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Resource Optimization for Cognitive Radio Based Device to Device Communication Under an Energy Harvesting Scenario

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ABSTRACT Device to device (D2D) communication has emerged as a potential candidate for next-generation communication networks to support higher data rates and minimize power consumption. The spectral and energy efficiency of D2D communication can further be improved using cognitive radio (CR) and radio frequency energy harvesting (RF-EH) technologies. Therefore, in this paper, a sum throughput maximization problem for a CR assisted D2D network is modeled considering the RF-EH mechanism. A joint optimization problem is formulated for sum-rate maximization of cellular and D2D users by considering power allocation, channel assignment, user pairing and transmission time ratio allocation. Then, the problem is transformed into a standard convex optimization problem subject to power constraints at individual nodes, interference constraint, and the individual rate. Furthermore, the secrecy capacity requirements of cellular and D2D nodes are also considered. The duality theory is used to decompose the problem into multiple sub-problems and Karush-Kuhn-Tucker conditions are exploited to provide the solution of the sub-problems. The simulation results are provided for the validation of our proposed schemes.

INDEX TERMS Base station assisted users, channel allocation, device to device users, power optimization, RF energy harvesting, user pairing.

I. INTRODUCTION

The number of cellular devices are increasing very rapidly with high intelligence and capabilities. It is necessary to investigate the emerging technologies to fulfill the advanced network requirements with the limited available resources. Cognitive radio (CR) and device-to-device (D2D) communication are the two emerging candidates to fulfill the high demands of advanced cellular network by making the efficient use of limited spectrum. Energy harvesting (EH) is another technology to cope with the energy issues. We have considered an EH enabled CR based D2D network to take maximum advantages of CR, D2D and EH technologies. Physical layer security is a challenging issue, specially in the CR and D2D networks and we have considered it in our network. In the below paragraphs of this section we have provide the detailed review of all these technologies one by one. In the 2^{nd} paragraph, we discuss that why we need the D2D and CR networks and then briefly discuss the both technologies individually in the 3^{rd} and 4^{th} paragraphs respectively. The 5^{th} and 6^{th} paragraphs provide the detailed review of physical layer security and EH respectively.

The major challenge of emerging networks is to provide high Quality of Services (QoS) to new applications like online gaming, audio/video streaming, etc. along with satisfying basic needs of cellular systems [1]. The radio spectrum has become one of the most valuable resources in modern cellular systems. Further, the tremendous increase in the number of cellular users burdened the base stations [2]. To handle these issues, the new technologies like D2D and CR have recently been introduced for modern communication networks [3], [4]. The D2D users can communicate directly with each other

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without involving the base station (BS). The benefits of D2D communication is the more effective usage of the frequency spectrum, lower end-to-end delays, and less transmission power [5]. The CR is also an efficient technique to solve the issue of spectrum deficiency. It allows secondary users to share the spectrum with primary network either in underlay or overlay mode [6], [7].

A number of challenges occur when the spectrum is shared between cellular and D2D users. To cope with interference management and spectrum sensing problems in D2D, various works have been reported in the literature [8]–[14]. The authors in [8] proposed search based and closed-form methods to optimize the throughput, subject to the maximum transmit power constraint at each node for different resource sharing modes. The work in [9] proposed a resource allocation scheme where resources are allocated to Cellular and D2D users in two different stages. In the first phase, resources are allocated to maximize the uplink and downlink data rates of cellular users and in the second stage, the resource allocation is performed for D2D users with minimum rate requirement of cellular users. The techniques for allocation of resources based on interference aware graphs were presented in [10]. The authors in [11] proposed a pricing based game theory for energy-efficient resource allocation in D2D and to extend this work, a distributed algorithm with less complexity was studied in [12]. The authors in [13] studied a multi-antenna system for a D2D assisted cellular network and proposed an algorithm based on a random search for channels and power allocations. The work in [14] proposed a cognitive channel allocations scheme for D2D users to achieve the spectrum efficiency and minimize the interference. The authors in [15] considered a dual-hop orthogonal frequency division multiplexing (OFDM) based D2D network and maximize the system sum-rate by power allocation and channel pairing using duality theory. A D2D assisted communication network in the presence of multiple eavesdroppers is investigated in [16] and an energy trading algorithm based on Stackelberg game is proposed to provide secure communication.

The authors in [17] investigated a sum-rate maximization problem while considering the power and interference constraints in CR networks. An underlay communication mode of CR network was studied in [18] where the joint problem of power optimization and user assignment was considered to maximize the sum throughput of all the users. The work in [19] proposed a convex optimization scheme for optimal resource allocation to enhance the sum data rate of relay enhanced CR network. The power allocation technique based on the majorization theory is proposed to maximize the minimum rate requirements of each transmitting node for cellular networks in [20]. To ensure the provision of minimum rate requirements of secondary users, the authors in [21] considered a CR network and studied geometric programs based power allocation technique. The authors in [22] investigated a coordinated beam-forming scenario to achieve the desired signal to interference noise ratio (SINR) by resource optimization using duality theory and KKT conditions. The authors in [23] studied a multi-user cognitive network to maximize the SINR of CR users while considering the interference constraints and proposed a geometric programming scheme for resource optimization. The authors in [24] investigated a CR network with multiple eavesdroppers and a two-stage algorithm is proposed to maximize the data rate of secondary users while providing secure transmission to primary nodes.

The main focus of the existing research work in D2D/CR networks has been on the interference minimization, power optimization, and the system throughput enhancement. Recently, in wireless systems, the physical layer security has gained attention from the researchers [25]. In the underlay communication mode, the interference can be exploited to jam the malicious nodes [26], [27]. The authors in [28] considered a D2D assisted communication network where D2D nodes can communicate bidirectionally with each other as well as act as relays for cellular transmissions. A security embedded interference avoidance scheme was proposed to minimize interference and maximize secrecy rate. The security solution schemes after a detailed analysis of application and physical layer security issues were proposed in [29]. The advantages/disadvantages of direct and relayed communication in terms of physical layer security for D2D transmissions were analyzed by the authors in [30]. An algorithm based on stochastic geometry was presented in [31], to improve the secrecy capacity of cellular links. The authors in [32] investigated a D2D enabled cellular network and present a resource optimization scheme based on outage probability to achieve the required secrecy rate of cellular users. A physical layer security problem was studied with up-link transmission in [33] and an algorithm named as kuhn Munkres (KM) was proposed for efficient channel allocations to achieve the desired goal.

