Energy Efficient Multicasting in Cognitive Radio Networks

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***Abstract*—In this paper, we study the problem of energy minimization for multicasting in cognitive radio networks, using omnidirectional and directional antennas. Our objectives are to build the multicast routing tree and schedule the secondary users' transmissions such that the total energy consumption is minimized. We consider in this paper the energy consumption due to channels switching, and we study the channel switching and scheduling dependency. We model the problem as a Multi-Layer Hyper Graph, then we formulate the optimization problem as Mixed Integer Linear Program (MILP). Moreover, we propose a heuristic algorithm to solve our problem in polynomial time. We also show how the primary users, directional antennas, the number of available channels and channel switching time per frequency jumping step affect the total energy consumption. The simulation results shows that our proposed algorithm achieves close performance to the optimal solution.**

***Index Terms*—Energy efficiency, cognitive radio network, multicast, routing, scheduling, directional antenna.**

I. Introduction

Multicasting in wireless networks is an essential service for many current and emerging applications. With the rapid demand and growth of applications in wireless communication, wireless communication and networking become significant contributors to energy consumption in the world [1]. Considering that the Information and Communication Technology (ICT) sector is responsible for approximately 5% of global electricity demands [2], we therefore need to make wireless networking more energy efficient in order to reduce the greenhouse gas emission.

Cognitive Radio Networks (CRN) is a promising technology for the next generation of wireless networks. The CRN has two types of users: Primary Users (PUs) and Secondary Users (SUs). The PU has a priority over the SUs in using the spectrum, where the SUs access the channel opportunistically when the PU is not available. In CRN, channels availabilities are heterogeneous where the SUs can have diverse sets of available channels. In order to optimize the network performance under multicasting, the multicast routing paths should be selected while considering channels heterogeneity. Furthermore, the multicast routing in CRN should consider the energy consumption due to channel switching when an SU receives message over one channel then forwards it though a different channel.

Energy efficient multicast and energy-aware networking with directional antennas have been well studied in traditional wireless networks [3]–[5]. However, energy efficient multicast in CRN has received little attention in the literature. In [6], the authors proposed an approximation algorithm for constructing the minimum multicast tree in CRN. The authors also studied the impact of the traffic load of the primary network on the energy consumption. In [7], the multicast problem using directional antennas in CRN is studied. The authors developed an optimization problem that optimizes the throughput of the CRN multicast. However, the energy efficiency of the multicasting in CRN is not considered in [7].

In this paper, we study the energy efficient multicast in CRN. We build the multicast routing tree and schedule the SUs' transmissions such that the total energy consumption is minimized. We consider the energy consumption due to channel switching, and we study the channel switching and scheduling dependency. Moreover, we study minimizing the energy consumption while considering omnidirectional and directional antennas. We formulate the optimization problem as a Mixed Integer Linear Program (MILP), then we propose a heuristic algorithm to solve the problem in polynomial time.

The rest of this paper is organized as follows. We introduce the system model in Section II, then we formulate the optimization problem in Section III. The heuristic algorithm for multicast energy minimization is proposed in Section IV. Finally, we show the simulation results in Section V, then we conclude our paper in Section VI.

II. System Model

We consider in this paper a multi-hop cognitive radio network with N^s SUs and N^p PUs using the TV white space spectrum. We assume that each SU has a single radio, and the channel availability is heterogenous, i.e., SUs may have different sets of available channels. The network is modeled using a generalized model of the multilayer hyper-graph proposed in [8]. Fig. 1 shows an example of a cognitive radio network that consists of 4 PUs and 6 SUs operating on 2 channels. PU_1^{Tx} transmits to PU_1^R and PU_2^{Tx} transmits to PU_2^R over channel 1 and 2, respectively. SU A, B and C can access channel 1, whereas SU C, D, E and F can access only channel 2.

All PUs and SUs operating on a certain channel are assigned to one layer. Since SU C can transmit and receive through channels 1 and 2, SU C is assigned to both layers. The dashed line in Fig. 1 represents that there is a switching delay when an SU receives a message over one channel and then forwards it to another channel. A hyper-edge (HE) is a set of a transmitting node that transmits with a certain transmission power level, and receiving nodes that can receive from that transmitting SU within one hop. Each node can transmit with a transmission power P_i and a beamwidth θ_i, where $P_{min} \leq P_i \leq P_{max}$ and $1° \leq \theta_i \leq 360°$. Hence, each transmitting node and its corresponding receiving nodes that can receive within one hop are grouped in one HE. Based on the transmission power of the transmitting node and the antenna direction and beamwidth, different HEs can be formed as shown in Fig. 1.

