Distributed Scheduling in MIMO Empowered Cognitive Radio Ad Hoc Networks

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Abstract—Two fast growing technologies, MIMO and cognitive radio (CR), can both effectively combat the transmission interference among links and thus increase the network throughput. MIMO exploits spatial degree of freedom (DoF) through spatial multiplexing and interference cancelation within the same frequency channel, while CR exploits all available frequency channels for transmissions. We consider an ad hoc network where each node is equipped with an array of cognitive radios. A radio can tune to a different channel and transmit independently, or transmit together with other radios on the same channel using MIMO mode. Additionally, different frequency and spatial channels could have different conditions. There is a big challenge for nodes to distributively coordinate in selecting a transmission channel and/or a spatial DoF taking advantage of this unprecedented flexibility and diversity of channels for a higher network performance. In this work, we mathematically model the opportunities and constraints for such a network with the objective of maximizing the weighted network throughput. We propose a centralized algorithm as our comparison benchmark, and a distributed algorithm to flexibly assign spectrum channel or spatial DoF exploiting the multiuser diversity, channel diversity and spatial diversity for a higher performance in a practical network. The algorithm further supports different transmission priorities, reduces transmission delay and ensures fair transmissions among nodes by providing all nodes with certain transmission probability. The performance of our algorithms are studied through extensive simulations and the results demonstrate that our algorithm is very effective and can significantly increase the network throughput while reducing the delay.

Index Terms—Cognitive radio, MIMO, scheduling, MAC, ad hoc network.

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1 INTRODUCTION

Cognitive radio (CR) techniques have received growing research interests in recent years. CR promises unprecedented flexibility in radio functionalities via the programmability at the lowest layer, which was once done in the hardware. Due to its spectrum sensing, learning, and adaptation capabilities, CR is able to address the heart of the problem associated with spectrum scarcity (via dynamic spectrum access (DSA)) and inter-operability (via channel switching). CR has been accepted as one enabling radio technology for the next-generation wireless communications [1], [2], and has been implemented for cellular communications [3], military applications [4], and public safety communications [5]. It is envisioned that CR will be employed as a general radio platform upon which numerous wireless applications can be implemented.

Instead of exploiting the spectrum opportunities, multiple-input multiple-out MIMO [6] techniques target to harvest the spatial channel gain through intelligent antenna and signal processing techniques. With multiple antennas at the transmitter and/or receiver, a MIMO system takes advantage of multiplexing to simultaneously transmit multiple data streams on the same channel to increase the wireless data rate and diversity to optimally combine signals from different trans-

mission streams to increase the transmission reliability and range. The benefits of MIMO lead many to believe it is the most promising technique of emerging wireless technologies. MIMO is prominently regarded as a technology of choice for next generation wireless systems such as IEEE 802.16, IEEE 802.11n, and the third and fourth generation cellular systems.

Currently, the advances of CR (see, e.g., [2], [7]–[9]) and MIMO (see, e.g., [10]–[15]) are largely independent and in parallel. Due to the challenge of each research direction, there is very limited work studying the two together to exploit both spectrum opportunities and spatial opportunities. Some recent studies [16]–[18] investigate the information gain by exploiting MIMO beamforming to constrain the interference towards the primary users instead of the joint exploration of spectrum and spatial resources. Without knowledge of primary user signatures, it is also hard to measure the channels and constrain the interference in reality. A recent work in [19] intends to understand the potential capacity gain with joint use of MIMO and CR. The implicit assumption that an antenna can simultaneously access multiple frequency bands makes it similar to conventional work on OFDM plus MIMO and fundamentally different from our framework. The paper focuses on forming an optimization framework, rather than provides an actual transmission algorithm. The ordering of transmissions may be difficult to realize distributively, and the OFDM kind of transmissions may apply to sub-carriers but not to wide spectrum channels. Different from work on multi-channel allocations [20]–[26] which normally assume all nodes access the same group of channels and mainly consider channel coordination, our design takes into account the difference in channel availability at different nodes as an

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inherent nature of cognitive radio transmissions, the different channel conditions and multi-user diversity, and particularly the opportunities and constraints of antennas in supporting concurrent MIMO and CR transmissions. We focus on addressing the challenge of exploiting concurrent MIMO and CR opportunities, while assuming the spectrum availability can be detected via various spectrum sensing techniques [27]–[32] proposed in the literature.

The goal of this work is to develop a distributed algorithm that can concurrently exploit the agility of CR and MIMO to benefit from both the opportunities of spare spectrum channels and spatial degree of freedom (DoF) for an overall higher throughput and lower delay in a multi-hop wireless network. Different antennas can transmit over different idle frequency channels to harvest the spectrum gain, while all or a subset of antennas of a node can also form a MIMO array to exploit the spatial gain. There is a tradeoff between the two options and how to assign transmission channels and antennas depend on many factors, including the network topology, the physical channel conditions, the node density, and the traffic patterns. Generally, we expect MIMO plays more roles when the available number of channels is small or the node density is high in a neighborhood. MIMO also could work better in a more severe channel condition. In addition, we consider the heterogeneity in transmission conditions of both spectrum channels and spatial channels. We coherently model all the options and develop scheduling algorithms to enable concurrent exploration of the two cutting-edge technologies to address the challenge of spectrum scarcity.

To our best knowledge, this is the first work that provides the cognitive distributed scheduling algorithm that takes into account the network and channel conditions and exploits benefits of both CR and MIMO for their seamless operations over an ad hoc network. Our contributions can be summarized as follows:

- We form a mathematical model to capture the opportunities and constraints of concurrent exploration of MIMO and CR techniques, taking into account the diversity of different frequency and spatial channels.
- We provide a centralized algorithm to solve the problem for performance reference, considering various diversities.
- We propose an adaptive and distributed scheduling algorithm to jointly allocate the spectrum channel and spatial DoF taking advantage of both CR and MIMO for an overall higher network performance. In addition, our algorithm exploits the potential of antenna selection and stream allocation taking advantage of the multiuser diversity, channel diversity and spatial diversity to further improve the network performance.

The remainder of this paper is organized as follows. In Section 2, we introduce the tradeoffs of different configurations of CR and MIMO, thus laying the foundation for mathematical modeling in Section 3 for joint optimization of CR and MIMO. Section 4 and 5 propose a centralized algorithm as a performance benchmark and a flexible distributed algorithm for application in a practical network, respectively. In Sec-

tion 6, we present simulation results, evaluate the algorithms performance, and validate the efficiency of our algorithms in comparison to other reference algorithms. Section 7 concludes the paper.

2 PRELIMINARY AND MOTIVATION

We consider a multi-hop CR ad hoc network with an antenna array at each node, and we call this network a MIMO-CRN. With its CR, a node is able to sense its environment and identify a set of available frequency channels for wireless communications. The set of available frequency channels at one node may be different from those at another node in the network. Two nodes can communicate only if they have at least one available channel in common, and a link can interfere with another link only if these two links operate on the same channel at the same time. Therefore, a CRN can exploit available spectrum and avoid the transmission interference via the use of different channels.

