Interference-Aware Cooperative Communication in Multi-Radio Multi-Channel Wireless Networks

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Abstract—There are a lot of recent interests on cooperative communication (CC) in wireless networks. Despite the large capacity gain of CC in small wireless networks with its capability of mitigating fading taking advantage of spatial diversity, cooperative communication can result in severe interference in large networks and even degraded throughput. The aim of this work is to concurrently exploit multi-radio and multi-channel (MRMC) technique and cooperative transmission technique to combat co-channel interference and improve the performance of multi-hop wireless network. Our proposed solution concurrently considers cooperative routing, channel assignment, and relay selection and takes advantage of both MRMC technique and spatial diversity in cooperative wireless networks to improve the throughput. We propose two important metrics, contention-aware channel utilization routing metric (CACU) to capture the interference cost from both direct transmission and cooperative transmission, and traffic aware channel condition metric (TACC) to evaluate the channel load condition. Based on these metrics, we propose three algorithms for interference-aware cooperative routing, local channel adjustment, and local path and relay adaptation respectively to ensure high performance communications in dynamic wireless networks. Our algorithms are designed to be fully distributed and can effectively mitigate co-channel interference and achieve cooperative diversity gain. To our best knowledge, this is the first distributed solution that supports cooperative communications in MRMC networks. Our performance studies demonstrate that our proposed algorithms can efficiently support cooperative communications in multi-radio multi-hop networks to significantly increase the aggregate throughput.

Index Terms—Cooperative communication, cooperative routing, relay assignment, channel assignment

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1 INTRODUCTION

AS an emerging technique for future wireless networks, cooperative communication (CC) has been proposed to take advantage of the broadcast nature of wireless communications and spatial diversity to improve the network performance [1], [2]. More specifically, relay nodes have been exploited to forward the replica of packets from the sources, and the destinations can combine multiple copies of the signal to better decode the original message. Taking advantage of spatial and multiuser diversities, CC can efficiently improve the network performance.

Despite the significant performance gain in small networks, recent research results show through both analysis and simulation that use of cooperative relays (CRs) in large-scale wireless networks can lead to severe interference which in turn results in higher packet loss and consequent throughput reduction [3], [4], [5]. Although relay nodes may help to increase the throughput of a single source and destination pair, a cooperative transmission (CT) often involves three transmission links (i.e., from the source to the relay, from the source to the destination, and from the relay to the destination). The increase of transmission links in a neighborhood leads to higher interference, thus reducing the network-wise performance. When the interference is severe, the performance can be even worse than without using cooperative transmissions. It is critical to reduce the interference for CC to work efficiently in a practical wireless network, especially when the network scale is large.

As another recent technique, multi-radio multi-channel (MRMC) has been exploited to alleviate the co-channel interference by supporting concurrent transmissions over orthogonal channels to improve the network capacity [6]. With the growth of modern wireless technologies, the cost of radio chips including those supporting 802.11 [7], [8] constantly reduces and more devices will be equipped with multiple radios.

In this paper, we will exploit MRMC to alleviate the interference in a network with cooperative communications for potentially much higher network performance. In cooperative networks, a routing path can be formed with a combination of cooperative transmissions and direct transmissions (DTs), and we call this kind of routing *cooperative routing*. The important and interesting question this paper tries to answer is: what is the maximum aggregate throughput of a multi-radio multi-channel network when the cooperative transmission is available? Current studies on cooperative communications in

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multi-hop wireless network generally assume the network nodes are equipped with only single-antenna [9], [10], [11], [12], [13], [14], [15], [16], [17], and it is unclear what capacity and performance gain can be achieved if nodes are equipped with multiple antennas. Despite the large potential benefit, it is highly non-trivial to make both CC and MRMC techniques to work seamlessly together. Some of the challenges are as follows.

First, the coupled cooperative routing problem and relay selection problem should be solved together. Different from conventional routing in MRMC networks where every node just needs to find the next-hop node to forward packets towards the destination, with cooperative routing, a neighbor of the transmitter not only needs to serve as a multi-hop transmission relay (MR) for packet forwarding but may also act as a cooperative relay of the transmitter for cooperative transmission. 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.

Second, there is a trade-off between alleviating co-channel interference and exploiting cooperative diversity. In single-radio single channel cooperative wireless networks, one-hop neighbors of a transmitter are candidate MR or CR nodes. A transmitter node can determine to use direct transmission and find an MR or cooperative transmission and find a CR to maximize the cooperative transmission gain. Although MRMC can largely relieve the co-channel interference, only the node which tunes to the same channel as that of the transmitter can act as an MR or a CR, which reduces the number of candidate relay nodes. This makes it important and challenging to consider radio-channel assignment along with cooperative communications.

Third, the use of cooperative relays in cooperative communications makes the network interference condition more complicated than that in a network with only direct transmissions, and it desires careful design to reduce the interference along with the finding of the cooperative routing path and channel assignment in MRMC cooperative networks.

In summary, there is an inter-dependence among cooperative routing, channel assignment, and relay selection. To enable cooperative communications in MRMC wireless networks and fulfill the full potential of both techniques, the three problems need to be systematically solved together.

In this paper, we propose the first practical and distributed solution to effectively exploit both MRMC technique and cooperative diversity to ensure higher performance of a multi-hop network with dynamic channel conditions and traffic flows. In our design, the cooperative routing at the network layer, channel assignment at the MAC layer, and cooperative communication at the physical layer will work interactively and seamlessly together.

Our contribution in this work can be summarized as follows:

- We introduce an important contention-aware channel utilization metric (CACU) which captures the interference cost from both direct transmission and cooperative transmission. Using CACU as the key routing metric, we propose an interference-aware cooperative routing algorithm.
- We propose a traffic-aware channel condition metric (TACC) to evaluate the channel load condition and trigger the channel adjustment procedure to relieve co-channel interference.
- We propose a feasible channel selection algorithm to ensure active flows (either involving direct transmission or cooperative transmission) to have continuous data transmissions during the channel adjustment process. To further prevent the network from being instable due to channel adjustment, we propose a chain puzzle detection sub-algorithm in the channel selection algorithm.
- We propose a local path and relay adjustment algorithm to further enhance the performance of active flows after channel adjustment.
- We have carried out extensive simulations to evaluate the performance of our proposed solution. The simulation results demonstrate the effectiveness of our solution and the significant aggregate throughput gains by incorporating cooperative transmission in MRMC multi-hop networks.

The remaining of this paper is organized as follows. Section 2 reviews the related works. We introduce our system model and problems in Section 3. We present our detailed algorithms on cooperative routing, channel assignment, and local path and relay adjustment in Sections 4, 5 and 6, respectively. The complete solution is presented in Section 7. Simulation results and analysis are given in Section 8. We conclude the work in Section 9.

2 RELATED WORK

Multi-hop wireless networks have attracted a lot of research interests, and various studies have been made to increase the network performance and support more advanced mobile computing and applications [18], [19], [20], [21], [22], [23], [24]. Different from existing studies, the aim of this paper is to take advantage of CC and spatial diversity from different users to improve the network capacity while leveraging MRMC technique to combat the increased co-channel interference associated with the use of CC technique. To design an efficient cooperative communication scheme in MRMC multi-hop wireless networks, cooperative routing, channel adjustment, and relay selection should be concurrently considered.

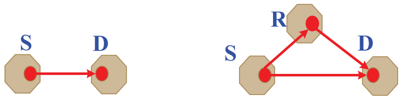
Channel assignment with routing has been proposed in non-cooperative wireless networks, where the major challenge is resulted from the inter-dependency of channel assignment and routing. For a given set of nodes and their traffic demands, the joint channel assignment and routing problem can be solved by centralized algorithms [25], [26], [27], [28], [29], [30], [31], [32]. Although centralized algorithms can be applied in the network planning or a static wireless network, they are difficult to work in dynamic networks. Distributed algorithms on joint channel assignment and routing are proposed in [33], [34], [35], [36], [37], [38], [39], where the algorithms only consider conventional one-to-one transmission. Cooperative communications can potentially improve the network performance by exploiting many-to-one transmissions to migrate fading, however, there is very limited work on enabling cooperative transmissions in MRMC networks.