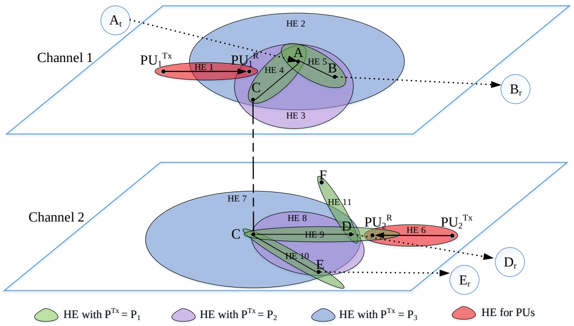


Fig. 1. Routing in Multilayers Hyper-Graph: HE 2 and HE 7 show the coverage when omnidirectional antennas are used, and $P^{Tx} = P_3$. All other HEs show the coverage when directional antennas are used, and $P^{Tx} = P_1$ or P_2.

Let $M = \{s, d\}$ be a multicast request, where s is the source SU, and $d = \{y_1, \ldots, y_{|d|}\}$ is the set of destination SUs. Suppose that there is a multicast request represented by a source SU, A, and destination SUs, B, D and E. Since SU A can transmit only over channel 1, we use a transmitting dummy node, A_t, to indicate that SU A tunes its radio to channel 1 as shown in Fig. 1. If SU A has more than one available channel, then the dummy node would be connected to SU A over the layer (channel) that optimizes its performance. For energy efficient routing, SU A should select the transmission powers that optimize energy consumption.

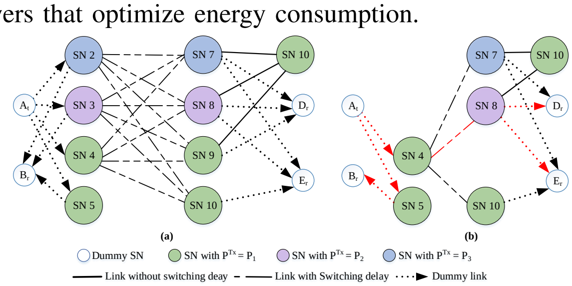


Fig. 2. Routing over the mapped graph: (a): Initial mapped graph. (b): The multicast routing over the mapped graph after removing SNs that cause interference to PUs.

To construct the multicast tree, we convert the multilayer hyper-graph to a mapped graph as shown in Fig. 2 (a). Each HE is represented by a Super-Node (SN), and we use HE and SN interchangeably in this paper. The transmitting SU and the destination SUs belonging to SN_i are represented by $s(SN_i)$ and $d(SN_i)$, respectively. Let V and $\overline{V}$ be the set of SNs for SUs and PUs, respectively. The mapped graph is represented by the graph $G(V, E)$, where E is the set of links that interconnect SNs $\in V$. The color of the SN represents the transmission power used by the transmitting SU corresponding to that SN. The dummy nodes and the dummy links indicate the source/destination SUs and the SNs belong to, respectively. A link with switching delay is a link that connects two SNs belonging to different layers. On the other hand, a solid line that goes from SN_i to SN_j indicates that $s(SN_j) \in d(SN_i)$.

After converting the multilayer hyper-graph to the mapped graph, we find the routing tree that minimizes energy consumption while protecting the PUs from interference. Fig. 2 (b) shows the mapped graph after removing the SNs $\in V$ that overlap with SNs $\in \overline{V}$. After removing SN_2, SN_3 and SN_9, we construct the multicast routing tree that minimizes the energy consumption while protecting the PUs from interference as shown in Fig. 2 (b).

We consider omnidirectional antennas for reception and both omnidirectional and the directional antennas for transmission. We assume the transmission medium to be free space, where the transmission power of $s(SN_i)$ is given by

$$P_i^r = P_i^{tx} G_t G_r \left(\frac{\lambda}{4\pi d_i}\right)^2 \qquad (1)$$

P_i^r is the received power, and we assume that the receiving power threshold is -80 dbm. P_i^{tx} is the transmission power of $s(SN_i)$, , λ is the transmission wavelength and d_i is the transmission range range of $s(SN_i)$. G_t and G_r are the gains of transmitting and receiving antennas, respectively. For the omnidirectional antennas, $G_t = G_r = 1$, whereas the gain of many practical directional antennas is approximated by [9]

$$G_t \approx \frac{30,000}{\theta\ \phi}. \qquad (2)$$

where θ and ϕ are azimuth and elevation angles in degree, respectively. Therefore, G_t of the transmitting directional antennas is approximated by equation (2).