Complementary to a CR's ability to handle the interference at the channel level, within a frequency channel, MIMO technique can mitigate co-channel interference by exploiting spatial degree of freedom (DoF). At the transmitter side, the number of data streams is limited by the number of antenna elements. Due to the broadcast nature of wireless communication, at the receiver side, a node will receive not only the data streams targeting to it, but also interference streams targeting to other nodes nearby. To successfully decode data streams at a receiving node, the total number of data streams and interference streams should be fewer than the number of antenna elements at the receiver.

Before formally formulating the problem, we provide a few case studies to illustrate the issues and opportunities with the concurrent use of these two advanced technologies together.

1. Transmissions over frequency channels versus spatial channels. The DoF of nodes can be flexibly used for transmission over frequency channels or spatial channels, and an antenna can only access one frequency channel at a time. In Fig. 1(a), node 1 transmits 3 data streams over channel b towards node 2 and 1 data stream towards node 4 over channel c, taking up its 4 DoF. Node 4, which uses 1 DoF to receive from node 1 over channel c, could spare its remaining 3 DoF to receive from node 3 over channel a. An optimum assignment of DoF over both frequency and spatial domain could allow more concurrent stream transmissions. For example, in Fig. 1(b), 8 data streams can be transmitted concurrently, 4 from node 1 to node 2 using the channel b and another 4 from node 3 to node 4 on channels a and c respectively.

2. Tradeoff between multiplexing and interference cancelation. In Fig. 2, six nodes each with two antennas run on the same channel and form three links, $1 \rightarrow 2$, $3 \rightarrow 4$, and $5 \rightarrow 6$. In the MIMO multiplexing mode [6] shown in Fig. 2(a), if any link X activates two data streams, then the other two links must keep idle to avoid colliding with or being collided by transmissions on the link X. For example, when node 1 transmits two data streams using both of its antennas through spatial multiplexing, it will create two interference streams at

(a) Via spatial multiplexing.

(b) Via interference cancellation.

Fig. 1. Frequency channels versus spatial channels.

node 6. Therefore, node 5 can no longer transmit any data stream to node 6. Similarly, if node 3 transmits any data stream, it will create additional interference to node 2, while node 2 has applied both of its antennas to receive data from node 1 and cannot spare any antenna to cancel the interference. Totally only two streams can be transmitted in this case. However, if each link only transmits one data stream, each receiver can use one antenna to receive data and the other to combat the interference from the interfering transmitter by decoding the interfering stream and removing it from the total received signal. As shown in Fig. 2(b), the network allows three simultaneous data steams, thus interference cancellation is exploited here to transmit more streams than simply using MIMO multiplexing.

A counter example is shown in Fig. 3. Each node has two antennas and all nodes transmit on the same frequency channel. With MIMO multiplexing, as shown in Fig. 3(a), both link $1 \rightarrow 2$ and link $3 \rightarrow 4$ can transmit two data streams, so there are totally four data streams in the network. However, when exploiting the benefit of MIMO interference cancellation, both link $5 \rightarrow 6$ and link $1 \rightarrow 2$ have one active data stream, while link $3 \rightarrow 4$ must keep idle to avoid colliding at node 6. In this case, the maximum total number of data streams is only two.

We can see from the above two examples that there is a tradeoff between MIMO multiplexing and interference cancellation. Given different network topologies, and different interference relationship among nodes, it is important to find the optimal strategy for maximizing the total number of data streams.

3. The impact of channel condition and diversity. The above examples only try to maximize the total number of concurrent number of data streams without considering the difference in channel conditions thus rate, which is over-simplified and easily fails in achieving a high network through-put in reality. In Fig. 2(a), when node 1 transmits 2 data streams to node 2, the two data streams have different channel gains. While in Fig. 2(b), node 1/3/5 each can select the better spatial channel among two possible ones to transmit to node 2/4/6, which takes advantage of the *spatial diversity* to further increase the capacity.

4. The Impact of decoding scheme. The other thing that impacts the link capacity is the decoding scheme at the receiver side. For example, the commonly used "Sequential Interference Cancelation" (SIC) decoding scheme normally decodes the strongest signal first. In Fig. 2(a), when two data streams are transmitted from node 1 to 2, the first stream decoded will

be impacted by the interference from the second one, thus the capacity of the link is compromised. In Fig. 2(b), however, each link has one data stream and one interference stream. If we vary the original SIC to decode the interferer first, the data stream can achieve a higher rate once the interference is cancelled. As a result, Fig. 2(b) can achieve a higher rate per stream in addition to transmitting a larger number of streams. Therefore, in a distributed cooperative transmission environment where interference and data transmissions are not from the same transmitter, it is beneficial to decode the interference streams first.

3 MATHEMATICAL MODELING

3.1 Modeling of MIMO-CRN

In a CR network, as different nodes may have different channel accessibility due to spectrum policy and interference, a common control channel (CCC) accessible to all nodes is used in the network to coordinate transmissions. For each neighboring node j, a node $i \in \mathcal{N}$ in a MIMO-CRN can access one available frequency channel in a set $\mathcal{B}_i$ not occupied by primary users, and has a packet queue $\mathcal{Q}_{ij}$. The set $\mathcal{B}_i$ may be different at different geographic locations and time, and the set of commonly available channels between nodes i and j can be denoted as $\mathcal{B}_{ij} = \mathcal{B}_i \bigcap \mathcal{B}_j$. Two nodes can communicate if and only if they have at least one common data channel and within the transmission range. Denote $\mathcal{A}_i$ as the set of antennas at node i. Each antenna can only access one channel at a time. In our work, we assume that all the nodes have the same number of antennas, A, for the convenience of presentation. Our scheme, however, can be easily extended to the case where each node has different number of antennas. With the use of multiple antennas at both the transmitter and the receiver, it is possible to apply different MIMO transmission strategies, e.g., exploiting all antennas to perform spatial multiplexed transmissions or using some of the antennas to cancel the interference, as introduced above. As we focus on concurrent exploration of CR and MIMO's ability to handle interference, we do not consider spatial diversity technology for range extension and leave this as our future work.

Before presenting algorithms for scheduling, we first mathematically model the problem and our objective is to maximize the weighted system throughput.

3.1.1 Transmission/Reception Constraints

We first present the constraints at the transmitters and receivers. To model the half-duplex nature of each node, we
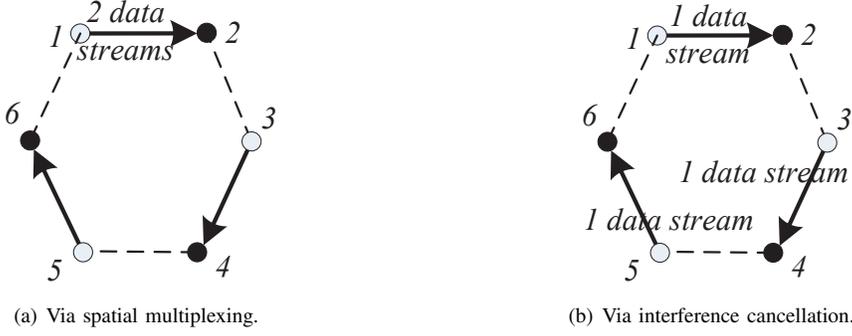
(a) Via spatial multiplexing.

(b) Via interference cancellation.

Fig. 2. MIMO spatial multiplexing V.S. interference cancellation A.