Energy-efficient techniques have been a key research area for the next generation communication networks [34]. Further with the increased number of transmitting devices it has also become necessary to reduce the energy consumption to provide green communication [35]. The emerging applications of wireless sensor networks i.e. internet of things (IoT), disaster management applications, health care systems, etc. needs to operate the systems for long-duration [36]. The Energy harvesting (EH) has emerged as a major candidate to increase the system's lifetime and enhance the energy efficiency [37]. The idea of radio frequency (RF) EH has emerged from the fact that every information-carrying signal contains energy that can be harvested and stored [38]. In simultaneous wireless information and power transfer (SWIPT) systems, the energy harvesting schemes based on power splitting and time splitting can be used [39]. A number of resource optimization techniques have been studied for EH enabled networks in the recent research works. The work in [40] studied the power optimization techniques to maximize the system sum throughput of an underlay CR network. An EH enabled, D2D assisted machine type communication network was investigated in [41], the detailed analysis of the coverage probability and the spectral efficiency using stochastic geometry was studied. The authors in [42] considered relay assisted communication network and proposed time splitting and power splitting based techniques for EH to enhance the system throughput. A time splitting based technique was proposed in [43] to harvest RF energy for secondary nodes with zero battery power, in an underlay CR network. A D2D assisted cognitive network with the RF energy harvesting was considered in [44], the authors optimize the transmission power only on primary nodes to maximize the D2D throughput. An energy harvesting based D2D network was investigated in [45] and sum-rate maximization problem was solved using an outer approximation algorithm for power allocations at cellular and D2D nodes while ensuring the required QoS. A mixed-integer nonlinear programming problem for a D2D assisted cellular network was solved to maximize the overall system throughput by power and channel allocations [46]. A lot of work has been carried out for resource optimization in D2D assisted cellular networks and CR networks separately. To use the limited available resources more efficiently, D2D assisted CR networks can be developed which have not been studied yet. Power limitation in wireless devices is a major issue which can be solved through RF-EH.

In this paper, we consider an RF-EH enabled multi-user underlay CR network. Our aim is to maximize the sum throughput of the secondary system subject to interference protection at the primary receivers. The users of the secondary system may have individual and different types of QoS requirements. In this work, we assume secondary users of two categories (i) security-sensitive users with limited battery powers e.g., small sensor nodes for military applications, and (ii) users who want to communicate with the outer world with guaranteed data rate e.g., multimedia services. Based on the secret nature of data, the first type of users can communicate directly with each other and thus are named as D2D users (DUs). Similarly, the other type of users send the data with the help of BS and are called as BS assisted users (BAUs).

Following are the main contributions of this work:

- A joint optimization problem is formulated to maximize the sum rate[1] of secondary network subject to minimum QoS guarantee for individual CR user, interference temperature limits of the primary user, individual power constraints at each secondary transmitter.
- Following are the major consideration of optimization:
  (a) power allocation at the BAUs.
  (b) The user paring between BAUs and DUs for orthogonal transmission in time.
  (c) The channel assignment to BAU-DU pairs.
  (d) The EH based power loading at DU transmitters.
  (e) The time fraction adaptation for different CR users.

[1]The total achievable rate of all the users in the system is referred to as the sum rate of the system.

- To solve the mixed binary integer programming problem, a dual decomposition framework is proposed to obtain the uncoupled optimization over different variables.
- The power allocations are obtained from convex optimization techniques while the user matching is found from the Hungarian algorithm.
- Finally, a sub-optimal approach is also presented and simulation results are provided to evaluate the performance of proposed schemes.

The organization of the rest of the paper is as follows: The system model and problem formulation are presented in Section II. Section III and IV explain the proposed optimization solution and proposed sub-optimal methods, respectively. Section V provides the simulation results and finally, the whole work is concluded in section VI.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We consider an RF-EH enabled CR network as shown in Fig. 1. There are two types of users in secondary network, the base station (BS) assisted users (BAUs) and the D2D users (DUs). The BAUs communicate through the BS and DUs communicate directly with each other. We consider up-link transmission where the BAUs and DUs share the radio resources in a time-division fashion such that orthogonal multiplexing is realized to avoid interference within the secondary system. Further, we consider that DUs harvest RF energy from BAU transmission and use it along with the battery power. It is assumed that there are multiple eavesdroppers (EDs) in the secondary network which overhears the information transmitted from each DU.

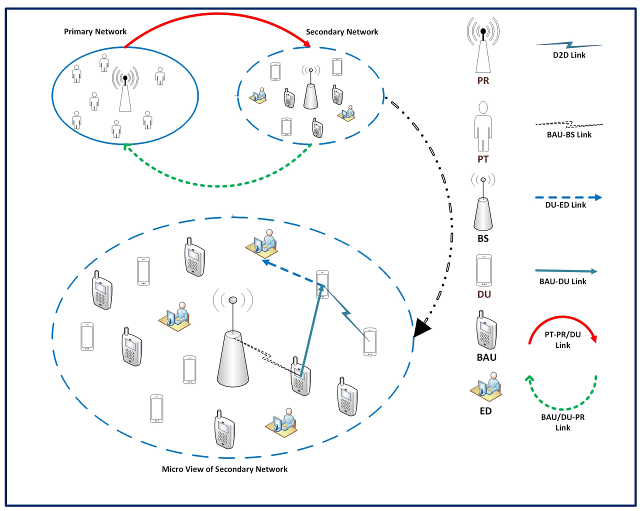

FIGURE 1. System model.

