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Cooperative Routing with Relay Assignment in Multi-radio Multi-hop Wireless Networks

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***Abstract*—Cooperative communication (CC) for wireless networks has gained a lot of recent interests. It has been shown that CC has the potential to significantly increase the capacity of wireless networks, with its ability of mitigating fading by exploiting spatial diversity. However, most of the works on CC are limited to single radio wireless network. To demonstrate the benefits of CC in multi-radio multi-hop wireless network, this paper studies a joint problem of multi-radio cooperative routing and relay assignment to maximize the minimum rate among a set of concurrent communication sessions. We first model this problem as a mixed integer programming (MIP) problem and prove it to be NP-hard. Then we propose a centralized algorithm and a distributed algorithm to solve the problem. The centralized algorithm is designed within a branch-and-bound framework by using the relaxation of the formulated MIP, which can find a global $(1+\varepsilon)$-optimal solution. Our distributed algorithm includes two sub-algorithms: a cooperative route selection sub-algorithm and a fairness-aware route adjustment sub-algorithm. Our simulation results demonstrate the effectiveness of the proposed algorithms and the significant rate gains that can be achieved by incorporating CC in multi-radio multi-hop networks.**

I. INTRODUCTION

In recent years, we have seen significant research interests in exploiting cooperative communications (CC) over distributed antennas to improve the transmission performance [1]. Taking advantage of the broadcast nature of wireless channels, one or more neighboring nodes can serve as relays and forward overheard packets from a sender to its target receiver, which can combine multiple copies of the packet to decode the original one. Therefore, by exploiting the inherent spatial and multiuser diversities, the cooperative communication technique can efficiently improve the network performance. This makes cooperative communications an emerging technique for future wireless networks.

Existing studies on CC are mostly based on the single radio networks [2]–[14]. With the constant reduction of hardware cost and the availability of cheap, off-the-shelf commodity hardware equipped with multiple radios, more and more wireless devices are equipped with multi-radio communication interfaces. This not only brings in the extra capacity gain for a single device and a wireless network formed with multi-radio nodes, but also creates more opportunities for cooperative communications. Although promising, there are very limited studies on exploiting the multi-radio capabilities for flexible cooperative communication to improve the multi-radio multi-hop wireless network performance.

This paper intends to provide some design guideline and demonstrate the benefits of CC in multi-radio multi-hop wireless networks. The existence of multi-radio devices in the network allows for more transmission opportunities and flexibilities, but also leads to more challenges in network design, especially the enabling of cooperative communications in multi-radio multi-hop networks.

With more radio interfaces, a node in the network can act not only as a cooperative relay for CC but also a transmission relay for multi-hop packet forwarding. The first challenging issue is how to assign relay nodes (either for CC or as a multi-hop relay) for each session. Fig. 1 shows examples of cooperative communication with each node equipped with two radios, where the dashed lines represent cooperative transmissions. In Fig. 1(a), the node r could use one radio as cooperative relay for session $s_1 \rightarrow d_1$, and the other radio as cooperative relay for session $s_2 \rightarrow d_2$. In Fig. 1(b), the node r could use one radio as cooperative relay for session $s_2 \rightarrow d_2$, and the other radio as a multi-hop relay for session $s_1 \rightarrow d_1$.

The capability for a node or a radio interface to serve as two different types of relay makes multi-radio cooperative routing and relay node assignment inter-dependent. The second challenging issue is how to solve the coupled multi-radio routing problem and relay assignment problems optimally together while taking into account the wireless interference arisen from both direct transmission and cooperative communication.

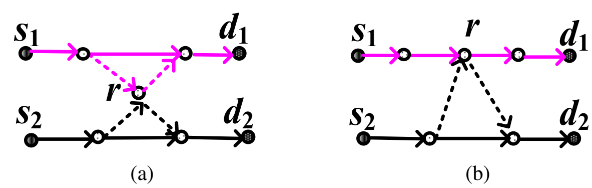


Fig. 1. CC in multi-radio multi-hop wireless network.

To address the above challenging issues, the aim of this work is to solve a joint problem of multi-radio cooperative routing and relay assignment to understand the benefits of applying CC in multi-radio multi-hop wireless networks. Compared to conventional single-radio CC studies, the introduction of multi-radio nodes significantly increases the flexibility in relay selection thus the performance gain as demonstrated in our performance evaluations. However, this also makes the problem much harder to solve. The objective of our work is to maximize the minimum rate among a set of concurrent communication sessions to increase the transmission fairness by considering the opportunities brought by cooperative communications and the limitation of the number of radios at network nodes. Our contributions can be summarized as follows:

- We first model the problem as a mixed integer programming (MIP) problem and prove it to be an NP-hard problem.
- To efficiently solve the problem, we propose a distributed algorithm with two steps. In the first step, an interference-aware cooperative route selection algorithm is proposed to select an optimal routing path with the maximum capacity for each newly arrival session. In the second step, a fairness-aware algorithm is proposed to adjust the path locally around the link overloaded with transmissions from multiple sessions.
- For performance reference, based on the relaxation of the formulated MIP, we propose a centralized algorithm within a branch-and-bound framework to provide an effective global $(1 + \varepsilon)$-optimal solution where ε is a desired approximation error bound.

We have carried out extensive simulations to evaluate the performance of our proposed algorithms. The simulation results demonstrate the effectiveness of our algorithms and the significant rate gains that can be achieved by incorporating CC in multi-radio multi-hop networks.

The rest of this paper is organized as follows: Section II presents related work. Section III describes the system model. In Section IV, we model this problem as a mixed integer programming (MIP) problem and prove it to be a NP-hard problem. We propose a distributed algorithm and a centralized algorithm to solve the problem in Section VI and Section V, respectively. Section VII presents simulation results to demonstrate the rate gains that can be achieved by exploiting CC in multi-radio multi-hop wireless networks. We conclude this paper in Section VIII.

II. RELATED WORK

We are not aware of any other work that concurrently considers interference aware cooperative routing and relay assignment for performance enhancement in multi-radio multi-hop wireless networks. Following we review some literature work that has certain parts relevant to our work.

A. Cooperative Communications

Cooperative communication is a physical layer technique. Built upon the work at the physical layer [15]–[19], applications and network protocols have mushroomed in single-radio wireless networks recently, either single-radio single-hop network [2]–[7] or single-radio multi-hop network [8]–[14].

The research focus of CC in single-radio single-hop wireless network is on the selection of the relay for a source-destination pair and resource allocation for the selected relay. In [2], Cai et al. study the problem of relay selection and power allocation, first over a simple network with only one source node, and then extending to the multiple-source case. In [3], the authors propose a distributed buyer/seller game theoretic framework over multiuser CC networks to stimulate cooperation and improve the system performance. In [4], Shi et al. study the relay assignment problem such that the minimum capacity among all source nodes is maximized. They propose an optimal polynomial time algorithm to solve the problem. Following this work, the authors in [5] study the relay assignment problem with interference mitigation. Aiming at maximizing network throughput with proportional fairness, the authors in [6] have investigated the joint relay selection and link scheduling problem in a relay-assisted wireless cellular network. The work in [7] targets to solve the relay assignment problem for maximizing the total capacity of all pairs in a more general sense where multiple source nodes can share same relay node.

However, the above studies for single-radio single-hop wireless network cannot be easily extended to a multi-hop wireless network.

There are some studies of CC in single-radio multi-hop wireless network. In [8], Khandani et al. study a minimum energy routing problem in a static wireless network and develop a dynamic-programming-based algorithm for finding the optimal route in an arbitrary network. However, their approach is limited to single session as opposed to multiple sessions that we have considered in this paper. In [9], Edmund et al. consider cooperative relay networks with multiple stochastically varying sessions, which may be queued within the network. Throughput optimal network control policies are studied that take into account queue dynamics to jointly optimize routing, scheduling and resource allocation, with the solutions constrained to the special case of parallel relay networks. The papers [10]–[12] propose heuristics schemes that first develop routing solutions to find a primary path, and then consider relay node assignment for CC according to the primary path. However, these solutions decouple routing and relay assignment, which makes the path found far from the optimal one.

In [13], the authors propose a distributed cooperative routing algorithm to construct a minimum-power route to guarantee certain throughput. In [20], the authors define a bandwidth and power aware cooperative multi-path routing problem over wireless multimedia sensor networks, and propose a polynomial-time heuristic algorithm to solve the problem. In [14], to illustrate the benefits of CC in multi-hop wireless networks, the authors solve a joint optimization problem of relay node assignment and flow routing for concurrent sessions.

The above results are restricted to a single-radio network. The presence of multi-radio nodes provides more opportunities for network capacity enhancement, with the radios possibly forwarding packets in the normal routing path or serving as relays for cooperative communications. The determination of the optimal functions for the radios is a challenging problem and has very limited work. Only the work in [21] studies CC in multi-radio multi-hop networks. It proposes a channel-on-demand mathematical model to maximize the capacity, and provides an optimal interface assignment algorithm for real-time flows. Different from our work in this paper, however, the approach proposed is run with the assumption that the routing path is given.

Therefore, current work on cooperative communications for multi-radio multi-hop wireless communication is very limited, which is the main focus of this paper.

