Computer Science and Information Systems 17(3):759–777 https://doi.org/10.2298/CSIS200216019C

# Maximize Concurrent Data Flows in Multi-radio Multi-channel Wireless Mesh Networks

Zhanmao Cao*,[1], Qisong Huang[1], and Chase Q. Wu[2]

[1] Department of Computer Science, South China Normal University
Guangzhou, Guangdong 510631, China
{caozhanmao,2018022617}@m.scnu.edu.cn

[2] Department of Computer Science, New Jersey Institute of Technology
Newark, New Jersey 07102, USA
chase.wu@njit.edu

**Abstract.** Multi-radio multi-channel (MRMC) wireless mesh networks (WMNs) have emerged as the broadband networks to provide access to the Internet for ubiquitous computing with the support for a large number of data flows. Many applications in WMNs can be abstracted as a multi-flow coexistence problem to carry out multiple concurrent data transfers. More specifically, links in different channel layers must be concatenated to compose multiple data transfer paths based on nodes' free interfaces and available channels. This is typically formulated as a combinatorial optimization problem with various stages including channel assignment, path computing, and link scheduling. This paper analyzes traffic behaviors and designs a coexisting algorithm to maximize the number of concurrent data flows. Simulations are conducted in combinatorial cases of channel and radio with various traffic requests of multiple pairs. The experimental results show the efficacy of the coexisting algorithm over a randomly generated topology. This scheme can be used to develop routing and scheduling solutions for various multi-flow network applications through prior computing.

**Keywords:** Concurrent flows, routing and scheduling, coexisting links, Wireless Mesh Networks.

## 1. Introduction

With rapid development of smart mobile terminals, data traffic requests converge to mesh routers, which form multiple data flows between multiple pairs. Wireless Mesh Networks (WMNs) have inherent advantages to serve ubiquitous communication as a broadband backbone. Increasingly, Multi-Radio Multi-Channel (MRMC) WMNs are believed to be the next-generation wireless backbone to address the challenge of heavy data flows [18]. Almost all applications in such network environments can be modeled as multi-flow tasks in a global wireless mesh topology. The fast growing demand for throughput in MRMC WMNs has led to a fundamental problem: how to assemble links to support multiple data flows with optimal performance in a coexisting manner, taking into consideration the limited resources in the network?

For traffic requests of multiple pairs $(s_i, d_i), i = 1, 2, ..., n$, a basic requirement is to enable continuous transmission without wireless interference. This is a fundamental and challenging problem that naturally boils down to a coexistence problem of concurrent flows, which must coexist and be activated along the paths for these specific pairs. Hence, the problem has a general meaning for different applications. As the data volume continues to increase, many applications need to transmit data between different pairs of nodes and it has become a common requirement to support concurrent flows. Due to the limited transmitting media and the wireless interference that obstructs the use of radios, it is challenging to design an efficient method that considers various factors simultaneously, such as interfaces, channels, interference, topology, traffic requests, and data size. To find the link group for optimal throughput in given deployment is meaningful, which help to reach a goal of capacity augmentation [3].

The challenge also arises from the problem's computational complexity. If we consider maximizing the number of concurrent flows or the throughput of source-destination pairs, the problem has been proved to be NP-complete [23]. A subproblem to decide a link schedule for optimal utilization of wireless resources has also been proved to be NP-hard [24]. Even in a simpler combinatorial case of multi-radio networks to meet a given set of rate demands through congestion control by considering channel assignment (CA) and traffic allocation, the problem still remains NP-hard [10]. Energy efficiency is another major concern as massive flows consume significant energy [26].

Cao *et al.* designed a joint routing and scheduling algorithm for multi-pair traffic requests based on a Cartesian Product of Graphs (CPG) model [5]. For the multi-pair or multi-flow problem, Cao *et al.* explored and addressed various issues in resource-aware situation [6]. They also designed a combinatorial scheme with consistent coexisting links over a topology of 64 nodes [11], and a co-existing scheme with optimal joint routing and scheduling [4]. More research efforts are needed in this line of research to support concurrent data flows in WMNs with limited resources.

Since the shortest-distance path does not account for the MRMC constraint, those well-known schemes such as Ad hoc On-Demand Distance Vector (AODV) routing cannot be directly applied to maximize the utilization of MRMC resources. To develop a concurrent transmission scheme for concurrent flows, we focus on the most important factors, including the radios $R$ of nodes, the set $C$ of available orthogonal channels, time slot $t$, topology $G$, and traffic requests $T_r$. This research sheds lights on several key points as follows:

- Formulate the multi-flow problem as a combinatorial optimization problem to achieve the maximum capacity of coexisting links over different channel layers under a channel decomposition model of CPG.
- Develop a link coexisting algorithm to support concurrent flows simultaneously.
- Evaluate the performance in terms of activated links, throughput, capacity, and delay in combinatorial situations.

The remaining sections are organized as follows: Section 2 provides a brief summary of related work. Section 3 builds an optimization model for maximum capacity and designs a coexisting algorithm. Section 4 evaluates the performance of the coexisting algorithm. Section 5 draws a conclusion of the work.

## 2. Related Work

Channel Assignment (CA) has been investigated in-depth through the use of graph coloring for interference avoidance. Almasaeid *et al.* proposed receiver based CA [2], in which they adjust the power and CA scheme in a strong restriction of cognitive radio WMN. The impact of network topology on channel resource utilization has been well recognized [22]. Interference-aware topology control has also been extensively studied for years [13,21]. Resource utilization also depends on the communication scheme. MRMC is able to significantly improve network capacity and reduce the cost of broadband WMN deployment [19]. The number of orthogonal channels and the number of radios per node determine the mesh capacity. The combined cases of critical resources should be compared to understand the relationship between throughput and other metrics.

Most of the existing work considered one aspect of routing, scheduling, or channel assignment. There is some limited work considering two or more of them. Jin showed that the routing and packet scheduling problem in general graphs is NP-complete [14]. It is even more challenging to optimize the use of wireless resources in WMNs, because one subproblem to determine an optimal link schedule has been shown to be NP-hard [24]. The subproblem only considering CA in mesh networks is similar to the least coloring problem of graph, which is NP-complete [23]. The joint routing and scheduling problem in WMNs is obviously more complicated. Even in a directional radio case, the transmission of multiple concurrent flows, which can be formulated as a mixed integer nonlinear problem, is inherently difficult to solve [25].

