\mathrm{T}_{u_{\mathrm{s}}},m} \in \{0, 1\}$ be an assignment factor indicating subcarrier $m$ is used for transmission between primary transmitter and primary receiver through secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ meaning that in both the first and the second hop, the same subcarrier is used. In addition, we define the variable $\eta_{\mathrm{T}_{u_{\mathrm{s}}},\mathrm{R}_{u_{\mathrm{s}}},m} \in \{0, 1\}$ as assignment factor indicating subcarrier $m$ is used by secondary transmitter $\mathrm{T}_{u_{\mathrm{s}}}$ for transmission to its secondary receiver $\mathrm{R}_{u_{\mathrm{s}}}$. Our objective is to maximize the transmission rate of secondary system under the secrecy rate constraint of

primary link and power constraint for primary link and total power constraint of secondary system, i.e.,

$$\max_{\mathbf{p},\boldsymbol{\rho},\boldsymbol{\eta}} \quad \sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\eta_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}R_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m} \tag{6}$$

$$\text{Subject To:} \quad \sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\rho_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}R^{\mathrm{S}}_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}\geq\bar{R}^{\mathrm{S,P}}, \tag{7}$$

$$\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\rho_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}\leq P^{\max}_{\mathrm{P}}, \tag{8}$$

$$\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\left(\rho_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+\eta_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}\right)\leq P^{\max}_{\mathrm{s}}, \tag{9}$$

$$\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\eta_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}\leq P^{\max}_{\mathrm{s}}, \tag{10}$$

$$\sum_{m=1}^{M}\left(\rho_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}+\eta_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}\right)=1,\quad \forall u_\mathrm{s}\in\mathcal{U}_\mathrm{s}, \tag{11}$$

$$\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\left(\rho_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}+\eta_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}\right)=1,\quad \forall m\in\mathcal{N}, \tag{12}$$

where (7) is the secrecy rate constraint for primary link, (8) is the transmit power constraint of primary link, (9) and (10) are transmit power constraints of secondary system in the first and second time slot, (11) and (12) state that in each time slot, each subcarrier is either used for primary transmission or secondary transmissionn.

## III. Solution Based on Dual Approach

The optimization problem in (6) is a mixed integer nonlinear nonconvex optimization problem [19]. To mitigate the combinatorial complexity incurred for optimal subcarrier assignment, a separable structure is pursued, and the dual decomposition method [19] is adopted. As we know that the dual decomposition approach leads to a near-optimal and computationally efficient solution [20].

First note that, in (1), one can assume that $R^m_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}}}=R^m_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R_p}}$ without violating the optimality. Therefore, the values of $p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}$ and $p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}n}$ in (7), (8), and (9), satisfy the followings

$$p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}=\frac{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}, \tag{13}$$

$$p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}=\frac{g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}, \tag{14}$$

where $p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}=p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}+p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}$.

The Lagrange function of the optimization problem (6) is given by

$$\begin{aligned}L(\mathbf{p},\theta,\zeta,\lambda,\gamma)&=\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}R_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}\\&+\theta\Big(\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}R^{\mathrm{S}}_{\mathrm{T_p},\mathrm{T}_{u_\mathrm{s}},m}-\bar{R}^{\mathrm{S,P}}\Big)\\&+\zeta\Big(P^{\max}_{\mathrm{P}}-\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}\Big)\\&+\lambda\Bigg(P^{\max}_{\mathrm{s}}-\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\left(p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}\right)\Bigg)\\&+\gamma\Big(P^{\max}_{\mathrm{s}}-\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}\Big),\end{aligned} \tag{15}$$

where $\theta$, $\zeta$, $\lambda$, and $\gamma$ are Lagrange multipliers corresponding to constraints (7), (8), (9), and (10), respectively, and $\mathbf{p}$ is the vector of transmit power variables.

Using the Lagrange function in (15), the dual function is given by

$$g(\theta,\zeta,\lambda,\gamma)=\max_{\mathbf{p}}L(\mathbf{p},\theta,\zeta,\lambda,\gamma), \tag{16}$$

and the corresponding dual optimization problem is given by

$$(\theta^*,\zeta^*,\lambda^*,\gamma^*)=\underset{\theta,\zeta,\lambda,\gamma\geq0}{\arg\max}\ g(\theta,\zeta,\lambda,\gamma). \tag{17}$$

In the sequel, we find the value of transmit power variables, secondary link selection and subcarrier allocation, and the value of dual variables.