(a) Via spatial multiplexing.

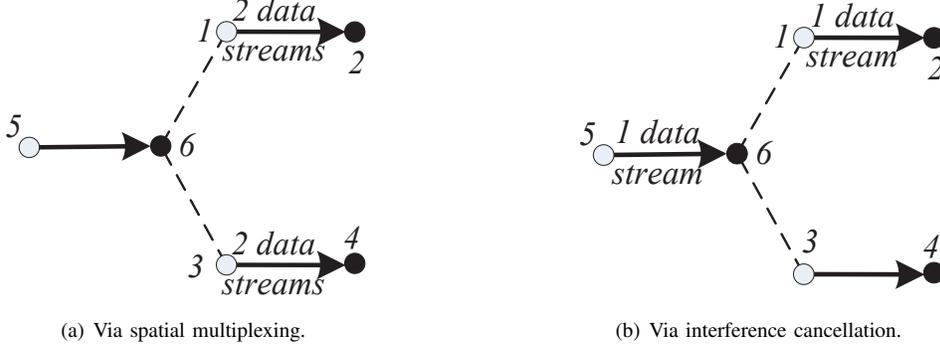(b) Via interference cancellation.

Fig. 3. MIMO spatial multiplexing V.S. interference cancellation B.

use two binary variables g_i and h_i to indicate node i's transmission/reception status, i.e., $g_i/h_i = 1$ if node i is transmitting/receiving and 0 otherwise. Then the half-duplex constraint can be represented as

$$g_i + h_i \leq 1 \qquad (i \in \mathcal{N}) . \tag{1}$$

To represent a node i's behavior on a channel b, we define a new set of binary variables g_i^b and h_i^b, where $g_i^b/h_i^b = 1$ if node i is transmitting/receiving on channel b and 0 otherwise.

Clearly, when node i is a transmitter, it must be transmitting on some channels; and if it is not transmitting on any of the available channels, it must not be a transmitter. Thus, we have

$$g_i^b \leq g_i \leq \sum_{b \in \mathcal{B}_i} g_i^b \quad (i \in \mathcal{N}, b \in \mathcal{B}_i) . \tag{2}$$

For the receiver case, similarly we have,

$$h_i^b \leq h_i \leq \sum_{b \in \mathcal{B}_i} h_i^b \quad (i \in \mathcal{N}, b \in \mathcal{B}_i) . \tag{3}$$

For a target receiver and a given channel b, the channel condition thus data rate is different when a different antenna is used. For the same antenna, the achievable data rate is different over different frequency channels. Therefore, when performing the scheduling algorithm at the transmitter side, we need to identify which antenna is actually selected for the transmission on a specific channel. We define $g_{i,k}^b = 1$ if node i is using its kth antenna for transmission on channel b, and 0 otherwise.

An antenna can only work on one channel at a time, thus

$$\sum_{b \in \mathcal{B}_i} g_{i,k}^b \leq 1 \qquad (i \in \mathcal{N}, k \in \mathcal{A}_i) . \tag{4}$$

Also when $g_{i,k}^b = 1$ for some antenna k, it means node i

is transmitting on channel b, then g_i^b must be 1. On the other hand, if $g_i^b = 0$, it means node i is not transmitting on channel b, then all its antennas will not use channel b, thus $g_{i,k}^b = 0$. This relationship can be represented as follows.

$$g_{i,k}^b \leq g_i^b \leq \sum_{k \in \mathcal{A}_i} g_{i,k}^b \qquad (i \in \mathcal{N}, b \in \mathcal{B}_i, k \in \mathcal{A}_i) . \tag{5}$$

Let $\mathcal{N}_i^b$ represent the set of neighbors of i that share the same channel b. To identify the packet transmitted out, we define the variable $g_{i,k}^{b,p} = 1$ if node i is using its kth antenna to transmit packet p on channel b, and $g_{i,k}^{b,p} = 0$ otherwise.

Similar to the analysis with constraints in equation (5), we have the following constraints on variables $g_{i,k}^{b,p}$.

$$g_{i,k}^{b,p} \leq g_{i,k}^b \leq \sum_{p \in \mathcal{Q}_i} g_{i,k}^{b,p} , \tag{6}$$

where $i \in \mathcal{N}, b \in \mathcal{B}_i, j \in \mathcal{N}_i^b, k \in \mathcal{A}_i, p \in \mathcal{Q}_{ij}$.

If a node is chosen to be a transmitter for its packet p, say $g_{i,k}^{b,p} = 1$, then the corresponding destination node of packet p, i.e., node j should be a receiver on the same channel via some antenna. That is, denoting a binary variable h_i^b to be 1 if node i is receiving packets on channel b, and 0 otherwise. Then $g_{i,k}^{b,p} = 1$ leads to $h_j^b = 1$. This can be represented as follows.

$$g_{i,k}^{b,p} \leq h_j^b \qquad (i \in \mathcal{N}, b \in \mathcal{B}_i, j \in \mathcal{N}_i^b, k \in \mathcal{A}_i, p \in \mathcal{Q}_{ij}) . \tag{7}$$

To facilitate concurrent transmissions from multiple nodes and antennas, our scheduling solution is slot-based, with which the time domain is divided into transmission durations (TD). A TD consists of control signal exchange and several time slots. The channel assignment and antenna allocation is fixed

for a TD. Note that an antenna can send out multiple packets targeting to the same receiver without exceeding the data rate over the channel, we have the following capacity constraint.

$$\sum_{p \in \mathcal{Q}_{ij}} g_{i,k}^{b,p} \cdot s_p \leq TD \cdot r_{i,k}^{b,j} , \qquad (8)$$

where s_p denotes the size of packet p, $r_{i,k}^{b,j}$ denotes the data rate on channel b between the antenna $k \in \mathcal{A}_i$ of the transmitter i and the receiver j, and $i \in \mathcal{N}, b \in \mathcal{B}_i, j \in \mathcal{N}_i^b, k \in \mathcal{A}_i$, and $p \in \mathcal{Q}_{ij}$. The data rate is impacted by the channel condition, signal strength, noise and interference levels.

We know that the total number of data streams for transmission or reception at a node is limited by its number of antennas. First we have the following constraints for a transmitter.

$$g_i \leq \sum_{k \in \mathcal{A}_i} g_{i,k}^b \leq g_i |\mathcal{A}_i| \qquad (i \in \mathcal{N}) . \qquad (9)$$

For a receiver, it needs to use its antennas for both data reception and interference cancellation. Denote the set of neighbor nodes of the receiver i on channel b as $\mathcal{N}_i^b$, then the antenna constraints at a receiver node is as follows.

$$\sum_{b \in \mathcal{B}_i} \left(h_i^b \sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b \right) \leq |\mathcal{A}_i| \qquad (i \in \mathcal{N}) . \qquad (10)$$

3.1.2 Objective

Our objective is to maximize the total weighted throughput during the transmission. Here the weight is represented as the priority of the packets. The objective can be mathematically formulated as follows:

$$\sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{A}_i} \sum_{b \in \mathcal{B}_i} \sum_{p \in \mathcal{Q}_{ij}} g_{i,k}^{b,p} \cdot pr(p) \cdot s_p \qquad (j \in \mathcal{N}_i^b) , \qquad (11)$$

where $pr(p)$ denotes the priority of the packet p. The packet priority depends on the service type and queuing delay, thus the consideration of priority helps to reduce the transmission delay. The value of $pr(p)$ is initially set to the service priority of the packet and increases as the queuing duration increases.