The upper bound on transmission rate of SN_i is given by

$$R_i = W \log_2(1 + \frac{P_i^{tx} G_t G_r \lambda^2}{(4\pi d_i)^2 N_0 W}) \qquad (3)$$

where W is the channel bandwidth and N_0 is the noise spectral density.

The required time to switch from the band associated with $s(SN_i)$, W_i, to the band associated with $s(SN_j)$, W_j, is given by

$$t_{ij}^{sw} = k|W_i - W_j| \qquad (4)$$

where k is a technology dependent parameter. The switching delay from/to a dummy SN, SN_k, to/from any non-dummy SN, SN_i, is zero, i.e. $t_{ki}^{sw} = 0$ /$t_{ik}^{sw} = 0$.

III. Energy Optimization for Multicast in CRN

In this section, we study the problem of optimizing the energy consumption for multicasting in CRN.

A. Scheduling and Routing Constraints

Let $I = \{I_1, \ldots, I_{|I|}\}$ be a set of all independent sets of links, where each independent set represents the set of links that can be scheduled for transmission at the same time. The transmission of all SNs are scheduled over a cycle T. Let Y_z be a variable representing the time share of I_z, where $0 \leq Y_z \leq 1$. Since only one independent set of links should be active at a time, we have the following constraint:

$$\sum_{z=1}^{|I|} Y_z \leq 1 \qquad (5)$$

A set I_z is active when all links belonging to it are scheduled for transmission at the same time for a duration of $Y_z T$. In this paper, we use the protocol interference model introduced in [10]. Let $L_i = (x, y)$ represents the position of $s(SN_i)$ on a two dimensional plane. For a successful reception of a transmission from $s(SN_a)$ to $s(SN_b)$ over a common channel, the following condition needs to be satisfied for any simultaneously transmitting SU_c:

$$(1+\delta)|L_a - L_b| \leq |L_c - L_b| \quad (6)$$

where δ is a positive value models the guard zone used to prevent neighboring SUs from transmitting simultaneously over a channel.

The SUs can access the spectrum only if they do not cause interference to the PUs. Let X_{ij}^z be a binary variable defined as follows:

$$X_{ij}^z = \begin{cases} 1, & \text{if link } (i,j) \text{ is scheduled to route the flow} \\ & \text{from } s \text{ to any destination when } I_z \text{ is active.} \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

To avoid using any link that causes interference to PUs while routing the multicast traffic, we use the following constraint:

$$X_{ck}^z \leq F(a,b,c), \forall a, b \in \overline{V}, \forall c, k \in V, 1 \leq z \leq |I|. \quad (8)$$

where $F(i,j,q)$ is an indicator function given by:

$$F(i,j,q) = \begin{cases} 0, & \text{if } (1+\delta)|L_i - L_j| > |L_q - L_j|, \text{ and } i, j \\ & \text{and } q \text{ are SNs belonging to one layer.} \\ 1, & \text{otherwise.} \end{cases} \quad (9)$$

SUs can cause interference to each other as well. Hence, the SUs transmission is scheduled in such a way that they do not interfere with each other. To achieve the condition in (6) when the omnidirectional antennas are used, we have

$$X_{ab}^z + X_{cw}^z \leq 1 + F(a,b,c), \\ \forall a, b, c, w \in V, a \neq c \neq w \neq b, 1 \leq z \leq |I|. \quad (10)$$

If directional antennas are used for transmission instead of omnidirectional antennas, then we rewrite constraint (10) as follows:

$$X_{ab}^z + X_{cw}^z \leq 1 + \psi(a,b,c), \\ \forall a, b, c, w \in V, a \neq c \neq w \neq b, 1 \leq z \leq |I|. \quad (11)$$

where

$$\psi(a,b,c) = \begin{cases} 0, & \text{if } s(SN_b) \in d(SN_a) \text{ and } s(SN_b) \in \overline{SN_c}. \\ 1, & \text{otherwise.} \end{cases} \quad (12)$$

and $\overline{SN_c}$ is the set of SUs located within the interference range of $s(SN_c)$.