We consider that there are M number of BAUs and the same number of DUs. Total M number of channels available for BAU and DU transmissions. Let t_i and τ_j be the times for which a frequency channel is allocated to ith BAU and jth DU transmitter, respectively. The primary receiver experience interference from all transmitters of secondary network and similarly both BAU and DU receivers, endure interference from primary transmitters.

The signal received at the BS and at the jth DU receiver are given by [47]

$$Y_{BAU,i} = \sqrt{p_i} h_{m,i} x_i + \omega_{c,i} + I_{nt,i}, \tag{1}$$

and

$$Y_{DU,j} = \sqrt{q_j} g_{m,j} y_j + \omega_{d,j} + I_{nt,j}, \tag{2}$$

respectively, where p_i and q_j are the transmission powers of ith BAU and jth DU transmitter, respectively. The $\omega_{c,i}$ and $\omega_{d,j}$ represent additive white gaussian noise (AWGN) with variance σ^2. The x_i and y_j are the symbols transmitted from ith BAU and jth DU transmitter, respectively. The $h_{m,i}$ represents the mth channel gain from ith BAU to BS and $g_{m,j}$ is the link gain between jth DU transmitter and receiver. The $I_{nt,i}$ and $I_{nt,j}$ are the interference experienced at BS and jth DU receiver, respectively, from the primary network.

Defining $R_{BAU,i}$ and $R_{DU,j}$ as the throughput of ith BAU and jth DU [47], [50], respectively, we have

$$R_{BAU,i} = t_i \log_2\left(1 + \frac{p_i |h_{m,i}|^2}{I_{nt,i} + \sigma^2}\right), \tag{3}$$

and

$$R_{DU,j} = \tau_j \log_2\left(1 + \frac{q_j |g_{m,j}|^2}{I_{nt,j} + \sigma^2}\right). \tag{4}$$

Under the proposed model, the receivers of secondary network experience interference from primary transmissions and may suffer from severe performance degradation. Thus, to make the system more practical, minimum Quality of Service for each secondary node must be ensured. We consider rate as a QoS parameter and define

$$R_{BAU,i} \geq G, \forall\, i = 1...M, \tag{5}$$

where G is the minimum rate requirement of each user. Based on the channel conditions, different users may achieve different rates. We take the same minimum rate threshold i.e., G for all users to provide a fair resource allocation. The DUs can not bear information sharing with any other node. The BS is not involved in DUs communication hence their signals are not as much strength as for BAUs. As there are a number of EDs in the network which listen to the transmission of each DU, hence it is necessary to secure the transmitted data. The secrecy rate requirement can be defined as follows:

$$(R_{DU,j} - R_{DU,j'}) \geq X \forall\, j = 1...M, \tag{6}$$

where

$$R_{DU,j'} = \tau_j \log_2\left(1 + \frac{q_j |\tilde{k}_i|^2}{I_{nt,\tilde{i}} + \sigma^2}\right). \tag{7}$$

The $\tilde{k}_i$ is the channel gain from jth DU transmitter to ED and $I_{nt,\tilde{i}}$ is the interference from the primary transmitter to ED. Let P_t be the total available power at each BAU and P_b is the battery power of each DU. The transmission power of a BAU cannot be more than the available power, hence

$$p_i \leq P_t, \forall\, i = 1...M. \tag{8}$$

Similarly, a DU transmitter can transmit its data with power q_j such that

$$q_j \leq P_b + t_i p_i \beta_j k_j, \forall\, j = 1...M, \tag{9}$$

where β_j is the energy harvesting ratio and k_j is the channel gain from BS to jth DU receiver. The second part on the right-hand side of (9) represents the harvested energy.

The BAUs produce interference to the primary receiver in the first time slot while the DU transmitters interfere in the second phase. To secure primary receiver from severe interference, the power and channel allocations at BAUs and DUs must satisfy

$$t_i p_i |\tilde{h}_{m,i}|^2 \leq I_{th}, \forall\, i = 1...M \tag{10}$$

and

$$\tau_j q_j |\tilde{g}_{m,j}|^2 \leq I_{th} \forall\, j = 1...M, \tag{11}$$

where I_{th} is the maximum acceptable interference threshold level of primary receiver, whereas $\tilde{h}_{m,i}$ and $\tilde{g}_{m,j}$ are the channel gains of ith BAU to the primary receiver and jth DU transmitter to the primary receiver, respectively. The t_i and τ_j are the fractions of transmission time allocated to BAU and DU transmitter, respectively. Thus

$$t_i + \tau_j = 1. \tag{12}$$

The different variables and notations used in this article are defined in table 1.

B. PROBLEM FORMULATION

Our objective is to maximize the overall system throughput by optimal channel and power allocations at secondary transmitters while guaranteeing minimum QoS to each BAU and DU. We seek channel allocations to BAUs/DUs in different time slots and RF-EH at DUs. We define the two variables $\zeta_{i,j}$ and $\gamma_{m,(i,j)}$ that ensures the BAU-DU pairing and channel allocation to a BAU-DU pair, respectively. The problem can be defined mathematically as

$$\max_{p_i, q_j, t_i, \tau_j, \zeta_{i,j}, \gamma_{m,(i,j)}} \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{m=1}^{M} \zeta_{i,j}\gamma_{m,(i,j)}\big(R_{BAU,i} + R_{DU,j}\big) \tag{13}$$

$$\text{s.t. } (5), (6), (8), (9), (10), (11), (12), \tag{14}$$

$$\sum_{i=1}^{M} \zeta_{i,j} = 1, \forall\, j = 1...M, \tag{15}$$

$$\sum_{j=1}^{M} \zeta_{i,j} = 1, \forall\, i = 1...M, \tag{16}$$

$$\sum_{m=1}^{M} \gamma_{m(i,j)} = 1, \forall\, i, j = 1..M. \tag{17}$$

The constraints (15) and (16) guarantee that one BAU can be paired with one and only one DU and vice verse. The (17) ensures that mth channel is uniquely allocated to (i, j)th BAU-DU pair only.