Despite the wide interests, cooperative communications can lead to increased interference, which results in transmission conflicts and data retransmission and consequently network performance degradation [22]. The interference problems have been noticed and studied by only a limited number of researchers [7], [23], [24]. Yang *et al*. [7] point out that the co-channel interference has become a prominent issue to apply cooperative communication techniques in wireless networks. Zhang *et al*. [24] further show that the performance degradation as a result of co-channel interference largely impacts the performance of multi-hop wireless networks.

Li et al. [25] study an energy and spectrum efficient cooperative communication problem in a one-hop multi-channel wireless network. The objective of the work is to find the optimal transmission power, relay assignment, and channel allocation such that the rate requirements of all users are satisfied and the total energy consumption is minimized. Although the network has multiple channels, each node is assumed to have only a single radio and can only access one channel at a time.

Considering only a simple network model, the solutions of [7], [22]–[25] are difficult to be extended to multi-radio multi-hop wireless networks to achieve the cooperative diversity gain in the presence of wireless interference.

B. Multi-radio Technique

Many studies [26]–[30] have been made to exploit multi-radio and multi-channel (MRMC) technique to combat the increased co-channel interference for higher network capacity. With multiple wireless radios (i.e., network interface card (NIC)), nodes within a neighborhood can send data through orthogonal channels without transmission conflicts, which leads to efficient spectrum utilization and increases the actual bandwidth available to the network.

Different from the above work which only considers conventional one-to-one direct transmission, cooperative communications can potentially improve the network performance by exploiting many-to-one transmissions to mitigate fading. The techniques proposed for direct transmissions can not be easily applied in cooperative wireless networks to achieve the cooperative diversity gain.

As a multi-radio technique, MIMO can achieve spatial diversity by employing multiple transmitter-receiver radio interfaces, which has attracted lots of interest recently [31]–[34]. The work in [31], [32] exploits the use of cooperative relay transmission in a MIMO-based ad hoc network to cope with harsh channel condition, while authors in [33] propose to deploy MIMO nodes as relays to assist weak links in wireless networks with the aim of reducing the number of relay nodes and providing performance provisioning. These efforts target to solutions at MAC layer scheduling and for deployment respectively without considering the routing. A node equipped with multiple radios does not ensure the node to form MIMO array and enjoy the MIMO benefits. Therefore, multi-radio communications and MIMO communications have been different research thrusts in the community.

To the best of our knowledge, this is the first work to demonstrate the benefits of CC in multi-radio multi-hop wireless networks. This paper considers a joint problem of interference-aware cooperative routing and relay node assignment, and proposes both centralized and distributed algorithm to solve the problem.

III. SYSTEMS MODEL

A. Network Scenario

We consider a multi-radio multi-channel multi-hop wireless network with n nodes contained in a set N, where each node is equipped with one or multiple wireless radios. There are multiple concurrent sessions in the network, denoted by a set $F = \{f_1, f_2 ... f_J\}$ of J. A session $f_i(s_i \rightarrow d_i)$ goes through the source node s_i and the destination node d_i, and the data for each session may traverse multiple hops in the network.

We assume that there are a total of l orthogonal channels in the network, denoted by C={ch_1, ch_2, ..., ch_l}, and there is no inter-channel interference. The set of working channels assigned to node i is denoted as C_i. Due to the interference constraints, there is no capacity benefit to assign two radios of a node with the same channel.

There are two types of relay nodes on a path from the source to the destination of a session. The first type is Cooperative Relay (CR) which is used for CC purpose (i.e., node r_7 of session 2 in Fig. 2). The second type is multi-hop Relay (MR) which operates at the network layer to relay the packets from a source over multiple hops to its destination (i.e., r_6 of session 2 in Fig. 2).

A node with multiple radios can serve as both CR and MR for multiple sessions. Similarly, a source node (or a destination node) can serve as a CR or MR for other sessions, and a single CR node can serve more than one session.

In the example of Fig. 2, there are three communication sessions. The dashed line represents a relay path through a CR relay node which serves for the purpose of cooperative communication while the solid line represents the normal data transmission path, and a node on the path serves as an MR. A relay nods with multiple radios can serve for multiple sessions and act in different roles (CR or MR) in different sessions. For example, node r_3 is the CR of both session 1 and session 2, while node r_4 is the CR of session 3 and is also used as an MR for the session 2. The node r_5 is used as MR to carry traffic for both sessions 1 and 3.

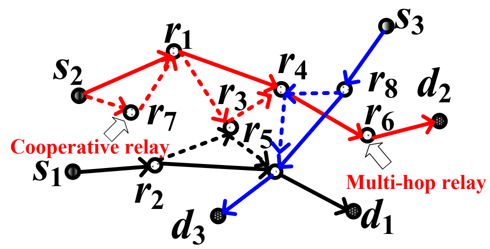


Fig. 2. A multi-radio multi-hop network consisting of multiple sessions.

B. Two Kinds of Transmission Modes

There are two transmission modes between any two nodes in the network considered, direct transmission (DT) and cooperative transmission. A direct transmission is carried directly between two neighboring nodes i and j over one link, where node i is the sender and node j is the receiver (i.e.,$s_1 \rightarrow r_2$ in Fig. 2). The cooperative transmission between two nodes x and z involves three links (x, y), (x, z), and (y, z), where the relay node y acts as a CR relay for the transmission between x and z (i.e., $r_2 \rightarrow r_5(r_3)$ in Fig. 2, where r_3 is the CR relay).

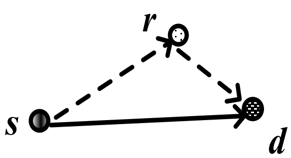


Fig. 3. A three-node CC model.

Fig. 3 shows a three-node CC model. In the cooperative transmission, a collaborative neighbor r overhears the signal from the source s to the destination d and forwards it to d. d combines two signal streams, $s \Rightarrow d$ and $r \Rightarrow d$ into a single stream that has a higher resistance to channel fading and noise and hence a higher probability of being successfully decoded.

A recent study [35] shows that the diversity gain achieved by exploiting multiple relay nodes is marginally higher than the diversity gain achieved by selecting the best relay. Therefore, we consider each hop of a session can select at most one relay node for CC as done in other related work [13], [14], [25].

The mechanism to accomplish CC is not unique. Between s and d under CC, there are two typical cooperative transmission modes including amplify-and-forward (AF) and decode-and-forward (DF) modes [36]. In [37], authors describe and compare the capacity of different cooperative transmission protocols and show that the AF-RAKE-based cooperative transmission protocol can achieve the maximum capacity. In AF-RAKE, after receiving signals from s, r amplifies and forwards them to d without demodulation or decoding. d uses a RAKE receiver to combine both signal streams of $s \Rightarrow d$ and $r \Rightarrow d$. The achievable rate under AF-RAKE mode between s and d with r as the relay [37] is given by

$$C(s, d, r, CC) = W * I_{AF}(s, d, r), \tag{1}$$

where

$$I_{AF}(s, d, r) = \log_2(1 + SNR_{sd} + \frac{SNR_{sr} * SNR_{rd}}{SNR_{sr} + SNR_{rd} + 1}) \tag{2}$$

$$SNR_{sd} = \frac{P_s}{\sigma_d^2} |h_{sd}|^2, SNR_{sr} = \frac{P_s}{\sigma_r^2} |h_{sr}|^2, SNR_{rd} = \frac{P_r}{\sigma_d^2} |h_{rd}|^2 . \tag{3}$$

W is the available bandwidth of channels at nodes s and r, h_{sd}, h_{sr}, h_{rd} represent the effects of path-loss, shadowing, and fading within its respective channel between nodes s and d, s and r, as well as r and d, respectively. σ_d^2 and σ_r^2 denote variance of the zero-mean background noise at nodes d and r, while P_s and P_r denote the transmission powers at nodes s and r respectively.

For the direct transmission mode, the achievable rate between s and d is expressed as

$$C(s, d, DT) = W \log_2(1 + SNR_{sd}) \tag{4}$$

IV. PROBLEM DESCRIPTION

In multi-flow multi-radio multi-hop wireless networks, a relay node with multiple radios can be shared and serve for multiple sessions, as shown in Fig.1. A challenging problem is how to efficiently assign relay nodes for each session while taking account of wireless interference from both direct transmission and cooperative communication.

In our problem formulation, we will jointly consider cooperative routing and relay assignment under three types of constraints: the constraint on relay nodes, the constraint on flow routing, and the constraint on link capacity. Following we first introduce the constraints.

Let a binary variable A_{uv}^k denote whether there is a link $u \rightarrow v$ through the channel ch_k. For direct communication, the receiver v needs to be within the communication range of the sender u, with u and v sharing a common channel:

$$A_{uv}^k = \begin{cases} 1 & v \in N(u) \ and \ k \in C_u \cap C_v, u \neq v \\ 0 & otherwise \end{cases} \tag{5}$$

where $N(u)$ denotes the one-hop neighbor set of node u.