Let $T_{ij}^{sw}(z)$ be the switching delay required when a flow is routed from SN_i to SN_j during subslot z. We define $T_{ij}^{sw}(z)$ as a variable since the switching delay required when the flow is routed from SN_i to SN_j depends on the SNs' transmission schedule. For the first subslot, i.e. z = 1, we have

$$T_{ij}^{sw}(1) = t_{ij}^{sw}, \forall i, j \in V \quad (13)$$

When $1 < z \leq |I|$, $T_{ij}^{sw}(z)$ value is determined by finding the switching delay between SN_k and SN_j, where SN_k is the most recent scheduled SN that is connected to SN_i. If there is no SN_k scheduled in the previous subslot, z-1, such that SN_i and SN_k are connected, then $T_{ij}^{sw}(z) = T_{ij}^{sw}(z-1)$. Otherwise, $T_{ij}^{sw}(z) = t_{kj}^{sw}$. Therefore,

$$(1 - X_{ik}^{z-1})T_{ij}^{sw}(z-1) + X_{ik}^{z-1} t_{kj}^{sw} \leq T_{ij}^{sw}(z), \\ \forall i, j, k \in V, 1 < z \leq |I|. \quad (14)$$

For the link between SN_i and SN_j, the switching delay, $T_{ij}^{sw}(z)$, and transmission time, $T_j^{tx}(z)$, during subslot z should not be greater than the duration of subslot z. Hence,

$$X_{ij}^z T_{ij}^{sw}(z) + X_{ij}^z T_j^{tx}(z) \leq Y_z T, \forall i, j \in V, 1 \leq z \leq |I|. \quad (15)$$

The flow to destination y over link (i,j) when I_z is active, $f_{ij}^z(y)$, is constrained as follows:

$$f_{ij}^z(y) \leq T_j^{tx}(z) R_j, \quad \forall i, j \in V, \forall y \in d, 1 \leq i \leq |I|. \quad (16)$$

Let l be the required flow of the multicast session. The flow routing constraints are given by

$$\sum_{z=1}^{|I|} \sum_{\forall i \in V \backslash s} f_{is}^z(y) = 0, \forall y \in d. \quad (17)$$

$$\sum_{z=1}^{|I|} \sum_{\forall j \in V \backslash y} f_{yj}^z(y) = 0, \quad \forall y \in d. \quad (18)$$

$$\sum_{z=1}^{|I|} \sum_{\forall j \in V \backslash s} f_{sj}^z(y) = l, \quad \forall y \in d. \quad (19)$$

$$\sum_{z=1}^{|I|} \sum_{\forall i \in V \backslash y} f_{iy}^z(y) = l, \forall y \in d. \quad (20)$$

$$\sum_{z=1}^{|I|} \sum_{\forall n \in V \backslash y} f_{ni}^z(y) = \sum_{z=1}^{|I|} \sum_{\forall j \in V \backslash s} f_{ij}^z(y), \\ \forall i \in V \backslash (s \cup y), \forall y \in d. \quad (21)$$

From the definition of X_{ij}^z in (7), $X_{ij}^z = 0$ if the link between SN_i and SN_j is not used to route the flow to any destination when I_z is active. Therefore,

$$X_{ij}^z \leq \sum_{k}^{|d|} f_{ij}^z(y_k), \forall i, j \in V, 1 \leq z \leq |I|. \quad (22)$$

On the other hand, $X_{ij}^z = 1$ if the link between SN_i and SN_j is used to route the flow at least to one destination when I_z is active. Hence,

$$\frac{f_{ij}^z(y)}{l} \leq X_{ij}^z, \forall y \in d, \forall i, j \in V, 1 \leq z \leq |I|. \quad (23)$$

Let $U(a,b)$ be an indicator function given by

$$U(a,b) = \begin{cases} 0, & \text{if } SN_a \text{ and } SN_b \text{ belong to different layers} \\ & \text{(channels) and } s(SN_a) = s(SN_b). \\ 1, & \text{otherwise.} \end{cases} \quad (24)$$

Since each SU has a single radio, it cannot transmit or receive over more than one channel at a time. Hence, we have the following two constraints:

$$X_{ij}^z + X_{qr}^z \leq 1 + U(i,q), \forall i, j, q, r \in V, 1 \leq z \leq |I|. \quad (25)$$

$$X_{ij}^z + X_{qr}^z \leq 1 + U(j,r), \forall i, j, q, r \in V, 1 \leq z \leq |I|. \quad (26)$$