Alicherry *et al.* formulated CA and routing as an *LP* problem by simultaneously considering the characteristics of interference, the number of channels and the number of radios [1]. Giannoulis *et al.* proposed an iterative method to optimize congestion control by considering CA and traffic allocation [10], and declared that the problem is still NP-hard, even in a simpler combinatorial case on CA for multi-radio networks to realize a given set of rate demands. After decomposing congestion control into two stages, they formulated a problem of MRMC congestion control (MRMC-CC). However, Giannoulis' optimization method does not account for CA concerning multi-pair requests in MRMC WMN scenarios. Taking one step further from the above work, we investigate the problem of joint routing, scheduling, and CA with resource-awareness under the guidance of a carefully designed network model.

Due to limited resources, the shortest-path routing is insufficient for WMNs [8]. To find the critical links by using Bayesian theorem, which are bottleneck links in a WMN, was reported with significant performance improvement [12]. JRCA-AODV is reported as a joint routing and channel scheme, which is a modification of AODV. The problem of counting all shortest paths in an MIMO triangular mesh, considering the number of interfaces and the number of channels, is studied for WMNs [7]. The shortest-path routing scheme only considers the least resource consumption for one stream, while neglecting the fact that overlapped nodes may exhaust resources quickly [15]. If one node has no free resource, it cannot forward any packet. Kim *et al.* discussed resource sharing by quantifying node resource usage [16]. Although there exist some efforts in this direction, resource-aware routing still remains largely unexplored.

To simplify CA, Cao *et al.* suggested a virtual model with Cartesian product of graphs (CPG), which decomposes the complex layered structure [7]. Cao *et al.* developed a Cartesian product of graphs (CPG) model to simplify channel assignment. They proposed a destination-oriented routing method over a triangular mesh. Furthermore, they counted the path number with CPG model. There is very limited study on the efficiency of combinatorial cases considering the number of radios, the number of channels, network topology, time slots, and traffic distributions simultaneously. Cao *et al.* addressed combinatorial routing using CPG model, which is conducive to CA. The goal of CA is take full usage of the radio resource, which is represented in interference-free or more coexisting active links at a moment. Furthermore, they proposed optimal schemes of combinatorial routing and scheduling for concurrent flows in their recent work [4]. The considered factors in the model in the latest work [11], i.e., the major parameters, are of available channels, radios equipped, topology, and traffic requests.

To avoid interferences between links and to reduce heavy congestion on intersected nodes, path finding/selection and link scheduling should be carried out based on actual available resources. Hence, a joint scheduling and routing scheme with CA is deeply coupled with the network topology, the number of node interfaces, and the number of available channels.

## 3. Coexisting patterns

A data flow is carried over a path between a node pair $(s_i, d_i)$, where $s_i$ denotes the source node, and $d_i$ denotes the destination node. A traffic request from one mesh node $s_i$ to another $d_i$ with data size $z_i$, $i = 1, 2, ..., \rho$. Traffic mode is denoted as $T_r = \{(s_i, d_i; z_i)|i = 1, 2, ..., \rho\}$. The set of all traffic requests within a given period defines the traffic situation $T_r$. Typical examples include FTP or some other real-time data transfer requests.

We can depict this data transfer process in a general way with the help of the Cartesian Product of Graphs (CPG) model. Let each channel layer select a sufficient number of links for composing data transfer paths, which are candidates for routing the traffic of pair $(s_i, d_i)$. Note that, as the number of data flows increases, the problem becomes very challenging due to the limited resources. To support the transmission for multi-pair traffic requests, we need to analyze several main factors. According to the CPG model, a routing and scheduling scheme should consider the number $|R|$ of radios, the number $|C|$ of available channels, the topology $G$ of the multi-radio multi-channel (MRMC) wireless mesh network (WMN), and traffic mode $T_r$. The four major factors are deemed to have main impacts on the WMN performance. The first two factors are main resources, as time is naturally considered when scheduling selected links. Topology is the base for identifying the interference relationship. In wireless mesh networks, the network topology should be considered in the beginning of the network deployment. Considering four factors simultaneously is far more complex compared with most of the existing work that considers only one or two factors, as in cognitive networks [20].

To take full advantage of MRMC resources, we need to focus on a certain performance metric for the mesh. In this work, we consider the maximum capacity for traffic requests in a given WMN as the optimization goal under certain constraints on the paths for routing or the links to be scheduled. We first explore the characteristics of links, combinatorial conditions, and active link numbers, and then formulate a combinatorial optimization problem. We design an algorithm to create coexisting paths for this problem and evaluate the performance of the algorithm in various combinatorial scenarios.

### 3.1. Model for Coexisting Links

We consider a WMN topology $G = (V, E), |V| = n, |E| = m$, where $E$ denotes the set of effective communications between neighbor nodes, not actual links in the wireless mesh. Only when a pair of nodes $(u, v)$ in $V$ are communicating with each other over the same channel $c_j$, $(u, v) \in E$ becomes a link at an assigned time slot $t$, denoted as $l^{(u,v)}_{c_j,t}$. If the channel $c_j$ has bandwidth $\omega_j$, the maximum capacity of the link is $\omega_j$. Obviously, the flow data rate of $l^{(u,v)}_{c_j,t}$ is bounded by $\omega_j$.

The maximum capacity depends on several critical factors: the traffic situation $T_r$, the resources of the mesh represented by $R$ and $C$, the topology, and the scheme for routing and scheduling concurrent flows of different pairs. $T_r = \{(s_i, d_i; z_i)|i = 1, 2, ..., \rho\}$ is the initial traffic situation. The resources of a mesh node $v_i$ include radio number $R[i]$ of and the set $C = \{c_1, c_2, ..., c_q\}$ of available channels, where $q$ is the total number of orthogonal channels. The topology is another important input of the problem as it affects route selection and node/link interference relation.

The path of node pair $(s_i, d_i)$ is denoted as $P_{(s_i,d_i)}$, or simply as $P_i$. The number of hops along $P_i$ from $s_i$ to $d_i$ is denoted as $\varrho_i$. We denote the $j^{th}$ hop of $P_i$ as $\hbar_j^{P_{(s_i,d_i)}}$, or $\hbar_j^{P_i}$ for brevity. The channel assigned to link $\hbar_j^{P_i}$ is denoted as $c_{ij} \in C$, and its corresponding bandwidth is denoted as $\omega_{ij}$. The capacity of $P_{(s_i,d_i)}$ is the sum of link capacities along $P_i$, denoted as $Cap(P_{(s_i,d_i)})$. The lower bound of $Cap(P_{(s_i,d_i)})$ is the minimum link capacity along $P_i$ multiplied by $\varrho_i$. Similarly, the upper bound of $Cap(P_{(s_i,d_i)})$ is the maximum link capacity multiplied by $\varrho_i$. The capacity of an active path $P_i$ is calculated as:

$$Cap(P_{(s_i,d_i)}) = \sum_{j=1}^{\varrho_i} \omega_{ij}. \tag{1}$$

Over a certain channel layer in the CPG model, the maximum number of links is determined by the topology. The choice of maximum links may not be unique, but the maximum number of coexisting links must match the number of node-pairs at all times. Let $\lambda$ be the maximum number of coexisting links in one channel layer. Then, the number of possible links over all $q$ channels in a given mesh can be estimated by its upper bound $q \cdot \lambda$. In fact, it is critical to cooperative arrange the channel for efficient scheduling as mentioned in paper [9].