III. PROPOSED OPTIMIZATION SOLUTION

The optimization problem in (13) is a binary integer programming problem. The functions in (3), (4) and (7) are non-convex in p_i, t_i, q_j and τ_j [49]. First, we convert these non-convex functions to convex by introducing the intermediate variables $S_i = p_i t_i$ and $Z_j = q_j \tau_j$. With this the transformed problem can be mathematically reformulated as follows:

$$\max_{S_i,Z_j,t_i,\tau_j,\zeta_{i,j},\gamma_{m,(i,j)}} \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{m=1}^{M} \zeta_{i,j}\gamma_{m,(i,j)}\Big(\tilde{R}_{BAU,i}+\tilde{R}_{DU,j}\Big) \tag{18}$$

$$\text{s.t. } \tilde{R}_{BAU,i} \geq G, \forall\, i = 1...M, \tag{19}$$
$$(\tilde{R}_{DU,j} - \tilde{R}_{DU,j'}) \geq X, \forall j = 1...M, \tag{20}$$
$$S_i \leq P_t, \forall i = 1...M, \tag{21}$$
$$Z_j \leq P_b + S_i\beta_j k_j, \forall j = 1...M, \tag{22}$$
$$(S_i|\tilde{h}_{m,i}|^2 \leq I_{TH}, \forall i = 1...M, \tag{23}$$
$$Z_j|\tilde{g}_{m,j}|^2) \leq I_{th}, \forall j = 1...M, \tag{24}$$
$$(12), (15), (16), (17), \tag{25}$$

where

$$\tilde{R}_{BAU,i} = t_i \log_2\left(1 + \frac{S_i|h_{m,i}|^2}{t_i(I_{nt,i}+\sigma^2)}\right), \tag{26}$$
$$\tilde{R}_{DU,j} = \tau_j \log_2\left(1 + \frac{Z_j|g_{m,j}|^2}{\tau_j(I_{nt,j}+\sigma^2)}\right), \tag{27}$$

and

$$\tilde{R}_{DU,j'} = \tau_j \log_2\left(1 + \frac{Z_j|\tilde{k}_i|^2}{\tau^j(I_{nt,\tilde{i}}+\sigma^2)}\right). \tag{28}$$

This reformulated problem is a mixed binary integer programming. To find the optimal solution, we use the duality theory as the difference between primal and dual problem reduces to zero in the multi-carrier system for a large number of carriers [50]. The dual problem associated with this problem is given by

$$\min_{\lambda1_i,\lambda2_j,\lambda3_i,\lambda4_j,\lambda5_i,\lambda6_j,\lambda7_{i,j}} D(\lambda1_i,\lambda2_j,\lambda3_i,\lambda4_j,\lambda5_i,\lambda6_j,\lambda7_{i,j}) \tag{29}$$

$$\text{s.t. } \lambda1_i \geq 0, \lambda2_j \geq 0, \lambda3_i \geq 0, \tag{30}$$
$$\lambda4_j \geq 0, \lambda5_i \geq 0, \lambda6_j \geq 0, \tag{31}$$
$$\lambda7_{i,j} \geq 0, \tag{32}$$

where $\lambda1_i$, $\lambda2_j$, $\lambda3_i$, $\lambda4_j$, $\lambda5_i$, $\lambda6_j$ and $\lambda7_{i,j}$ are the dual variables, while the objective function in (29) is

$$D(\lambda1_i, \lambda2_j, \lambda3_i, \lambda4_j, \lambda5_i, \lambda6_j, \lambda7_{i,j}) = \max_{S_i,Z_j,t_i,\tau_j,\zeta_{i,j},\gamma_{m,(i,j)}} L, \tag{33}$$
$$\text{s.t. } (15), (16), (17), \tag{34}$$

where L is the Lagrangian associated with (18) and is defined as

$$\begin{aligned} L = \sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{m=1}^{M} \Big(&\zeta_{i,j}\gamma_{m,(i,j)}\left(\tilde{R}_{BAU,i} + \tilde{R}_{DU,j}\right) \\ &+\lambda1_i(\tilde{R}_{BAU,i} - G) + \lambda2_j(\tilde{R}_{DU,j} - \tilde{R}_{DU,j'} - X) \\ &+\lambda3_i(P_t - S_i) + \lambda4_j(P_b + S_i\beta_j k_j - Z_j) \\ &+\lambda5_i(I_{th} - S_i|\tilde{h}_{m,i}|^2) + \lambda6_j(I_{th} - Z_j|\tilde{g}_{m,j}|^2) \\ &+\lambda7_{i,j}(1 - t_i - \tau_j)\Big). \end{aligned} \tag{35}$$

For the given user pairing and sub-carrier allocation the problem in (33) becomes

$$D(\lambda1_i, \lambda2_j, \lambda3_i, \lambda4_j, \lambda5_i, \lambda6_j, \lambda7_{i,j}) = \max_{S_i,Z_j,t_i,\tau_j} L. \tag{36}$$

Now (36) is a standard convex optimization problem and Karush Kuhn Tucker (KKT) conditions can be exploited to find the optimal solution [49]. The KKT conditions are necessary as well as sufficient for the optimality of convex problems. Thus we obtain

$$\frac{t_i|h_{m,i}|^2}{S_i|h_{m,i}|^2+t_i\phi_i}(\lambda1_i+1)-\lambda3_i+\lambda4_j\beta_j k_j-\lambda5_i|\tilde{h}_{m,i}|^2=0 \tag{37}$$

and

$$\begin{aligned} \frac{\tau_j|g_{m,j}|^2}{Z_j|g_{m,j}|^2+\tau_j\phi_j}(\lambda2_j+1) - \frac{\lambda2_j\tau_j|\tilde{k}_i|^2}{Z_j|\tilde{k}_i|^2+\tau_j\phi_{i'}} \\ - \lambda4_j - \lambda6_j|\tilde{g}_{m,j}|^2 = 0. \end{aligned} \tag{38}$$