Moreover, an SU cannot receive and transmit at the same time. Therefore, we have the following constraint:

$$X_{ij}^z + X_{jq}^z \leq 1 + \zeta(i,j), \forall i,j,q \in V, 1 \leq z \leq |I|. \quad (27)$$

where $\zeta(i,j)$ is given by

$$\zeta(a,b) = \begin{cases} 0, & \text{if } s(SN_b) \in d(SN_a). \\ 1, & \text{otherwise.} \end{cases} \quad (28)$$

The traffic over any link flows in one direction, i.e.,

$$X_{ij}^z + X_{ji}^z \leq 1, \forall i,j \in V, 1 \leq z \leq |I|. \quad (29)$$

B. Optimization Problem

Our objective is to minimize the energy consumption, which is given by:

$$\sum_{z=1}^{|I|} \sum_{i \in V} \sum_{j \in V \setminus i} X_{ij}^z T_{ij}^{sw}(z) P_{ij}^{sw} + X_{ij}^z T_j^{tx}(z) P_j^{tx} \quad (30)$$

where P_{ij}^{sw} is the switching power to switch between the bands associated with $s(SN_i)$ and $s(SN_j)$. The objective function in (30) and constraint (14) and (15) are nonlinear because of the multiplication of X_{ij}^z with $T_{ij}^{sw}(z)$ and X_{ij}^z with $T_{ij}^{tx}(z)$. Moreover, constraint (14) is nonlinear because of the multiplication of X_{ik}^{z-1} with $T_{ij}^{sw}(z-1)$. Since X_{ij}^z is binary number and $T_{ij}^{sw}(z)$ and $T_j^{tx}(z)$ are continuous variables, the problem can be linearized by replacing the product of X_{ij}^z and $T_{ij}^{sw}(z)$ by $\gamma_{ij}^{sw}(z)$, the product of X_{ij}^z and $T_j^{tx}(z)$ by $\gamma_{ij}^{tx}(z)$, and the product of X_{ik}^z and $T_j^{tx}(z)$ by $\gamma_{ijk}^{sw}(z)$. $\gamma_{ij}^{sw}(z)$ is constrained as follows:

$$0 \leq \gamma_{ij}^{sw}(z), \forall i,j \in V, 1 \leq z \leq |I|. \quad (31)$$

$$\gamma_{ij}^{sw}(z) \leq T_{max}^{sw} X_{ij}^z, \forall i,j \in V, 1 \leq z \leq |I|. \quad (32)$$

$$\gamma_{ij}^{sw}(z) \leq T_{ij}^{sw}(z), \forall i,j \in V, 1 \leq z \leq |I|. \quad (33)$$

$$T_{ij}^{sw}(z) - (1 - X_{ij}^z) T_{max}^{sw} \leq \gamma_{ij}^{sw}(z), \forall i,j \in V, 1 \leq z \leq |I|. \quad (34)$$

where T_{max}^{sw} is the maximum switching delay.

Moreover, the constrains on $\gamma_{ij}^{tx}(z)$ are given by

$$0 \leq \gamma_{ij}^{tx}(z), \forall i,j \in V, 1 \leq z \leq |I|. \quad (35)$$

$$\gamma_{ij}^{tx}(z) \leq T X_{ij}^z, \forall i,j \in V, 1 \leq z \leq |I|. \quad (36)$$

$$\gamma_{ij}^{tx}(z) \leq T_j^{tx}(z), \forall i,j \in V, 1 \leq z \leq |I|. \quad (37)$$

$$T_j^{tx}(z) - (1 - X_{ij}^z) T \leq \gamma_{ij}^{tx}(z), \forall i,j \in V, 1 \leq z \leq |I|. \quad (38)$$

The constraints on $\gamma_{ijk}^{sw}(z)$ are:

$$0 \leq \gamma_{ijk}^{sw}(z), \forall i,j,k \in V, 1 \leq z \leq |I|. \quad (39)$$

$$\gamma_{ijk}^{sw}(z) \leq T_{max}^{sw} X_{ik}^z, \forall i,j,k \in V, 1 \leq z \leq |I|. \quad (40)$$

$$\gamma_{ijk}^{sw}(z) \leq T_{ij}^{sw}(z), \forall i,j,k \in V, 1 \leq z \leq |I|. \quad (41)$$

$$T_{ij}^{sw}(z) - (1 - X_{ik}^z) T_{max}^{sw} \leq \gamma_{ijk}^{sw}(z), \forall i,j,k \in V, 1 \leq z \leq |I|. \quad (42)$$