We consider the three links for cooperative communication (i.e., from the sender to the receiver, from the sender to the relay, and from the relay to the receiver) as a *virtual cooperative link*, with the sender, relay, and the receiver assigned with a common channel. A binary variable B_{uv}^{wk} denotes whether there is a virtual cooperative link $u \rightarrow v(w)$ through the channel ch_k and the relay w:

$$B_{uv}^{wk} = \begin{cases} 1 & v \in N(u) \ and \ w \in N(u) \cap N(v) \\ & and \ k \in C_u \cap C_v \cap C_w, w \neq u, w \neq v \\ 0 & otherwise \end{cases} \tag{6}$$

We further define a binary variable $y_{j:uv}^k$ to denote whether or not a direct link $u \rightarrow v \,|ch_k$ is selected by the session j:

$$y_{j:uv}^k = \begin{cases} 1 & link \ u \rightarrow v \,|ch_k \ \ is \ selected \ by \ session \ j \\ 0 & otherwise \end{cases} \tag{7}$$

Similarly, we define a binary variable $x_{j:uv}^{wk}$ to indicate whether or not a virtual cooperative link $u \to v(w)\,|ch_k$ is selected by session j:

$$x_{j:uv}^{wk} = \begin{cases} 1 & link\ u \to v(w)\,|ch_k\ \ is\ selected\ by\ session\ j \\ 0 & otherwise \end{cases} \tag{8}$$

A. Constraint on Relay Nodes

For each hop (u, v), node u can transmit data to node v through either direct transmission or cooperative transmission:

$$\sum\nolimits_{w \in N} x_{j:uv}^{wk} + y_{j:uv}^{k} \leq 1 \ (j \in F, k \in C) \tag{9}$$

B. Constraint on Flow Routing

Given a session, a direct link is formed between only one transmitter and one receiver:

$$\sum_{k \in C_u \cap C_v} \sum_{u \in N}^{u \neq v} y_{j:uv}^{k} \leq 1\,(j \in F, v \neq s_j) \tag{10}$$

$$\sum_{k \in C_u \cap C_v} \sum_{v \in N}^{v \neq u} y_{j:uv}^{k} \leq 1\,(j \in F, u \neq d_j) \tag{11}$$

Similarly, a virtual cooperative link is also formed between one transmitter and one receiver:

$$\sum_{k \in C_u \cap C_v} \sum_{u \in N}^{u \neq v, u \neq w} x_{j:uv}^{wk} \leq 1\,(j \in F, v \neq s_j) \tag{12}$$

$$\sum_{k \in C_u \cap C_v} \sum_{v \in N}^{v \neq u, v \neq w} x_{j:uv}^{wk} \leq 1\,(j \in F, u \neq d_j) \tag{13}$$

Denote $f_{j:uv}^{k}$ and $f_{j:uv}^{wk}$ as a session j's flow rate on the direct link $u \to v\,|ch_k$ and virtual cooperative link $u \to v(w)\,|ch_k$, respectively. For an intermediate node, the outgoing flow rate should be equal to the incoming flow rate:

$$\begin{aligned} &\sum_{k \in C_u \cap C_w} \sum_{u \in N}^{u \neq w, u \neq d_j} \left(y_{j:uw}^{k} f_{j:uw}^{k} + \sum_{t \in N}^{t \neq u, t \neq w} x_{j:uw}^{tk} f_{j:uw}^{tk} \right) \\ &= \sum_{k \in C_w \cap C_v} \sum_{v \in N}^{v \neq w, v \neq s_j} \left(y_{j:wv}^{k} f_{j:wv}^{k} + \sum_{t \in N}^{t \neq v, t \neq w} x_{j:wv}^{tk} f_{j:wv}^{tk} \right) \\ &(j \in F, w \in N, w \neq s_j, w \neq d_j) \end{aligned} \tag{14}$$

Each hop (u, v) can transmit data using either direct transmission or cooperative transmission, thus a session's outgoing link and incoming link can be either a direct link or a virtual cooperative link. Therefore, the two side of (14) can have at most one non-zero term. On the left side of Eq.(14), because of the constraint in Eq(9), if the incomming link exploits direct transmission, then $y_{j:uw}^{k} = 1$ and the term $y_{j:uw}^{k} f_{j:uw}^{k}$ is non-zero and the term $\sum_{t \in N}^{t \neq u, t \neq w} x_{j:uw}^{tk} f_{j:uw}^{tk}$ is zero. Otherwise if the incomming link exploits the cooperative transmission, $\sum_{t \in N}^{t \neq u, t \neq w} x_{j:uw}^{tk} = 1$ and the term $\sum_{t \in N}^{t \neq u, t \neq w} x_{j:uw}^{tk} f_{j:uw}^{tk}$ is non-zero and $y_{j:uw}^{k} = 0$ and the term $y_{j:uw}^{k} f_{j:uw}^{k}$ is zero.

Similarly, on the right side of Eq.(14), if the outgoing link exploits direct transmission, then $y_{j:wv}^{k} = 1$ and the term $y_{j:wv}^{k} f_{j:wv}^{k}$ is non-zero. Otherwise if the outgoing link exploits cooperative transmission, then $\sum_{t \in N} x_{j:wv}^{tk} = 1$ and the term $\sum_{t \in N}^{t \neq v, t \neq w} x_{j:wv}^{tk} f_{j:wv}^{tk}$ is non-zero.

C. Constraint on Link Capacity

We denote by R_I the interference range, which is $q \times R_T$ where $q \geq 1$ and R_T is the communication range. A communication between u and v may block other transmissions within the R_I range of either u or v.

In particular, we have the following two principles to identify whether two links in a cooperative wireless network interfere with each other or not.

Principle 1. For direct transmissions, we consider a link $A \to B$ to be the interference link of another link $C \to D$ if A and B work on the same channel of C and D, and at least one of the node pairs, pair(A, C), pair(A, D), pair(B, C), and pair(B, D) is within R_I.

Principle 2. If node A transmits data to node B with the help of a cooperative relay R, we consider the cooperative link $A \to B\,(R)$ to interfere with another link $C \to D$ if A, B, and R work on the same channel of C and D, and at least one of the node pairs, pair(A, C), pair(A, D), pair(B, C), pair(B, D), pair(R, C), and pair(R, D) is within R_I.

According to the TDMA schedule adopted in the MAC layer, if a channel is equally shared among competing links, the available capacity of a direct transmission link $u \to v\,|ch_k$ can be calculated as

$$C^k\,(u, v, DT) = \frac{C\,(u, v, DT)}{|I_k\,(u, v)| + 1} \tag{15}$$

where $C\,(u, v, DT)$ (calculated by (4)) is the link capacity of a direct link, $I_k(u, v)$ denotes the link set that interferes with the link $u \to v\,|ch_k$, $|I_k\,(u, v)|$ denotes the size of $I_k(u, v)$.

The available capacity of a virtual cooperative link $u \to v(w)\,|ch_k$ can be calculated as

$$C^k\,(u, v, w, CC) = \frac{C\,(u, v, w, CC)}{|I_k\,(u, v, w)| + 1} \tag{16}$$

where $C\,(u, w, v, CC)$ (calculated by (1)) is the link capacity of a virtual cooperative link, $I_k(u, v, w)$ denotes the link set that interfere with this virtual cooperative link.

Depending on whether a link being direct or cooperative, the capacity constraint for the aggregate flows traversing the link through ch_k must not exceed the link capacity as follows:

$$\sum_{j \in F} f_{j:uv}^{k} \leq C^k\,(u, v, DT) \tag{17}$$

$$\sum_{j \in F} f_{j:uv}^{wk} \leq C^k\,(u, v, w, CT) \tag{18}$$

D. Problem Formulation

The objective of this paper is to maximize the minimum flow rate among all active flows via interference-aware cooperative routing and relay assignment. Following the flow constraint in (14), although a session may traverse multiple hops, the flow rate of every hop in the session is the same. Therefore, we use the rate of the first hop to denote the flow rate. More formally, for a given session (s_j, d_j), denote the end-to-end flow rate (or throughput) as R_j, where

$$R_j = \sum_{k \in C_{s_j} \cap C_v} \sum_{v \in N}^{v \neq s_j} \left(y_{j:s_j v}^k f_{j:s_j v}^k + \sum_{t \in N}^{t \neq v, t \neq s_j} x_{j:s_j v}^{tk} f_{j:s_j v}^{tk} \right) \quad (19)$$

Let R_{min} demote the minimum flow rate among all flows, i.e.,

$$R_{\min} = \min_{j \in F} R_j \quad (20)$$

Our objective is to maximize R_{min} as follows:

$$\begin{array}{ll} Max & R_{\min} \\ s.t. & (9)(11)(10)(13)(12)(14)(17)(18) \\ \multicolumn{2}{l}{R_{\min}, f_{j:uv}^k, f_{j:uv}^{wk} \geq 0 (j \in F, k \in C, u, v, w \in N, w \neq u, w \neq v)} \\ \multicolumn{2}{l}{x_{j:uv}^{wk}, y_{j:uv}^k \in \{0, 1\} \; (j \in F, k \in C, u, v, w \in N, w \neq u, w \neq v)} \end{array} \quad (21)$$

where R_{min}, $f_{j:uv}^k$, $f_{j:uv}^{wk}$, $x_{j:uv}^{wk}$ and $y_{j:uv}^k$ are optimization variables.