From (37) we obtain

$$\frac{S_i^*}{t_i} = \frac{|h_{m,i}|^2(\lambda1_i+1) - \lambda3_i\phi_i+\lambda4_j\beta_j k_j\phi_i-\lambda5_i|\tilde{h}_{m,i}|^2\phi_i}{\lambda4_j\beta_j k_j|h_{m,i}|^2 - \lambda5_i|\tilde{h}_{m,i}|^2|h_{m,i}|^2 - \lambda3_i|h_{m,i}|^2}, \tag{39}$$

similarly, from (38) we get

$$\frac{Z_j^*}{\tau_j} = \frac{-B_j \pm \sqrt{B_j^2 - 4A_jC_j}}{2A_j}, \tag{40}$$

where

$$\begin{aligned} A_j &= -\lambda4_j|g_{m,j}|^2|\tilde{k}_i|^2 - \lambda6_j|g_{m,j}|^2|\tilde{g}_{m,j}|^2|\tilde{k}_i|^2, \\ B_j &= (\lambda2_j+1)|g_{m_j}|^2|\tilde{k}_i|^2 - \lambda2_j|\tilde{k}_i|^2|g_{m_j}|^2 - \lambda4_j|g_{m_j}|^2\phi_{i'} \\ &\quad -\lambda4_j\phi_j|\tilde{k}_i|^2 - \lambda6_j|\tilde{g}_{m_j}|^2|g_{m,j}|^2\phi_{i'} - \lambda6_j|g_{m,j}|^2\phi_j|\tilde{k}_i|^2, \\ C_j &= (\lambda2_j+1)|g_{m,j}|^2\phi_{i'} - \lambda2_j|\tilde{k}_i|^2\phi_j - \lambda4_j\phi_j\phi_{i'} \\ &\quad -\lambda6_j|\tilde{g}_{m,j}|^2\phi_j\phi_{i'}, \\ \phi_i &= I_{nt,i}+\sigma^2, \phi_j = I_{nt,j}+\sigma^2 \text{ and } \phi_{i'} = I_{nt,i'}+\sigma^2. \end{aligned}$$

TABLE 1. Table for defining different notation.

$Y_{BAU,i}$	Signal received at BS from ith BAU.
$Y_{DU,j}$	Signal received at jth DU receiver.
p_i	Power applied at ith BAU.
q_j	Power applied at jth DU transmitter.
P_t	Power budget available at each BAU.
$I_{nt,i}$	Interference from PT to BS.
$I_{nt,j}$	Interference from PT to jth DU receiver.
$I_{nt,i'}$	Interference from PT to eavesdropper.
P_b	Power budget available at each DU transmitter.
$h_{m,i}$	Channel gain of ith BAU to BS link.
$g_{m,j}$	Channel gain of jth D2D link.
$\tilde{h}_{m,i}$	Channel gain of ith BAU to PR link.
$\tilde{g}_{m,j}$	Channel gain of jth DU transmitter to PR link.
$\omega_{c,i}$	Additive white gaussian noise (AWGN) with variance σ^2.
$\omega_{d,j}$	AWGN with variance σ^2.
σ^2	Noise variance.
x_i	Symbol transmitted from ith BAU to BS.
y_j	Symbol transmitted from jth DU transmitter to DU receiver.
t_i	Time for which BAU transmission occurs over ith link.
τ_j	Time for which transmission of jth DU transmitter occurs.
$\lambda 1_i$	Dual variables associated with rate constraint of ith BAU.
$\lambda 2_j$	Dual variables associated with secrecy rate constraint of jth DU tranmitter.
$\lambda 3_i$	Dual variables associated with power consumption of ith BAU.
$\lambda 4_j$	Dual variables associated with power consumption of jth DU transmitter.
$\lambda 5_i$	Dual variables associated with Interference constraint.
$\lambda 6_j$	Dual variables associated with Interference constraint.
$\lambda 7_{i,j}$	Dual variables associated with fractions of time.
BS	Base station.
BAU	Base station assisted users.
DU	Device to Device user.
PT	Primary transmitter.
PR	Primary Receiver.

Next, we find the optimal values of t_i and τ_j. Unfortunately, the structure of the problem does not allow to find the closed-form solution for these variables. Nevertheless, the optimal solution t_i^* and τ_j^*, can be found from search over two variables which maximize the sum rate assuming each takes discrete value. Using these values, the S_i^* and Z_j^* are obtained from (39) and (40), respectively.

Substituting the values of (39), (40), t_i^* and τ_j^* in (33), we get

$$\begin{aligned} &D(\lambda 1_i, \lambda 2_j, \lambda 3_i, \lambda 4_j, \lambda 5_i, \lambda 6_j, \lambda 7_{i,j}) \\ &\quad = \max_{\zeta_{i,j}, \gamma_{m,(i,j)}} F, && (41) \\ &\quad\quad \text{s.t. } (15), (16), (17). && (42) \end{aligned}$$

Next, we find the optimal channel allocation for a valid user pair i.e., for $\zeta_{i,j} = 1$. The dual function in (41) can be written as

$$\begin{aligned} &D(\lambda 1_i, \lambda 2_j, \lambda 3_i, \lambda 4_j, \lambda 5_i, \lambda 6_j, \lambda 7_{i,j}) \\ &\quad = \max_{\gamma_{m,(i,j)}} \hat{F}, && (43) \\ &\quad\quad \text{s.t. } (17). && (44) \end{aligned}$$

The optimal solution in (43) find BAU-DU pairs that maximize F i.e.

$$\gamma^*_{m,(i,j)} = \begin{cases} 1, & \text{for } m = \arg\max_m F \\ 0, & \text{otherwise.} \end{cases} \quad (45)$$