After introducing the thee new variables, we rewrite constraint (14) and (15) as follows:

$$\begin{aligned} T_{ij}^{sw}(z-1) - \gamma_{ijk}^{sw}(z-1) + X_{ik}^{z-1} t_{kj}^{sw} \leq T_{ij}^{sw}(z), \\ \forall i,j,k \in V, 1 < z \leq |I|. \end{aligned} \quad (43)$$

$$\gamma_{ij}^{sw}(z) + \gamma_{ij}^{tx}(z) \leq Y_z T, \forall i,j \in V, 1 \leq z \leq |I|. \quad (44)$$

When we consider omnidirectional antennas, then the optimization problem is formulated as follows:

$$\textbf{Minimize}: \sum_{z=1}^{|I|} \sum_{i \in V} \sum_{j \in V \setminus i} \gamma_{ij}^{sw}(z) P_{ij}^{sw} + \gamma_{ij}^{tx}(z) P_j^{tx} \quad (45)$$

Subject to:

Constraints (5-13), (16-23), (25-27), (29), (10), (31-44).

$$0 < f_{ij}^z(y) \leq l, \text{integer}, \forall i,j \in V, \forall y \in d, 1 \leq z \leq |I|. \quad (46)$$

$$0 < T_{ij}^{sw}(z) \leq T_{max}^{sw}, \forall i,j \in V, 1 \leq z \leq |I|. \quad (47)$$

$$0 < T_{ij}^{tx}(z) \leq T, \forall i,j \in V, 1 \leq z \leq |I|. \quad (48)$$

$$X_{i,j}^z \in \{0,1\}, \forall i,j \in V, 1 \leq z \leq |I|. \quad (49)$$

When directional antennas are used, we replace constraint (10) in the optimization problem above by (11).

IV. A Heuristic Algorithm for Solving the Energy Efficient Multicast in CRN

In section III, the formulated optimization problem after the linearization is a Mixed-Integer Linear Program (MILP), which is NP-Hard [11]. Therefore, we propose in this section a heuristic algorithm, Algorithm 1, that solves the optimization problem in polynomial time. The inputs to Algorithm 1 are the mapped Hyper-Graph $G(V,E)$ and a multicast request M represented by a source, s, and a set of destination nodes $d = \{y_1, \ldots, y_{|d|}\}$.

We assume that a cost, J_{ij}, is assigned to each link $x_{ij} \in E$ in term of energy consumption, where J_{ij} is given by

$$J_{ij} = t_{ij}^{sw} P_{ij}^{sw} + \frac{l}{SN_j^r} P_j^{tx} \quad (50)$$

where SN_j^r is the rate of $s(SN_j)$. In line 3, Algorithm 1 finds a minimum cost multicast tree by approximating the minimum Steiner tree. We approximate the minimum Steiner tree using a modified version of Nearest Participant First (NPF) Algorithm [12]. Instead of constructing the multicast tree by connecting the closest destination to the tree first, we use a randomized approach. We select a different order to connect the destination nodes to the multicast tree. In our proposed modified NPF algorithm, we first find all possible orders of selecting the destination nodes. Then, we select $|d|$ orders randomly out of all possible orders and construct $|d|$ multicast trees accordingly. Finally, we select one multicast tree out of the $|d|$ multicast trees that minimizes energy consumption.

After creating the multicast routing tree, we find the conflicting SNs that cannot be scheduled for transmission at the same subslot, as shown in line 4. We discussed in [13] when two SNs

Algorithm 1: Energy-Efficient Multicast Algorithm

Input: Mapped Hyper-Graph $G(V, E)$ and a multicast request $M = \{s, d\}$, $d = \{y_1, \ldots, y_{|d|}\}$.
Output: Minimum energy multicast tree, $T(M)$.