On the other hand, some recent studies have been performed on cooperative routing and relay selection in single-radio multi-hop wireless networks. Khandani et al. [9] study a minimum energy routing problem in a static wireless network and develop a dynamic-programming-based algorithm for finding the cooperative path. However, the work only considers single flows while we consider multiple flows in this paper. In [10], Yeh and Berry consider multiple stochastically varying flows and propose throughput network control policies to take into account queue dynamics for joint optimization of routing, scheduling and resource allocation. The solutions are constrained to the special case of parallel relay networks. The papers [11], [12], [13] 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. These solutions decouple path finding and relay assignment, which make the path different from that found by optimal cooperative routing. In [14], the authors propose a distributed cooperative routing algorithm to construct a minimum-power route to guarantee certain throughput. In [15], the authors define a bandwidth-power aware cooperative multi-path routing (BPCMPR) problem in wireless multimedia sensor networks, and propose a polynomial-time heuristic algorithm CMPR to solve the problem. In [16], to illustrate the benefits of cooperative transmission in multi-hop wireless networks, the authors solve a joint optimization problem of relay node assignment and flow routing for concurrent flows. In [40], the authors study the problem of relay selection for joint scheduling, routing and power allocation in multi-flow wireless networks.

Multiple radios on wireless devices provide more opportunities for network capacity enhancement, but exploiting additional radios in cooperative communications is a challenging problem and has very limited work. Only the work in [17] studies cooperative transmission in multi-radio multi-hop networks. It proposes a channel-on-demand (COD) mathematical model to maximize the capacity and an interface assignment algorithm for real-time flows. Different from our work, the proposed approach assumes that the routing path is given and the mapping of channel to radio is static.

In addition to problems above, existing work on cooperative communications over multi-hop networks either ignores the increased interference due to cooperative transmission or assumes there exist orthogonal channels to concurrently transmit different flows. These studies have no consideration on the issue of channel assignment, while channel assignment directly impacts the network topology and interference which further impacts the performance of cooperative transmission in MRMC network. Without considering the interference, existing schemes proposed for cooperative transmissions may be subject to significant performance degradation.

Li et al. [41] study an energy and spectrum efficient cooperative communication (ESCC) 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 solution of [41] is difficult to be extended to multi-radio multi-hop wireless networks to achieve the cooperative diversity gain.



(a) Direct transmission (b) Cooperative transmission

Fig. 1. Two kinds of transmission modes.

To the best of our knowledge, this is the first work that provides a distributed and practical solution to enable cooperative transmissions in dynamic MRMC multi-hop wireless networks. Our scheme exploits MRMC technique to effectively reduce the interference brought by cooperative communications, and takes advantage of both MRMC technique and cooperative diversity to significantly increase the network performance.

3 SYSTEM MODEL AND PROBLEM

In this section, we first introduce our network model, then present our problem and a motivation example. Finally, we give an overview on our solution.

3.1 Network Model

We consider a multi-hop cooperative wireless network where a node can be equipped with multiple radios. We call this network MRMC cooperative wireless network. There are N nodes in the network. Each node i in the network is equipped with one or more radio interfaces (wireless NIC), represented by $I(i)$. Each radio can serve as a transmitter or a receiver on a channel at a given time. We assume there are a total of K orthogonal channels in the network, numbered $Ch_1, Ch_2, \ldots, Ch_K$, and there is no inter-channel interference. The channel assignment is trivial if the number of orthogonal channels available is at most the minimum number of radios per node $I(i)$, since in this case every node must be assigned all the channels. This paper assumes K is larger than $\max_{i \in N} I(i)$. A radio is capable of selecting a working channel from the set of orthogonal channels, and the set of working channels of node i is denoted as $w(i)$. Due to the interference constraints, there is no capacity benefit in equipping two different radios of a node with the same channel.

There are multiple concurrent flows, denoted by a set $F = \{F_1, F_2, \ldots, F_M\}$ of M flows. The data for each flow may traverse multiple hops in the network. A flow $F_i(S_i \rightarrow D_i)$ goes through a pair of source node and destination node, denoted as S_i and D_i, respectively.

There are two transmission modes between any two nodes in the network considered, direct transmission and cooperative transmission, as shown in Fig. 1.

Direct transmission mode is widely employed in current wireless networks, where a source node transmits its signal directly to a destination node. The achievable rate of $C_{DT}(S,D)$ between S and D is expressed as

$$C_{DT}(S,D) = W * \log_2(1 + SNR(S,D)). \tag{1}$$

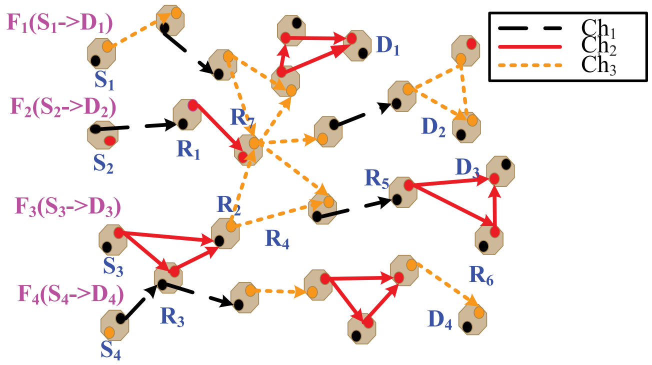


Fig. 2. The MRMC cooperative network.

A cooperative transmission involves three nodes and three links. Specifically, a collaborative neighbor R overhears the signal from source S and forwards the signal to the destination D, which then 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.

The mechanism to accomplish CT is not unique. In [3], 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, R receives signals from S and 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 of $C_{CT}(S,R,D)$ between S and D with R as relay under AF-RAKE mode [3] is given by

$$C_{CT}(S,R,D) = W * \log_2\Bigg(1 + SNR(S,D) + \frac{SNR(S,R) * SNR(R,D)}{SNR(S,R) + SNR(R,D) + 1}\Bigg), \tag{2}$$

where

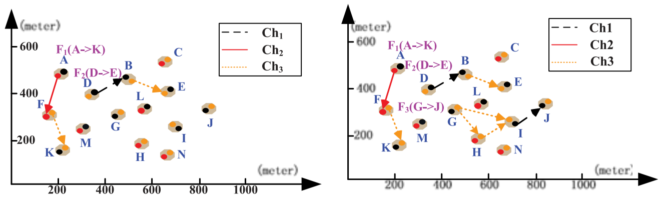
$$SNR(m,n) = \frac{P_m}{\sigma_n^2}\left|h_{m,n}\right|^2. \tag{3}$$

In the above equation, P_m denotes the transmission power at node m. $h_{m,n}$ captures the effects of path-loss, shadowing, and fading within the channel between m and n. The noise components throughout the paper are modeled as white Gaussian noise (AWGN). σ_n^2 denotes variance of the background noise at nodes n .

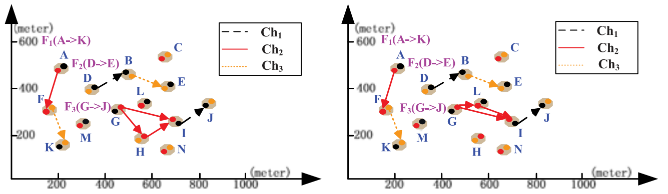
The work in [42] shows that for a single hop, the diversity gain obtained by exploiting multiple relay nodes is marginally higher than that can be obtained by selecting the best relay. We therefore only consider one relay node for cooperative transmission between each sender and receiver in this paper.

Relay nodes in the network can be categorized into two types based on their functions: a CR which operates at the physical layer for cooperative transmission (i.e., node R_6 in flow F_3 in Fig. 2), and a multi-hop relay (MR) which operates at the network layer to relay packets from a source over multiple hops to its destination (i.e., node R_1 in flow F_2 in Fig. 2). A node with multiple radios can serve as both CR and MR for multiple flows. For example, R_3 acts as CR relay in F_3, but MR relay for F_4. More complex function roles can be found on R_7, which acts as CR relay in both F_1 and F_3, and MR relay in F_2.

In a cooperative wireless network, a cooperative routing path could be a combination of cooperative transmissions and direct transmissions. For example, in Fig. 2, the flow $F_3(S_3 \to D_3) = S_3 \xrightarrow{Ch_2} R_2(R_3) \xrightarrow{Ch_3} R_4(R_7) \xrightarrow{Ch_1} R_5 \xrightarrow{Ch_2} D_3(R_6)$, where the first hop link $l^{Ch_2}_{S_3R_2(R_3)}$, the second hop link $l^{Ch_3}_{R_2R_4(R_7)}$ and the fourth hop link $l^{Ch_2}_{R_5D_3(R_6)}$ adopt cooperative transmission mode with nodes R_3, R_7 and R_6 acting as CR relays respectively, while the third hop link $l^{Ch_1}_{R_4R_5}$ adopts the direct transmission mode with both R_4 and R_5 being MR relays.



(a) Initial network topology (b) New flow arrives



(c) Adjustment of channel (d) Relay selection adjustment

Fig. 3. Motivation example.

3.2 Problem Description and Motivation Example

This paper aims to provide a cross-layer solution in MRMC cooperative wireless networks to solve the problem of Joint multi-hop Cooperative routing, Channel assignment and Relay selection so that the aggregate throughput of all active flows is maximized. To help understand the significance of our problem, we first give a motivation example to show that only channel assignment and cooperative routing cannot achieve the good performance in MRMC cooperative wireless networks.