However, the traffic situation may contain not only one-hop communications, but also many-hop communications for $P_i$. Generally, we need to concatenate several links, which are distributed in different channel layers, to compose the paths for the current $T_r = \{(s_i, d_i; z_i)|i = 1, 2, ..., \rho\}$. We have $\hbar^{P_i}_{j,c_k,t} = 1$, if the link is scheduled; else, $\hbar^{P_i}_{j,c_k,t} = 0$. Obviously, the capacity is also limited by the size of $T_r$. Hence, the maximum capacity, as the optimization objective, is represented by

$$\max \sum_{i=1}^{\rho} \sum_{j=1}^{\varrho_i} \sum_{k=1}^{q} \sum_{t=1}^{T} \hbar^{P_i}_{j,c_k,t} \cdot \omega_k. \tag{2}$$

Clearly, the link count of a node is limited by its radios. If node $v_i$ is a link's receiver over $c_j$, we denote this link as $l^{\triangleright,v_i}_{c_j,t}$; if node $v_i$ is a link's sender, we denote this link as $l^{v_i,\triangleright}_{c_j,t}$. Hence, $l^{\triangleright,v_i}_{c_j,t} + l^{v_i,\triangleright}_{c_j,t} \leq R[i], \forall i$. Here, $\triangleright$ denotes the direction of the radio from/to a certain node.

If there are several paths sharing one connection over channel $c_j$, say $l_{c_j,t}^{(u,v)}$, then the minimum sum of the link capacities for those sharing paths must be less than $\omega_j$.

In the CPG model, the links of a path are distributed in various channel layers as shown in [7]. The links in one channel layer are collected in a greedy way to have sufficient interference-free links for an initial path and other interference-free links to support other paths. The critical step is to find the best fit for path edges and interference-free links. However, the combinations of links in different layers are restricted by the paths of different pairs. The combinatorial nature makes the problem extremely challenging.

We attempt to design a heuristic scheme to find as many required links as possible and generate multiple coexisting link groups. Based on the model and the coexisting properties discussed above, we design our scheme as shown in Algorithm 1, where the coexisting links are combined to maximize the number of coexisting paths.

### 3.2. The Link Coexistence Algorithm

To simultaneously activate as many paths as possible, it is necessary to make full use of the network resources. In the CPG model, we understand that one-hop paths cannot always meet the demands for concurrent flows in practice. Let $C(v_i)$ denote the set of all available channels of router $v_i$, and let $c_j(v_i)$ denote the channel assignment operation, which assigns channel $c_j$ to router $v_i$. We use $I_{Free}$ to denote the set of links without interference over a certain channel, i.e., every two links in $I_{Free}$ satisfy the interference-free relation. In fact, for a specific topology, $I_{Free}$ holds over any channel.

We use $L_t$ to denote the set of all links that satisfy $I_{Free}$ at time $t$, i.e., $L_t \bowtie I_{Free}$. Here, $\bowtie$ means "satisfy the right-side relation". If new links are added into $L_t$, the interferences have to be examined.

Based on the models constructed in Section 3.1, we design Algorithm 1 to optimize resource utilization. It produces the maximum link groups at time $t$. As a result, the links in $L_t$ are combined to form as many paths as possible for multiple pairs $(s_i, d_i), i = 1, 2, ..., \rho$.

## 4. Performance Evaluation

Topology is the first factor to be considered in wireless mesh networks, because it determines the interference relation between routers. To evaluate the performance of Algorithm 1, we conduct a set of simulations in combinatorial cases $R \times C = \{4, 8, 12, 16, 20\} \times \{8, 16, 32, 64\}$ with an MRMC WMN topology, as shown in Fig. 1. This topology has 77 nodes, which are generated randomly in NS3 with distance constraints.

### 4.1. Simulations in Combinatorial Cases

The performance of a WMN depends on several critical factors: the traffic situation $T_r$, the resources of the mesh represented by $R$ and $C$, the topology, and the scheme for routing and scheduling concurrent flows of different pairs. Given a region, the router deployment is typically fixed. Hence, we consider one topology in our simulations. In addition, we do not include any base station (BS) in the network topology. Traffic $T_r$ is selected from four groups of different traffic types, each of which has 80 pairs. Each $T_r$

**Algorithm 1** Link coexistence algorithm for concurrent flows

Input: Topology $G$, the set $R$ of node radios, and the set $C$ of available channels, traffic mode $T_r = \{(s_i, d_i; z_i) | i = 1, 2, ..., \rho\}$.

Output: $L$, the set of coexisting links combined to support concurrent flows.

**Require:** $|R| \geq 0 \wedge |C| \geq 0$;

**Ensure:** $\omega_i \geq 0$;

$t := 0$;
$i := 1$;
$j := 1$;
**for** ($t = 0$ to $T$) **do**
  **while** ($i < \rho$) **do**
    **if** ($\exists$ path $P_i \wedge \forall v_h \in P_i, r(v_h) > 0$) **then**
      **if** ($\forall i, h, (v_h \in P_i) \wedge (v_h \neq s_i) \wedge (v_h \neq d_i) \wedge (c(v_h) > 0)$) **then**
        Choose $c_j \in C(v_{i_{h-1}}) \cap C(v_{i_h})$, and let $c_j(l_t^{(v_{i_{h-1}}, v_{i_h})})$;
        **if** $L_t \cup_i \{l_{c_j,t}^{(v_{i_{h-1}}, v_{i_h})}\} \bowtie I_{Free}$ **then**
          $L_t := L_t \cup \{l_{c_j,t}^{(v_{i_{h-1}}, v_{i_h})}\}$;
      **else** $\{P_i$ has a node with no free resources$\}$
        $i := i + 1$;
  $t := t + 1$;
output $L := \bigsqcup_t \{L_t\}, \{t \in (0, T)\}$.