Then the optimization problem can be formulated as follows.

$$\max \quad \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{A}_i} \sum_{b \in \mathcal{B}_i} \sum_{p \in \mathcal{Q}_{ij}} g_{i,k}^{b,p} \cdot pr(p) \cdot s_p \qquad (j \in \mathcal{N}_i^b),$$
$$\text{s.t.} \qquad \text{Constraints } (1) - (10).$$

In this formulation, g_i, g_i^b, $g_{i,k}^b$, $g_{i,k}^{b,p}$, h_i, h_i^b are optimization variables and s_p, $r_{k,i}^b$, $\mathcal{A}_i$, $pr(p)$ are given constants. Because of the nonlinear term $h_i^b \sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b$ in (10) and integer variables, the problem is in the form of Mixed Integer Non-Linear Programming (MINLP).

3.2 A Linearization Reformulation

Due to the nonlinear term in the above formulation, it requires much more efforts to solve such an optimization problem. Mature commercial packages, e.g., CPLEX, cannot easily handle an MINLP. A closer examination of the above formulation shows that we can actually reformulate the original problem and make it simpler. Now define a new variable θ_i^b as follows.

$$\theta_i^b = h_i^b \sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b \qquad (i \in \mathcal{N}, b \in \mathcal{B}_i) . \qquad (12)$$

The physical meaning of θ_i^b is the number of DoFs that costs node i for data reception and interference cancelation on channel b. With θ_i^b, (10) can be rewritten as:

$$\sum_{b \in \mathcal{B}_i} \theta_i^b \leq |\mathcal{A}_i| \qquad (i \in \mathcal{N}) . \qquad (13)$$

Let $A_i = |\mathcal{A}_i|$. Now, a set of new constraints for θ_i^b are required. For the binary variable h_i^b, we have the following two constraints: $h_i^b \geq 0$, $1 - h_i^b \geq 0$. Similarly, for $\sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b$, we have: $\sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b \geq 0$, $A_i - \sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b \geq 0$. Multiplying each constraint involving h_i^b by one of the two constraints involving $\sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b$, and replacing the product term with the new variable θ_i^b, we have the following new constraints.

$$\theta_i^b \geq 0 \qquad (14)$$
$$\theta_i^b \leq \sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b \qquad (15)$$
$$\theta_i^b \leq A_i \cdot h_i^b \qquad (16)$$
$$\theta_i^b \geq A_i \cdot h_i^b + \sum_{j \in \mathcal{N}_i^b} \sum_{k \in \mathcal{A}_j} g_{j,k}^b - A_i \qquad (17)$$

It can be verified that for the case when h_i^b is a binary variable, (12) is equivalent to the constraints in (14) to (17). Therefore, we have a new formulation as follows.

$$\max \quad \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{A}_i} \sum_{b \in \mathcal{B}_i} \sum_{p \in \mathcal{Q}_{ij}} g_{i,k}^{b,p} \cdot pr(p) \cdot s_p \qquad (j \in \mathcal{N}_i^b) ,$$
$$\text{s.t.} \qquad \text{Constraints } (1) - (9), (13) - (17).$$

In this new problem formulation, g_i, g_i^b, $g_{i,k}^b$, $g_{i,k}^{b,p}$, h_i, h_i^b, θ_i^b are optimization variables and s_p, $r_{k,i}^b$, $\mathcal{A}_i$, $pr(i_p)$ are given constants. This new formulation is in the form of Integer Linear Programming (ILP) which can be handled by commercial package, e.g., CPLEX, to obtain the optimal objective value.

4 CENTRALIZED ALGORITHM

An ILP problem is NP-hard in general, and needs exponential time complexity to find a solution. Although the above formulation can be solved by a commercial package, it is not suitable for the practical implementation. In this section, we develop an efficient centralized algorithm to solve the problem where all the queue and stream information is assumed to know at a central controller. The design and performance of the centralized algorithm provide a benchmark for the distributed algorithm.

4.1 Initialization

At the beginning of the algorithm, the central controller collects all the information from nodes. The information of a node i includes its channel availability, the set of neighboring nodes, the condition of each frequency channel between an antenna

and a neighboring node, the packets in queue and their priority. Based on the neighboring information, the central controller creates a directed graph G_0 to indicate the connection and interfering relationship between nodes without specifying the antenna and frequency channel assignment. Each node in the network is represented by a vertex. For any node pair (i, j), if i has packets targeted for j, there is a data edge from i to j; if the transmission of i interferes with the receiving of j, there is an interference edge from i to j. The information and the connected graph are updated in each transmission duration.

4.2 Greedy Scheduling

For a transmission duration t where $t = 1, 2, \ldots$, the central controller iteratively performs the following steps based on a weighted directed graph G_{t-1}.

1) **Pre-Scheduling Update**
   This step is performed at the beginning of a transmission duration. As modeled in Section 3, each node i in the network keeps a queue $\mathcal{Q}_{ij}$ with packets targeted for each neighboring node j, and the queues are updated in each interval. The priority of packet p, denoted as $pr(p)$, depends on the service type and queueing time. The queue priority is the cumulative priority of packets in queue with $Q_{ij}^{prio} = \sum_{p \in \mathcal{Q}_{ij}} pr(p)$, and is a weight associated with the data stream edge from node i to j in the updated connected graph G_t.
   The optimal solution, formed by selected data stream edges, is a subgraph of G_t and denoted as G_{opt}. We also create another subgraph called block graph G_b to save the edges that cannot be scheduled in the current duration. At the beginning of each transmission duration, both G_{opt} and G_b are set to $\emptyset$, and each node is allowed to be either a transmitter or a receiver.

2) **Stream and Channel Allocation**
   The central controller selects the edge with the highest weight from G_t, denoted as $e_h = (s_h, d_h)$ where s_h and d_h are the source and destination nodes of e_h respectively.

   - Construct a set to include the stream quality of the selected edge with all the available antenna and channel combinations: $S_h = \{Q(k,b)|e_h = (s_h, d_h), k \in A_{s_h}, b \in \mathcal{B}_{s_h, d_h}\}$ where A_{s_h} is the set of unused antennas at s_h, and $\mathcal{B}_{s_h, d_h}$ is the set of available channels between s_h and d_h. $Q(k,b)$ is the stream quality factor for the stream between the antenna k and the node d_h via the channel b. The stream quality depends on the transmission power of the stream and the channel condition between the transmitter antenna and the receiver node of this stream. For a given total transmission power at a node, if more streams are selected from the node to be transmitted, the transmission power for each stream will reduce. This will reduce the signal to interference and noise radio of the stream at the receiver thus the corresponding rate the stream can support.

   - Find the largest element in S_h, denote it as $Q_{\max}$, and the corresponding transmitter node, receiver node, antenna, channel as $s_{\max}$, $d_{\max}$, $k_{\max}$ and $b_{\max}$ respectively. Note that $s_{\max} = s_h$ and $d_{\max} = d_h$. For the convenience of presentation, we also denote the edge formed by $s_{\max}$ and $d_{\max}$ as $e_{\max}$.