Now we are left with to find the optimal user pairing $\zeta^*_{i,j}$. Substituting (45) in (43), we obtain

$$\begin{aligned} &D(\lambda 1_i, \lambda 2_j, \lambda 3_i, \lambda 4_j, \lambda 5_i, \lambda 6_j, \lambda 7_{i,j}) \\ &\quad = \max_{\zeta_{i,j}} F^*, && (46) \\ &\quad\quad \text{s.t. } (15), (16), && (47) \end{aligned}$$

where $F^* = \max \hat{F}$. Let F be a a M X M matrix with the (i, j)-th entry $[F]_{i,j} = F^*_{i,j}$. The matrix F can be assumed as a profit matrix and it can be solved efficiently using the Hungarian algorithm. To solve the dual problem in (29) after obtaining optimal values of primal variables (p_i, q_j, t_i, τ_j, $\zeta_{i,j}$, $\gamma_{m,(i,j)}$), the sub-gradient method provides the optimal solution. The sub-gradient updates are given by

$$\begin{aligned} \lambda w_{i,(L+1)} &= (\lambda w_{i,(L)} + \delta_L \pi_{w,i}), \text{ for } w = 1, 3, 5, && (48) \\ \lambda w_{j,(L+1)} &= (\lambda w_{j,(L)} + \delta_L \pi_{w,j}), \text{ for } w = 2, 4, 6, && (49) \\ \lambda w_{(i,j),(L+1)} &= (\lambda w_{(i,j),(L)} + \delta_L \pi_{w,(i,j)}), \text{ for } w = 7, && (50) \end{aligned}$$

where δ_L is the step size. The values of all of primal and dual variables are updated at each iteration L. The optimal values are obtained at the convergence of dual variables, where

$$\begin{aligned} \pi_{1,i} &= t_i \log_2\left(1 + \frac{p_i |h_{m,i}|^2}{I_{nt,i} + \sigma^2}\right) - G, \\ \pi_{2,j} &= \tau_j\left(\log_2\left(1+\frac{q_j|g_{m_j}|^2}{I_{nt,j}+\sigma^2}\right) - \log_2\left(1+\frac{q_j|k_{i,j}|^2}{I_{nt,i'} + \sigma^2}\right)\right) - X, \\ \pi_{3,i} &= P_t - t_i p_i, \quad \pi_{4,j} = P_b + t_i p_i \beta_j k_j - \tau_j q_j, \\ \pi_{5,i} &= I_{th} - t_i P_i |\tilde{h}_{m,i}|^2, \quad \pi_{6,j} = I_{th} - \tau_i q_j |\tilde{g}_{m,j}|^2, \end{aligned}$$

and

$$\pi_{7,(i,j)} = 1 - (t_i + \tau_j).$$

At convergence, we obtain the optimal solution S_i^*, Z_j^*, t_i^*, τ_j^*, $\zeta^*_{i,j}$ and $\tau^*_{m,(i,j)}$. Thus, all the optimization parameters in the original problem have been obtained except those of p_i and q_j. The optimal power values for all transmitting nodes can be found as

$$p_i^* = \frac{S_i^*}{t_i^*}, \ \forall i, \ \text{and } q_j^* = \frac{Z_j^*}{\tau_j^*}, \ \forall j. \quad (51)$$

This completes our solution.

IV. PROPOSED SUB-OPTIMAL SCHEME

The proposed method in the previous section provides a joint optimization solution for all variables. Different optimization parameters are updated at each sub-gradient iteration and are dependent on the values obtained in the previous iteration. This may result in slow convergence. Specifically, the Hungarian algorithm has complexity $O(M^3)$ and with I number of iteration, the complexity may become significant. Moreover, the values of time fraction for BAUs and DUs orthogonal multiplexing is obtained from the global search. A small step-size in the search space provides the near-optimal solution, however, it may also result in a large number of iterations.

In this section, we propose a sub-optimal step-wise approach to obtain an efficient solution.These schemes provide noticeable results but in very less time as compared to the method provided in previous section. These schemes are fast because no global searching is involved and less number of features depend on one another. Following steps are involved.

A. CHANNEL ALLOCATION AND USER PAIRING

As a first step, we obtain the channel allocation and the BAU-DU pairing. The idea is to exploit the channel gains and interference over different links and allocate each channel to the user for with the link can promise best performance. Our objective is to maximize the overall rate of the secondary network, as the achievable rate of a user may fall below the minimum requirement if the interference at the selected link is very high. It is intuitive to allocate a channel to the user with highest value of channel gain-interference ratio. Specifically, we first find the channel allocation (m^*, i) and (m^*, j) for ith BAU and jth DU, respectively, such that

$$(m^*, i) = \arg\max_{i} \frac{h_{m,i}}{I_{nt,i}}, \quad \forall m, \tag{52}$$

and

$$(m^*, j) = \arg\max_{j} \frac{h_{m,j}}{I_{nt,j}}, \quad \forall m. \tag{53}$$

Thus, the channel allocation is obtained i.e., m^*th channel is allocated ith BAU and jth DU. Finally, we obtain the secondary user pairing such that the ith BAU and jth DU which have been assigned common channel i.e. m^* are paired with each other. Note that, this technique provides the channel allocation and user pairing solution in just one iteration and is less complex as compared to the iterative framework of the previous section.

B. POWER AND TIME ALLOCATION

For the obtained channel assignment and user pairing, we can find the power and time fraction following a similar step. To reduce the complexity further, we here propose a direct method to calculate the transmission slot for BAUs and DUs.