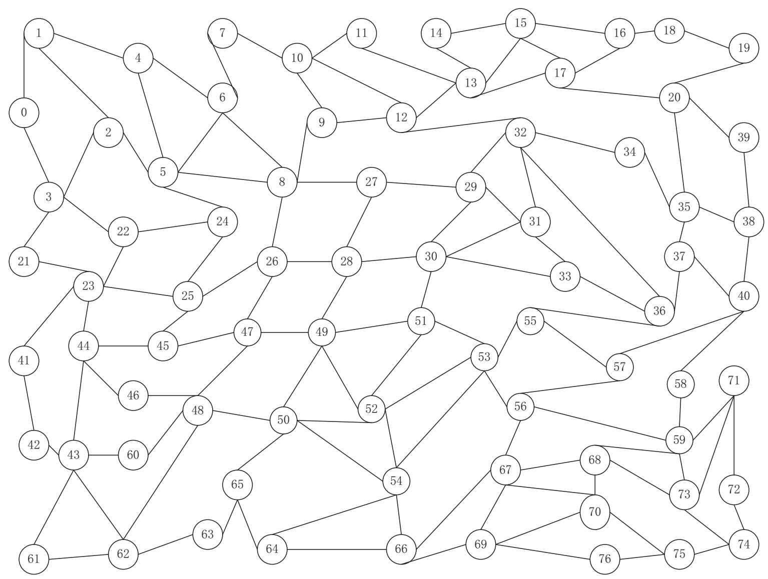


**Fig. 1.** The WMS topology with 77 routers.

is randomly generated between $(s_i, d_i)$ pair with data size $z_i > 0$. $R$ and $C$ are critical resources in WMNs, playing a significant role in the stage of path planning and routing. The combinatorial cases are constructed based on $R \times C$.

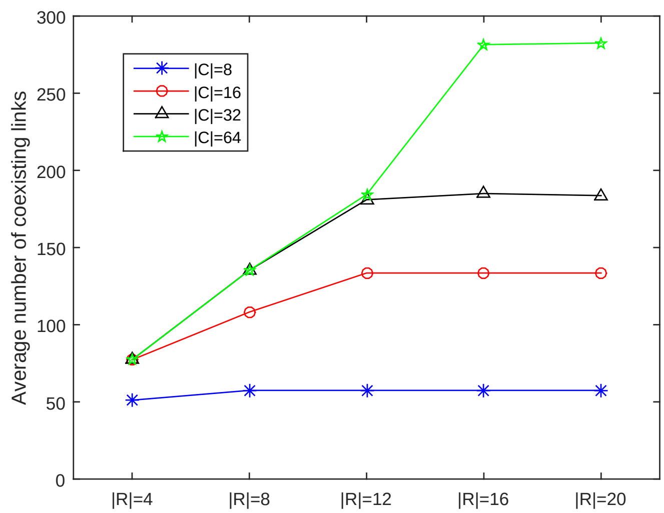



**Fig. 2.** The average number of activated links in the topology.

In the topology as shown in Fig. 1, we have $C = \{8, 16, 32, 64\}$, $R = \{4, 8, 12, 16, 20\}$, and $|T_r| = 80$. We first need to find out the number of simultaneously activated links. The number of coexisting links for the combinations is plotted in Fig. 2. As links for different pairs are simultaneously activated, the more links are activated, the more packets are forwarded. The simulation also presents an interesting phenomenon: when $|R| = 12$, channel count $|C| = 32$ is sufficient to use the interface resources. Having more channels may not improve the number of simultaneous links with $|R| = 12$. Also, increasing the number of interfaces may not improve the number of simultaneous links with $|C| = 32$, as shown in Fig. 2. We refer to the situation $|R| = 12 \wedge |C| = 32$ as a hand-shake match. Similarly, $|R| = 16 \wedge |C| = 64$ is another hand-shake match. The best use of free resources may sustain nearly up to 290 links in the given mesh.

The average capacities are measured to evaluate the performance of the coexisting algorithm for the combinations of $R \times C = \{4, 8, 12, 16, 20\} \times \{8, 16, 32, 64\}$. The multi-pair requests form a random group of 80 pairs, i.e., $|Tr| = 80$. Generally, more resources equipped in the mesh promise a higher capacity. However, we note that if there are only 8 available channels, the capacity cannot be improved further by increasing the number of radios. Furthermore, in the case of $|C| = 16$ or $|C| = 32$, the upper capacity limit can be reached with $|R| = 12$. Similarly, in the case of $|C| = 64$, the upper capacity limit can be reached with $|R| = 16$. Generally, the mesh provides a large capacity as shown in Fig. 3.

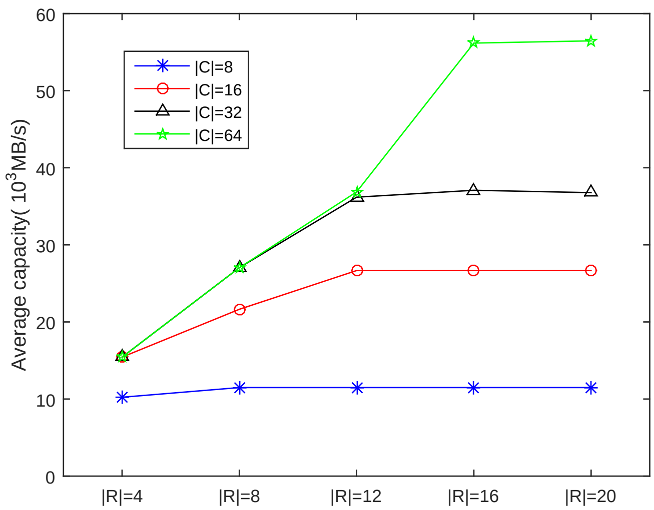



**Fig. 3.** The average capacity with $R \times C = \{4, 8, 12, 16, 20\} \times \{8, 16, 32, 64\}$.

The above two simulations are conducted with traffic requests $|Tr| = 80$, while the data size is set to be sufficiently large for continuous transmission during one period. The topology is randomly generated with 77 nodes under distance constraints. The simulations are based on the combinations of resources $R = \{4, 8, 12, 16, 20\}$ and $C = \{8, 16, 32, 64\}$.

The following simulation is designed to examine the performance of the proposed coexisting algorithm. Note again that there are no base stations in the topology. Further simulations are conducted to measure the performance in terms of average throughput, average activated link number, and average capacity of the whole network. We consider different combinatorial cases of $C \times R = \{8, 16, 32, 64, 128\} \times \{4, 8, 12, 16\}$. Here, we reduce the scenario of radio number, while increasing that of channels. Resource utilization is estimated via link number, capacity, throughput in $R \times C$ combinatorial cases, with $|T_r| = 80$ of four types of traffic requests.

As described in the model analysis, the algorithm finds coexisting links and combines them to form paths of different pairs. The links are activated simultaneously in a time slot without interference. This suggests counting the average number of activated links during a time period for performance evaluation. The more links are activated, the better the performance it should be. The performance measurements are plotted in Fig. 5.