   - Tentatively add $e_{\max}$ with the antenna assignment $k_{\max}$ and channel assignment $b_{\max}$ to G_{opt}. Check whether (10) is still satisfied for G_{opt}.
     - If not, remove $e_{\max}$ from G_{opt}, and remove the elements in $Q(k,b)$ corresponding to $k = k_{\max}$ and $b = b_{\max}$ from S_h, as the assignment $k_{\max}$ and $b_{\max}$ for $e_{\max}$ is infeasible to be scheduled. If $S_h = \emptyset$, remove the edge $e_{\max}$ from G_t and add it to G_b, as $e_{\max}$ is infeasible to be scheduled with any assignment of antenna and channel.
     - Else, mark $s_{\max}$ as a transmitter node and $d_{\max}$ as a receiver node if they are not currently marked yet. Assign $e_{\max}$ to the antenna $k_{\max}$ and channel $b_{\max}$, add $e_{\max}$ along with the channel allocation information to G_{opt}, and update $A_{s_{\max}}$. Remove the set of edges with $s_{\max}$ as the receiver node or $d_{\max}$ as the transmitter node from G_t and add them to G_b. Meanwhile, if any node associated with $e_{\max}$ becomes fully loaded (i.e., (9) or (10) now becomes equation), delete all edges that may overload the node from G_t and add them to G_b. Delete elements associated with $k_{\max}$ from S_h.

3) **End Check**
   Check whether there is still any edge in G_t. If yes, go to (2); else go to (4);

4) **Post-scheduling Update**
   Schedule the transmissions according to the graph G_{opt} generated. Add the edges in G_b back to G_t, which will be used for the scheduling in the next transmission duration.

4.3 Algorithm Properties

The proposed centralized scheduling algorithm has the following property.

Property 1: For any edge (together with antenna and channel information) that is not scheduled, and the corresponding queue has a higher priority than the scheduled queue with the lowest priority, the scheduling will not be feasible if this edge is added, i.e. (9) or (10) cannot be satisfied.

With this property, we can prove that the centralized algorithm achieves a fixed approximation ratio compared with the optimum solution that obtains the highest aggregate data rate.

Theorem 1: The proposed centralized algorithm can achieve an approximation ratio of $1/(((2 + max_{i \in \mathcal{N}}|\mathcal{A}_i|)max_{i \in \mathcal{N}}|\mathcal{N}_i| + 2) \cdot |\bigcup_{i \in \mathcal{N}} \mathcal{B}_i|)$, where $\mathcal{N}_i$ is the set of neighboring nodes of node i.

Proof: The worst case of the algorithm is that all data streams are scheduled on the same channel. In such case, the performance degenerates to one channel case, where the approximate ratio of the algorithm to the optimal is proved to be $1/((2 + max_{i \in \mathcal{N}}|\mathcal{A}_i|)max_{i \in \mathcal{N}}|\mathcal{N}_i| + 2)$ [14]. Therefore,

in MIMO-CRN, the improvement factor of the optimal is upper bounded by the number of channels $|\bigcup_{i \in \mathcal{N}} \mathcal{B}_i|$). To conclude, the proposed centralized algorithm can achieve an approximation ratio of $1/(((2 + max_{i \in \mathcal{N}}|\mathcal{A}_i|)max_{i \in \mathcal{N}}|\mathcal{N}_i| + 2) \cdot |\bigcup_{i \in \mathcal{N}} \mathcal{B}_i|)$. $\square$

5 DISTRIBUTED ALGORITHM

A centralized scheduling algorithm involves a high communication overhead and computation complexity, and is not suitable for a network with dynamic topology. In this section, we develop a distributed algorithm which takes advantage of multiuser diversity, channel diversity, and spatial diversity, to maximize the weighted throughput. As the centralized case, our distributed scheduling is also slot-based. Note that slot synchronization is currently achievable in the IEEE802.11 family of protocols [11], and the channel negotiations between nodes also facilitate synchronization. In each transmission duration (TD), our distributed algorithm contains several phases, namely, transmitter selection, channel measurement, channel assignment, data stream allocation, and data transmission. During each phase, nodes compete in transmitting out the control messages using Carrier Sense Multiple Access (CSMA)-based scheme over the common control channel.

The common channel and different data channels may have different transmission ranges. The neighbor relation among nodes on a channel is based on the received signal strength measured, and does not change frequently. To facilitate transmission negotiation, a transmitter will send the signaling message at a large enough power so it can reach all its neighbors on data channels. As our focus is on the efficient MAC scheduling of channel and antenna resources in a MIMO-CRN, the detailed procedure of finding network topology is beyond our scope.

There is a significant challenge for nodes to coordinate in selecting both the channel and antenna to use in a distributed manner. The scheduling algorithm in each phase tries to consider the transmission priority and the channel conditions while reducing the transmission collision and interference.

5.1 Transmitter Selection

As a result of the half-duplex nature of wireless communications, there is a need of selecting a set of nodes to be the transmitters in a TD. Instead of randomly selecting several nodes as transmitters, our algorithm adaptively chooses transmitters such that a queue with the higher priority would be transmitted with a higher probability to reduce the transmission delay, while also introducing some randomness for transmission fairness.

In a meshed network enabled with MIMO and CR, a transmitter can transmit simultaneously to multiple receivers with one-to-many transmission, while multiple transmitters can also transmit simultaneously to a receiver with many-to-one transmission. Both types of transmission can be carried over multiple frequency channels or multiple spatial channels. Specifically, in many-to-one transmission, multiple transmitters can transmit concurrently over the same frequency channel forming cooperative-MIMO transmission with the receiver, which takes advantage of the spatial DoF to reduce the number of frequency channels occupied. Although one-to-many transmission can be also supported over the same frequency channel, it costs DoFs of each receiver to cancel the interference from transmissions towards other receivers. In addition, the maximum power of the transmitter needs to be divided among several streams, leading to a lower per-steam capacity. It is also hard to make a decision at the transmitter when different receivers take conflicting stream allocation choices. Therefore our selection is more favorable to a multiuser cooperative transmission in a many-to-one format.

We consider a node with packets to transmit as an *active* node. To facilitate the selection of a subset of nodes to be transmitters in the neighborhood, we introduce a threshold parameter P^{TX}, which is estimated by each node based on the priority values of all nodes in its neighborhood. In order not to exceed the decoding capacity of any node during the data transmission phase, the number of streams that can be simultaneously transmitted in the neighborhood is constrained. To avoid unnecessary channel measurement and reduce processing complexity at a receiver, the number of transmitters in a neighborhood is also constrained to TX, which can be calculated by a node i as:

$$TX = \begin{cases} |\mathcal{N}_i - \mathcal{B}_i| & \text{if } 2|\mathcal{B}_i| < |\mathcal{N}_i| \ , \\ |\lceil \mathcal{N}_i/2 \rceil| & \text{otherwise.} \end{cases}$$

This is because the number of concurrent transmissions in the neighborhood of a node i is limited by two major factors: the number of available channels if the number of neighboring nodes is relatively high, i.e. $2|\mathcal{B}_i| < |\mathcal{N}_i|$; or the number of transmitting nodes thus the total traffic. In the first case, the number of receivers is set to be equal to the number of channels $\mathcal{B}_i$, and many-to-one transmission is exploited over the same frequency channel to improve the throughput. If there are sufficient number of channels, half of the nodes can serve as active transmitters to maximally support the concurrent number of transmissions using the available channels.