### A. Obtaining Transmit Power Variables

Using (13) and (14) in (15), to obtain dual function as in (16), we take derivative of Lagrange function with respect to $p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}mn}$ to obtain (18) whose solution is given by (19), where $h_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}mn}$, $h^e_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}mn}$, and $\lambda_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}mn}$ are defined in the following, respectively,

$$h_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}=\frac{g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}, \tag{20}$$

$$h^e_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}=\frac{g_{T_\mathrm{p}em}g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}, \tag{21}$$

$$\lambda_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}=\frac{2}{\theta}\frac{\zeta g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+\lambda g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R_p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}. \tag{22}$$

Taking derivatives of Lagrange function with respect to $p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}$ and $p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}$, respectively, we obtain the following equations

$$\frac{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}}{1+g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}}-\gamma=0, \tag{23}$$

$$\frac{\partial L(\mathbf{p},\theta,\zeta,\lambda,\gamma)}{\partial p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}=\frac{\theta}{2}\left(\frac{\frac{g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}}{1+\frac{g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}-\frac{\frac{\max_{e\in\mathcal{E}}(g_{T_\mathrm{p}em})g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}}{1+\frac{\max_{e\in\mathcal{E}}(g_{T_\mathrm{p}em})g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}\right)-\frac{\zeta g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+\lambda g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+g_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}}=0. \quad (18)$$

$$p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}=\frac{1}{2}\Big[\sqrt{\Big(\frac{1}{\max_{e\in\mathcal{E}}(h^e_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m})}-\frac{1}{h_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}\Big)^2+\frac{4}{\lambda_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}\Big(\frac{1}{\max_{e\in\mathcal{E}}(h^e_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m})}-\frac{1}{h_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}\Big)}-\Big(\frac{1}{\max_{e\in\mathcal{E}}(h^e_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m})}+\frac{1}{h_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}}\Big)\Big]^+. \quad (19)$$

$$\frac{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}}{1+g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}}-\lambda=0, \quad (24)$$

whose solutions are, respectively, given by

$$p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}=\left[\frac{1}{\gamma}-\frac{1}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}}\right]^+, \quad (25)$$

$$p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}=\left[\frac{1}{\lambda}-\frac{1}{g_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}}\right]^+. \quad (26)$$

### *B. Secondary Link Selection and Subcarrier Allocation*

Now, we determine which secondary links should cooperate with primary link and each secondary link should work on which subcarrier. First sing (16), we obtain the following functions

$$\psi^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}=\theta R^\mathrm{S}_{\mathrm{T}_\mathrm{p},\mathrm{T}_{u_\mathrm{s}},m}-\zeta p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}-\lambda p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}, \quad (27)$$

$$\psi^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}=R_{\mathrm{T}_{u_\mathrm{s}},\mathrm{R}_{u_\mathrm{s}},m}-\gamma p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}-\lambda p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}. \quad (28)$$

We obtain the tuple $(\mathrm{T}^*_{u_\mathrm{s}},m^*,n^*)$ such that we have

$$(\mathrm{T}^*_{u_\mathrm{s}},m^*)=\underset{u_\mathrm{s}\in\mathcal{S}_{\mathcal{U}_\mathrm{s}},m\in\mathcal{S}_\mathcal{M}}{\arg\max}\ \psi^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}, \quad (29)$$

and the tuple $(\mathrm{T}^*_{u^\mathrm{s}},m_{*\prime},n_{*\prime})$ such that we have

$$(\mathrm{T}^*_{u'_\mathrm{s}},m^{*'})=\underset{u_\mathrm{s}\in\mathcal{S}_{\mathcal{U}_\mathrm{s}},m\in\mathcal{S}_\mathcal{M}}{\arg\max}\ \psi^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}, \quad (30)$$

where $\mathcal{S}_\mathcal{M}$ and $\mathcal{S}_{\mathcal{U}_\mathrm{s}}$ are the set of available subcarriers in the first time slot and the second time slot and the set of secondary users, respectively. We set $\rho_{\mathrm{T}_\mathrm{p},\mathrm{T}^*_{u_\mathrm{s}},m^*}=1$ if $\psi^1_{\mathrm{T}^*_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m^*}\geq\psi^2_{\mathrm{T}^*_{u'_\mathrm{s}}\mathrm{R}^*_{u'_\mathrm{s}}m^{*'}}$ and set $\eta_{\mathrm{T}^*_{u'_\mathrm{s}},\mathrm{R}_{u'_\mathrm{s}},m^{*'}}=1$ if $\psi^1_{\mathrm{T}^*_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m^*}<\psi^2_{\mathrm{T}^*_{u'_\mathrm{s}}\mathrm{R}^*_{u'_\mathrm{s}}m^{*'}}$.

