Abstract—Recently, there has been a great interest in cognitive radio networks. In addition, the use of subchannel allocation and power distribution in OFDM systems have been discussed in the literature and proven to help improve the capacity performance in cooperative networks. Therefore, in this paper we propose to add a primary source-destination pair to the secondary system in a cognitive radio network. We also provide the analysis of a subchannel and power allocation in cognitive networks. The optimal solution for such a problem is shown to be exponentially complex computationally. Therefore, we propose a suboptimal algorithm to reduce the complexity and achieve a close to optimal solution for which the subchannel allocation and power distribution among transmitters in the secondary system are performed in two steps. In the power allocation step, for each source-relay and relay-destination pair, peak interference power constraints of the primary system are being considered simultaneously. Simulation results are presented showing that the performance of the proposed suboptimal algorithm approach performs asymptotically to the optimal algorithm solution, which proves the correctness of this approach.

I. INTRODUCTION

Allocation of resource such as power and frequency has been regarded as one of effective ways to improve the capacity of wireless communication networks. In cooperative OFDM system, the subchannel and power allocation (SPA) determines the throughput of the networks. Meanwhile, as the growth of cognitive radio networks, there is intense interest in systems built of multiple levels, in which interference exists between subsystems. Most of recent works on cognitive radio networks are about spectrum sensing, i.e., spectrum interference avoidance. Researchers rarely consider the power interference between primary and secondary users. The tradeoff of increasing transmission capacity while maintaining an acceptable interference needs to be studied.

First, the main idea of cooperative communication is proposed in [1] and several efficient cooperative protocols and their outage behaviors were presented in [2]. The capacity of multi-hop radio networks is analyzed in [3]. In [4] a two-hop communication scheme using OFDM modulation is analyzed, with one source, one amplify-and-forward (AF) relay and one destination considered. In [5] the information rate of OFDM and OFDMA networks with one source-destination pair and multiple relays working in unicast method is examined. In [6] unicast in selective OFDMA relaying with multi-hop is discussed. No diversity gain can be obtained if the entire OFDM block chooses the same relay with the highest combined SNR. The above studies are restricted in either single hop or unicast. As far as we know, neither a multicast nor a broadcast cooperative network which includes multiple relays and multiple destinations has yet to have been built.

Next, in traditional spectrum policies, spectrum sharing which allows the operation of the secondary system as long as it does not affect the transmission of the primary users is a possible way to fully exploit the under-utilized spectrum. In such cognitive radio networks, we should make sure that the secondary users transmission power will not exceed the interfering power constraints. Unfortunately, there are few studies considering this problem. In [8], the authors propose a power control scheme in spectrum sharing mode to maximize the ergodic rate of the secondary user which consists one transmitter and one receiver. In [9], both the transmission power of the cognitive user and the interference power constraint of the cognitive user to primary user are studied.

Therefore, in this paper, the tradeoff of throughput and power consumption of a practical sensor network model working in broadcast mode is proposed and studied. Moreover, we make the network a cognitive one, in which the secondary system can not affect the primary user while transmitting information with the best possible resource allocation.

The rest of this paper is organized as following. Section II provides the first system model and assumptions. In this model, there is only one relay station in the secondary system. Section III theoretically analyzes resource allocation under peak power constraints in the proposed model. A suboptimal solution for subchannel and power allocation in the entire network is presented in section IV. After analyzing the first model, in section V we provide a promoted model which contains multiple relays in the secondary system. Its optimal and suboptimal SPA are shown in section VI and section VII. A selective relaying algorithm for multi-relay case is also studied. Finally, we conclude our work in section IX.

II. SYSTEM MODEL

We assume an OFDMA-based decode-and-forward cooperative network. This network combines one primary system and one secondary system, as shown in detail in Figure 1.

A. Secondary System

1) Traffic Manner: In the secondary system, we do broadcasting from a secondary source (S) node to a set of secondary destination (D) nodes. Let \( M = \{1,2,...,M\} \) be
the set of \( S_D \) nodes. There is one secondary relay \((S_R)\) station combining the secondary source node and all secondary destination nodes. In the first stage, \( S_S \) transmits its packets to \( S_R \). In the second stage, \( S_R \) transmits the received packets to all \( S_D \)s, while \( S_S \) remains idle. Perfect time and frequency synchronization among nodes are assumed, and the relay station can fully decode the received packets, re-encode them, and then forward them to the destination nodes.