We observe that the number of activated links increases with the resources. However, for a certain $|R|$, the average link number has an upper bound even if $|C|$ is doubled. This can be verified in cases of $|R| = 4$ with $|C| = 16$, $|R| = 8$ with $|C| = 32$, and $|R| = 12$ with $|C| = 64$. In particular, $|R| = 16$ with $|C| = 64$, where $|C|$ is doubled to 128. Here, the activated link number does not increase accordingly. This observation indicates that radios and channels may have some match pattern in the performance. To deploy a local-

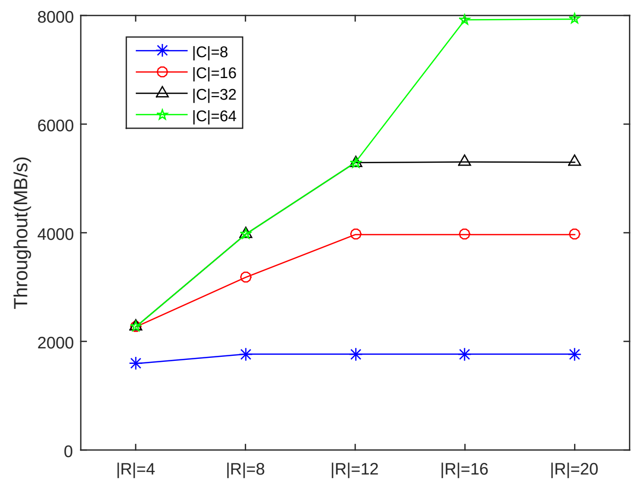



**Fig. 4.** The average throughput with $C \times R = \{8, 16, 32, 64\} \times \{4, 8, 12, 16, 20\}$.

area WMN, a careful pre-computation to find the matching pattern may save engineering time and investment cost.

A combinatorial simulation is shown in Fig. 6. Note that there are some patterns between radio number and channel number, as the throughput reaches a plateau at a certain channel number for one radio number, because the radio number has a certain limitation to the performance. For example, when $|R| = 4$, the performance has a jump from $|C| = 8$ to $|C| = 16$. But there is no improvement even if the channel number is increased to 128. We refer to this situation as a match of $R$ with $C$ from the view of performance. A similar pattern repeats for $|R| = 8, 12$, and 16. Correspondingly, $|R| = 8, 12$, and 16 match with $|C| = 32, 32$, and $64$, respectively. This calls for further simulations or comparisons in those matching cases.

In one scheduling period, as the combinatorial routing chooses different link patterns according to different traffic requests, the actual capacity may change with the heuristic start and traffic requests. We further conduct experiments to evaluate the robustness of the algorithm in terms of the average capacity. The simulations are conducted with four groups of 80 pair traffic requests each over the topology in Fig. 1, in the combinatorial resource cases of $C \times R = \{8, 16, 32, 64, 128\} \times \{4, 8, 12, 16\}$. This may also help determine if the simulations for throughput and capacity are consistent with each other. If they are consistent, the results would support the robustness of the proposed algorithm. The performance measurements are plotted in Fig. 7, which shows that the results do match the average throughput.

The simulations show that the number of interfaces $R$ and the number of available channels have a certain fitness. In the case of the average activated links with $C \times R = \{8, 16, 32, 64, , 128\} \times \{4, 8, 12, 16\}$, as shown in Fig.4, we understand that the efficiency of channel resource is limited by the number of node interfaces. In the case of $|R| = 12$, the performances are the same for $|C| = 32$ and $|C| = 64$. This phenomenon indicates

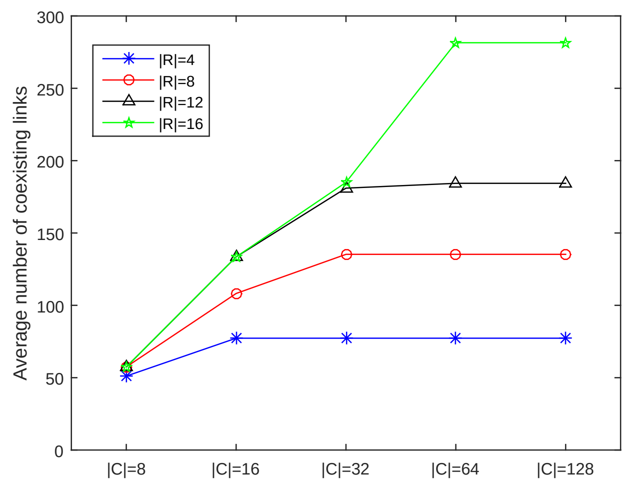



**Fig. 5.** The average number of activated links with $C \times R = \{8, 16..., 128\} \times \{4, ..., 16\}$.

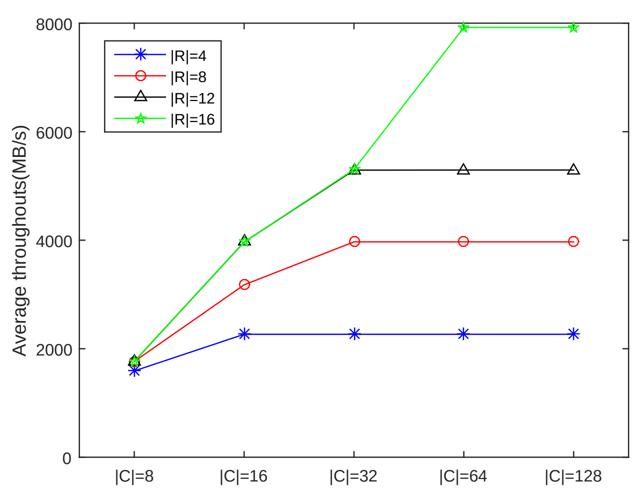



**Fig. 6.** Average throughput with $C \times R = \{8, 16, 32, 64, 128\} \times \{4, 8, 12, 16\}$.

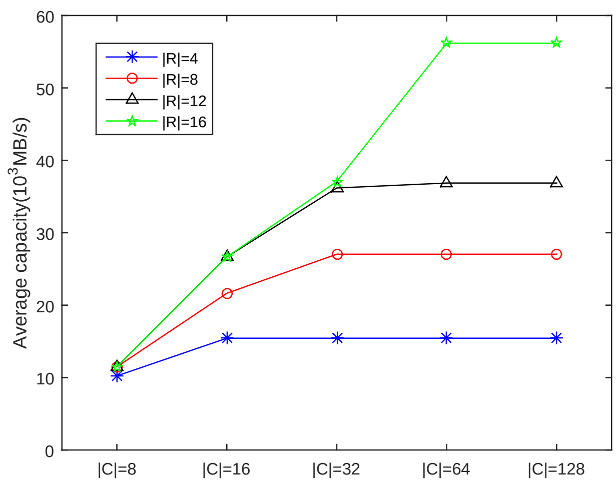



**Fig. 7.** Average capacity with $C \times R = \{8, 16, 32, 64, 128\} \times \{4, 8, 12, 16\}$.

that the most efficient number of channels is 32, as the throughput is upper bounded at $|C| = 32$. In this topology, $|R| = 12$ may be combined with $|C| = 32$ as the most efficient pattern. Allocating more channels to the given deployment region may result in the waste of resource.