### *C. Dual Problem*

To solve the dual optimization problem (17), we use subgradient approach. In this approach, the Lagrangian multipliers are updated as follows:

$$\theta^{t+1}=\Big[\theta^t-s^{t+1}_\theta\ \triangle\ \theta^t\Big]^+, \quad (31)$$

$$\zeta^{t+1}=\Big[\zeta^t-s^{t+1}_\zeta\ \triangle\ \zeta^t\Big]^+, \quad (32)$$

$$\lambda^{t+1}=\Big[\lambda^t-s^{t+1}_\lambda\ \triangle\ \lambda^t\Big]^+, \quad (33)$$

$$\gamma^{t+1}=\Big[\gamma^t-s^{t+1}_\gamma\ \triangle\ \gamma^t\Big]^+. \quad (34)$$

where $\triangle\ \theta^t$, $\triangle\ \zeta^t$, $\triangle\ \lambda^t$, and $\triangle\ \gamma^t$ are subgradients at iteration $t$ which are given, respectively, as follows:

$$\triangle\ \theta=\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}R^\mathrm{S}_{\mathrm{T}_\mathrm{p},\mathrm{T}_{u_\mathrm{s}},m}-\bar{R}^{\mathrm{S,P}}, \quad (35)$$

$$\triangle\ \zeta=P^{\max}_\mathrm{P}-\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}p_{T_\mathrm{p}\mathrm{T}_{u_\mathrm{s}}m}, \quad (36)$$

$$\triangle\ \lambda=P^{\max}_\mathrm{s}-\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}\Big(p_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_\mathrm{p}m}+p^2_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}\Big), \quad (37)$$

$$\triangle\ \gamma=P^{\max}_\mathrm{s}-\sum_{u_\mathrm{s}\in\mathcal{U}_\mathrm{s}}\sum_{m=1}^{M}p^1_{\mathrm{T}_{u_\mathrm{s}}\mathrm{R}_{u_\mathrm{s}}m}. \quad (38)$$

We showed our proposed resource allocation algorithm in Fig. 1.

s1. Initialize dual variables to $\theta(0), \zeta(0), \lambda(0), \gamma(0)$,
s2. Update transmit powers, i.e., at each iteration based on the values of dual variables in previous iteration
s2.1. Update the variables $p_{\mathrm{T}_{u_s}\mathrm{R}_{\mathrm{p}}m}$, $p^1_{\mathrm{T}_{u_s}\mathrm{R}_{u_s}k}$ and $p^2_{\mathrm{T}_{u_s}\mathrm{R}_{u_s}k}$ using (19), (25), and (26), respectively
s2.2. Update the variable $p_{T_{\mathrm{p}}\mathrm{T}_{u_s}m}$ using (13)
s2.3. Update the variable $p_{\mathrm{T}_{u_s}\mathrm{R}_{\mathrm{p}}m}$ using (14)
s3. Perform subcarrier allocation, i.e.,
s3.1. Set $S_{\mathcal{M}} = \{1, \ldots, N\}, \mathcal{S}_{\mathcal{U}_s} = \mathcal{U}_s$
s3.2. Set $\boldsymbol{\eta} = \mathbf{0}$, and $\boldsymbol{\rho} = \mathbf{0}$
s3.3. Construct tuples $(\mathrm{T}^*_{u_s}, m^*)$ using $(\mathrm{T}^*_{u_s'}, m^{*'})$ using (29) and (29)
s3.4. Set $\rho_{\mathrm{T_p},\mathrm{T}^*_{u_s},m^*} = 1$ if $\psi^1_{\mathrm{T}^*_{u_s}\mathrm{R_p}m^*} \geq \psi^2_{\mathrm{T}^*_{u_s'}\mathrm{R}^*_{u_s'}m^{*'}}$
s3.5. Set $\eta_{\mathrm{T}^*_{u_s'},\mathrm{R}_{u_s'},m^{*'}} = 1$ if $\psi^1_{\mathrm{T}^*_{u_s}\mathrm{R_p}m^*} < \psi^2_{\mathrm{T}^*_{u_s'}\mathrm{R}^*_{u_s'}m^{*'}}$
s3.6. Set $S_{\mathcal{M}} = S_{\mathcal{M}} - \{m^*\}$ and $\mathcal{S}_{\mathcal{U}_s} = \mathcal{S}_{\mathcal{U}_s} - \{u^*_s\}$ if $\rho_{\mathrm{T_p},\mathrm{T}^*_{u_s},m^*} = 1$
s3.7. Set $S_{\mathcal{M}} = S_{\mathcal{M}} - \{m^{*'}\}$ and $\mathcal{S}_{\mathcal{U}_s} = \mathcal{S}_{\mathcal{U}_s} - \{u^{*'}_s\}$ if $\eta_{\mathrm{T}^*_{u_s'},\mathrm{R}_{u_s'},m^{*'}} = 1$
s3.8. If $S_{\mathcal{M}} \neq \emptyset$ go to s3.2
s4. Update dual variables using subgradient approach, i.e.,
s4.1. Update the variable $\theta$ using (31)
s4.2. Update the variable $\zeta$, using (32)
s4.3. Update the variable $\lambda$ using (33)
s4.4. Update the variable $\gamma$ using (34)
s5. If the stopping criterion is not satisfied go to step 2.
s6. end