2) Subchannel Utilization: Let \( \mathbb{N} = \{1, 2, \ldots, N\} \) be the set of orthogonal subchannels. In the link from \( S_S \) to \( S_R \), and in the links from \( S_R \) to \( S_D \)s, a specific node-to-node pair can only occupy one subchannel. We assume this is a sensor network, where \( \text{N} < \text{M} \). Therefore, there have to be some different \( S_D \)s using the same subchannel. The subchannel \( n \) used in the first stage may or may not be the same with the subchannel \( j \) used in the second stage. To achieve a better transmission power utility, the subchannel election could depend on the subchannel allocation (SA) \([10]\) and \([11]\).

B. Primary System

1) Traffic Manner: In the primary system, only one source-destination pair is adopted, which are primary source \((P_S)\) node and primary destination \((P_D)\) node. \( P_S \) communicates directly with \( P_D \).

2) Subchannel Utilization: Assume the secondary system communicates with the primary system with a special set of subchannels (e.g., licensed bands), which is mutually exclusive with the set of secondary system’s subchannels. So we do not need to worry about the subchannel allocation for primary users when we consider that of the secondary system. Note that we are not considering the vacant primary spectrum arrangement for secondary users. Instead, the power interference between primary and secondary users is our concern.

C. Power Interference Between Systems

We assume perfect channel state information (CSI) is available at both the transmitter and the receiver of \( S_S \) and \( S_R \). Moreover, we assume that the primary source transmission will not cause too much interference to \( S_R \) and \( S_D \) (Because there is only one more one-parameter constraint, which is easy to solve, so we omit it here). Thus the interference from the primary system to the secondary system can be neglected. In the first time slot, while \( S_S \) is transmitting packets to \( S_R \), there is an interference to \( P_D \). Identically, in the second time slot, while \( S_R \) is transmitting packets to \( S_D \)s, there is also an interference to \( P_D \). The peak power interference constraints should be considered to avoid severe interference to primary users.

In the model built above, we consider the throughput of the secondary system. Since a secondary packet should be sent from \( S_S \) to \( S_R \) first, and then from \( S_R \) to all the \( S_D \)s, the throughput capacity is determined by the smallest capacity of all related links, i.e., the \( S_S-S_R \) link and all \( S_R-S_D \) links. The achievable capacity is presented as

\[
R_{nj}(\text{tn}) = \frac{B}{N} \min \left\{ \log_2 \left( 1 + \frac{P_1(n)G_1(n)}{N_0} \right), \min \log_2 \left( 1 + \frac{P_2(j,m)G_2(j,m)}{N_0} \right) \right\}
\]

where \( N_0 \) is the double-sided noise power spectral density level, and we assume that it is equal to unity. \( G_1(n) \) and \( G_2(j,m) \) are the channel power gains for the selected sub-channel \( n \) from \( S_S \) to \( S_R \) and subchannel \( j \) from \( S_R \) to the \( m \)th \( S_D \), respectively. We also let \( P_1(n) \) and \( P_2(j,m) \) denote the transmission power of the above two kinds of selected subchannels, respectively. \( \text{tn} \) is the set of \( S_D \)s that uses subchannel \( j \).

III. Optimal Subchannel And Power Allocation

In this section, we formulate the optimization problem and present the optimal subchannel and power allocation algorithm for the secondary system.

The throughput of this system is determined by the minimum capacity of its associated subchannels. Therefore, we maximize the minimum rate of \( S_S \) subject to the overall transmission power constraints. We assume the available power for \( S_S \) is large enough for its transmission to \( S_R \), since there is only one source-relay pair. The available overall transmission power for the second stage transmission in secondary system is \( P_T \). Then this optimization problem can be presented as

\[
\max_{P_1(n), P_2(j,m), \rho_{nj}(m)} \min \sum_{m=1}^{M} \sum_{n \in \mathbb{N}} \rho_{nj}(m) R_{nj}(\text{tn})
\]

with the constraints

\[
C1. \sum_{m=1}^{M} \sum_{j \in \mathbb{N}} P_2(j,m) \leq P_T \quad P_2(j,m) \geq 0 \quad \forall m, j
\]

\[
C2. \sum_{j=1}^{N} \rho_{nj}(m) = 1 \quad \forall m
\]

\[
C3. \quad a_s P_1(n) \leq Q
\]

\[
C4. \quad a_r \left[ \sum_{m=1}^{M} \sum_{j \in \mathbb{N}} P_2(j,m) \right] \leq Q
\]