Fig. 3 is an MRMC cooperative wireless network consisting of 14 nodes. The small solid dots in each node denote the radios. There are three orthogonal channels available, denoted by Ch_1, Ch_2 and Ch_3. For simplicity, we assume that all the links are free of transmission error, and the raw capacity of each link can be calculated by Eq. (1) or Eq. (2) depending on the transmission mode. The communication range and interference range are set to 250 and 550 m. The network is connected under an initial channel assignment [31] to guarantee the connectivity of network to transmit any possible flows over multiple hops.

Initially, there are two flows with their routing paths $F_1(A \to K) = A \xrightarrow{Ch_2} F \xrightarrow{Ch_3} K$ and $F_2(D \to E) = D \xrightarrow{Ch_1} B \xrightarrow{Ch_3} E$, as shown in Fig. 3a. According to Eq. (1), the raw capacity of links in these two flows can be calculated directly: $C_{DT}(A,F)=61.189\,Mbps$, $C_{DT}(F,K)=65.9819$ $Mbps$, $C_{DT}(D,B)=73.1874\,Mbps$, $C_{DT}(B,E)=78.8452$ $Mbps$. On channel Ch_3, there are two co-channel links that interfere with each other, link $l_{FK}^{Ch_3}$ passed by flow F_1 and link $l_{BE}^{Ch_3}$ passed by flow F_2. A straight-forward way to avoid interference is to apply TDMA to fairly allocate time slots to different flows. As a result, the available capacity of these two links becomes $C_{DT}'(F,K)=C_{DT}(F,K)/2=32.9909$ $Mbps$, $C_{DT}'(B,E)=C_{DT}(B,E)/2=39.4226\,Mbps$. Assume that all flows transmit a packet at the peak link data rate through a rough calculation that neglects the overhead cost. Constrained by the bottleneck rate of the path, the end-to-end throughput of $Flow_1$ and $Flow_2$ are $min\{C_{DT}(A,F),C_{DT}'(F,K)\}=32.9909\,Mbps$ and $min\{C_{DT}(D,B),C_{DT}'(B,E)\}=39.4226\,Mbps$. The aggregate network throughput of these two flows is $32.9909+39.4226=72.4135\,Mbps$.

In Fig. 3b, a new flow $F_3(G\to J)$ arrives. To obtain higher cooperative diversity in the network, the potential route for F_3 is chosen as $F_3(G\to J)=G\xrightarrow{Ch_3}I(H)\xrightarrow{Ch_1}J$, where H acts as the CR relay in the flow path. Similarly, the raw capacity of each hop links $l_{GI(H)}^{Ch_3}$, and $l_{IJ}^{Ch_1}$ can be calculated, with $C_{DT}(I,J)=91.8365\,Mbps, C_{CT}(G,H,I)=51.3242$ $Mbps$. However, there are two co-channel links that interfere with each other on the channel Ch_1, and three co-channel links on the channel Ch_3, respectively. The available capacity of these links are calculated as: $C_{DT}'(A,F)=C_{DT}(A,F)=61.189\,Mbps, C_{DT}'(F,K)=C_{DT}(F,K)/3=21.90$ $Mbps, C_{DT}'(D,B)=C_{DT}(D,B)/2\ =\ 36.5937\,Mbps, C_{DT}'(B,E)=C_{DT}(B,E)/3\ =26.2817\,Mbps, C_{CT}'(G,H,I)=C_{CT}(G,H,I)/3=17.1\,Mbps, C_{DT}'(I,J)=C_{DT}(I,J)/2=45.9182Mbps$. As a result, the end to end throughput of $Flow_1$, $Flow_2$ and $Flow_3$ are $min\{61.189,21.90\}=21.90\,Mbps$, $min\{36.5937,26.2871\}=26.2817\,Mbps$ and $min\{17.1,45.9182\}=17.1$ $Mbps$. The aggregate throughput of the whole network is $21.90+26.2817+17.1=65.2637\,Mbps$. Although there are three concurrent transmission flows, the aggregate throughput decreases about 10 percent compared with that in Fig. 3a.

With the above-selected routes, we apply channel assignment to improve the network performance. In Fig. 3c, we change the channel of node G , H, and I from the overloaded channel Ch_3 to the least-used one Ch_2, which reduces the number of interfering links on channel Ch_3 from three to two. The raw capacity of links on the paths of the three flows becomes $C_{DT}'(A,F)=C_{DT}(A,F)/2=30.5945\,Mbps, C_{DT}'(F,K)=C_{DT}(F,K)/2=32.9909\,Mbps, C_{DT}'(D,B)=C_{DT}(D,B)/2=36.5937\,Mbps, C_{DT}'(B,E)=C_{DT}(B,E)/2=39.4226\,Mbps, C_{CT}'(G,H,I)=C_{CT}(G,H,I)/2=25.6621\,Mbps$, $C_{DT}'(I,J)=C_{DT}(I,J)/2=45.9182\,Mbps$. As a result, the end-to-end throughput of $Flow_1$, $Flow_2$ and $Flow_3$ are 30.594, 36.5937 and 25.6621 Mbps respectively. The aggregate throughput of the three flows in the network is $30.5945+36.5937+25.6621=92.8503\,Mbps$. The performance is improved almost 42 percent compared with that in Fig. 3b.

Based on the above channel assignment, transmitter nodes would further check whether there exists a better relay node which can be utilized to obtain a better cooperative capacity gain. As shown in Fig. 3d, node G can select node L instead of H as the relay node to further improve the performance. The available capacity of cooperative transmission can be calculated as $C_{CT}'(G,L,I)=C_{CT}(G,L,I)/2=66.5462/2=33.2731\,Mbps$. As a result, the end to end throughput of $Flow_1$, $Flow_2$ and $Flow_3$ are 30.594, 36.5937 and 33.2731 Mbps. After relay adjustment, the aggregate throughput of the whole network is $30.5945+36.5937+33.2731=100.4613\,Mbps$, which is nearly 1.5 times that in Fig. 3b.

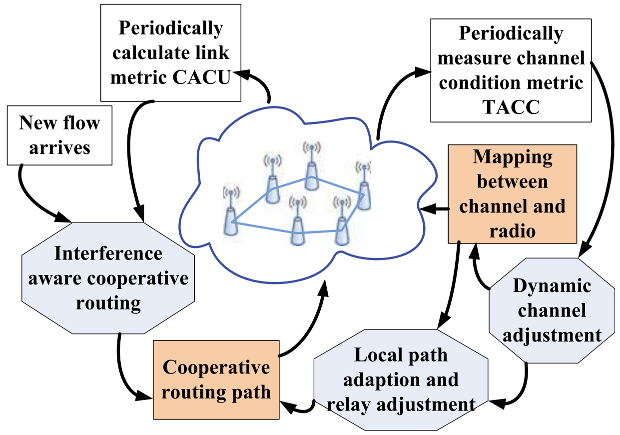


Fig. 4. Solution framework.

The above example demonstrates that considering only channel assignment and cooperative routing is not enough for achieving the maximum performance in MRMC cooperative wireless networks. Channel assignment interacts with path selection and relay selection, and these three elements should be simultaneously considered.

3.3 Solution Overview

Existing studies have demonstrated that the joint optimization problem of routing and channel assignment in multi-radio multi-channel wireless network is NP [34], the joint optimization problem of relay selection and cooperative routing is also NP [16]. Compared to the above problems where each considers only two issues, our problem considers three issues and can be generally proven to be NP-hard.

To solve the problem, we propose a solution framework which is formed with three important components as illustrated in Fig. 4: interference-aware cooperative routing, dynamic channel adjustment, and local path and relay adjustment.

First, to obtain cooperative gain and reduce co-channel interference, every node periodically calculates the routing metric of contention-aware channel utilization). Based on this metric, when new flow arrives, an interference-aware cooperative routing algorithm is run distributively to find the cooperative routing path and select MR and CR nodes along the path.

Second, to adapt to dynamic traffic changes, every node periodically measures the channel condition and calculates TACC metric. When a node's working channel is detected to be overloaded according to the TACC value, a dynamic channel adjustment algorithm is triggered to switch the highly loaded channel to a lightly loaded one to relieve the co-channel interference, and the mapping between channels and radios are locally changed accordingly.

Third, as channel adjustment changes the network topology, a local path segment and relay adjustment algorithm is followed by switching the flow traffic to a new path segment locally according to the new topology.

In following sections, we will introduce the detailed algorithms for each part.

4 COOPERATIVE ROUTING

To quantify the available capacity of a link in MRMC cooperative wireless networks, in this section, we first introduce a new routing metric, called *contention-aware channel utilization*. Based on the metric, we propose an interference-aware cooperative routing algorithm to better exploit the benefit of cooperative diversity for a higher cooperative transmission performance.