Fig. 1. The algorithm for solving the proposed optimization problem using dual approach.

### D. Complexity Analysis

Utilizing the results presented in [19], the number of iterations required to achieve $\delta$-optimality, in a problem with $X$ constraints is in order of $O\left(\frac{X^2}{\delta^2}\right)$. Moreover, in each iteration, it is required to obtain subcarrier allocation for all $N$ sub-carriers. Therefore, in each iteration, subcarrier allocation equation is obtained $Y$ times where $Y$ is the total number of assignment variables. Consequently, the total computational complexity is in order of $O\left(\frac{YX^2}{\delta^2}\right)$.

In this paper, the proposed optimization problem which is solved by dual decomposition method has $3 + 2N(U_s + 1) + U_s$ constraints. Moreover, the total number of assignment variables are $A_1$ and $A_2$ for the first and second hops, respectively, where $A_1 = A_2 = U_s N^2$. Accordingly, the total computational complexity corresponding to dual decomposition solution is summed up to $O\left(\frac{(A_1+A_2)(3+2N(U_s+1)+U_s)^2}{\delta^2}\right)$. .

## IV. Simulation Results

Now, we provide simulations results for our proposed scheme. The network under study is the downlink of a cognitive radio network which consists of one OFDM primary user and a set of non-OFDM (single carrier) secondary users (links) distributed over the primary users coverage area. In addition, the eavesdropper is randomly located in the network area. We assume that each secondary link can transmit over each of the available subcarriers by adjusting its hardware facilities, but at each instance, it can adopt single carrier transmission over one of the available subcarriers. We assume that the channels are Rayleigh fading and hence, the channel gains are exponentially distributed with unit average received power.

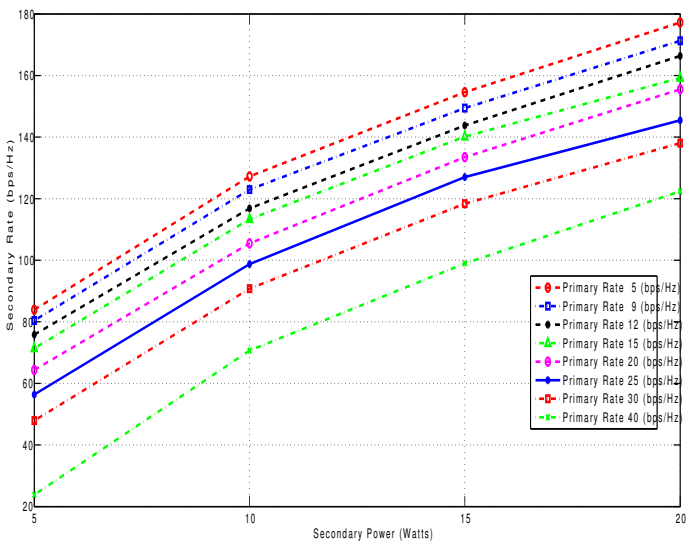


Fig. 2. The effect of changing the transmit power constraint of secondary users on the system throuput.