First, from the definition of variables S_i and Z_i, we find the power allocation from (39) and (40). Please note that for this we do not need the values of time fraction variables. Then, From (12), we have

$$\tau_j = 1 - t_i, \tag{54}$$

With this the constraints in (5), (6), (8), (9), (10) and (11) provide

$$t_i \geq \frac{G}{\Lambda_{BAU,i}}, \quad t_i \geq \frac{q_j - P_B}{q_j + p_i \beta_J k_j}, \quad t_i \geq 1 - \frac{I_{TH}}{q_j |\tilde{g_{m,j}}|^2}, \tag{55}$$

and

$$t_i \leq \frac{\Lambda_{DU,j} - \Lambda_{DU,j'} - X}{\Lambda_{DU,j} - \Lambda_{DU,j'}}, \quad t_i \leq \frac{P_T}{p_i}, \quad t_i \leq \frac{I_{TH}}{|p_i \tilde{h}_{m,i}|^2}, \tag{56}$$

where

$$\Lambda_{BAU,i} = \log_2\left(1 + \frac{p_i |h_{m,i}|^2}{I_{nt,i} + \sigma^2}\right), \tag{57}$$

$$\Lambda_{DU,j} = \log_2\left(1 + \frac{q_j |g_{m,j}|^2}{I_{nt,j} + \sigma^2}\right), \tag{58}$$

and

$$\Lambda_{DU,j'} = \log_2\left(1 + \frac{q_j |\tilde{k}_i|^2}{I_{nt,\tilde{i}} + \sigma^2}\right). \tag{59}$$

From this, we define

$$t_{i,UB} = \max\left(\frac{G}{R_{BAU,i}}, \frac{q_j - P_B}{q_j + p_i \beta_J k_j}, \frac{q_j |\tilde{g_{m,j}}|^2 - I_{TH}}{q_j |\tilde{g_{m,j}}|^2}\right),$$
$$t_{i,LB} = \min\left(\frac{R_j - R'_j - X}{R_j - R'_j}, \frac{P_T}{p_i}, \frac{I_{TH}}{|p_i \tilde{h}_{m,i}|^2}\right),$$
$$\tau_{j,UB} = 1 - t_{i,UB}, \text{ and } \tau_{j,LB} = 1 - t_{i,LB}.$$

For these time fraction values, the corresponding rates at BAUs and DUs are denoted as $\tilde{R}_{BAU,i}(t_{i,UB})$, $\tilde{R}_{BAU,i}(t_{i,LB})$, $\tilde{R}_{DU,j}(\tau_{j,UB})$ and $\tilde{R}_{DU,j}(\tau_{j,LB})$. Now the values of time fraction are chosen which maximizes the sum rate. Finally, using these power allocation and the obtained time fraction, the dual variables are updated similar to the previous section. Note that, the objective in both techniques proposed in this section is to maximize the sum rate of the secondary network. Hence, both frameworks work together in alliance to maximize the total rate of the network.

V. SIMULATION RESULTS

In this section, the performance evaluation of the proposed solutions is provided through the simulation results. The radio resources used were Rayleigh fading channels obtained from Gaussian random variable distributions. The minimum values of both P_t and P_b are taken to be 5W. The values of G, X and, I_{th} are set to 1, 0.5 and 6 b/s/HZ, respectively. In the Fig. 2, 3, 4, 5 and Fig. 6 "OPT" and "SOPT" represent the optimization solutions provided in section III and section IV, respectively. The results of the proposed optimal (OPT) and sub-optimal (SOPT) methods are compared with fixed time method (T-SCH) and random channel allocation scheme (CH-SCH). In T-SCH the transmission times of BAUs and DUs are equal i.e. $t_i = \tau_j = 0.5$. The CH-SCH scheme

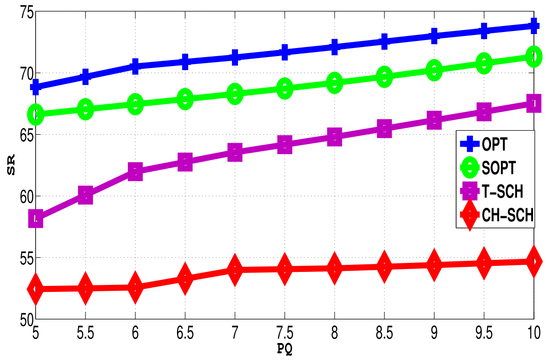

FIGURE 2. Sum-rate versus power.

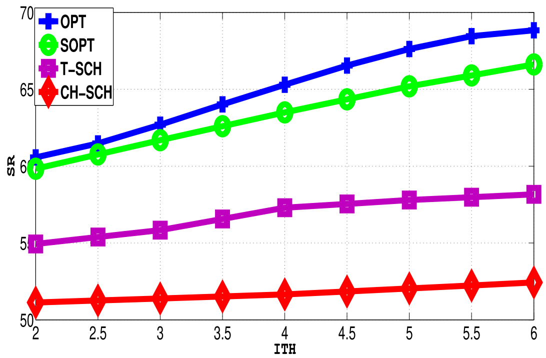

FIGURE 3. Sum-rate versus interference threshold level.

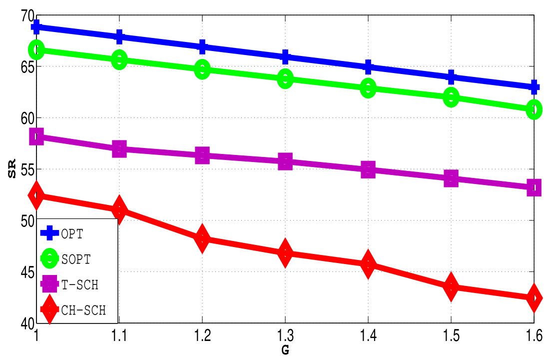

FIGURE 4. Sum-rate versus data rate.

presents the results when a channel is allocated randomly to BAU and DU transmitter.

The Fig. 2 shows the results of sum rate (SR) of system versus the total available powers at BAU and D2D nodes. We define a new variable Z and set $Z = P_t = P_b$ i.e., assume equal power budgets at each transmitting node. It can be observed that the system sum-rate increases as we increase the battery powers of transmitting nodes in the network. Sum-rate means the total system throughput. It is clear that the performance of the OPT scheme is much better than the other schemes i.e., SOPT, T-SCH, and CH-SCH. As we increase the Z, the SR also increases for all the schemes but the gap between the OPT scheme with SOPT and T-SCH decreases at relatively higher values. This decrease in the gap is due to the interference constraint because the OPT scheme optimizes powers more intelligently at lower values but at a

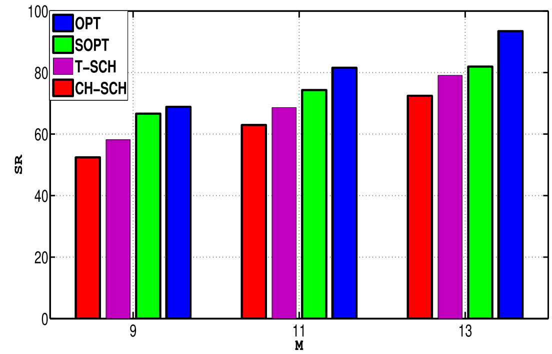

FIGURE 5. Sum-rate versus number of users.