1 Initialize: $G^{'}(V, E) = G(V, E)$, $Iteration = 0$.
2 **while** *(No feasible tree is found and* $Iteration < MaxIteration$*))* **do**
3 Find an approximate minimum Steiner tree using modified NPF algorithm [12], $T(M)$, from $G^{'}(V, E)$.
4 Find the conflicting SN_s.
5 Schedule the SN_s accordingly using graph coloring algorithm [14].
6 Find the set of the independent sets I.
7 Update the switching delay for each link according to the transmission schedule.
8 For each $I_z \in I$, find the link, e_z, which has the maximum delay.
9 Calculate the time share w_z of each $I_z \in I$ as follows: $w_z = \frac{e_z}{T}$.
10 **if** *(*$\sum_{z=1}^{|I_z|} w_z T \leq T$*)* **then**
11 $T(M)$ is feasible energy-efficient multicast tree.
12 **else**
13 Find $I_q \in I$ which has the largest time share, w_q. Remove any link $e \in I_q$ with delay equals to the delay of e_q from $G^{'}(V, E)$.
14 Iteration++

conflict with each other in Many-to-Many communication. The reasons for conflicts can be summarized as follows:

1) Let SN_A, SN_B and SN_C be SNs such that $s(SN_B) \in d(SN_A)$ and $s(SN_B) \in \overline{SN_C}$, then SN_A conflicts with SN_B, where $\overline{SN_C}$ is the set of SUs located within the interference range of $s(SN_C)$.
2) Since each SU has a single radio, an SU cannot receive and send at the same time. Therefore, SN_A conflicts with SN_B if $s(SN_B) \in d(SN_A)$.
3) Since each SU cannot transmit over more than one channel at a time, then any two SNs conflict with each other if they belong to different layers and have the same source SU.
4) Each SU cannot receive messages over different channels at the same time. Let SN_A, SN_B, SN_C and SN_D be SNs such that SN_A is connected to SN_B and SN_C is connected to SN_D. SN_A conflicts with SN_C if $s(SN_B) = s(SN_D)$.

In line 5, we use the graph coloring algorithm in [14] to schedule the transmission of all SNs. After finding the conflicting SNs, we build the conflict graph CG used by graph coloring algorithm. The SN with higher rate requires fewer time slots compared with the SNs with lower rates. Therefore, each SN is assigned a weight such that the SNs with the highest rate are assigned rate 1 and all other SNs are assigned rate $\lceil \frac{\text{Max Rate}}{\text{SN's Rate}} \rceil$. After that, we can find the transmission schedule such that all non-conflicting SNs can be scheduled for the transmission at the same time slot. In line 6, each group of SNs that can be scheduled for transmission at the same time slot is considered an independent set, and the union of these independent sets is set I.

As we presented in section III, the switching delay of the link x_{ij} may depend on the transmission schedule of SN_j. Therefore, we show in line 7 that the switching delays are updated after the scheduling. In lines 8-9, we find the time share for each independent set. Then, we check the feasibility of the multicast tree in lines 10-11. If the multicast tree is not feasible, then we remove from $G^{'}(V, E)$ the links with largest delay that belong to the independent set with the largest time share. Then, Algorithm 1 iterates until finding a feasible multicast tree, $T(M)$, or the maximum number of iteration is reached.

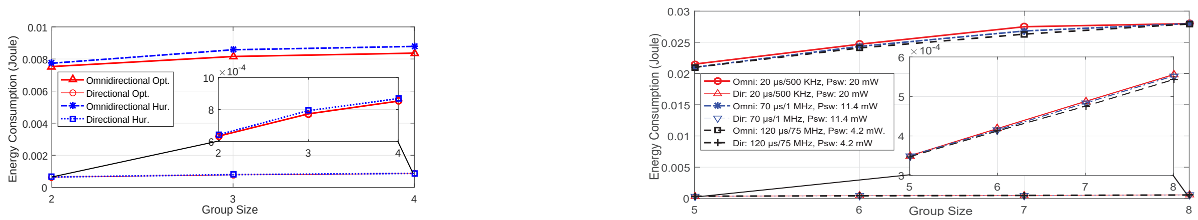
V. Simulation Results

We present in this section the simulation results for energy efficient multicasting in CRN. In our simulation, we used CPLEX and C++ to solve the optimization problem and the heuristic algorithm, respectively. We considered multi-hop cognitive radio networks with 15-30 SUs, 2-14 PUs, 4-8 channels, 2-8 multicast group size and θ equals 15°, and the energy consumption is averaged for 30 networks generated randomly. The switching time is 120 μs per 75 MHz step and the switching power is 4.2 mW [15], W is 6 MHz, frequency bands are from 614 MHz to 662 MHz, ϕ is 20°, N_0 is -174 dbm/Hz, δ is 0.1, P_j^{tx} values are 50, 75 and 100 mW, R_j is 100 bps, l is 10 Mb, T is 0.5 ms and Algorithm 1 iterations is 100.