In the first simulation, we assume that the transmit power constraints for the primary user is set to $P_{\mathrm{P}}^{\max} = 40$ Watts. We set the number of subcarriers to $N = 64$ which is also the number of secondary users. We change the transmit power constraint of secondary users and compute the achievable rate of secondary users. We plot the results for different values for secrecy rate of the primary user in Fig. 2. As could be seen from the figure, increasing the transmit power of the secondary users will increase the achievable rare of the secondary system while increasing the secrecy rate requirement for primary user will decrease the total rate of secondary system. This is because with increasing the secrecy rate of the primary user, more resources, i.e., subcarriers and transmit power of secondary system, will be assigned to the transmission of primary user and hence, less resource remains for secondary transmission.

In the next simulation, we study the effect of primary

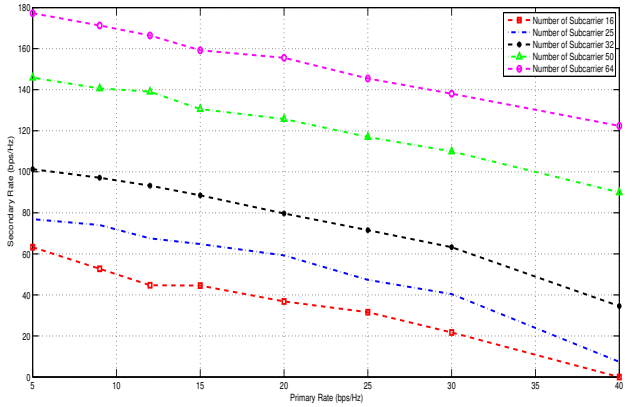


Fig. 3. The effect of changing the primary secrecy rate requirements for various number of subcarriers.

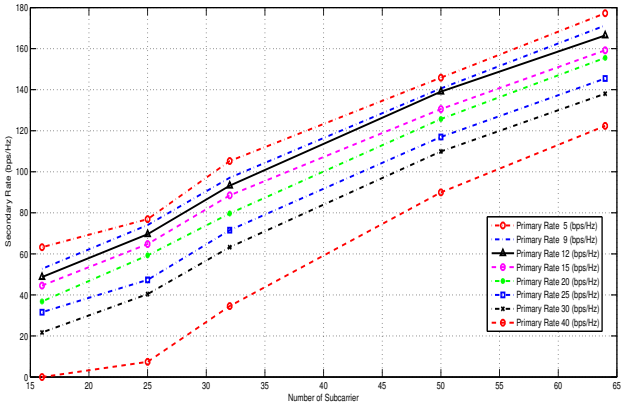


Fig. 4. The effect of changing the number of available subcarriers on secondary rates for various primary secrecy rate requirements.

user's secrecy rate as well as the number of subcarriers (or secondary users) on the system throughput. To see the effect of the increasing the primary user's secrecy rate on the secondary system throughput, we set the transmit power constraints for the primary user and the secondary users, respectively, to $P_{\mathrm{P}}^{\max} = 40$ and $P_{\mathrm{S}}^{\max} = 20$ Watts. We change the secrecy rate of the primary user and compute the total rate of the secondary system and plot the results for different number of subcarriers (or secondary users) in Fig. 3. As the primary user demands for more secrecy rate, the system throughput decreases. In additions, increasing the number of subcarriers will increase the total rate of the secondary system because in such a case, the multiuser diversity gain of the system will increase.

In additions, to explicitly see the effect of the number of secondary users on the system throughput, we plot the achievable rate of the secondary system versus the number of subcarriers in Fig. 4.

Finally, we study the effect of the number of eavesdropper on the achievable rat of the secondary system. The result is shown in Fig. 5. It is seen that as the number of eavesdroppers increases, the rate of secondary system decreases. This is because increasing the number of eavesdroppers increases the multiuser diversity gains of them and hence, satisfying the secrecy rate of the primary user demands higher resources. Therefore, less resource remains for the secondary system to transmit its information.

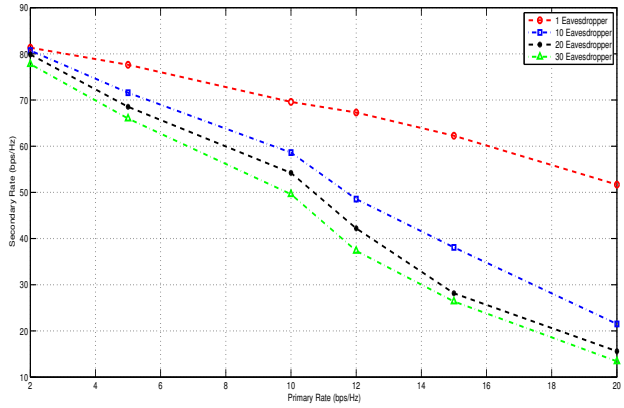


Fig. 5. The effect of changing the number of eavesdroppers on secondary rates.