Theorem 1: The max-min cooperative routing problem in cooperative wireless networks defined in (21) is NP-hard.

Proof: Although a cooperative transmission consists of three links, as mentioned earlier, we treat them as a *virtual cooperative link*. Multiple sessions can be transmitted concurrently over different channels. After these simplification, the max-min cooperative routing problem can be translated to an un-splittable max-min bandwidth allocation problem, which is a known NP-hard problem [38]. ■

V. DISTRIBUTED ALGORITHM

For practical implementation of cooperative communication in multi-radio multi-channel multi-hop wireless networks, we propose a Distributed joint Flow Routing and Relay node Assignment algorithm (DFRRA), which includes two steps. In the first step, an interference-aware Cooperative Route Selection algorithm (CRS) is proposed to select an optimal cooperative routing path. In the second step, a Fairness Aware Routing Adjustment algorithm (FARA) is proposed to adapt the route locally by considering the link competition among multiple sessions.

A. Distributed Cooperative Route Selection Algorithm

For each active session, our proposed CRS will search for a routing path with the maximum end-to-end capacity taking into account the wireless interference. In a cooperative network, a cooperative path could be formed with a combination of cooperative transmissions and direct transmissions, as shown in Fig.4. This makes the path finding difficult. For each transmission hop, CRS not only needs to select the forwarding node and the working channel of each hop but also to determine the transmission mode as well as the relay node in case that a cooperative transmission mode is the option.

1) Routing Metric

To facilitate path selection, we define a routing metric of a hop (x, y) as the maximum available capacity among all possible channels through two possible transmission modes

$$CMetric(x, y) = \max_{ch_k \in C_x \cap C_y, \text{mode} \in DT, CC} \{C(x, y, ch_k, \text{mode})\}, \quad (22)$$

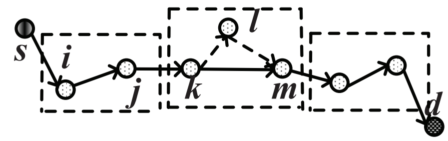


Fig. 4. Example of cooperative route.

where $C(.)$ is the available link capacity and $C_x \cap C_y$ is the feasible set of channels both nodes x and y are assigned with, and the transmission between nodes x and y can be either direct when $mode = DT$ or cooperative when $mode = CT$.

If a link is fairly shared by multiple sessions, the routing metric in Eq.(22) can be further expressed as:

$$CMetric(x, y) = \max_{ch_k \in C_x \cap C_y} \left\{ \frac{C^k(x,y,DT)}{NSS(x,y,DT)+1}, \max_{r \in R} \left\{ \frac{C^k(x,y,r,CT)}{NSS(x,y,r,CT)+1} \right\} \right\} \quad (23)$$

where $R = N(x) \cap N(y)$ is the candidate relay set for hop (x, y) on channel ch_k. $C^k(x, y, DT)$ and $C^k(x, y, r, CT)$ can be calculated by (15) and (16). $NSS^k(x, y, DT)$ and $NSS^k(x, y, r, CT)$ denote the number of sessions selecting the corresponding link $x \to y\,|ch_k$ or the virtual cooperative link $x \to y(r)\,|ch_k$, respectively. Therefore, $\frac{C^k(x,y,DT)}{NSS(x,y,DT)+1}$ and $\frac{C^k(x,y,r,CT)}{NSS(x,y,r,CT)+1}$ are the available link capacity for a new flow to select the corresponding direct link or virtual cooperative link.

According to the routing metric in (22), a sender node x can determine if it will take direct transmission or cooperative transmission, and the channel to use for transmission. In the case that a cooperative transmission is needed, the selected relay node will be informed.

Fig.5 shows an example on routing metric calculation for the hop (x, y) where there are two feasible channels ch_1 and ch_2. In case that ch_1 is used, the available link capacity under the direct transmission is 18, while the capacity under the cooperative transmission going through candidate relays r_1, r_2, r_3 is 20, 23, 21 respectively. Among these options, the capacity for the cooperative transmission through r_2 is the maximum and has the value 23 as shown in Fig.5(b). If x transmits data to y through ch_2, the maximum capacity is 24, which is achieved when choosing the cooperative transmission with r_1 as the relay node, as shown in Fig.5(d).

Thus, according to (22), the routing metric of hop (x, y) is 24 which is the maximum available capacity between ch_1 and ch_2, as shown in Fig.5(e). As a result, ch_2 is the selected working channel and r_2 is the selected cooperative relay for hop (x, y).

2) Routing Algorithm

The routing path selection can be realized through our proposed CRS, a distributed Cooperative Route Selection algorithm which is modified from AODV and based on the routing metric $CMetric$.

Current AODV-based routing protocols are designed only for one-to-one direct transmission instead of cooperative communications. In this paper, we propose a novel routing metric CMetric. To facilitate finding the cooperative path with maximum capacity, different from AODV, in our CRS design,

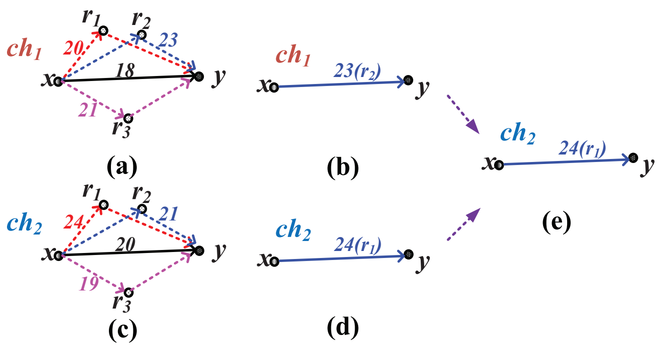


Fig. 5. Example of routing metric calculation.

the RREQ message carries the information of the capacity of the path segment from the source to the previous hop and the routing metric CMetric of the last hop.

CRS consists of three major parts, including source node behavior, the behavior of an intermediate node when receiving RREQ (Route Request) and the behavior when receiving RREP (Route Reply).

- Source Node Behavior

Algorithm 1 shows the behavior of the source node in CRS. For a new arriving session, when a source s intends to send packets to a destination d, s first checks its routing table to see whether it has a valid path. If so, s begins to send packets to the next hop towards the destination; otherwise, it searches for the path by broadcasting a RREQ message to its one-hop neighbors, which rebroadcast the message until it reaches the destination node.

Algorithm 1 Behavior of Source Node s

if s has a valid path to d in its routing table **then**
  s begins to send packet to the next hop towards the destination d
else
  for node z in $N(s)$ **do**
    according to (22), node s calculates the routing metric of the outgoing link(s, z) (denoted as P_{sz}), which identifies the optimal transmission mode, the working channel, and the optimal relay if cooperative transmission is selected.
    insert the calculated routing metric information P_{sz} into RREQ.
  end for
  insert $\mathrm{P}_s = +\infty$ into RREQ, where P_s denotes the maximum end-to-end capacity from s to s, and broadcast the RREQ.
end if

- Intermediate Node Behavior When Receiving RREQ

In order to reduce the routing overhead, in our CRS, an RREQ message can be transmitted and forwarded by an intermediate node only when it is forwarded along a path with better capacity from the source node to the intermediate node.

Assume the capacity of the path segment from the source s to x is P_x, which is set to 0 initially and kept at node x. As shown in Algorithm 2 (in step 2 and step 3), when an intermediate node x in the network receives an RREQ from its upstream node z, if the RREQ message is received in duplication and the current capacity of the path segment

Algorithm 2 Behavior of an Intermediate Node x When Receiving RREQ

1: Once RREQ message is received from node z, node x obtains P_z (the maximum capacity of path segment from s to z), and P_{zx} (the routing metric of link(z, x)). Node x calculates the maximum capacity of path segment from s to x following $\mathrm{P}'_x = \min(\mathrm{P}_{zx}, \mathrm{P}_z)$.
2: **if** node x has ever received another RREQ of source s and $\mathrm{P}'_x \leq \mathrm{P}_x$, where P_x is the latest maximum capacity of path segment from s to x kept in node x, **then**
3:   node x drops the RREQ.
4: **else if** node x is the destination d and x waits for some time interval after it receives an RREQ message at the first time **then**
5:   node x chooses the optimal path which is the one with the maximum end-to-end capacity from all the RREQ messages received within the interval.
6:   node x generates and sends an RREP message to the source.
7: **else**
8:   node x updates the maximum capacity of path segment from s to x by using $P_x = P'_x$.
9:   node x records node z, which will lead a reverse path to the source.
10:   node x creates a new RREQ message.
11:   **for** node y in $N(x)$ **do**
12:     according to (22), node x calculates its outgoing link(x, y)'s routing metric $CMetric(x, y)$ (denoted as P_{xy}), which identifies the optimal transmission mode, the working channel, and the optimal relay if the selected transmission mode = CC; insert the newly calculated information P_{xy} into RREQ.
13:   **end for**
14:   insert the maximum capacity of path segment from s to x, P_x into RREQ and broadcast it.
15: **end if**

from the source s to node x, denoted as P'_x, is smaller than the recorded one P_x, node x will discard the RREQ and stop forwarding, where P_x is the latest maximum capacity of the path segment from s to x kept in node x and $P_x{}' = \min(P_{zx}, P_z)$ (where P_z and P_{zx} are carried by the received RREQ). Compared to traditional AODV-related protocols, such a design can not only prevent transmission loop but also reduce the RREQ messages by avoiding forwarding messages from inferior upstream paths, which largely reduces the routing overhead.