Constraint C1 denotes that the power summation of secondary relays should not exceed \( P_T \), which can also be treated
as the peak transmission power constraint of the secondary system. C2 indicates that in the secondary system, each node-to-node pair can use only one subchannel at each stage. C3 and C4 are cognitive radio networks power allocation constraints, limiting the peak interference power from the secondary system to the primary system. The $a_s$ and $a_r$ are the channel gains from $S_S$ and $S_R$ to $P_D$, respectively. $Q$ denotes the peak interference power constraint of $P_D$.

C1 and C4 can be combined as

$$\sum_{m=1}^{M} \sum_{j, m \in N} P_2(j, m) \leq \min \left( P_T, \frac{Q}{a_r} \right)$$  \hspace{1cm} (4)

As indicated in Eqn. 1, the maximum throughput of subchannel $j$ is achieved when

$$P_2(j, m)G_2(j, m) = P_2(j, m')G_2(j, m') \ \forall m, m'$$  \hspace{1cm} (5)

Therefore, the power for an individual link is

$$P_2(j, m) = \frac{P_2(j, m)G_2(j, m)}{G_2(j, m)}$$  \hspace{1cm} (6)

Let $P_{req}$ be the required transmission power of a subchannel for a reliable reception of 1 bit/symbol when the channel gain is equal to unity. A successful transmission should satisfy

$$P_2(j, m)G_2(j, m) = P_{req}$$  \hspace{1cm} (7)

We calculate the power consumption of subchannel $j$ as

$$P_2(j) = \sum_{m\in j_m} \frac{P_2(j, m)}{G_2(j)}$$  \hspace{1cm} (8)

where $j_m$ represents the set of destinations that subchannel $j$ links. $G_2(j)$ is the equivalent channel gain of subchannel $j$.

$$G_2(j) = \frac{1}{\sum_{m\in j_m} G_2(j, m)}$$  \hspace{1cm} (9)

Then the throughput of subchannel $j$ is given by

$$R_j = \sum_{n=1}^{N} \sum_{m\in j_m} \frac{B}{N} \rho_{nj}(m) \log_2 \left( 1 + \frac{P_2(j)G_2(j)}{N_0} \right)$$  \hspace{1cm} (10)

Here, we neglect the capacity constraint of the first stage because we have assumed the power for it is large enough for transmission. Therefore, the optimal problem now can be presented as

$$\max_{P_1(n), P_2(j, m), \rho_{nj}(m)} \min R_j$$  \hspace{1cm} (11)

To get a convex function, we substitute $-\min R_j$ as $z$, and relax $\rho_{nj}(m)$ to real number within interval $(0,1]$ to represent the portion of time that subcarriers $n$ and $j$ occupied by $S_Dm$. The convexity of $z$ is shown in Appendix. Therefore, the problem is deduced to

$$\max_{P_1(n), P_2(j, m), \rho_{nj}(m)} -z$$  \hspace{1cm} (12)

This optimization problem is a standard convex optimization problem, which can use the Karush-Kuhn-Tucker (KKT) conditions to solve. However, the computational complexity increases exponentially with the increment of $M$ and $N$. We propose a suboptimal algorithm in the next section.

IV. SUBOPTIMAL SUBCHANNEL AND POWER ALLOCATION

To lower the computational complexity of the optimization, we provide a suboptimal subchannel and power allocation algorithm in this section, which will be linear in $M$ and $N$.

A. Subchannel Allocation With SP

We assume equal power distribution in this subchannel allocation step. The capacity of each link will only depend on the channel gain in a monotonic increasing trend. Therefore, our goal is to get the equivalent channel gain as high as possible. In Table 1, we show the algorithm of assigning the $N$ subchannels to the $M$ $S_D$s.