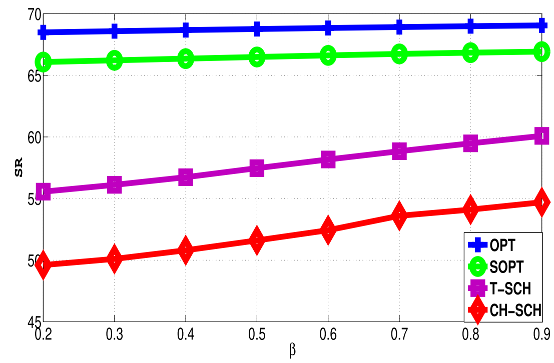

FIGURE 6. Sum-rate versus energy harvesting ratio.

point, the availability of more power becomes useless due to the increase in the interference. The difference between the CH-SCH scheme and all of the other schemes increases with the increase of Z.

The impact of increasing I_{th} on SR is presented in the Fig. 3. It is clear from the results that, as we increase the interference threshold value the system's sum-rate also increases for all proposed schemes. It means that it depends on how much interference can be tolerated. The more the I_{th} level, the more transmission power can be applied and the more throughput can be achieved. So if the more interference can be tolerated then more SR can be achieved and vice verse. The simulations validate that the OPT scheme outperforms the SOPT scheme and other solutions. It can be observed from the results that the initial gap between the OPT and SOPT is very low at the low interference thresholds and with the increase in the I_{th} the gap also increases. It means that the optimization scheme "OPT", performs more effectively at the higher I_{th} levels. This is due to the fact that it is more flexible to optimize powers at the higher interference thresholds and power optimization becomes hard at lower values of I_{th}. The gap between OPT solution and the other schemes i.e., the SOPT, T-SCH and CH-SCH increase with an increase in I_{th}. Hence the OPT method is more efficient than all other proposed methods to get the higher SR.

The Fig. 4 presents the performance evaluation of proposed techniques when the data rate requirements of BAUs increase. It can be examined that the system SR decreases for all schemes at higher rate requirements of individual BAU nodes. Nevertheless, the OPT scheme gives much higher sum throughput than the SOPT, T-SCH and the CH-SCH schemes. The reason behind decreasing behavior of SR with the increase in G is that more resources are required for the users having channels with bad gains to fulfill their rate requirements. The more resources can be allocated to the users which have a good response if the rate constraint value is low. Hence it becomes more critical to optimize power, channel allocations and time division at the higher data rate thresholds. The slopes of OPT and SOPT schemes are almost constants for all the rate threshold values i.e., the gap between them does not change with the increase or decrease of G. The gap between CH-SCH increases with all other schemes with the increase in G. The reason behind this is that it becomes more difficult to achieve higher individual QoS requirements for users with bad channel gains. More transmission time will be required for users with bad channel gains hence the individual rate of users having channels with higher gains will decrease and this cause in decrease in overall SR.

To see the effect of proposed schemes for a different numbers of BAU and DU pairs in the secondary network, we plot the results in Fig. 5. It can be seen that the sum throughput is directly proportional to the number of user pairs 'M'. The performance of the proposed OPT scheme is much better than the other proposed solutions. The difference between the OPT and SOPT gets bigger with the increase in M, it means that the performance of the OPT scheme is more efficient for the increased number of transmitting nodes. The gap between SOPT and T-SCH reduce with an increase in the number of users. So for a large number of users any of these schemes can be used. Further, we can observe that the ratio of increase in TSCH and CH-SCH almost remains the same with the increasing number of users.

In the last, to validate the performance of proposed techniques for increasing values of energy harvesting ratio β, the results are presented in Fig. 6. The results show that the OPT scheme gives much higher sum throughput as compare S-OPT, T-SCH and CH-SCH. As the value of β increases, the system's sum-rate also increases for all proposed solutions. The increase in SR for each unit increase in β, for OPT and SOPT is almost similar but the change in SR for T-SCH and CH-SCH is very noticeable. Although the rate of change of SR is higher for both of T-SCH and CH-SCH methods but still the results of OPT and SOPT are very impressive. The relatively higher increase in the slope of T-SCH and CH-SCH is due to the fact that for each unit increase in β the more RF energy is harvested hence more transmission power of DUs and more SR is achieved. The both of OPT and SOPT schemes utilize the available power budget in a more efficient way even at lower powers available and there does not occur big change in SR with the more harvested energy because of the interference factor.

VI. CONCLUSION

In this paper, we consider power allocations, user pairing, channel assignments, time splitting and RF energy harvesting for a CR based D2D network. The interference is caused by the BAUs and DUs towards the primary network. The objective is to maximize the sum-rate of the system by power allocations at individual nodes and channel assignments to the user pairs while fulfilling the individual data rate and secrecy rate requirements of BAU and D2D users respectively. The D2D users harvest RF energy from the BAU transmissions. Proposed solutions are derived using duality theory under the given constraints. Simulation results provided for the validation of derived solutions, which shows that the system's sum-rate can be increased by increasing the power budgets, energy harvesting ratio, number of cellular and D2D users and the interference threshold. The OPT-SCH always performs better than the other solutions. In the future, this work can be extended to fulfill the required QoS of different applications. Furthermore, the bit error rate improvement can be considered to make the system more efficient.

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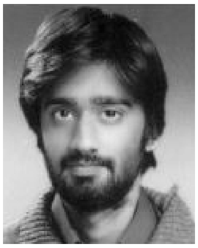

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