4.1 Cooperative Routing Metric

Multiple transmissions through links assigned to the same channel will create interference, which would greatly reduce the network throughput. There are several existing routing metrics proposed for multi-hop wireless networks. Hop count is a basic routing metric widely used in routing protocols such as DSR [43], AODV [44], and DSDV [45]. To further consider the wireless channel condition and interference, several improved metrics are also proposed, including ETX [46], WCETT [47], MIC [48], and CCM [34].

The above routing metrics target for one-to-one direct transmissions between two nodes in conventional wireless networks. In cooperative wireless networks, the routing metric should consider multiple-to-one cooperative transmissions. As a cooperative transmission involves three links, it may cause more interference in the network, thus reducing the transmission performance. To facilitate the finding of more efficient cooperative routing path for higher throughput, the routing metric should concurrently consider the transmission mode selection and interference impact.

To characterize radio transmissions in the presence of interference and identify the co-channel interference links of a given link, two receiver-driven interference models are proposed in the literature, the Physical Model [49] and the Protocol Model [50] .

Our design does not depend on a specific model used. For the convenience of presentation and design, we simply apply a protocol model to illustrate our algorithms in this paper.

We consider link $l_{AB}^{Ch_i}$ to be the co-channel interference link of another link $l_{CD}^{Ch_i}$ if A and B work on the same channel of C and D, and at least one of node pairs (A, C), (A, D), (B, C), and (B, D) is within the interference range.

A cooperative transmission may involve three nodes. We consider cooperative link $l_{AB(R)}^{Ch_i}$ to interfere with another link $l_{CD}^{Ch_i}$ if A, B, and R work on the same channel of C and D, and at least one of node pairs (A, C), (A, D), (B, C), (B, D), (R, C), and (R, D) is within the interference range.

In cooperative wireless networks, there are two transmission modes, direction transmission between two nodes or cooperative transmission with the help of a relay node between a transmission pair. If a node x transmits data to a node y through the direct transmission, the available capacity $C_{DT_a}(x, y, Ch_i)$ of the direct transmission link $l_{xy}^{Ch_i}$ is equal to the link capacity $C_{DT}(x, y)$ (calculated using Eq. (1)) deducted by the traffic load of its co-channel interference links:

$$C_{DT_a}(x, y, Ch_i) = C_{DT}(x, y) - \sum_{j \in I_{Ch_i}(l)} t(j), \tag{4}$$

where $t(j)$ denotes the traffic load on link j, $I_{Ch_i}(l)$ is the set of co-channel interference links of $l_{xy}^{Ch_i}$.

Similarly, if node x transmits data to node y with the help of cooperative relay z, the available capacity $C_{CT_a}(x, z, y, Ch_i)$ of a cooperative transmission link $l_{xy(z)}^{Ch_i}$ can be calculated as

$$C_{CT_a}(x, z, y, Ch_i) = C_{CT}(x, z, y) - \sum_{j \in I_{Ch_i}(l)} t(j), \tag{5}$$

where $C_{CT}(x, z, y)$ is the capacity of the link $l_{xy(z)}^{Ch_i}$ (calculated using Eq. (2)), $I_{Ch_i}(l)$ is the set of co-channel interference links, $t(j)$ denotes the traffic load on link j.

Therefore, the available capacity of a link (x, y, Ch_i) can be defined as the maximum available capacity among all possible transmission modes

$$\begin{aligned} &CACU(x, y, Ch_i) = \max\{C_{DT_a}(x, y, Ch_i), \\ &\max_z\{C_{CT_a}(x, z, y, Ch_i) : z \in N_{Ch_i}(x) \quad and \quad N_{Ch_i}(y)\}\}, \end{aligned} \tag{6}$$

where $N_{Ch_i}(x)$ and $N_{Ch_i}(y)$ denote the set of neighbors of nodes x and y on the channel Ch_i. Obviously, $CACU(x, y, Ch_i) = C_{DT_a}(x, y, Ch_i)$ if the available capacity of direct transmission is larger than the available capacity of the cooperative transmission, otherwise, $CACU(x, y, Ch_i) = \max_z\{C_{CT_a}(x, z, y, Ch_i) : z \in N_{Ch_i}(x) \quad and \quad N_{Ch_i}(y)\}\}$.

Multiple radios on a node are generally assigned with orthogonal channels. A pair of nodes x and y may have multiple channels be the same. Based on Eq. (6), the routing metric of link (x, y) is defined as the maximum available capacity among all common channels as follows:

$$CACU(x, y) = \max_{Ch_i \in w(x) \cap w(y)} CACU(x, y, Ch_i), \tag{7}$$

where $w(x)$ and $w(y)$ denote the working channel set of node x and y, respectively. CACU metric in (7) captures the interference cost from both direct transmission and cooperative transmission. Therefore, CACU can be applied to facilitate finding a transmission path with lower interference thus higher capacity. Based on the metric, a node x can decide it will take direct transmission or cooperative transmission, and determine the channel to use for transmission. In the case that a cooperative transmission is needed, the selected relay node will be informed.

4.2 Cooperative Routing Algorithm

In this paper, we modified ad hoc on-demand distance vector (AODV) routing [44] to implement our distributed interference aware cooperative routing algorithm to establish the maximum capacity path while considering the flow routing and relay selection, as shown in Algorithm 1. The derived CACU metric is applied to construct the cooperative path.

Algorithm 1. Interference Aware Cooperative Routing

```
Input: A newly arrival flow with the source $s$ and the destination $d$
Output: Source $s$ finds the cooperative routing path to the destination with each next hop's MR/CR relay and its transmission mode
For source node $s$.
When $s$ intends to send packets to a destination $d$, it checks its routing table to see whether it has a valid path to $d$.
If so, it begins to send packet to the next hop towards the destination; otherwise, it searches for the path to the destination as follows.
for each neighbor node $z$ of $s$ do
    according to Eq. (7), node $s$ calculates the outgoing $link(s, z)$'s CACU metric which indicates the available capacity from $s$ to $z$, denoted as $P_{sz}$, inserts $P_{sz}$ into RREQ.
end for
Insert $P_s = +\infty$ into RREQ, where $P_s$ denotes the maximum end-to-end capacity from $s$ to $s$, broadcast the RREQ.
For intermediate node $x$ receiving a RREQ from node $y$.
From RREQ message received, node $x$ obtains $P_y$ (the maximum end-to-end capacity from $s$ to $y$), and $P_{yx}$ (the available capacity from $y$ to $x$). Node $x$ calculates the maximum end-to-end capacity from $s$ to $x$ following $P_x = \min(P_{yx}, P_y)$.
if node $x$ has received this RREQ before and $P_x \leq P_{x'}$, where $P_{x'}$ is the maximum end-to-end capacity from $s$ to $x$ which is maintained and updated at node $x$ when the node receives the RREQ before then
    node $x$ drops the RREQ.
else if node $x$ is not the destination and does not have a current route to the destination then
    node $x$ updates the maximum end-to-end capacity from $s$ to $x$ by using $P_x$.
    for each neighbor $z$ of $x$ do
        according to Eq. (7), node $x$ calculates its outgoing $link(x, z)$'s CACU metric, denoted as $P_{xz}$, inserts $P_{xz}$ into RREQ.
    end for
    Insert the maximum end-to-end capacity from $s$ to $x$, $P_x$ into RREQ.
    Broadcast the RREQ.
else if node $x$ is the destination or has a current route to the destination then
    node $x$ generates a route reply.
end if
```

When a source has data to transmit but does not have a path to the destination, it broadcasts a route request (RREQ) for that destination. When an intermediate node receives RREQ, if it is the destination or has a current route to the destination, it generates a route reply (RREP). Otherwise, the node needs to rebroadcast the RREQ with a set of parameters inserted: the CACU metric for each of its outgoing link calculated based on Eq. (7), and the maximum capacity from the source to itself calculated based on Algorithm 1.

5 CHANNEL ADJUSTMENT

As shown in the motivation example of Section 3.2, the channel adjustment can reduce co-channel interference, and thus increase the aggregate throughput. The main function of channel adjustment is to switch one node's working channel from an overloaded one to a lightly loaded one to obtain better throughput. For practical implementation of the channel adjustment in a cooperative wireless network, we need to answer two basic questions: (1) Which channel to switch to? (2) How to keep the network stable and well connected during the channel adjustment?