If node x is the destination, it can wait for some time interval. It then chooses the path which has the maximum end-to-end capacity from all the RREQ received within the interval, and sends a RREP back to the source.

Otherwise, node x first updates the capacity from source s to node x as $P_x = P'_x$, and then records a reverse route to node z, which will allow the finding of a reverse path to the source that originates the RREQ. Finally, node x creates and rebroadcasts a new RREQ message by inserting P_x and the hop metrics between itself and all its neighbors.

- Intermediate Node Behavior When Receiving RREP

Let NSS (Number of Shared Sessions) denote the number of sessions that a link is selected to serve during the CRS procedure, which is set to 0 initially. As shown in (23), NSS has been utilized to calculate the routing metric of a link, and it will be used in the next subsection to guide the local adjustment of path segments.

Once a link x is selected in the routing path, when the sender of x receives the RREP message, it first increases the link's NSS by 1, i.e. $NSS_x = NSS_x + 1$. If the cooperative communication mode is exploited by the link, the sender of x also lets the selected virtual cooperative link to increase its NSS by 1. Then the link sender will forward the RREP message back to the upstream node on the reverse path to the source.

After receiving the RREP message, the source forwards its data packets along the selected path to the destination with the transmission mode and the working channel on each hop set to the one determined during the path finding process.

B. Fairness Aware Route Adjustment Algorithm

The proposed CRS can select good cooperative routing path for each session when the session arrives. However, the old session's end-to-end capacity may decrease when the network has newly arrival sessions because the newly arrival sessions may in turn bring serious transmission competitions on wireless channel and impact the performance of the old sessions. To address this issue, we propose a Fairness Aware Route Adjustment (FARA) algorithm. Our design intends to increase the minimum transmission capacity of all the sessions.

1) Notation and Definition

If multiple paths selected by different sessions go through some common links, it would result in the resource competition at these links, and additional procedures need to be taken. Alternatively, we can change the session to a candidate path which doesn't include the competition link to obtain a better end-to-end capacity. To reduce the side effect associated with a path change, we restrict the path adjustment and relay assignment to be local around the competition link to maximize the minimum rate of different sessions.

Let $R_j(i,k)$ denote the set of feasible path segments between the node pair (i,k) for session j. If one path segment in $R_j(i,k)$ is selected by the proposed CRS, then obviously it has the maximum capacity between the node pair (i,k) for session j when this session arrives, and we denote the corresponding path segment as $O_{p_j}(i,k)$.

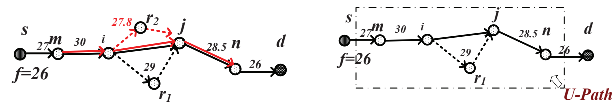
The candidate path segment between a node pair (i,k) for session j, denoted as $Can_j(i,k)$, is a feasible path segment which has the largest capacity among the ones in $R_j(i,k) - O_{p_j}(i,k)$ and the NSS of each link on the path segment is not larger than NASS (the Number of Allowable Shared Sessions) of a link. NASS can be calculated with Eq.(26).

Assume that a link $i \to j\,|ch_k$ (or a virtual cooperative link $i \to j(w)\,|ch_k$) is overloaded with a large NSS value and the link is selected by flow f. Let m and n be the upstream node and downstream node of this link. Based on the CRS algorithm proposed in Section V-A, we design a candidate path segment finding algorithm which includes the following two steps:

- ***Step 1.*** Mark the overloaded link $i \to j\,|ch_k$ (or $i \to j(w)\,|ch_k$) unreachable.
- ***Step 2.*** Apply the CRS algorithm proposed in Section V-A to look for a cooperative routing path segment from m to n that all links on the path segment have their NSS smaller than their NASS; Return the path segment as the candidate one for $m \to n$ for transmission of flow f.

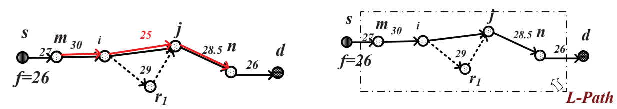
The algorithm is designed based on the CRS algorithm in Section V-A, and the overhead in this procedure mainly includes the control message to apply the CRS algorithm to look for the local path segment, which is generally small.

As shown in the Fig. 6(a), the maximum capacity of the path segment $r_1 \to r_4$ is 28.8. Assume the overloaded link is $r_6 \to r_7$. A candidate path segment is the one that has the maximum capacity among all other feasible path segments (See Fig. 6(b)) between r_1 and r_4 except the original one selected by the session. As shown in the Fig. 6(c), the candidate path segment for $r_1 \to r_4$ is $r_1 \to r_2 \to r_3 \to r_4$.



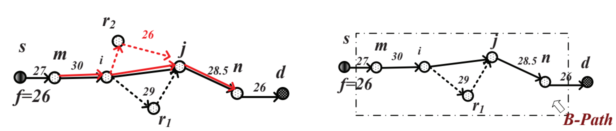
(a) (b)

Fig. 7. Example of U-path.



(a) (b)

Fig. 8. Example of L-path.



(a) (b)

Fig. 9. Example of B-path.

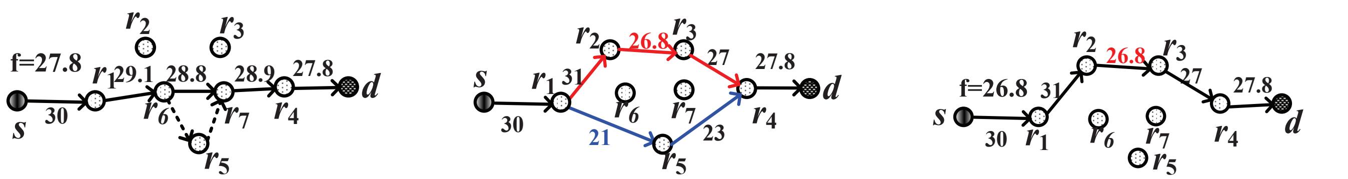
Based on the definition of candidate path segment, we have the following definitions.

U-Path: Given $O_{p_j}(i,k)$, if the capacity of its $Can_j(i,k)$ is larger than the end-to-end capacity of session j, then we call $O_{p_j}(i,k)$ a U-Path.

L-Path: Given $O_{p_j}(i,k)$, if the capacity of its $Can_j(i,k)$ is smaller than the end-to-end capacity of session j, then we call $O_{p_j}(i,k)$ a L-Path.

B-path: Given $O_{p_j}(i,k)$, if the capacity of its $Can_j(i,k)$ is equal to the end-to-end capacity of session j, then we call $O_{p_j}(i,k)$ a B-path.

Fig.7, Fig.8 and Fig.9 show the examples of U-path, L-Path and B-Path, respectively. The path segment of $m \to i \to j\,(r_2) \to n$ in Fig.7, the path segment of $m \to i \to j \to n$ in Fig.8, and the path segment of $m \to i \to j\,(r_2) \to n$ in Fig.8 are the candidate path segments. The capacities of these candidate path segments are 27.8, 25, 26, which are respectively larger, lower and equal to the end-to-end capacity of the corresponding sessions. According to the definition, the original path segments of $m \to i \to k\,(r_1) \to n$ in Fig.7, Fig.8 and Fig.9 are U-path, L-Path and B-Path, respectively.



(a) (b) (c)

Fig. 6. Example of Candidate link .

2) Algorithm design

Given any path segment $p \in R_j(i,k)$, the path segment must be one type of U-Path, L-Path and B-path. Among the NSS path segments belonging to different sessions, assuming there are n_1 U-paths, n_2 L-Path and n_3 B-Path, we have $NSS = n_1 + n_2 + n_3$.

Given a link x that is selected by NSS_x sessions, the end-to-end capacity of these sessions are $P_1, P_2, \cdots, P_{NSS_x}$, (the end-to-end capacity is calculated based on all links along the path except the competition link x), the available capacity of this link is $C(x)$ ($C(x)$ calculated with Eq.(15) or Eq.(16) depending on the transmission mode of the link, then the relationship of NASS of this link and the end-to-end path capacity of these sessions can be expressed as

$$\frac{C(x)}{NASS_x} \geq \min\{P_1, P_2, \cdots, P_{NSS_x}\}, \tag{24}$$

that is

$$NASS_x \leq \frac{C(x)}{\min\{P_1, P_2, \cdots, P_{NSS_x}\}}. \tag{25}$$

Furthermore, because $NASS_x$ is an integer, we have

$$NASS_x = \left\lfloor \frac{C(x)}{\min\{P_1, P_2, \cdots, P_{NSS_x}\}} \right\rfloor, \tag{26}$$

where $\lfloor * \rfloor$ is floor function and $\lfloor y \rfloor$ is the largest integer not larger than y.