An active node i can calculate P^{TX} as:

$$P^{TX} = \frac{TX * \sum_{j \in \mathcal{N}_i} Q_{ij}^{prio}}{\sum_{j \in \mathcal{N}_i} \sum_{k \in \mathcal{N}_j} Q_{jk}^{prio} + \sum_{j \in \mathcal{N}_i} Q_{ij}^{prio}} \ . \quad (18)$$

It then generates a random number γ_i with the value uniformly distributed in the range $[0, 1]$. If $\gamma_i < P^{TX}$, node i *self-decides* to be a transmitter; otherwise, it has no right to transmit. The use of a random number gives each node a chance to serve as a transmitter, and also facilitates each node to independently determine if it can serve as a transmitter in a time slot. On the other hand, as an active node with a higher priority has a higher P^{TX} value, a node with a higher service level and/or larger load and hence longer delay has a higher chance of being selected as the transmitter node. Our selection algorithm thus supports QoS and load balancing while ensuring certain fairness. This self-selection scheme avoids extra signaling overhead for transmitter selection.

5.2 Channel Assignment

After a node self-decides to be a transmitter, it will select a set of receiver nodes for its data transmission. To support QoS and different service levels, a transmitter node i first sorts $\mathcal{Q}_{ij}$ for all $j \in \mathcal{N}_i$ in the descending order of queue's priority. It then iteratively selects j as its receiver based on the sorted queue priority. For each transmitter node i, up to $|\mathcal{A}_i|$ receivers will be selected. The set of receivers selected by the transmitter node i is denoted as i^{RC}.

With different channel availability, it is necessary for a transmitter and a receiver to negotiate channel usage over the common channel before transmissions. To better exploit the channel diversity while reducing the communication and channel measurement overhead, we propose a weight-based channel assignment algorithm which contains two phases, one at the transmitter nodes and the other at the receiver nodes, as described below.

Distributed Channel Assignment Algorithm

1) **Step 1: channel selection at the transmitter nodes**
   At this step, a transmitter node selects a set of channels to cover its intended receivers. To better utilize the node and queue information, each transmitter node i assigns each channel b a weight w_i^b as follows.

$$w_i^b = \frac{\sum_{j:j \in i^{RC}, b \in \mathcal{B}_{ij}} Q_{ij}^{prio}}{|\{u : u \in \mathcal{N}_i^b, u \text{ is a receiver}\}|} \ .$$

   The weight for a channel b is higher under two conditions: 1) It is available for transmission between nodes i and j which are associated with a higher priority queue Q_{ij}^{prio}, and 2) The channel is shared among more intended receivers, which reduces the number of channels to measure thus measurement overhead and also allows the transmitter to flexibly select a receiver with a better channel condition to send packets later. On the other hand, the weight is reduced when many unintended receivers share the same channel, so a transmitter tries to use a different channel exploiting the spectrum flexibility to reduce the interference. Note that the channels that can be accessed by a node does not change very quickly, so a node is aware of the channels accessible by its neighbors. The transmitter will sort and then select the set of channels based on their weights. On the one hand, as explained in Section 5.1, many-to-one transmission has several advantages over one-to-many transmission on the same channel. The transmitter node is encouraged to select an individual channel for each intended receiver. On the other hand, the more channels are selected, the more channel measurement overhead. To trade off between the two, we select the subset b_i from $\mathcal{B}_i$ with $|b_i| = \min(|\mathcal{B}_i|, |i^{RC}|)$. The transmitter will select $|b_i|$ channels from the high weight to the low weight, and then pass the selection result along with each channel's weight to the receivers.

2) **Step 2: channel selection at the receiver nodes**
   It is easy to see that a receiver node may receive several different channel selection results if multiple transmitters intend to send the packets to the receiver, with the total candidate channels being the superset of these selected channels. Since a receiver j can work on at most $|\mathcal{A}_j|$ channels, symmetrically, it will further reduce the number of channels to $|\mathcal{A}_j|$ based on the refined weight w_j^b for each channel b as follows:

$$w_j^b = \frac{\sum_{i:i \in j^{TX}, b \in \mathcal{B}_{ij}} Q_{ij}^{prio}}{|\{u : u \in \mathcal{N}_j^b, u \text{ is a transmitter}\}|} \ ,$$

   where j^{TX} represents the neighboring transmitters of j. From the numerator of the weight, we can see the receiver prefers to select the channel that can be shared by more transmitters to enable many-to-one cooperative MIMO transmission on the same channel to reduce the number of channels occupied. From the denominator, the receiver tries to select channels different from interfered transmitters (i.e., the channel with fewer sharing transmitters) to reduce the interference.
   This channel selection result, along with a channel measurement sequence will be sent back to the transmitters for their final channel assignment. Transmitters will base on this sequence to send their training signals. Measurement of the same channel can be carried at the same time with orthogonal training signals to reduce the overhead.

3) **Step 3: channel assignment finalization at transmitters**
   The transmitter node now finalizes the channels to be the ones selected by both itself and the corresponding receivers, and announces the channel to measure as well as the IDs of the selected target receiver nodes. The transmitter will avoid using the channels that have been selected by not-intended neighboring receivers which send back the channel selection results earlier.

5.3 Channel Measurement and Stream Allocation

In the distributed scheduling, the stream allocation decision can be made either at the transmitter nodes or at the receiver nodes, and there is a tradeoff for taking either of the options. We propose a distributed stream allocation algorithm which makes decision first at the receiver nodes based on the measured channel conditions and finalizes the decision at the transmitter nodes to concurrently consider the priority and quality of the streams and constrain the number of data and interference streams to be within the decoding capability of the receivers.

Distributed Stream Allocation Algorithm

1) **Step 1: actions at the transmitter nodes**
   The transmitter node broadcasts a training signal over the selected data channels through all antennas simultaneously using orthogonal waveforms, while the corresponding receivers tune their antennas to the channels to measure.

2) **Step 2: actions at the receiver nodes**
   After a receiver node j decodes the information sent from all the selected transmitter nodes in its neighborhood, it learns the channel condition from each transmitter on all possible channels. For each incoming stream,

the receiver node records the following parameters: transmitter node id, transmitter antenna id, channel id. The stream allocation scheme of a selected receiver node is then as follows.

3) **Step 3: pre-allocation at the receiver side.**
For each incoming stream, the objective from Section 3 is estimated by multiplying the queue's priority with the channel gain which can be obtained from the channel measurement result. Then the streams can be sorted in the descending order of this objective values. Therefore, among the streams with the same priority, the ones with the better channel conditions will be selected, which exploits the multi-user diversity and spatial diversity to improve the capacity. Denote the sorted streams for the receiver node j as S_j, and the set of streams selected by the receiver node j as X_j, then the receiver selects the streams as follows.