5.1 Channel Condition Metric

Before presenting the detailed channel adjustment algorithm, we first introduce a traffic-aware channel condition metric to evaluate the channel load condition. The TACC of node i on channel Ch_m is defined as the channel utilization calculated as the summation of the co-channel traffic load within this node's two hops:

$$TACC_i(Ch_m) = \sum_{j \in N_{Ch_m}(i)} \left(t\left(l_{ij}^{Ch_m}\right) + \sum_{k \in N_{Ch_m}(j)} t\left(l_{jk}^{Ch_m}\right) \right), \quad (8)$$

where $N_{ch_m}(i)$ is node i's neighbor set on channel Ch_m, $t(l_{ij}^{Ch_m})$ denotes the traffic load on link $l_{ij}^{Ch_m}$, while j and k represent the one-hop and two-hop neighbors of node i, respectively. The average traffic conditions may be obtained by attaching the information with periodical topology maintenance messages such as Hello over two-hops.

5.2 Candidate Channel Calculation

When a node finds that the TACC of a working channel exceeds a threshold θ_1, i.e., $TACC_i(Ch_m) \geq \theta_1$, it will trigger a channel adjustment process. The node needs to identify a set of feasible candidate channels and selects the best one to switch to.

To improve the network throughput with channel switching, the condition of the candidate channel Ch_b should be better than the condition of the current channel Ch_a. However, the channel adjustment may lead channel Ch_b to be overloaded and result in potential network instability. To avoid this problem, the following two conditions should be satisfied:

$$TACC_i(Ch_b) + Tload_i(Ch_a) \leq \theta_2, \quad (9)$$

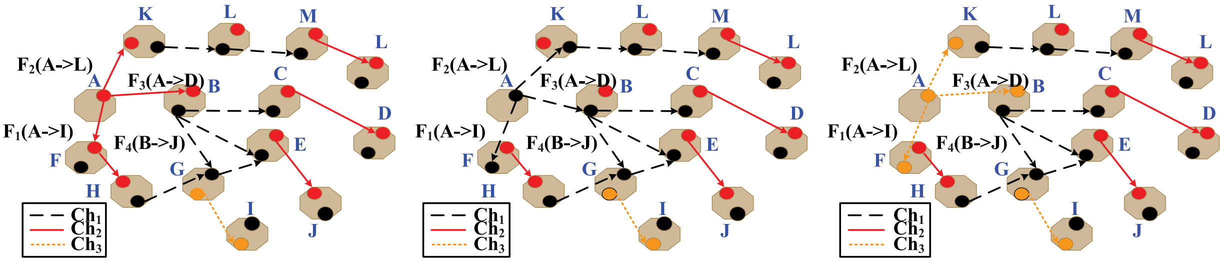
$$TACC_j(Ch_b) + Tload_i(Ch_a) \leq \theta_2, \quad (10)$$

where node j is within two hops of node i, $Tload_i(Ch_a)$ is the total traffic load of all links on the original channel Ch_a, expressed as

$$Tload_i(Ch_a) = \sum_{j \in N_{Ch_a}(i)} t(l_{ij}^{Ch_a}). \quad (11)$$

We set θ_2 in (9) to $\theta_2 = 0.9 * \theta_1$ so that the TACC of the new channel after the channel switching is less than 90 percent of TACC trigger threshold to avoid another channel switching and maintain the network stability.

Fig. 5 shows an example of channel adjustment procedure. There are four flows in the network, $F_1(A \rightarrow I)$,



(a) Before channel adjustment (b) Switch A's channel to Ch_1 (c) Switch A's channel to Ch_3

Fig. 5. An example of channel adjustment.

$F_2(A \rightarrow L)$, $F_3(A \rightarrow D)$, and $F_4(B \rightarrow J)$. When node A finds that Ch_2 is overloaded, it tries to find another channel to switch to. If node A uses Ch_1 as the new channel, then nodes K, B and F need to switch to Ch_1 to get connected with node A. This will change the traffic load of F_1, F_2 and F_3 on original links $l_{AK}^{Ch_2}$, $l_{AB}^{Ch_2}$, and $l_{AF}^{Ch_2}$ to the links $l_{AK}^{Ch_1}$, $l_{AB}^{Ch_1}$, and $l_{AF}^{Ch_1}$ on the new channel Ch_1. However, this will make Ch_1 overloaded and trigger another channel adjustment, which makes the network unstable. Therefore, Ch_1 is not the feasible candidate channel for node A because it does not satisfy condition in Eq. (9). Instead, according to Eq. (9), node A finds that Ch_3 is the candidate channel and the traffic load is switched from Ch_2 to Ch_3 as shown in Fig. 5c.

Besides considering the condition in Eq. (9) to avoid network instability, to justify the extra channel switching overhead, the gains in terms of TACC should be larger than a given threshold θ_3 :

$$\frac{Before\_TACC_i(Ch_a)}{After\_TACC_i(Ch_b)} \geq \theta_3, \tag{12}$$

where $Before\_TACC_i(Ch_a)$ is the original TACC value of the working channel Ch_a before channel switching, while $After\_TACC_i(Ch_b) = TACC_i(Ch_b) + Tload_i(Ch_a)$ is the TACC value of the working channel Ch_b after the channel switching.

Obviously, to obtain a positive benefit of channel switching, θ_3 in (12) should be larger than 1. Moreover, channel adjustment may involve a significant switching overhead such as switching delay and traffic interruption, and frequent channel switching will result in oscillation and severely impact the network performance. Therefore, θ_3 should be set by well considering the tradeoff between the switching overhead and the benefit of channel switching. According to [35], in our simulation, θ_3 is set to 1.2. That is, after the channel adjustment, the TACC of the new channel should be at least 20 percent less than that of the original one.

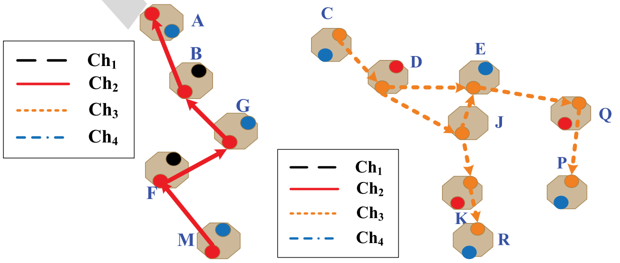
Only when conditions of Eq. (9), Eq. (10), and Eq. (12) are satisfied, the node can switch its working channel from Ch_a to Ch_b. To preserve the current flows' connectivity and stability, connectivity checking should be applied to further identify the feasible channel, which is discussed in next section.

5.3 Connectivity and Chain Puzzle Checking

In an MRMC cooperative network, two nodes may have more than one pair of radios connected. If node i and node j have two pairs of radios directly connected with each other, the channel adjustment does not impact their connectivity. If nodes i and j have only one radio connected with each other over a channel, the channel adjustment may interrupt the transmission of an active flow carried over the link (i, j). To maintain the connectivity of the active flow, the channel switching may be carried by a chain of nodes, with each node on the chain having only a single common channel. We define this problem as *chain puzzle*.

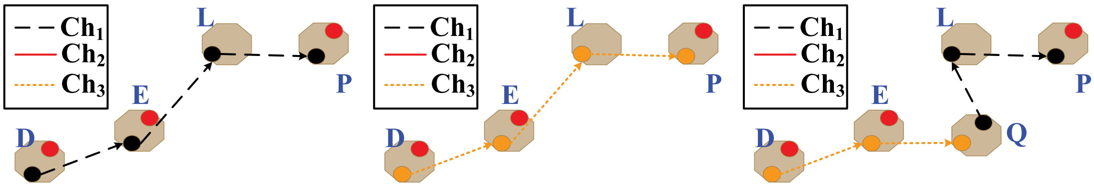
Compared to the network with only node-to-node transmission, cooperative transmission may be more prone to the chain puzzle problem. Fig. 6 give two examples to illustrate the chain puzzle problem under direct transmission and cooperative transmission, respectively. In Fig. 6a, assume that flow $F_1(M \rightarrow A)$ transmits over the link between nodes M and F using channel Ch_2, if the channel needs to be switched to Ch_3, node F's single-channel neighbor G must switch to Ch_3. Similarly, after node G switches its channel, node G's single-channel neighbor B has to switch to Ch_3 too, which will also lead channel switching from node A and thus result in the chain puzzle problem. In Fig. 6b, D, E, J work together for cooperative transmission. Assume that nodes C and D currently transmitting over channel Ch_3 wants to switch to Ch_1, nodes E and J are D's single-channel neighbors. To maintain the flow's connectivity, nodes E, J should switch channel from Ch_3 to Ch_1. As a result, K, R, Q, and P also need to switch their working channel from Ch_3 to Ch_1. Chain puzzle again happens.

Chain puzzle checking becomes an important issue in channel adjustment procedure because chain puzzle may cause a number of practical problems. First, a large number of nodes may be involved in a channel switch when chain puzzle happens, which could result in a high overhead. Second, it is difficult to synchronize the switching action among all nodes involved because the signaling used for negotiation needs to propagate through many hops. In the worst case, this may result in flow



(a) Direct transmission (b) Cooperative transmission

Fig. 6. Chain puzzle problem.