The simulation results show that there exists a best match of $|R| = 16\&|C| = 64$. At this match, we achieve almost the same highest throughput, for both combinatorial cases $R \times C = \{4, 8, 12, 16, 20\} \times \{8, 16, 32, 64\}$ and $C \times R = \{8, 16, 32, 64, 128\} \times \{4, 8, 12, 16\}$. We also observe that the experimental results are consistent in both cases of different resource deployment schemes, which illustrates the robustness of Algorithm 1.

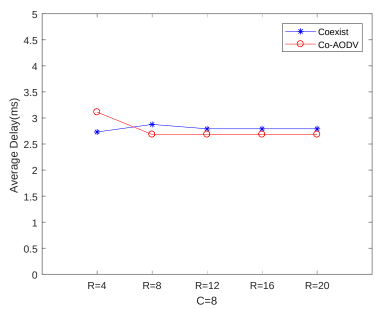
### 4.2. Comparison Experiments

We compare the proposed scheme with AODV for performance evaluation. As AODV can not be directly applied to the MRMC situation, we modify AODV to work in the multiple-channel situation, which is referred to as co-AODV. The comparisons are divided into three groups, which are shown in three figures with subgraphs. Fig. 8, Fig. 9, and Fig. 10 plot the comparison results of delivery delay, packet delivery ratio, and throughput, respectively. In each group, the comparison is made in four subcases: 1) $C \times R = \{8\} \times \{4, 8, 12, 16, 20\}$, 2) $C \times R = \{16\} \times \{4, 8, 12, 16, 20\}$, 3) $C \times R = \{32\} \times \{4, 8, 12, 16, 20\}$, and 4) $C \times R = \{64\} \times \{4, 8, 12, 16, 20\}$.

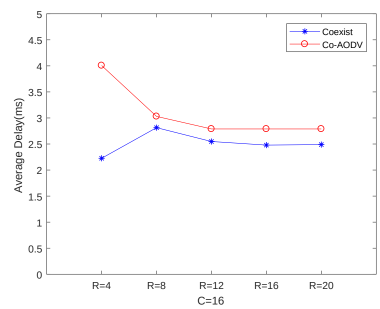
In Fig. 9, we measure the packet delivery ratio ($PDR$), which is defined as the total number of successfully received packets $p_{rece}$ divided by the total number of sent packets $p_{send}$, i.e.,

$$PDR = \frac{p_{rece}}{p_{send}} \times 100\%. \tag{3}$$

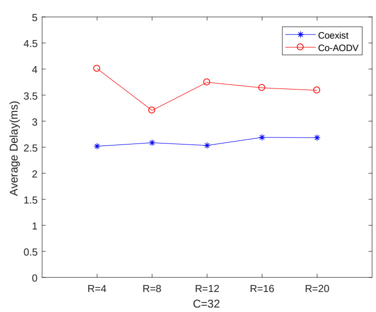
The average PDR measurements show that Algorithm 1 works efficiently for MRMC WMNs. With less resources as shown in Fig. 9(a), it achieves a performance close to