<table>
<thead>
<tr>
<th>Step 1 :</th>
<th>Initialization: Set all the equivalent gains of $N$ subchannels infinite. For all $n \in N$, assign the subchannel to $S_S$. A link which maximizes $G_2(n)$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2 :</td>
<td>a: For each subchannel, find the one with the highest equivalent gain, say, the $j$th subchannel. b: For the found $j$, search a unassigned $S_D$ with the maximum $G_2(j, m)$, say, the $m$th $S_D$. c: Assign the $j$th subchannel to this $S_D$.</td>
</tr>
<tr>
<td>Step 3 :</td>
<td>If all the $S_D$s have been assigned a subchannel, the subchannel allocation is complete. Else, repeat step 2.</td>
</tr>
</tbody>
</table>

B. Power Distribution With A Fixed SA

For a fixed subchannel allocation (SA) given in the above section, the power distribution algorithm is shown in this section. The optimization problem now is

$$\max_{P_1(n), P_2(j, m), \rho_{nj}(m)} -z$$  \hspace{1cm} (14)

$$\begin{align*}
C1. & \quad -z \leq R_j \\
C2. & \quad \sum_{j=1}^{N} P_2(j) \leq \min \left( P_T, \frac{Q}{a_r} \right) \\
& \quad P_2(j) \geq 0 \ \forall j \\
C3. & \quad a_sP_1(n) \leq Q
\end{align*}$$  \hspace{1cm} (15)
A. System Description

1) Traffic Manner: Quite the same as the first model, in the first stage, \( S_S \) transmits its packet to all \( S_R \)s, and \( S_R \)s do receiving only. In the second stage, \( S_R \)s transmit the received packets to all \( S_D \)s, and \( S_S \) remains idle.

2) Subchannel Utilization: In the links from \( S_S \) to \( S_R \)s, and in the links from \( S_R \) to \( S_D \)s, a specific node-to-node pair can only occupy one subchannel. A sensor network is still assumed, where \( N < M \).

The primary system is the same with the one in the single-relay model.

B. Interference Between Systems

Right now there are multiple secondary relays, which will result in multiple channel gains from those relays to the primary user. The object of peak interference power constraints now is the summation of those \( S_R \)-to-\( P_D \) power.

The achievable data rate of one transmission is

\[
R_{nj}(k, m) = \frac{B}{N} \min \left\{ \min_{1 \leq k < N} \left( 1 + \frac{P_1(n, k)G_1(n, k)}{N_0} \right), \min_{1 \leq m < N} \left( 1 + \frac{P_2(j, m)G_2(j, m)}{N_0} \right) \right\}
\]

where \( k \) and \( m \) represent the arrangement of relay nodes and destination nodes that subchannel \( n \) links in \( S_S-S_R \) links and subchannel \( j \) links in \( S_R-S_D \) links, respectively. \( P_1(n, k) \) and \( G_1(n, k) \) denote the power allocated for subchannel \( n \) to the \( k \)th \( S_R \) and its channel gain, respectively. Identically, \( P_2(j, m) \) and \( G_2(j, m) \) denotes the power allocated for subchannel \( j \) from the \( k \)th \( S_R \) to the \( m \)th \( S_D \) and its channel gain, respectively. \( N_0 \) is the double-sided noise power spectral density level, and we assume it equals to unity.

VI. OPTIMAL SOLUTION FOR MULTI-RELAY MODEL

In this section, we deduce an optimal solution for Eqn. 19. By arranging the subchannels and power, we maximize the minimum subchannel capacity in either stage, and pick the minimum one of the two of them.

To obtain the maximum value of Eqn. 19, the similar method is applied. We obtain the power consumption of subchannel \( n \) and \( j \), respectively.

\[
P_1(n) = \frac{P_{req1}}{G_1(n)}, \quad P_2(j) = \frac{P_{req2}}{G_2(j)}
\]

The equivalent channel gains of subchannel \( n \) and \( j \) are

\[
G_1(n) = \frac{1}{\sum_{k=1}^{K} G_1(n, k)}, \quad G_2(j) = \frac{1}{\sum_{k=1}^{K} \sum_{m=1}^{M} G_2(j, m)}
\]