(a) Original topology (b) Chain puzzle happen (c) Chain puzzle not happen

Fig. 7. Two hop chain puzzle checking.

transmission interruption. Therefore, before a node switches its working channel, chain puzzle should be checked to identify feasible candidate channel to avoid switching channel sequentially, and maintain the network's stability. To facilitate chain puzzle checking, we propose two different Connectivity Rules according to different transmission modes:

- **Connectivity Rule 1**: If any node-pair of a direct transmission link passed by an active flow is originally connected, the node-pair should remain connected after the channel switching.
- **Connectivity Rule 2**: If any three nodes in an active cooperative transmission are originally connected, they should remain directly connected under a new channel.

Based on above two connectivity rules, we propose a local two-hop chain puzzle checking sub-algorithm, as shown in Algorithm 2. When node A checks a new channel Ch_i and finds that (through the communication with its neighbor which needs to switch channel with it) there exists a node which is not within its two-hop distance but also needs to switch channel to preserve the connectivity of the current flows, the chain puzzle may happen and Ch_i is not a feasible channel for channel adjustment. The results of chain puzzle checking algorithm depend on the topology of the network. We give two examples to show the results of chain puzzle checking.

Algorithm 2. The Chain Puzzle Checking Algorithm

```
Input: A candidate channel $Ch_i$, channel adjustment triggering
    node $A$, and its set of upstream and downstream one-hop
    neighbors $N_{Ch_m}(A)$ on old channel $Ch_m$, the set of neigh-
    bor nodes within node $A$'s two hops, denoted as $N_{two}(A)$.
Output: Whether candidate channel $Ch_i$ is feasible candidate
    channel.
for node $j$ in $N_{Ch_m}(A)$ do
    According to connectivity rule 1 and connectivity rule 2,
    node $j$ identifies its two-hop neighbors which should
    switch their working channels to $Ch_i$ when node $j$
    switches its working channel from $Ch_m$ to $Ch_i$. Put such
    nodes into node set $N_{temp}(j)$.
    Node $j$ sends the node set $N_{temp}(j)$ to node $A$
    if node $A$ finds $N_{temp}(j)$ is not a subset of $N_{two}(A)$ then
        Channel switching will propagate beyond the two hops
        of node $A$ and results in the chain puzzle problem.
        $Ch_i$ is not a feasible channel, return False.
    end if
end for
Return True.
```

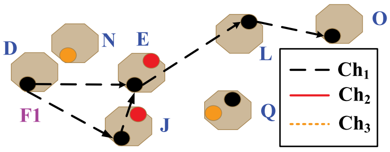
In Case I shown in Fig. 7a, assume nodes D and E are transmitting using channel Ch_1, and node D finds its working channel Ch_1 is overloaded and channel Ch_3 is currently the least used channel. Before node D switches its working channel to Ch_3, node D will check whether the topology contains chain puzzle based on its two-hop information. In Fig. 7b, if node D switches the channel to Ch_3 with node E, E finds nodes L and P should switch their working channel to Ch_3 at the same time to preserve the flow's connectivity. After node E exchanges this information locally with node D, node D will check whether these two nodes L and P are within its two hop or not. From 7b, node P is a two-hop neighbor of node E, while it is not within two-hop of node D. According to Algorithm 2, chain puzzle may happen and Ch_3 is not a feasible channel.

In Case II shown in Fig. 7c, if there exists a node Q near node E, the result of chain puzzle checking is totally different. In this topology, node E and node Q have one common working channel Ch_3, and also node Q and L have one common working channel Ch_1. As a result, with the help of Q, L and P are connected with E without need of switching their working channel when node D switches its working channel to Ch_3 with node E. Chain puzzle may not happen. We can conclude that Ch_3 is a feasible channel for the channel adjustment in this case.

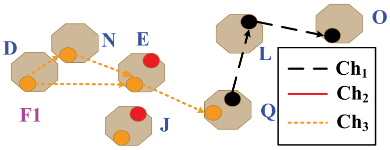
Based on the chain puzzle checking algorithm, the feasible channel selection algorithm can be presented as in Algorithm 3

Algorithm 3. Feasible Channel Selection Algorithm

```
Input: The orthogonal channels available, channel adjustment
    triggering node $A$ and its overloaded working channel
    $Ch_a$.
Output: The selected channel for node $A$ to switch to
Find channel $Ch_b$ among orthogonal channels available that
    satisfies $TACC_i(Ch_b) + Tload_i(Ch_a) \leq \theta_2, TACC_j(Ch_b) + Tload_i(Ch_a) \leq \theta_2$, and $\frac{Before\_TACC_i(Ch_a)}{After\_TACC_i(Ch_b)} \geq \theta_3$ as the candidate
    feasible channel, and insert $Ch_b$ into the feasible channel set.
Sort the candidate feasible channels in the descending order
    in a List according to the value of $\frac{Before\_TACC_i(Ch_a)}{After\_TACC_i(Ch_b)}$.
for $Ch_i$ in List do
    According to connectivity rule 1 and connectivity rule 2,
    check whether $Ch_i$ may cause chain puzzle by applying
    Algorithm 2.
    if chain puzzle does not happen under $Ch_i$ then
        $Ch_i$ is the selected feasible channel to switch to, and
        return $Ch_i$.
    end if
end for
```



(a) Initial routing and relay assignment



(b) Routing and relay adjustment

Fig. 8. Local path adaptation and relay adjustment.

6 LOCAL PATH ADAPTATION AND RELAY ADJUSTMENT

After channel adjustment, the network topology may change. To make flow transmissions continuous under the new topology, some flows may need to adapt their path segments, channels or relays locally.

As shown in Fig. 8a, an active flow $F_1(D \to O)$ exists in the network with its original route $F_1(D \to O) = D \xrightarrow{Ch_1} E(J) \xrightarrow{Ch_1} L \xrightarrow{Ch_1} O$. After nodes D, E, J adjust their working channel from Ch_1 to Ch_3, node E and node L are not directly connected. Thus, flow F_1 should switch its path locally from $E \xrightarrow{Ch_1} L$ to $E \xrightarrow{Ch_3} Q \xrightarrow{Ch_1} L$. Moreover, after D and E switch their working channel from Ch_1 to Ch_3, besides node J, node N may have the opportunity to support cooperative transmission and provide a higher cooperative gain. As a result, node D would select node N as the relay node instead of J.

To make the network stable, the path adaptation and relay adjustment should be performed locally and the corresponding traffic flows should also switch to new path segments. Based on the cooperative routing algorithm in Algorithm 1, we design a local path adaptation and relay adjustment algorithm as shown in Algorithm 4.

Algorithm 4. Local Path Adaptation and Relay Adjustment Algorithm

```
Input: Channel adjustment triggering node $A$, the set of active
    flows which pass through node $A$, denoted as $S$. Node $A$'s
    set of upstream and downstream two-hop neighbors in
    current active flows on the original routing paths, denoted
    as $u(S)$ and $d(S)$, respectively.
Output: Updated path segments and relay selections around
    node $A$ for active flows
According to Eq. (7), node $A$ and its one-hop neighbor
  nodes, and nodes in $u(S)$ and their one-hop neighbor nodes
  update their outgoing links' CACU metric, identify the
  selected transmission mode, relay and working channel for
  these links according to CACU value.
Applying the cooperative routing algorithm in Algorithm 1,
  find the local cooperative path segments with updated
  relays from $A$ to its two-hop downstream nodes in $d(S)$,
  and from node $A$'s two-hop upstream nodes in $u(S)$ to $A$ .
```

7 COMPLETE SOLUTION

We first present the complete solution, and then analyze the convergence behavior of the proposed solution.

7.1 Solution

The complete algorithm of joint cooperative routing, channel adjustment and relay selection is shown in Algorithm 5. To handle the dynamic wireless environment, nodes in the network execute the algorithm locally as follows.

Algorithm 5. Complete Algorithm of Joint Cooperative Routing, Channel Assignment, and Relay Selection

```
When a new flow arrives
Apply interference-aware cooperative routing in Algorithm 1
  to find the cooperative transmission path with MR and CR
  relays selected along the path.
When the TACC timer expires at a node $i$
Node $i$ calculates TACC metric for its working channels following Eq. (8).
for $Ch_m$ in $w(i)$, where $w(i)$ is the set of node $i$'s working
  channel do
  if $TACC_i(Ch_m) \geq \theta_1$) then
    Apply Algorithm 3 to identify the feasible channel for
      channel adjustment, let $Ch_a$ be the feasible channel
      selected.
    Set node $i$'s channel adjustment timer equal to $\frac{1}{TACC_i(Ch_m)}$.
    When the channel adjustment timer expires, node $i$
      switches its working channel to $Ch_a$, and then applies
      Algorithm 4 to complete local path segment adaptation
      and relay adjustment for all active flows passing node $i$
  end if
end for
```

When a new flow arrives, the interference-aware cooperative routing algorithm is applied to find the cooperative routing path with the maximum end-to-end available capacity and with the MR and CR relays selected along the path. Every node periodically evaluates the traffic conditions of a channel by calculating the TCAA metric according to (8) and checking whether its working channel is overloaded. If so, the node first applies Algorithm 3 to identify the feasible channel to switch to. Then the channel adjustment will be triggered, which is followed by the local path adaptation and relay adjustment through Algorithm 4 for uninterrupt transmissions and better performance.