> Initial $X_j = \emptyset$
> $counter_1 = 1$
> **for** $counter_2 = 1$ to $|\mathcal{S}_j|$ **do**
>   **if** $S_{j\,counter2}$ does not share any specific antenna of a transmitter node with the previous selected streams in X_j **then**
>   put $S_{j\,counter2}$ into the set X_j
> $++counter_1$
>   **if** $counter_1 = |\mathcal{A}_j|$ **then**
>   break
>   **end if**
>   **end if**
> $++counter_2$
> **end for**

After the stream allocation, the receiver node broadcasts this result and tune their antennas to the channels associated with its stream allocation result.

4) **Step 4: final stream allocation at the transmitter side**
As a transmitter would receive several different stream allocation results from all its intended receivers and other receivers it interferes with, a transmitter needs a further decision on the stream allocation based on its own knowledge such that: (1) The weighted throughput is as high as possible, which again considers the stream priority as well as exploits multi-user diversity and spatial diversity for a higher throughput; (2) The stream allocation will not create conflicting use of its antennas; (3) Reduce the chance of assigning multiple streams on the same channel thus interference. To achieve these goals, a transmitter node i performs the following stream allocation algorithm where X_i denotes the set of streams that i selects, and S_i denotes the set of stream allocation result i receives from its neighboring receiver nodes.

> Sort S_i in the descending order based on their objective values
> Initial $X_i = \emptyset$
> $counter_1 = 1$
> **for** $counter_2 = 1$ to $|\mathcal{S}_i|$ **do**
>   **if** $S_{i\,counter2}$ does not share any channel with different receiver nodes or share any antenna with the previous selected streams in X_i **then**
>   Add $S_{i\,counter2}$ into the set X_i

> $++counter_1$
>   **if** $counter_1 = |\mathcal{A}_i|$ **then**
>   break
>   **end if**
>   **end if**
> $++counter_2$
> **end for**

After the stream allocation, the transmitters will start data transmission. The intended receivers will decode the data using the modified SIC which decodes the interfering signals first, then the data streams sorted by the signal strength until all are decoded.

Note the unscheduled data packets will be kept in the queue and scheduled in the next duration. Their priority gets higher as their queueing time increases, and will have a higher chance of being scheduled in future slots.

5.4 Analysis of Signaling Overhead

In this section, we briefly analyze the signaling overhead of the proposed distributed algorithm, specifically, distributed channel assignment in Section 5.2 and distributed stream allocation in Section 5.3 which both involve signaling exchanges.

In step 1 of the channel assignment algorithm, after determining a set of candidate channels, the transmitter broadcasts a message to announce the selection results along with the weight of each pre-selected channel over the common control channel. The length of the message is $O(|b_i|)$. In step 2, the receiver broadcasts its preferred channels on the common channel. The length of the message is $O(|A_j|)$. In step 3, the finalized channel selection result for training purpose is broadcast over the common control channel so receives can tune to the corresponding channels. As the selected number of channels will not be more than $|k_i| = \min(|A_i|, |b_i|)$, the length of the message is $O(|k_i|)$.

For the stream allocation algorithm, the signaling for step 1 is for sending the training sequence. The total number of signaling message is lower than the number of antennas multiplying the number of selected channels, which is $|A_i||k_i|$. With use of orthogonal codes, the messages can be sent over all all antennas concurrently over each channel. In step 3, there is only one signaling at the common control channel. The length of the message for node j is $O(|A_j|)$. No signaling message is required for steps 2 and 4.

Note that the number of transmitters in a neighborhood around a node N_i is constrained by TX, which depends on the number of neighbors of the node N_i and the number of available channels around. The number of candidate receivers is constrained by $N_i - TX$. The number of a specific type of messages broadcast in a neighborhood depends on the number of transmitters and receivers, and thus N_i and the number of available channels.

6 PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed algorithms through simulations. We consider an ad hoc network with random topology. Nodes are distributed uniformly over a $1200m \times 1200m$ area. Each node has a transmission

range of $250m$. The MIMO channel between node pair is modeled based on the node distance with path attenuation loss factor set as 3.5, and the small-scale fading coefficients following the Rayleigh model. White Gaussian noise with $SNR = 10dB$ is added to include environment noise and interference that cannot be canceled. If not otherwise specified, the number of nodes in the network is 80, the number of antenna elements at each node is 4 for all the algorithm simulations, and the number of available frequency channels in the network is 5. The set of available frequency channels at each node is randomly selected from this 5-channel pool.

As we are not aware of any distributed scheme existing for concurrent exploration of CR and MIMO, to demonstrate the effectiveness of our scheduling algorithms and the benefit of using many-to-many cooperative transmission by taking advantage of MIMO over CR, the performance of our algorithms is compared with: (1) a random algorithm; (2) a CR-only model where MIMO transmission is disabled but each node has multiple antennas to exploit multiple frequency channels. In the random algorithm, the nodes randomly make decisions on the transmitter selection, channel assignment, and stream allocation. In a CR only model, many-to-one and one-to-many transmissions via the *same* channel through MIMO are not allowed. In addition, any interference at a receiver on the same channel will fail the reception. For the convenience of presentation, we use CENT_ALG and DIST_ALG to represent the proposed centralized and distributed algorithms respectively, RAND_ALG and CR_ALG to represent the reference random algorithm and the algorithm for CR mode only.

The metrics we use for comparison are the aggregate data rate and normalized delay, with the unit of data rate for the results being Bit/s/Hz. We have added a sentence to specify in the third paragraph of section VI. Aggregate data rate is the total data rates of the network averaged over the number of transmission durations. Delay time is defined as the number of transmission durations a packet waits in the queue before it is successfully transmitted. We evaluate the impact on performance due to the variation of node density, total available channels, and number of DoFs.

Impact of node density: We vary the number of nodes in the area from 40 to 100. The CENT_ALG has the global information on all available channels, spatial DoFs, and channel conditions. The more flexibility to explore in transmissions, the more difficult for a distributed algorithm to compete with a centralized algorithm. Even so, in Fig. 4(a), the data rate of DIST_ALG still reaches about 70% that of CENT_ALG, which shows that our distributed scheduling is promising. Compared with other reference algorithms, DIST_ALG achieves more than 1.5 times the data rate of CR_ALG, and doubles and even triples the data rate of RAND_ALG. This demonstrates that the data rate can be greatly increased in an ad hoc network via many-to-many cooperative transmissions by fully exploiting multiuser diversity, channel diversity, and spatial diversity for a higher channel gain. Moreover, as the number of nodes in the network increases, the data rates of both the proposed CENT_ALG and DIST_ALG increase by exploiting the spatial domain DoFs. However, the data rate of CR_ALG becomes saturated,

while the data rate of RAND_ALG even decreases at a high node density, as the two algorithms reach their capacity limits and a large number of nodes lead to more collisions thus throughput reduction. On the other hand, in Fig. 4(b), the delay of our DIST_ALG is really close to our CENT_ALG, while RAND_ALG has a significantly higher delay compared to other algorithms. This is because our DIST_ALG design takes into consideration of the system objective whenever possible to maximize the weighted throughput, where the weight is calculated based on the delay in our simulation to trade-off between data rate and delay.