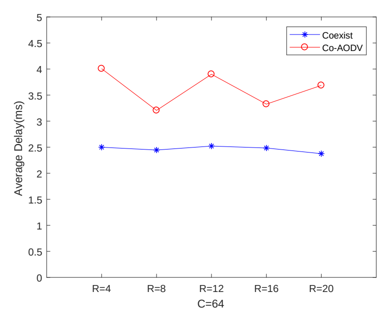

(a) $C \times R = \{8\} \times \{4, ..., 20\}$




(b) $C \times R = \{16\} \times \{4, ..., 20\}$

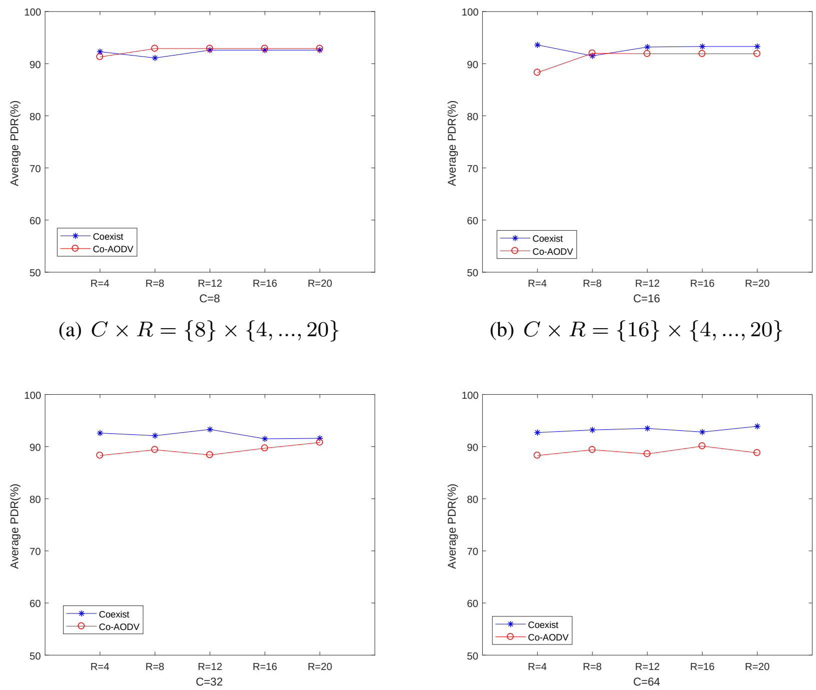



(c) $C \times R = \{32\} \times \{4, ..., 20\}$




(d) $C \times R = \{64\} \times \{4, ..., 20\}$

**Fig. 8.** Average delay comparison with AODV.




(a) $C \times R = \{8\} \times \{4, ..., 20\}$

(b) $C \times R = \{16\} \times \{4, ..., 20\}$

(c) $C \times R = \{32\} \times \{4, ..., 20\}$

(d) $C \times R = \{64\} \times \{4, ..., 20\}$

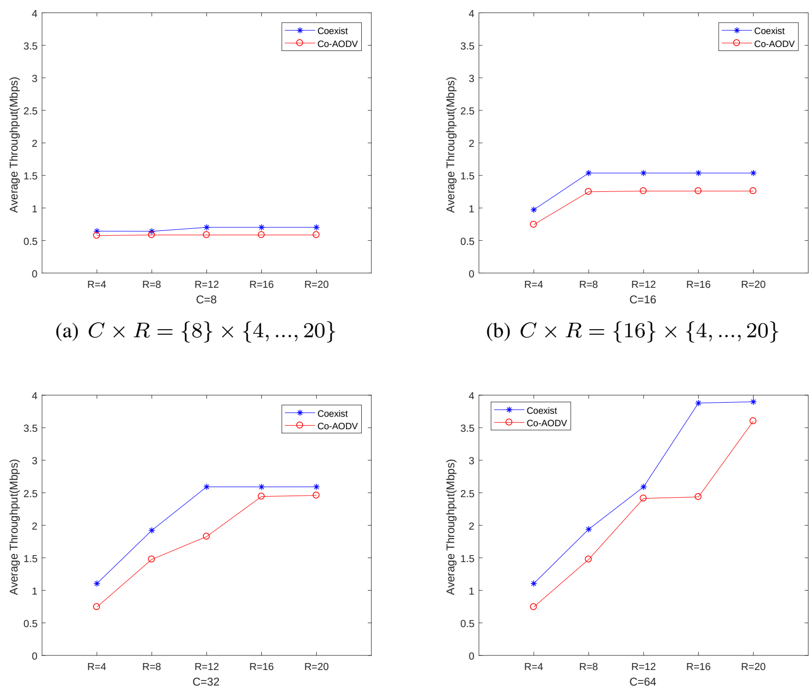
**Fig. 9.** Comparison of packet delivery ratio (PDR) with AODV.

AODV. With more resources, it increasingly outperforms AODV as shown in Figs. 9(b), 9(c), and 9(d).

We also compare our algorithm with AODV in terms of throughput. Similarly, we conduct experiments in four sub-problems as above, but with focus on throughput performance.

These results show that Algorithm 1 outperforms AODV in terms of average throughput in the combined cases, which illustrate the resource utilization efficiency of the proposed algorithm. We observe a $R \times C$ pattern where the throughput jumps at $C = 32$ *when* $R = 12$ as shown in Fig. 10(c) and $C = 64$ *when* $R = 16$ as shown in Fig. 10(d). This observation suggests a deployment scheme with matched radios and channels in this given region.

In order to investigate the performance of our proposed scheme, it is necessary to compare in maximum throughput, see Fig. 11. We conducted a group of combinatorial comparisons. The simulation results show that co-AODV works well when there are less resources. Meanwhile, the coexisting scheme outperforms significantly with $C = 32, C = 64$ and $R = 8, 12, 16, 20$. Notice that the simulations can also be affected by traffic situations, the efficiency assessment of an algorithm should primarily depends on the average throughput.



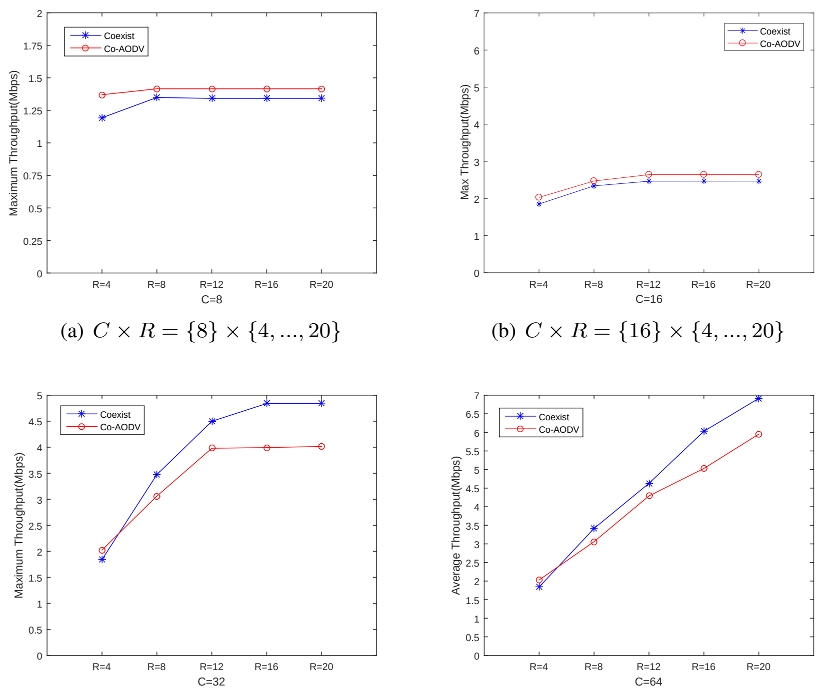

(a) $C \times R = \{8\} \times \{4, ..., 20\}$

(b) $C \times R = \{16\} \times \{4, ..., 20\}$

(c) $C \times R = \{32\} \times \{4, ..., 20\}$

(d) $C \times R = \{64\} \times \{4, ..., 20\}$

**Fig. 10.** Average throughput comparison with AODV.




(a) $C \times R = \{8\} \times \{4, ..., 20\}$

(b) $C \times R = \{16\} \times \{4, ..., 20\}$

(c) $C \times R = \{32\} \times \{4, ..., 20\}$

(d) $C \times R = \{64\} \times \{4, ..., 20\}$

**Fig. 11.** Maximum throughput comparison with co-AODV.

## 5. Conclusion

Based on the channel layered CPG model, we formulated the optimal capacity problem for concurrent flows in MRMC WMNs as a combinatorial optimization problem to maximize the number of coexisting links over different channel layers. We analyzed the optimization objective and the corresponding constraints, and designed a link coexisting algorithm to meet the demands for maximum transmission. The proposed algorithm is based on a heuristic greedy strategy, which specifically accounts for the complexity of concatenating links into paths.

To approach the optimal performance, combinatorial techniques are used to decompose coexisting paths into channel layers. Simulation results show that this algorithm provides an effective solution by making full use of available resources. Three sets of simulations illustrate the robustness of the algorithm and the performance improvement in comparison with AODV, in terms of delay, PDR, and average throughput. The network topology and $\{Tr, R, C\}$ together determine a joint routing and scheduling scheme, which can be used to pre-compute routes and schedules for various multi-flow tasks. Considering the complexity of this problem, as we noticed there are attempts by machine learning in the field, such as work [17], using machine learning in WMNs may be a new direction in our future research.