Now the throughput is

\[
R_{nj} = \frac{B}{N} \min \left\{ \log_2 \left( 1 + \frac{P_1(n)G_1(n)}{N_0} \right), \log_2 \left( 1 + \frac{P_2(j)G_2(j)}{N_0} \right) \right\}
\]
Hence, the equivalent optimization problem can be expressed as
\[
\begin{align*}
\text{min} & \quad \max_{P_1(n)\rho_{nj}(k,m)} \min_{k=1}^{K} \sum_{k=1}^{K} \rho_{nj}(k,m)R_{nj} \\
\text{max} & \quad \min_{k=1}^{M} \sum_{m=1}^{M} \rho_{nj}(k,m)R_{nj}
\end{align*}
\]
with constraints
\[
\begin{align*}
C1. & \quad \sum_{n\in N} P_1(n) \leq \min \left( P_{T1}, \frac{Q}{a_s} \right) \\
C2. & \quad \sum_{j\in N} P_2(j) \leq P_{T2} \\
C3. & \quad \sum_{j=1}^{N} \rho_{nj}(k,m) = 1 \quad \forall k \\
C4. & \quad \sum_{n=1}^{N} \rho_{nj}(k,m) = 1 \quad \forall m \\
C5. & \quad \sum_{k=1}^{K} a_{rk} P_{2k} \leq Q
\end{align*}
\]

P_{T1} and P_{T2} are available power for S_S - S_R links and S_R - S_D links, respectively. P_{2k} denotes the power allocated to the subchannels that start from the kth S_R. It is given by
\[
P_{2k} = \sum_{m=1}^{M} P_{2k}(j,m)
\]

This optimization problem also has a computational complexity that increases exponentially with the increment of K, M and N. We propose a suboptimal solution in the next section.

VII. SUBOPTIMAL SOLUTION FOR MULTI-RELAY MODEL

In this section, we allocate the resource for the multi-relay model. As mentioned in the above section, the primary system now has a tighter constraint to the power allocation in the secondary system, as shown by C1 and C5 in Eqn. 24.

A. Subchannel Allocation

We allocate the subchannels for the secondary system in the same way as in the first model. Allocate the subchannels from S_S to S_Rs first exactly according to the above SA method, with K subchannel gains. Then allocate the subchannels from S_Rs to S_Ds with K\times M channel gain options.

B. Power Distribution With A Fixed SA

With a fixed SA, we can adopt the Lagrangian multiplier method to obtain P_1(n, k) and P_{2k}(j, m). However, the constraint Q has to be considered here. In the first stage, we can simply lower the available power by C1 in Eqn. 24. But in the second stage, we have to redistribute the power of S_Rs according to C2 and C5 in Eqn. 24.

If C5 can not be satisfied, we pick the P_{2k} from the highest one to the lowest one, decrease them as \( P_{2k} = P_{2k} - \frac{P_{2k}}{P_{T2}} \) in turn, until C5 is satisfied. If one loop can not achieve this, start from the highest P_{2k} again.

After power redistribution for each S_R, we have finished the whole suboptimal algorithm. The computational complexity is KMN, which is linear in N and M.

C. Selective Relaying of Multi-Relay networks

Given a multi-relay two-hop network, the destinations could have the ability to choose their preferred relay stations by rearranging the SA sequence as follows.

-Step 1 - Subchannel allocation for relay-destination stage: The S_Ds choose their preferred S_Rs according to subchannel quality. The selected set of S_Rs is named as S_RC.

-Step 2 - Subchannel allocation for source-relay stage: The network controller allocates subchannels to S_Rs within the set of S_RC.

As we can see from the above algorithm, the spectrum resource is saved in the source-relay stage. In unselective relaying, S_S has to send the packet to all S_Rs, with no consideration for the necessity. But in this selective relaying approach, S_Rs are selected by S_Ds first, i.e., only the necessary ones need receive the packet from S_S in step 2.

VIII. SIMULATION RESULTS

In this section, we compare the performance of the proposed suboptimal algorithms with the optimal algorithms. Note that we choose the unselective relaying algorithm for multi-relay model to simulate. The distance from S_Rs to S_S and S_Ds are set to be the same. In real life, the different distances contribute to various channel gains, in which we present in our simulations. Each subchannel is modeled as AWGN with path loss factor 3.