## V. Conclusions

In this paper, we proposed a cooperative communication scheme in which secondary users help primary user to maintain its secrecy rate requirement. Each secondary link works as a decode and forward relay and sent primary user information to its destination. As a reward, the remaining secondary links gain access to the network resources and can transmit their own information. We formulated our resource allocation scheme as an optimization problem and solved it using dual Lagrange approach. By simulations, we evaluated out proposed scheme in various situations.

## References

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, February 2005.

[2] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 203–213, January 2008.

[3] W. D. Lu, Y. Gong, S. H. Ting, X. L. Wu, and N. T. Zhang, "Cooperative ofdm relaying for opportunistic spectrum sharing: Protocol design and resource allocation," *IEEE Transactions On Wireless Communications*, vol. 11, no. 6, pp. 2126–2135, June 2012.

[4] A. Zarrebini-Esfahani and M. R. Nakhai, "Secondary spectrum access and cell-edge coverage in cognitive cellular networks," *IET Communications*, vol. 6, no. 8, pp. 845–851, May 2012.

[5] W. Liang, S. X. Ng, and L. Hanzo, "Cooperative communication between cognitive and primary users," *IET Communications*, vol. 7, no. 17, pp. 1982–1992, November 2013.

[6] J. He, C. Xu, and L. Li, "Power saving for cooperative spectrum sharing-based cognitive radios under primary user short-term rate protection," *IET Communications*, vol. 6, no. 9, pp. 1097–1103, June 2012.

[7] M. Tao and Y. Liu, "Spectrum leasing and cooperative resource allocation in cognitive OFDMA networks," *Journal of Communications and Networks*, vol. 15, no. 1, pp. 102–110, February 2013.

[8] W. Lu and J. Wang, "Opportunistic spectrum sharing based on full-duplex cooperative OFDM relaying," *IEEE Communications Letters*, vol. 18, no. 2, pp. 241–244, February 2014.

[9] N. Zhang, N. Lu, N. Cheng, J. W. Mark, and X. Shen, "Cooperative spectrum access towards secure information transfer for CRNs," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 11, pp. 2453–2464, November 2013.

[10] Y. Xu, L. Wang, C. Fischione, and V. Fodor, "Distributed spectrum leasing via vertical cooperation in cognitive radio networks," *IEEE Transactions On Wireless Communications*, vol. 15, no. 2, pp. 1588–1601, February 2016.

[11] S. Shen, X. Lin, and T.-M. Lok, "Dynamic spectrum leasing under uncertainty: Modeling, analysis and algorithms," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 11, pp. 5149–5159, November 2015.

[12] A. D. Wyner, "The wire-tap channel," *Bell System Technical Journal*, vol. 54, pp. 1355–1387, 1975.

[13] V. N. Q. Bao, N. Linh-Trung, and M. Debbah, "Relay selection schemes for dual-hop networks under security constraints with multiple eavesdroppers," *IEEE Transactions On Wireless Communications*, vol. 12, no. 12, pp. 6076–6085, December 2013.

[14] B. Han, J. Li, and J. Su, "Optimal relay assignment for secrecy capacity maximization in cooperative ad-hoc networks," in *2013 IEEE International Conference on Communications (ICC)*. Budapest, Hungary, June 2013, pp. 6128–6132.

[15] Y. Liu, J. Li, and A. P. Petropulu, "Destination assisted cooperative jamming for wireless physical-layer security," *IEEE Transactions on Vehicular Technology*, vol. 8, no. 4, pp. 682–694, April 2013.

[16] K. Lee, O. Simeone, C. b. Chae, and J. Kang, "Spectrum leasing via cooperation for enhanced physical-layer secrecy," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4672–4678, November 2013.

[17] P. N. Son, D. Har, and H. Y. Kong, "Smart power allocation for secrecy transmission in reciprocally cooperative spectrum sharing," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 11, pp. 5395–5400, November 2015.

[18] A. Al-Talabani, Y. Deng, A. Nallanathan, and H. X. Nguyen, "Enhancing secrecy rate in cognitive radio networks via multi-level stackelberg game," *IEEE Communications Letters*, vol. 20, no. 6, pp. 1112–1115, June 2016.

[19] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[20] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Transactions on Communications*, vol. 54, no. 7, pp. 1310–1322, July 2006.