Given a link x, if $NSS_x > NASS_x$, we need to adjust the routing path selection and relay assignment around the competition link. As a basic principle of our Fairness Aware Routing Adjustment (FARA) algorithm, in order not to reduce the capacity of the sessions that go through the L-Path, the competition link will first switch some or all U-Paths and B-Paths to their candidate path segments. Among the L-Paths, we give resource preference to the ones with lower capacity. We consider two cases in our algorithm:

Case A: $0 \leq n_2 \leq NASS_x$. The competition link x keeps all L-Path, as well as $NASS_x - n_2$ U-Path or B-Path the same, and randomly switches $NSS_x - NASS_x$ path-segments among $n_1 + n_3$ (U-Paths and B-Paths) to their candidate path segments for the corresponding sessions.

Case B: $n_2 > NASS_x$. The competition link x first switches all the U-Paths and B-Paths to their candidate path segments. Then it sorts the capacity of n_2 candidate paths, and switches the top $n_2 - NASS_x$ ones to go through their candidate path segments.

One example of Case B is shown in Fig.10. In the example, there are three sessions using link $r_9 \rightarrow r_{10}$ through three path segments, $r_1 \rightarrow r_9 \rightarrow r_{10} \rightarrow r_2$, $r_3 \rightarrow r_9 \rightarrow r_{10} \rightarrow r_4$, and $r_5 \rightarrow r_9 \rightarrow r_{10} \rightarrow r_6$, as shown in Fig. 10(a). The end-to-end capacities of these three sessions are 25.3, 23.8 and 23, respectively. We assume that $NASS = 2$ for link $r_9 \rightarrow r_{10}$. Therefore, we need to switch one path segment among the three ones to its candidate path segment. Fig. 10(b) shows the three corresponding candidate path segments, $r_1 \rightarrow r_2(r_7)$, $r_3 \rightarrow r_5(r_8) \rightarrow r_6 \rightarrow r_4$, $r_5 \rightarrow r_6$, with the capacity 24.1, 21.5 and 22 respectively. Among all these three sessions, the capacity of the candidate path segment in session 1 has the highest value. According to our algorithm, we switch $r_1 \rightarrow r_9 \rightarrow r_{10} \rightarrow r_2$ for session 1 to $r_1 \rightarrow r_2(r_7)$ as shown in Fig. 10(c). After the switch, the capacity of the three paths corresponding to different sessions are 24.1, 23.8 and 23.

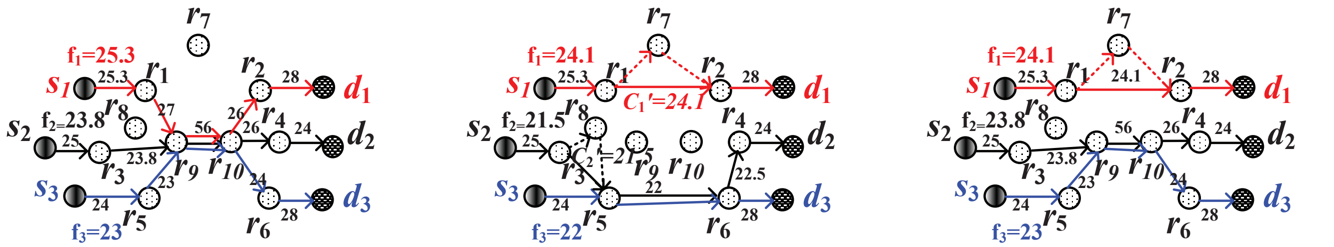
Another example of Case A is shown in Fig.11. In this example, the end-to-end capacities of the three sessions are 25.3, 25 and 24, respectively. Fig. 11(b) shows the three candidate path segments of the corresponding three sessions which do not involve the competition link $r_9 \rightarrow r_{10}$, $r_1 \rightarrow r_2(r_7)$, $r_3 \rightarrow r_5(r_8) \rightarrow r_6(r_9) \rightarrow r_4$, $r_5 \rightarrow r_6(r_9)$, with the capacity 27, 25.5 and 25.6 respectively. According to our algorithm, because all the capacities of candidate path segments of the three sessions are larger than the capacity of their end-to-end paths, we can randomly switch one path to its candidate path, as shown in Fig.11(c). After the switch, the capacity of the three sessions remains the same as that before switch.

3) Ripple Effect Reduction

It is worth pointing out that we follow an important principle to identify the candidate path segment: the candidate path segment should not include the links whose NSS is not smaller than $NASS$.

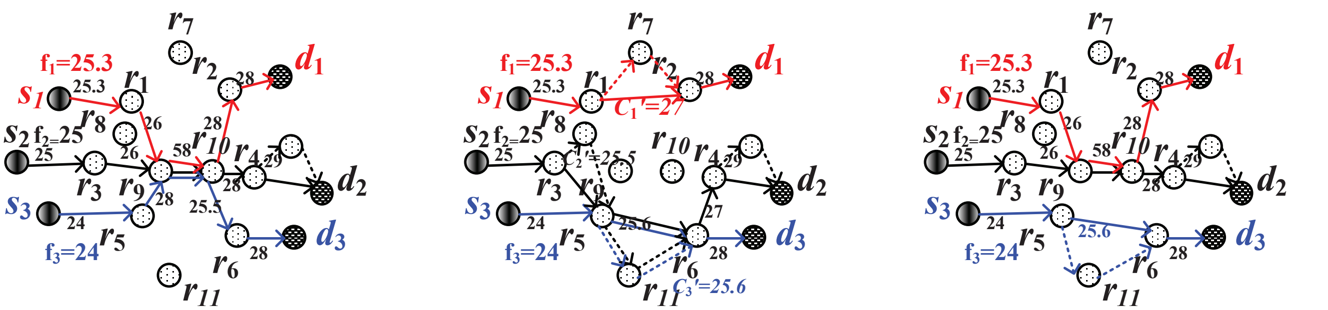
The purpose of introducing this rule is to avoid network instability as a result of triggering FARA to run in the switched candidate path segment thus subsequent rounds of route adjustments. If any link on the candidate path segment has NSS larger than $NASS$, it may need to restart another FARA algorithm after additional sessions are switched to this path segment. This will lead to instability. Ideally, for each candidate path segment, we should check its impact on network stability before activating the candidate path segment to route traffic for a session. Checking stability of network, however, is a time consuming task. Instead, we propose the simple rule.

We call the result of triggering FARA to run around some overloaded links on the candidate path as $Ripple\ Effect$. We call $Ripple\ Effect$ link as the one on the candidate path whose NSS is not smaller than NASS. To reduce the ripple



(a) (b) (c)

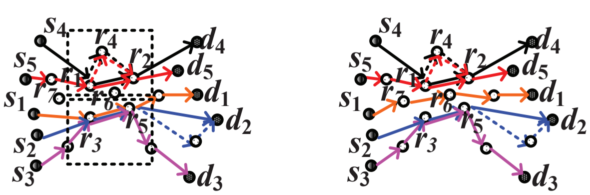
Fig. 10. Example of FARA procedure with $n_2 > NASS$.



(a) (b) (c)

Fig. 11. Example of FARA procedure with $0 \le n_2 \le NASS$.

effect, in this paper, we simply avoid selecting candidate paths containing ripple effect links. In case there does not exist a candidate path segment without introducing the ripple effect, multiple sessions may share a link, and different sessions can be coordinated in transmissions using the MAC layer scheme such as CSMA or TDMA.



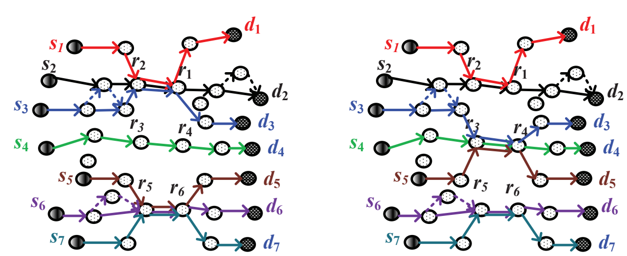
(a) (b)

Fig. 12. Example of ripple effect discussion.

We illustrate this scenario by an example in Fig. 12. Link $r_3 \rightarrow r_5$ is shared by three sessions and link $r_1 \rightarrow r_2(r_4)$ is shared by two sessions. The NASS of link $r_3 \rightarrow r_5$ and link $r_1 \rightarrow r_2(r_4)$ are 2. We assume that link $r_3 \rightarrow r_5$ will invoke FARA algorithm and select to change session 1 to go through link $r_1 \rightarrow r_2(r_4)$. As a result of path switching, link $r_1 \rightarrow r_2(r_4)$ would have three sessions going through it, and then would have to invoke another FARA algorithm. This effect may be propagated along a chain of such neighboring links with NSS larger than their NASS. If session 1 does not select to go through link $r_1 \rightarrow r_2(r_4)$ for its data transmission, link $r_1 \rightarrow r_2(r_4)$ may not have to invoke another FARA algorithm. Therefore, in the above example, link $r_7 \rightarrow r_6$ instead $r_1 \rightarrow r_2(r_4)$ should be selected for session 1, as shown in Fig. 12(b).