If each node independently makes a local channel adjustment decision, multiple channel adjustment requests may be received simultaneously by a node, which either leads to request message collisions or inconsistent requests (if all messages are successfully received). To reduce the chance of simultaneous transmissions of channel adjustment messages, we design a channel adjustment timer which introduces a random delay before the message sending according to the channel load, and the timer can be set as follows:

$$T_{iCh_m} = \frac{1}{TACC_i(Ch_m)}. \tag{13}$$

From (13), obviously, the node with a higher channel load, i.e., a larger TACC value, has a lower average timer value thus an earlier chance of adjusting its overloaded channel.

When the channel load is high, the data transmissions should be switched from an overloaded channel to a light-loaded channel. In Algorithm 5, the channel load is measured with the metric TACC and updated when the TACC timer goes off. A smaller TACC timer would allow for more frequent update of the TACC value at high measurement cost, while a larger TACC timer for smaller measurement cost would make the TACC metric less accurate. In this paper, we set the TACC timer adaptively according to the traffic pattern in the network taking into account the trade-off between the accuracy of TACC metric and the measurement cost. If the traffic load is high, the TACC timer reduces but remains above a minimum timeout value T_{min}. If the traffic load is low, the TACC timer increases but not beyond a maximum timeout value T_{max}. In this paper, we set $T_{min} = 20\ ms$ and $T_{max} = 300\ ms$ according to the channel monitoring duration mentioned in [51].

7.2 Convergence Analysis

Algorithm 5 provides a flexible way to adapt routing, channel assignment and relay selection according to the changes of channel condition and traffic load in the wireless network. Our cooperative routing algorithm is designed based on ADOV, so the computation cost and message cost on routing selection are comparable to ADOV. According to the channel assignment in Algorithm 3, to select the channel for switching, the complexity is $O(K)$, where K is the number of the orthogonal channels in the system. Moreover, according to Eq. (6), the complexity to identify the best relay for a cooperative routing hop is $O(NC)$, where NC is the number of common neighbor nodes of both the sender and receiver of a cooperative routing hop.

In [52], the author gives the formal analysis of convergence of AODV protocol. Our cooperative routing algorithm is designed based on ADOV, which proves to converge in the literature. The use of cooperative routing in our design creates a virtual link consisting of the sender, receiver and relay, which does not change the converging feature of the routing scheme. Local path segment adaptation and relay adjustment are designed following the cooperative routing algorithm, thus the overall routing scheme we propose will also converge. Therefore, we only need to show that the process of channel adjustment can converge and reach a stable state.

Theorem 1. *If every node selects its channel and adjusts the channel following the Algorithm 6, within a finite number of channel changes by nodes, the channel assignment reaches a stable state where nodes stop channel update.*

Proof. Consider that node i selects its channel following Algorithm 4 when it finds that its channel is overloaded and begins to switch its channel from Ch_i to $Ch_{i'}$ at time t, and completes the change at time $t' > t$. For any other node j, let Ch_j and $Ch_{j'}$ be j's channel at time t and t', respectively. In algorithm 5, we have the channel adjustment timer set following the Eq. (13). This makes the chance for node j to change its channel simultaneously with node i very small, so we have $Ch_j = Ch_{j'}$.

For node i, our proposed channel switching condition in Eq. (9) ensures that $Ch_{i'}$ selected to switch to satisfies the condition that $TACC_i(Ch_{i'}) + Tload_i(Ch_i) \leq \theta_2 < \theta_1$, in order to prevent node i from changing its working channel again right after switching its channel from Ch_i to $Ch_{i'}$.

With the assumption that there is no inter-channel interference, node i's channel switching only impacts nodes that work on $Ch_{i'}$. For node j which works on $Ch_{i'}$ but beyond the two hops of node i, node i's channel switching does not affect j's interference level, and we have $TACC_j(Ch_{i'}, t') = TACC_j(Ch_{i'}, t)$. Because node i is the only one that changes the channel between time t and t', for each node j working on $Ch_{i'}$ and within the two hops of node i, the channel condition at time t' is $TACC_j(Ch_{i'}, t') = TACC_j(Ch_{i'}, t) + Load_i(Ch_i)$ (where $Load_i(Ch_i)$ is the total original traffic load of node i on Ch_i switched to $Ch_{i'}$ and within two hops of node j). Obviously, we have $Load_i(Ch_i) \leq TLoad_i(Ch_i)$ and thus $TACC_j(Ch_{i'}, t') \leq TACC_j(Ch_{i'}, t) + TLoad_i(Ch_i)$ according to Eq. (11). Moreover, according to our channel switching condition in Eq. (10), we have $TACC_j(Ch_{i'}, t') \leq \theta_2 < \theta_1$, which will not trigger another channel switching from node j.

Therefore, although our channel adjustment depends only on the information that is available within its local domain and is designed to be distributed, the channel adjustment process can self-stabilize and thus help the network to reach the stable state. □

8 SIMULATION RESULTS AND ANALYSIS

In this section, we use simulations to evaluate the performance of our proposed algorithms.

8.1 Simulation Setting

In our simulation, unless otherwise specified, the simulation setting is as follows. 30 nodes are generated one by one in random locations in a $1000 \times 1000\,m$ area. Each new node is ensured to get connected with existing nodes in the network, and the initial channel assignment is done according to [31] to guarantee the connectivity of network to transmit possible flows over multiple hops. A node is equipped with two radio interfaces, and has the maximum transmission range set to 250 meters. There are a total of 11 orthogonal channels in the network, and the default number of flows in the network is set as $M = 5$.

Although ns-3 and Omnet++ are widespread simulator, cooperative communication is a physical layer technique, and can be very hard to simulate in ns-3 and Omnet++ if it is not completely impossible. Following the simulation setup in ref [14], [16], [40], [41], we evaluate the performance of our proposed algorithm through extensive simulations using MATLAB. Specifically, following the parameter setting in [16], we set the bandwidth of each channel to $W = 22MHz$, the maximum transmission power at every node to $1W$. For simplicity, we assume that $h_{m,n}$ only considers the distance between nodes m and n and is given by $\left|h_{m,n}\right|^2 = ||m,n||^{-4}$, where $||\mathrm{m,n}||$ is the distance (in meters) between m and n and the path loss index is 4. We assume the variance of noise is 10^{-10}W at all nodes. TACC trigger threshold θ_1 in Algorithm 5 is set to 200. According to the conditions described in Section 5.2, we set θ_2 in Algorithm 3 to $\theta_2 = 0.9 * \theta_1 = 180$ to help maintain network stability, and θ_3 in Algorithm 3 to 1.2 to balance the switching overhead and benefit of channel switching.

There is no existing work studying cooperating communications with routing in multi-radio multi-channel cooperative wireless networks. We evaluate the effectiveness of our algorithms for joint cooperative routing, channel assignment, and relay selection and the benefit of cooperative communication in multi-radio multi-channel networks by comparing the results from six different implementation schemes.

We implement two different cooperative transmission schemes in an MRMC cooperative network. The first is our proposed Algorithm 5, denoted as CT_adjustment. When a new flow arrives, a cooperative routing path with the maximum available capacity and well selected relays is found according to the Algorithm 5. To reduce co-channel interference, every node periodically checks its channel utilization to calculate channel metric TACC and initiates the channel adjustment procedure when the node finds a working channel is overloaded. Following the channel adjustment, the algorithm for local path segment adaptation and relay adjustment is executed. Different from the first scheme, in the second scheme, we apply the cooperative routing algorithm in Algorithm 1 to find the cooperative path, without applying channel adjustment or local path adaptation and relay adjustment. The second scheme is denoted as CT_No-adjustment.