Figure 3 shows the simulation results for the first single-relay model. We set N=5 and M=10. In Figure 3, with the growth of the overall transmission power, the throughput of this system increases at the same time. However, at the end they stop increasing, because the peak interference power constraints of the primary system limit the transmission power of the secondary system. We can see from the simulation that the suboptimal algorithm performance approaches the optimal one. Identically, in Figure 4 for multi-relay model, we set K=5, M=10 and N=4. For the same reason, the throughput of this system increases with the growth of the overall transmission power of the secondary system, but it stops growing for the peak interference power constraints. Although the suboptimal resource allocation algorithms perform not as well as the optimal algorithms when the available power is low, they approach asymptotically the optimal algorithms as transmitting power goes higher. Therefore, we can say that the suboptimal algorithms can fully allocate the subchannel and power resources well when the available power is large enough, which is more practical in reality. This way, the proposed suboptimal algorithms successfully lower the computational complexity from exponential to linear in the number of relays, destinations and subchannels.
the following function be any value on the half-open interval of (0,1]. Considering
reinterpreted as the sharing factor of the \( m \) working in broadcast way with single relay and multiple relays
best possible throughput, we analyze the secondary systems
subchannels and power among nodes well to achieve the
resource and energy in practical application.

A relaying algorithm is addressed. It helps save both spectru m
relaying algorithm can substitute the
algorithms are shown in the simulation results, verifying
the complexity to be linear in the above factors. The compar-
z, the objective function in Eqn. 11 is deduced to a standard
optimization problem is shown here. First, relax the constr ain
ρ and destinations. To achieve a lower complexity, we propose
the growth of the number of subchannels, secondary relays
of the primary system into consideration. However, the opti mal
optimization problem is shown here. First, relax the constr ain
ρ
IX. CONCLUSION

In this paper, the OFDMA-based cooperative cognitive
radio networks are studied. With the goal of allocating the
subchannels and power among nodes well to achieve the
best possible throughput, we analyze the secondary systems
working in broadcast way with single relay and multiple relays one after the other. In the meantime, we make this network a cognitive one by taking the peak interference power constraints of the primary system into consideration. However, the optimal algorithm has an exponential computational complexity with the growth of the number of subchannels, secondary relays and destinations. To achieve a lower complexity, we propose two suboptimal algorithms for either models, which decrease the complexity to be linear in the above factors. The comparisons of performances of optimal algorithms and suboptimal algorithms are shown in the simulation results, verifying that the proposed suboptimal algorithms can substitute the optimal algorithms in practice. At last, an approach of selective relaying algorithm is addressed. It helps save both spectrum resource and energy in practical application.

APPENDIX

Proof of convexity of the objective function in the relaxed
optimization problem is shown here. First, relax the constrain
that the users can only use one subchannel. Thus, \( \rho_{n,j}(m) \) is
reinterpreted as the sharing factor of the \( m \)th \( S_{n,j}D_j \), which can be any value on the half-open interval of \((0,1] \). Considering the following function

\[
f(\rho_{n,j}(m), P_2(j)) = \rho_{n,j}(m) \log_2\left(1 + \frac{P_2(j)G_2(j)}{N_0}\right)
\]

Substitute \( G_2(j)/N_0 \) as \( H(j) \). The Jacobian of
\( f(\rho_{n,j}(m), P_2(j)) \) is calculated as

\[
\nabla f(\rho_{n,j}(m), P_2(j)) = \left[\begin{array}{c}
\log_2 \left(1 + P_2(j)H(j)\right) \\
\rho_{n,j}(m)H(j)
\end{array}\right]
\]

The Hessian of \( f(\rho_{n,j}(m), P_2(j)) \) is calculated as

\[
\nabla^2 f(\rho_{n,j}(m), P_2(j)) = \frac{1}{\ln 2} \begin{bmatrix}
H(j) & 0 \\
0 & 1 - \frac{\rho_{n,j}(m)H(j)}{1 + P_2(j)H(j)}
\end{bmatrix}
\]

Since \( \rho_{n,j}(m), P_2(j) \) and \( H(j) \) are all positive, the Hessian of
\( f(\rho_{n,j}(m), P_2(j)) \) is negative semidefinite and, hence, \( f(\rho_{n,j}(m), P_2(j)) \) is concave. As we substitute \( \min R_j \) as
z, the objective function in Eqn. 11 is deduced to a standard convex optimization problem Eqn. 12, with convex constraints
Eqn. 13.

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