4) Avoidance of Route Adjustment Conflict

If each link independently makes a local route adjustment decision, multiple route adjustment requests may be received simultaneously by a link, which may lead to a route adjustment collision and decision conflict at the link. This will further make the link be a *Ripple Effect* link, and invoke another FARA algorithm again.



(a) (b)

Fig. 13. Example of route adjustment conflict.

We illustrate route adjustment conflict problem by an example in Fig. 13. In Fig.13(a), link $r_2 \rightarrow r_1$ and $r_5 \rightarrow r_6$ are all shared by three sessions, but the $NASS$ of these two links are 2. If link $r_2 \rightarrow r_1$ and $r_5 \rightarrow r_6$ invoke FARA algorithm independently, link $r_3 \rightarrow r_4$ may be selected in session 3 ($s_3 \rightarrow d_3$) and session 5 ($s_5 \rightarrow d_5$) after route adjustment, as shown in Fig.13(b). As a result of path switching, link $r_3 \rightarrow r_4$ would have three sessions going through, and then would have to invoke another FARA algorithm.

To mitigate this problem, we introduce a random delay before a link w invokes FARA algorithm when the link detects that itself is shared by multiple sessions with the NSS_w larger than its $NASS_w$, and the timer can be set as follows:

$$Timer_w = \frac{1}{NSS_w - NASS_w} + random\left(0, g\right), \qquad (27)$$

where the random number within $(0, g)$ is added to reduce collisions and decision conflicts from multiple requests of route adjustment. The link with a higher load, i.e., a larger gap of $NSS_w - NASS_w$, has a lower average timer value thus an earlier chance of adjusting its local route.

C. Convergence Analysis

In [39], the author gives the formal analysis of convergence of AODV protocol. Our cooperative routing algorithm (CRS) is designed based on AODV, and it is clear that the process of our CRS converges. Therefore, we only need to show that the process of route adjustment can converge and reach a stable state.

Theorem 2: If every overloaded link invokes FARA algorithm to adjust its local path segment following the procedure in Section V-B, within a finite number of path segment switches, the network will reach a stable state where all links stop the route adjustment.

Proof: Consider that a link i invokes FARA algorithm when detecting that it is overloaded ($NSS_i > NASS_i$) and begins to switch some of its sessions on link i to their candidate path segments at time t, and completes the path segment switches at time t' ($t' > t$). According to the procedure in Section V-B, $NSS_i - NASS_i$ sessions should switch their transmissions to the candidate path segments. Let P_i denote the link set on the candidate path segments.

In Section V-B4, we have the route adjustment timer set following the Eq.(27). This makes the chance for any other link j to trigger its local route adjustment simultaneously with link i very small. Therefore, at the time t', only links in P_i would be the new links (besides the links originally involved in sessions) that may trigger a route adjustment.

According to the principle in candidate-path-segment selection in Section V-B3, the candidate path segment should not include a link whose NSS is not smaller than its NASS. Therefore, these route switches will not make the links in P_i trigger another route adjustment.

Therefore, although our route adjustment depends only on the information available within a local domain and is designed to be distributed, the route adjustment process can self-stabilize and help the network to reach the stable state. ■

VI. CENTRALIZED ALGORITHM

For performance reference, we further propose a centralized algorithm. As one of the approaches to solving Integer Programming (IP) problems [40], branch-and-bound method finds the optimal solution to an IP by efficiently enumerating the points in the feasible region. Based on branch-and-bound framework, we propose a Centralized joint Flow Routing and Relay Assignment algorithm (CFRRA) to solve the MIP problem in (21), as shown in algorithm 3.

The basic idea of CFRRA is as follows. By using the relaxation in step 3, we can efficiently compute a global upper bound, UB, for problem in (21). This relaxation solution either yields a feasible solution to the problem or, if not feasible, it can be used as a starting point for a local search to find a feasible solution. This feasible solution then serves to provide a global lower bound, LB, and an incumbent solution to the problem. The branch-and-bound process proceeds by tightening LB and UB through a series of partitions over the problem domain, and terminates when $UB \leq (1+\varepsilon)LB$ is satisfied, where $\varepsilon > 0$ is some desired approximation error.

Algorithm 3 Centralized Joint Flow Routing and Relay Assignment Algorithm (CFRRA)

1: Let the optimal solution $\varphi^* = \phi$ and the initial lower bound $LB = 0$.
2: Let the initial problem list contain only the original problem in (21), denoted by P_1.
3: Construct the relaxation for P_1 by relaxing the constraint $x_{j:uv}^{wk}, y_{j:uv}^{k} \in \{0,1\}$ to $x_{j:uv}^{wk}, y_{j:uv}^{k} \in [0,1]$, and solve it. Denote the solution to this relaxation as φ_1 and its objective value as the upper bound UB_1.
4: Select a problem P_z that has the highest upper bound (designated as UB) among all the problems in the problem list.
5: Find, if necessary, a feasible solution φ_z via a local search algorithm for P_z. Denote the objective value of φ_z by LBz.
6: If $LBz > LB$, then let $\varphi^* = \varphi_z$ and $LB = LBz$. If $UB \leq (1+\varepsilon)LB$, then stop with the $(1+\varepsilon)$-optimal solution φ^*; else, remove all problems $P_{z'}$ having $UB_{z'} \leq (1+\varepsilon)LB$ from the problem list.
7: Select a binary $x_{j:uv}^{wk}$ or $y_{j:uv}^{k}$ and branch on the dichotomy of its values being 0 or 1.
8: Remove the selected problem P_z from the problem list, construct two new problems P_{z1} and P_{z2} based on the foregoing branching step.
9: Compute two new upper bounds UB_{z1} and UB_{z2} by solving the programming relaxations of P_{z1} and P_{z2}, respectively.
10: If $UB_{z1} > (1+\varepsilon)LB$ then add Problem P_{z1} to the problem list. If $UB_{z2} > (1+\varepsilon)LB$ then add Problem P_{z2} to the problem list.
11: If the problem list is empty, stop with the $(1+\varepsilon)-$ optimal solution φ^*. Otherwise, go to Step 4.

VII. SIMULATION RESULTS

We present some simulation results to demonstrate the rate gain by jointly applying interference-aware cooperative routing and relay assignment in multi-flow multi-radio multi-channel wireless networks. In this section, we first describe the simulation setup, and then present the simulation results.

A. Simulation Setup

We evaluate the performance of our proposed algorithms through extensive simulations using MATLAB. There are 12 orthogonal channels in the network in total, and the default number of sessions in the network is set to 4. Following the parameter setting in [14], we set the bandwidth W of each channel to 22 MHz, the maximum transmission power at every node to 1 W. The channel gain contains the path loss and the Rayleigh fading coefficient. White Gaussian noise with the variance 10^{-10} W is added to include environment noise impact.

In the simulations, 60 nodes are generated randomly in a 1000m $\times$ 1000m area. Each node is equipped with 3 radios, and the maximum communication range is set to 250 meters. The interference range is set to twice the communication range and will change with the communication range varies.

There is no existing work studying cooperative communications with multi-flow routing in multi-radio multi-channel networks. We implement eight routing algorithms in different network scenarios for performance comparisons, which are introduced as follows.

1) For performance comparison, we implement our proposed centralized algorithm CFRRA in Algorithm 3 in a multi-radio multi-channel cooperative networks with $\varepsilon = 0.1$ in the algorithm, denoted as CFRRA-MRMC-CC.
2) We implement our proposed multi-flow multi-radio multi-channel cooperative routing algorithm DFRRA in Section V which includes two sub-algorithms: the cooperative routing sub-algorithm in Section V-A and the fairness-aware route adjustment in Section V-B, denoted as DFRRA-MRMC-CC.
3) The CRS algorithm in Section V-A is applied to find the maximum end-to-end cooperative path which has the maximum capacity for each new session. We implement the CRS scheme in a multi-radio multi-channel cooperative wireless network, denoted as CSC-MRMC-CC.
4) Different from the third scheme, we implement the CRS in a single-radio single-channel cooperative wireless network where each node is assigned with the same channel, denoted as CSC-SRSC-CC.
5) Different from the third scheme, we implement CRS in a single-radio multi-channel cooperative wireless network where each node is assigned with a channel randomly selected from the set of orthogonal channels, denoted as CSC-SRMC-CC.
6) We implement a non-cooperative routing algorithm in which the Bellman-Ford path algorithm is applied to search for the maximum end-to-end capacity path for each new session in multi-radio multi-channel wireless network, denoted as Bellman-MRMC-NC.
7) Different from the sixth scheme, we implement the non-cooperative routing algorithm in single-radio single-channel wireless network, denoted as Bellman-SRSC-NC.
8) Different from the sixth scheme, we implement the non-cooperative routing algorithm in single-radio multi-channel wireless network, denoted as Bellman-SRMC-NC.

Note that the last three algorithms Bellman-MRMC-NC, Bellman-SRSC-NC, and Bellman-SRMC-NC consider a non-cooperative wireless network which only consists of flow routing for each session.

In the last six algorithms, if multiple sessions select the same link, TDMA type scheduling can be applied at the MAC layer to allocate time slots to different active sessions based on certain fairness rule.