We compare the optimal solution of the optimization problem with the solution of the proposed heuristic algorithm in Fig. 3 (a). 15 SUs and 7 pairs of transmitting and receiving PUs are distributed randomly over a 400 m by 400 m area. It is shown that the performance of the proposed heuristic algorithm is very close to the optimal solution. Fig. 3 (a) shows that the total energy consumption increases by increasing the multicast group size. It can clearly be seen that the use of directional antennas reduces energy consumption significantly compared with the case when omnidirectional antennas are used. This reduction in energy consumption can reach 90% as shown in Fig. 3 (a).

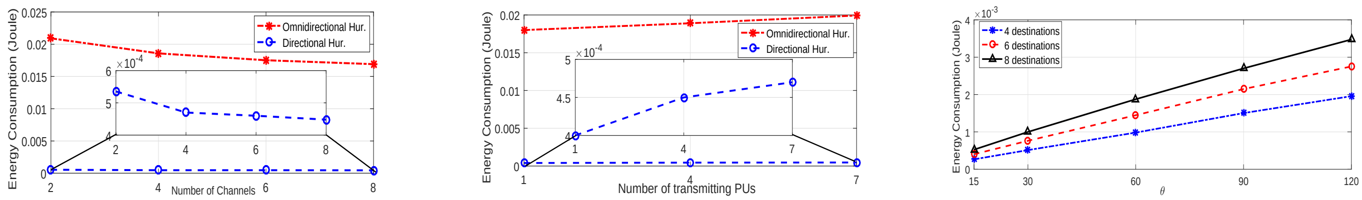
Fig. 3 (b) shows the total energy consumption when three Phase-Locked Loops (PLL) are used with different switching times, frequency jumping steps and switching power [15]–[17]. These different parameters affect the total energy consumption as shown in Fig. 3 (b). By comparing all three PPLs, the best energy saving is achieved when the switching time is 120 μs for 75 MHz step and the switching power is 4.2 mW. Hence, these parameters should be selected carefully in order to minimize the total energy consumption.

In the following figures, we consider larger networks with 30 SUs and up to 14 PUs distributed randomly over a 800 m by 800 m area. Fig. 4 (a) shows the effect of the number of available channels on the total energy consumption. A channel may not be available to certain SUs due to a PU's transmission. When the number of available channel is larger, then the SUs



(a) (b)

Fig. 3: Energy consumption versus group size: (a) Optimal and heuristic solutions: 15 SUs, 6 PUs and 4 channels (b) The effect of settling times, frequency jumping steps and switching power on energy consumption: 30 SUs, 6 PUs and 8 channels



(a) (b) (c)

Fig. 4: Energy consumption versus: (a) Number of available channels: 30 SUs, 6 PUs and 5 destinations, (b) Number of transmitting PUs: 30 SUs, 8 Channels and 5 destinations, (c) Directional antenna azimuth angles: 30 SUs, 8 channels and 6 PUs.

may have a higher chance to build the multicast routing tree and schedule the transmission with lower energy consumption. Fig. 4 (b) shows the effect of increasing the number of transmitting PUs on the total energy consumption. A larger number of transmitting PUs may lead to a fewer number of available channels and more energy consumption. Fig. 4 (b) shows that the performance deteriorates when the number of PUs increases.

Fig. 4 (c) shows the effect of the antenna azimuth angle on the energy consumption of different multicast group sizes. As the azimuth angle decreases, the total energy consumption decreases. It is shown that the differences between the energy consumptions of the different multicast group sizes decrease as the azimuth angle decreases. Adjusting the antennas to transmit with a smaller azimuth angle allows more power to be transmitted in the direction of the intended receivers and less power toward other nodes. Interestingly, transmitting with a smaller azimuth angle can reduce the interference between SUs and also between PUs and SUs. Therefore, more non conflicting SNs can be scheduled for routing the multicast request.

VI. Conclusion

We studied in this paper energy efficient multicasting in CRN while considering both omnidirectional and directional antennas. We modeled our optimization problem as an MILP, then we proposed a heuristic algorithm that can solve the problem in polynomial time. We considered energy consumption that results from switching from a channel to another channel, and we showed the dependency between channel switching and the transmission schedule.

To achieve our goal, we built the multicast routing tree and scheduled the SUs' transmissions such that the total energy is minimized. The simulation results show that the performance of our proposed algorithm is close to the optimal. We showed that selecting different PLL technologies can affect the total energy consumption. Moreover, we showed that a higher channel availability and a smaller azimuth angle for the directional antennas can result in more energy saving.

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