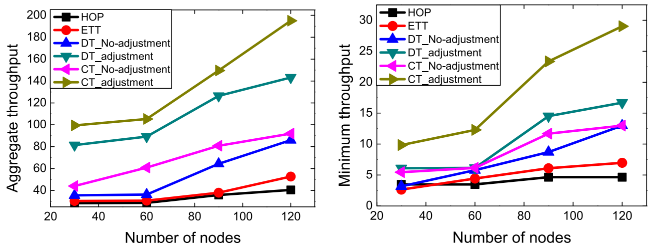
We also implement four additional schemes based on direct transmission without considering cooperative transmission. The first DT scheme is denoted as DT_No-adjustment, where we use the available capacity calculated in Eq. (7) as the routing metric and apply Algorithm 1 to find the path with the maximum available capacity for each flow. In the second scheme, denoted as DT_ adjustment, channel and local path segment adjustment proposed in Sections 5 and 6 are applied periodically to obtain better performance. The third and fourth schemes take two different routing metrics proposed in the literature to find the routing path: a HOP scheme which uses hop count as the basic routing metric and finds the shortest path for each flow, and an expected transmission time (ETT) scheme which takes the ETT in [34] as the routing metric to capture the packet transmission time in a time unit. ETT is an interference-aware routing metric, and higher interference will result in a higher ETT value. Without applying cooperative communications, there is no cooperative relay assignment mechanism in these schemes.

8.2 Simulation Results

8.2.1 Impact of Node Density

To investigate how the node density impacts the network performance, we vary the number of nodes D from 30 to 120 in the network. When the number of nodes increases, the set of candidate relay nodes for CR and MR becomes larger. Therefore, the aggregate rate and minimum rate under all routing schemes increase, as shown in Fig. 9.

Among all the routing schemes, the aggregate throughput and the minimum throughput increase the fastest under our CT_adjustment. With well designed algorithms for path selection, channel adjustment and relay selection, our CT_adjustment can more effectively exploit the resources of relay nodes and multiple channels to achieve high cooperative gain when the number of nodes is large.



(a) Aggregate throughput (b) Minimum throughput

Fig. 9. Throughput results under network with different node density.

Our CT_adjustment has the largest aggregate throughput and minimum throughput. At the node density 120, the aggregate throughput of our CT_adjustment is 382, 270, 276, 127, 36, 112 percent higher than those of HOP, ETT, DT_No-adjustment, DT-adjustment, CT_No-adjustment, CT-adjustment, respectively. The minimum throughput of our CT_adjustment is 527, 317, 235, 124, 74, 124 percent higher than those of HOP, ETT, DT_No-adjustment, DT-adjustment, CT_No-adjustment, respectively.

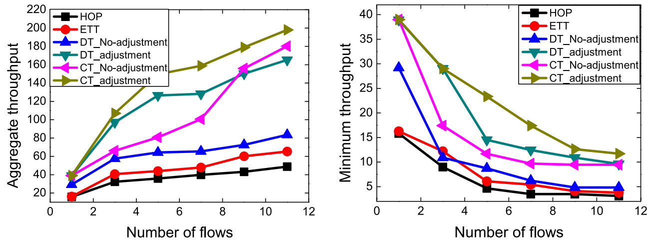
Although the performance under CT_No-adjustment is much better than that under DT_No-adjustment, the performance under DT_adjustment is better than that under CT_No-adjustment. As discussed in the introduction, under CT_No-adjustment, although relay nodes can help to increase the capacity of a transmission pair, cooperative transmissions may also cause interference to more network nodes and consequently significant performance degradation.

Compared with CT_No-adjustment, our CT-adjustment can obtain much larger cooperative transmission gain, which demonstrates the effectiveness of our algorithms in relieving the interference raised by cooperative relays. The performance gain is also attributed to our algorithms for channel adjustment and adaptation of local path segments and relays. By exploiting the MRMC technique, the co-channel interference is alleviated, which is the key reason for the throughput improvement.

8.2.2 Impact of Flow Number

To investigate how the number of flows impacts the network performance, we vary the number of flows M from 1 to 11 in the network while setting the number of nodes $D = 90$. In Fig 10, as the number of flows increases, the aggregate throughput increases, while the minimum throughput decreases as expected due to the increase of competition among flows for accessing the wireless media.

When $M = 1$, our CT_adjustment achieves the same performance as CT_No-adjustment, while our CT_adjustment outperforms CT_No-adjustment in both aggregate rate and minimum rate when the number of flows $M > 1$. This is because when $M = 1$, the relay with two radios are sufficient to serve the session with low interference. As the number of flows increases, compared to CT_No-adjustment, the gain of our CT_adjustment is seen to increase initially and then reduce. Taking into account the co-channel interference and contention among links in the TACC metric, our



(a) Aggregate throughput (b) Minimum throughput

Fig. 10. Throughput results under network with different number of flows.

local adaption algorithms of channel adjustment and local path segment and relay adjustment can effectively alleviate co-channel interference and obtain a larger cooperative communication gain initially. When the number of flows is very large, however, there are very few candidate relays to exploit, so the gain starts to decrease.

Similar to the results of Fig. 9, compared to other schemes, our CT_adjustment can achieve the best network performance with the largest aggregate throughput and largest minimum flow throughput.

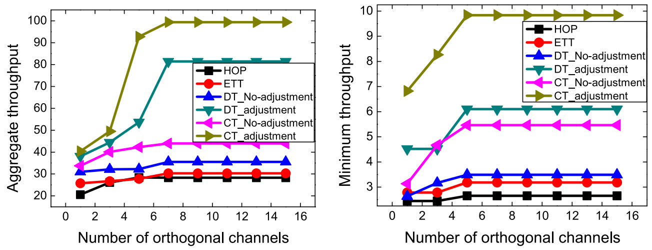
8.2.3 *Impact of the Number of Orthogonal Channel*

We vary the number of orthogonal channels from 1 to 15 in the network while setting other parameters to the default values. As shown in Fig. 11, the aggregate network throughput and minimum flow throughput achieved by all the routing schemes increase when the number of orthogonal channels increase initially, while remaining the same when the number of channels is big enough for the tested five flows. As each node has only two radio interfaces and the traffic in the network is limited, extra channels cannot be fully utilized. Therefore, increasing the number of channels can not unboundedly increase the performance of the routing schemes for the tested five flows.

We also observe that CT_adjustment scheme can take advantage of available orthogonal channels to significantly increase the throughput and achieve the best performance. When the number of channels is larger than 5, our CT_adjustment achieves 251, 228, 180, 22, 126 percent higher aggregate throughput compared to HOP, ETT, DT_No-adjustment, DT-adjustment, CT_No-adjustment, respectively.

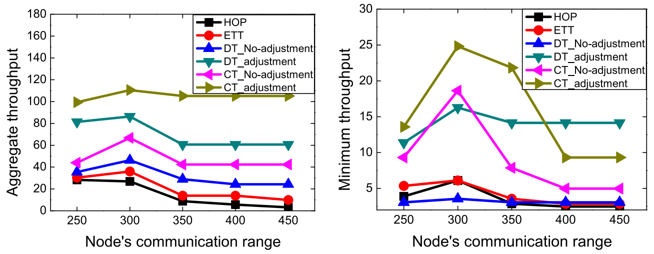
8.2.4 *Impact of Communication Range*

We vary node's transmission range from 250 to 450 in the network. As shown in Fig. 12, the aggregate network throughput and minimum throughput under all the routing schemes increase when the transmission range increases initially, but reduce when the node's transmission range further increases until the transmission range reaches a big value, and remain the same after the transmission range reaches a large value.



(a) Aggregate throughput (b) Minimum throughput

Fig. 11. The impact of number of orthogonal channels.



(a) Aggregate throughput (b) Minimum throughput

Fig. 12. The impact of node's communication range.

The reasons are as follows. On the one hand, the increase of communication range thus the number of network links allow for more opportunities to select higher capacity routes with better CR and MR relays. The initial increase of transmission range also helps to increase network connectivity and find a better transmission path. On the other hand, it also increases the interference and hence reduces the routing performance. Therefore, it does not help to use too high transition power. There is a tradeoff between extending the communication range for more relays and reducing the interference range. As all 30 nodes are randomly located in the limited area of 1000m * 1000m, when the transmission range is larger than 400, nearly all nodes are within the transmission range and interference range of other nodes. Therefore, the performance under all routing schemes remains the same when the transmission range increases further from 400 to 450.

9 CONCLUSION

To fulfill the full potential of cooperative transmission in MRMC cooperative networks, we propose a solution in which cooperative routing at the network layer, channel assignment at the MAC layer, and cooperative communication at the physical layer can work coherently together to maximize the network throughput. Our solution effectively exploits both MRMC technique and cooperative diversity to significantly improve the performance of multi-hop wireless networks with dynamic channel condition and traffic flow. We have carried out extensive simulations to evaluate the performance of our proposed solution. The simulation results demonstrate that cooperative communication can achieve a large capacity gain in MRMC wireless networks under well designed algorithms for joint cooperative routing, channel assignment, and relay assignment. Compared to direct transmission in multi-radio multi-channel, cooperative transmission in Multi-radio multi-channel can largely increase the aggregate throughput.

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