We evaluate the performance of our distributed algorithm DFRRA-MR-CC under different node density, number of sessions, number of radio interfaces on a node, and the communication ranges. Unless otherwise specified, the default number of nodes in the network is 60, the number of sessions is 4, each node is equipped with 3 radios, and the communication range is 250 meters. A simulation result is obtained by averaging over 20 runs of simulations.

B. Simulation Result

1) Impact of node density

In Fig.14, the aggregate rate and minimum rate (in term of kbps) under all routing algorithms increase as the number of nodes increases, as there are more candidate relay nodes.

Compared with the aggregate rate of single-radio network Bellman-SRSC-NC, the rate of the multi-radio network DFRRA-MRMC-CC is about 6-8 times. The introduction of multi-radio nodes with multi-channel significantly increases the flexibility in relay selection and decreases the wireless interference thus achieving higher performance gain. Compared to CRS-MRMC-CC, CRS-SRSC-CC, CRS-SRMC-CC, Bellman-MRMC-NC, Bellman-SRSC-NC, and Bellman-SRMC-NC, we find that our two multi-radio multi-channel cooperative routing algorithms, the centralized CFRRA-MRMC-CC and the distributed DFRRA-MRMC-CC, have the largest aggregate rate and minimum rate. Compared to Bellman-MRMC-NC, DFRRA-MRMC-CC can increase up to 78% the aggregate transmission rate. This demonstrates the significant performance gain achieved by incorporating CC in multi-radio multi-channel multi-hop wireless networks.

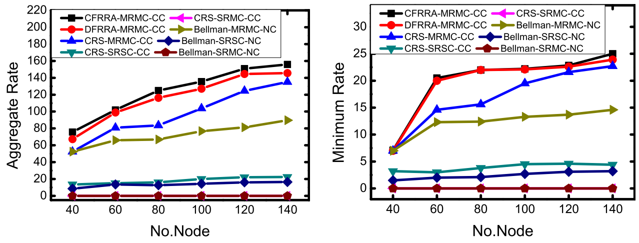
In a multi-channel wireless network, two nodes can communicate only if they are assigned a common channel. For a single radio wireless network, a node can be assigned at most one channel. If the channel assigned to the node is randomly selected, nodes in the single-radio multi-channel network has a limited number of neighbors. Thus there are limited number of links in the network, and the curves of CRS-SRMC-CC and Bellman-SRMC-NC are close to x axis as shown in Fig.14.

Moreover, compared to CRS-MRMC-CC, our DFRRA-MRMC-CC can obtain up to 40% and 41% higher aggregate rate and minimum rate, respectively. This indicates that the Fairness-Aware Route Adjustment algorithm (FARA) proposed in Section V-B and included in DFRRA-MRMC-CC can effectively resolve the resource competition among different sessions and ensure higher minimum throughput across sessions. CRS-MRMC-CC simply coordinates transmissions through TDMA when multiple sessions share links, which will compromise the performance. When the number of relay nodes is small, there may be more relay competitions among different sessions. Our FARA algorithm can more effectively adapt the relay selections on competitive routing segments to increase the aggregate rate.

2) Impact of the number of sessions

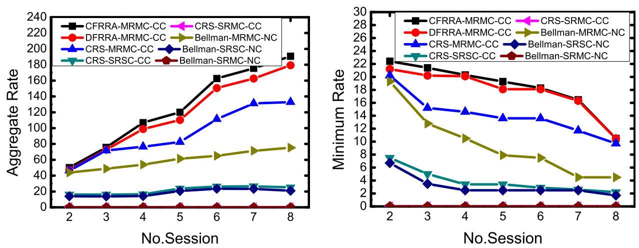
In Fig 15, as the number of sessions increases, the aggregate rate increases, while the minimum rate decreases. This is as expected. The larger number of sessions bring higher competitions on the relay nodes and channel resources in the network, which results in larger interference thus the reduction of the minimum throughput.

The two multi-radio cooperative routing algorithms, CFRRA-MRMC-CC and DFRRA-MRMC-CC, have much better performance compared to other routing algorithms. Compared with CRS-MRMC-CC, our DFRRA-MRMC-CC



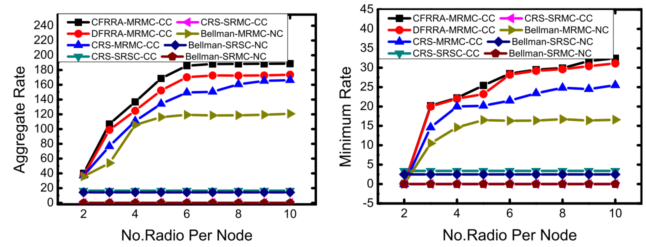
(a) aggregate rate (b) minimum rate

Fig. 14. Impact of node density.



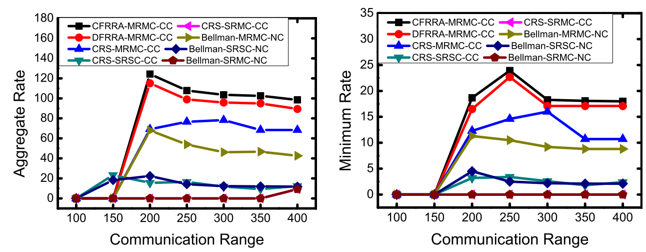
(a) aggregate rate (b) minimum rate

Fig. 15. Impact of number of sessions.



(a) aggregate rate (b) minimum rate

Fig. 16. Impact of number of radios.



(a) aggregate rate (b) minimum rate

Fig. 17. Impact of the communication range.

achieves the same performance when the number of sessions is 2, and achieves higher aggregate rate and minimum rate when the number of session is larger than 2. When the number of sessions is small, the relay nodes and channels are sufficient to serve all sessions. In Fig.15(b), compared with CRS-MRMC-CC, as the number of sessions increases, the gain of our DFRRA-MRMC-CC is seen to increase initially and then reduce. Our FARA algorithm can effectively mitigate link competition initially, but the performance of DFRRA-MRMC-CC suffers when the number of sessions is very large and there are very few candidate relays to exploit.

3) Impact of the number of radios

When varying the number of radios from 2 to 10 in Fig. 16, the aggregate rate and minimum rate achieved by CFRRA-MRMC-CC, DFRRA-MRMC-CC, CRS-MRMC-CC, and Bellman-MRMC-NC increase, as there are more relay and transmission channel options. As CRS-SRSC-CC and Bellman-SRSC-NC are single-radio routing algorithms, the number of radios don't have impact on their performance as in Fig. 16. Similar to the reason of Fig 15, due to limited links in single-radio multi-channel networks, the curves of CRS-SRMC-CC and Bellman-SRMC-NC are close to x axis.

The performance of DFRRA-MRMC-CC outperforms CRS-MRMC-CC when there are competitions in relay and link access, which demonstrates that our DFRRA-MRMC-CC can make use of relay and channel resource more efficiently.

Compared to Bellman-MRMC-NC, our DFRRA-MRMC-CC can obtain up to 30% and 37% higher aggregate rate and minimum rate respectively, which demonstrates that cooperative transmissions outperform direct transmissions in multi-radio multi-channel multi-hop wireless networks.

4) Impact of the communication range

In order to observe the effect brought by the transmission distance, we vary the communication range from 100 to 400 meters in the network. As shown in Fig.17, when the communication range is very small, the aggregate rate and minimum rate for all the routing schemes are zero because nodes have limited number of neighbors and there are limited links in the wireless networks. The aggregate rate and minimum rate for all the routing schemes increase initially. However, with the further increase of the communication range, the throughput reduces until the communication range reaches a certain value, then maintains a stable throughput.

On the one hand, the increase of the communication range leads to higher number of links thus more options to select relays and next-hop nodes. The initial increase of communication range also helps to increase the network connectivity and find a better transmission path. On the other hand, a larger communication range also creates higher interference and hence reduces the routing performance. Therefore, it is not helpful to use too high transmission power to increase the communication range. Similar to the results in Fig.14, Fig.15, and Fig.16, our scheme CFRRA-MRMC-CC and DFRRA-MRMC-CC show better performance compared with other schemes in Fig.17.

In summary, all the simulation results demonstrate that, our distributed algorithm DFRRA-MRMC-CC is seen to achieve the performance close to the bound provided by the centralized algorithm CFRRA-MRMC-CC while running much more efficiently.

VIII. CONCLUSION

This paper studies a joint problem of cooperative routing and relay assignment in multi-hop and multi-radio networks to maximize the minimum rate among a set of concurrent communication sessions. We first model this problem as a mixed integer programming (MIP) problem and prove it to be NP-hard. Then we propose a centralized algorithm and a distributed algorithm to solve the problem. The centralized algorithm can guarantee the finding of a global $(1+\varepsilon)$-optimal solution. The distributed algorithm can be applied to find an efficient cooperative route with polynomial complexity. We have done extensive simulations to evaluate the performance, and our results demonstrate the effectiveness of the proposed algorithms and the significant rate gains that can be achieved by incorporating CC in multi-radio multi-hop networks. Although we use AF as the CC mode in this paper, it is worth pointing out that our algorithms do not depend on specific CC mode to function.

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