Impact of the available number of frequency channels: We vary the number of available frequency channels from 3 to 10 in the network. In Figure 5, our DIST_ALG still achieves $60\% - 70\%$ data rate of CENT_ALG. Without the global information and scheduling as CENT_ALG, our DIST_ALG is still the best among all. Again, it achieves more than 1.5 times the data rate of CR_ALG, and doubles, even triples, the data rate of RAND_ALG. This is because DIST_ALG can concurrently take advantage of multiuser diversity, channel diversity, and spatial diversity. From Fig. 5(a), as expected, all algorithms achieve a higher data rate as the number of available frequency channels increases in the network. As for the absolute increase amount of data rate, DIST_ALG increases nearly 100 while CR_ALG and RAND_ALG increase barely more than 50. This result is interesting. It indicates that as the number of channels increases, it allows for more transmission flexibility and hence the performance increase with the interplay of frequency domain and spatial domain transmission opportunities. In the network simulated, the available channels at each node is different and smaller than the total channels. Therefore, the increase in the data rate is not proportional to the total number of system channels. In Fig. 5(b), again we verify that our DIST_ALG has the delay very close to CENT_ALG, while the other two reference distributed algorithms suffer from a high delay.

Impact of spatial DoFs: To demonstrate the benefit of MIMO many-to-many cooperative transmission by exploiting spatial diversity, we vary the number of DoFs at each node. According to Fig. 6(a), again, we can see DIST_ALG achieves more than 60% the data rate of CENT_ALG. This, together with Fig. 4(a) and Fig. 5(a), demonstrates the robustness of DIST_ALG as it can achieve more than 60% data rate of CENT_ALG under different circumstances, even though the significant challenge in coordination among nodes to explore various flexibility. As the number of DoFs at each node increases, both CENT_ALG and DIST_ALG can effectively exploit the new transmission opportunity via either MIMO multiplexing or MIMO interference cancelation, therefore leading to an increase in data rate. In contrast, the rates of CR_ALG and RAND_ALG have only a slight increase when the number of DoFs increases from 1 to 2, beyond which the rates of both algorithms become flat. With CR_ALG, the system bottleneck is the number of available channels, while a practical device often has a limitation on the number of frequency bands to operate.

Given more DoFs at each node, RAND_ALG tries to exploit more transmission opportunities blindly. When a node
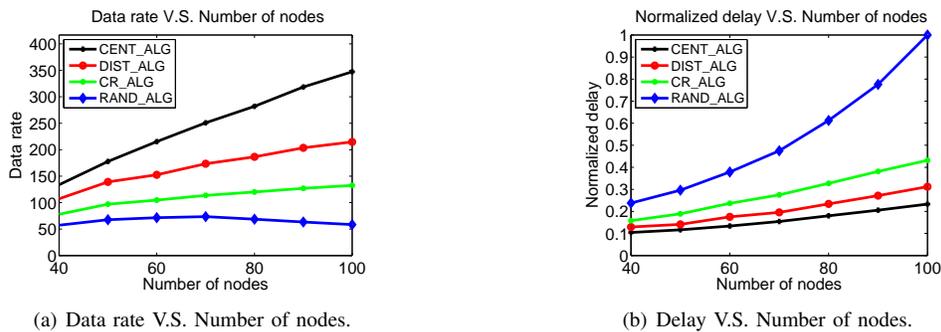
(a) Data rate V.S. Number of nodes.

(b) Delay V.S. Number of nodes.

Fig. 4. MIMO-CRN performance with varying number of nodes

(a) Data rate V.S. Number of channels.

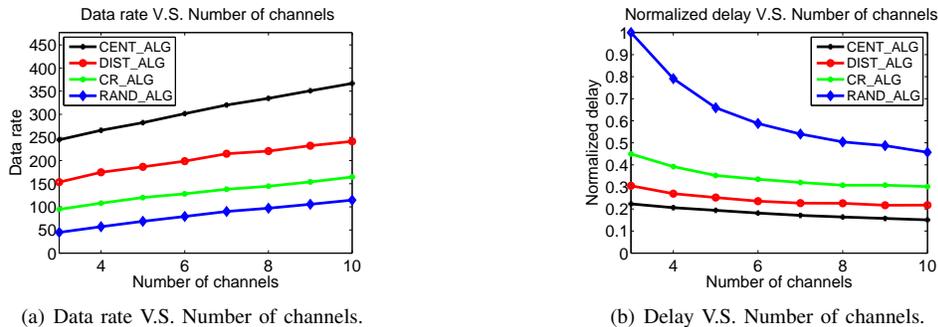(b) Delay V.S. Number of channels.

Fig. 5. MIMO-CRN performance with varying number of channels

transfers more data streams with a randomly picked channel, it has a higher chance to collide with other transmissions. As explained in Section 2, both variations in channel conditions and SIC decoding will have a significant impact on the final network performance. As a result, with the increase of DoFs at each node, the increase of throughput is not proportionally. From Fig. 6, again, we can see that DIST_ALG and CENT_ALG have very close delay, and RAND_ALG suffers from a high delay.

7 CONCLUSIONS

In this work, we have studied the scheduling problem in a MIMO-empowered CR network. We show that the unique characteristics associated with MIMO and CR make this problem much more complex and difficult than that for an ad hoc network based on the traditional radios. We formulate the scheduling problem as an MILP to maximize the weighted data rate by considering the traffic demand, service requirements, and network load. We carefully model various constraints due to the availability of frequency channels, the limited number of antennas, and the different channel conditions in order to increase the data rate while reducing the interference. We propose a centralized and a distributed scheduling algorithms to fully exploit the agility of both CR and MIMO as well as multiuser diversity, channel diversity, and spatial diversity for a a higher network performance. Our algorithm opportunistically selects transmitter nodes, transmission channels and antennas while considering the QoS and fairness among nodes. Nodes in a neighborhood can operate on different available channels or cooperatively form a many-to-many virtual MIMO array on the same channel. The performance results demonstrate that our proposed algorithms are very efficient in coordinating

transmissions in a MIMO-CRN. Our distributed algorithm achieves much higher data rate than reference algorithms. When the MIMO ability are turned off, the system suffers from severe performance degradation, which demonstrates the benefit and necessity of incorporating CR with MIMO to achieve performance boost in future wireless networks.

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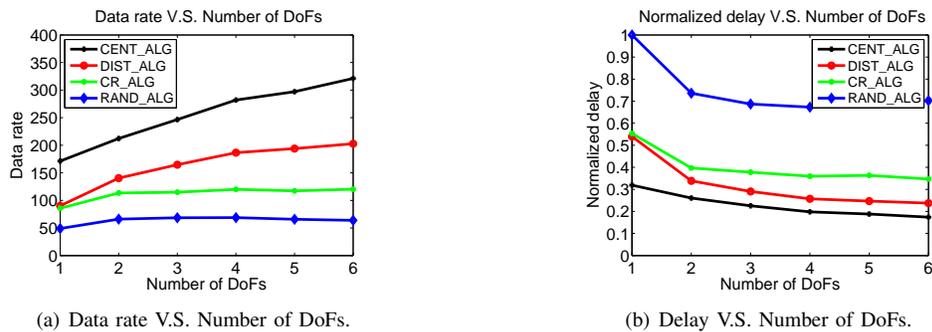
(a) Data rate V.S. Number of DoFs.

(b) Delay V.S. Number of DoFs.

Fig. 6. MIMO-CRN performance with varying number of DoFs

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