## References

1. Alicherry, M., Bhatia, R., Li, L.E.: Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks. In: Proceedings of the 11th Annual International Conference on Mobile Computing and Networking. pp. 58–72. ACM MobiCom '05 (2005)
2. Almasaeid, H.M., Kamal, A.E.: Receiver-based channel allocation in cognitive radio wireless mesh networks. IEEE/ACM Transactions on Networking 23(4), 1286–1299 (2015)
3. Ashraf, U.: Capacity augmentation in wireless mesh networks. IEEE Transactions on Mobile Computing 14(7), 1344–1354 (2015)
4. Cao, Z., Huang, Q., Wu, Q.C., Kong, W., Hou, A.: On a coexisting scheme for multiple flows in multi-radio multi-channel wireless mesh networks. In: Communications in Computer and Information Science 1163. pp. 3–11. Springer (2019)
5. Cao, Z., Wu, C.Q., Berry, M.L.: An optimization scheme for routing and scheduling of concurrent user requests in wireless mesh networks. Computer Science and Information Systems 14(3), 661–684 (2017)
6. Cao, Z., Wu, C.Q., Berry, M.L., Wang, Y.: Resource-aware routing and scheduling in multi-radio multi-channel wireless mesh networks. In: IEEE Wireless Communications and Networking Conference Workshops (WCNCW). pp. 248–253. International Workshop on Big Data with Computational Intelligence for Wireless Networking'2018 (2018)
7. Cao, Z., Wu, Q., Zhang, Y., Shiva, S.G., Gu, Y.: On modeling and analysis of mimo wireless mesh networks with triangular overlay topology. Mathematical Problems in Engineering p. Article ID 185262 (2015), http://www.hindawi.com/journals/mpe/aa/185262/
8. De Couto, D.S., Aguayo, D., Chambers, B.A., Morris, R.: Performance of multihop wireless networks: Shortest path is not enough. ACM SIGCOMM Computer Communication Review 33(1), 83–88 (2003)
9. Deng, X., Luo, J., He, L., Liu, Q., Li, X., Cai, L.: Cooperative channel allocation and scheduling in multi-interface wireless mesh networks. IEEE Transactions on Mobile Computing 12, 1–12 (2019)

10. Giannoulis, A., Salonidis, T., Knightly, E.: Congestion control and channel assignment in multi-radio wireless mesh networks. In: Sensor, Mesh and Ad Hoc Communications and Networks, 2008. SECON'08. 5th Annual IEEE Communications Society Conference on. pp. 350–358. IEEE (2008)
11. Huang, Q., Cao, Z., Shan, Z.: Combinatorial routing and scheduling scheme for multiple concurrent flows in wireless mesh networks. Journal of South China Normal University (Natural Science Ed.) 52(1), 122–128 (2020)
12. Iqbal, S., Abdullah, A.H., Ahsan, F., Qureshi, K.N.: Critical link identification and prioritization using bayesian theorem for dynamic channel assignment in wireless mesh networks. Wireless Networks 24, 2685–2697 (2018)
13. Jang, H.C., Fang, R.W.: Interference-aware topology control in wireless mesh network. In: Proceedings of the International Conference on Mobile Technology, Applications, and Systems. pp. 1–7. MTAS'08 (2008)
14. Jin, F., Arora, A., Hwang, J., Choi, H.A.: Routing and packet scheduling in wimax mesh networks. In: Proc. of the 4th IEEE International Conference on Broadband Communications, Networks and Systems (BROADNETS). pp. 574–582 (2007)
15. Jun, J., Sichitiu, M.L.: Mrp: Wireless mesh networks routing protocol. Computer Communications 31(7), 1413–1435 (2008)
16. Kim, T.S., Yang, Y., Hou, J.C., Krishnamurthy, S.V.: Joint resource allocation and admission control in wireless mesh networks. In: Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, 2009. WiOPT 2009. 7th International Symposium on. pp. 1–10. IEEE (2009)
17. Kuskonmaz, B., Ozkan, H., Gurbuz, O.: Machine learning based smart steering for wireless mesh networks. Ad Hoc Networks 88, 98–111 (2019)
18. Larsson, E.G., Edfors, O., Tufvesson, F., Marzetta, T.L.: Massive mimo for next generation wireless systems. IEEE Communications Magazine 52(2), 186–195 (2014)
19. Liu, Q., Jia, X., Zhou, Y.: Topology control for multi-channel multi-radio wireless mesh networks using directional antennas. Wireless Networks 17(1), 41–51 (2011)
20. Maheen, I., M. A., R., Md, Mamun-Or-Rashid, e.a.: Traffic engineering in cognitive mesh networks: Joint link-channel selection and power allocation. Computer Communications 116, 212–224 (2018)
21. Maleki, E.N., Mirjalily, G.: Fault-tolerant interference-aware topology control in multi-radio multi-channel wireless mesh networks. Computer Networks 110, 206–222 (2016)
22. Marina, M.K., Das, S.R., Subramanian, P.: A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks. Computer Networks 54, 241–256 (2010)
23. Ramachandran, K.N., Belding-Royer, E.M., Almeroth, K.C., Buddhikot, M.M.: Interference-aware channel assignment in multi-radio wireless mesh networks. In: INFOCOM. vol. 6, pp. 1–12 (2006)
24. Ramanathan, S., Lloyd, E.L.: Scheduling algorithms for multihop radio networks. IEEE/ACM Transactions on Networking (TON) 1(2), 166–177 (1993)
25. Roh, H.T., Lee, J.W.: Channel assignment, link scheduling, routing, and rate control for multi-channel wireless mesh networks with directional antennas. Journal of Communications and Networks 18(6), 884–891 (2016)
26. Shu, T., Wu, C.Q.: Energy-efficient mapping of large-scale workflows under deadline constraints in big data computing systems. Elsevier FGCS (2018), doi.org/10.1016/j.future.2017.07.050

**Zhanmao Cao** received his PhD in 2011, from School of Computer Science and Technology, South China University of Technology, Guangzhou, China. He is Associate Professor

in School of Computer, South China Normal University. He is interested in developing algorithms for application problems, wireless mesh networks, bioinformatics, and machine learning. He proposed algorithms BTA and DC-BTA for multiple sequence alignment. He is now working on modeling, routing and scheduling algorithms for WMNs, as well as applications of machine learning.

**Qisong Huang** is a graduate student of grade 2018 in School of Computer, South China Normal University. His research is on WMN communication algorithms and simulations.

**Chase Wu** completed his Ph.D. dissertation at Oak Ridge National Laboratory and received his Ph.D. degree in computer science from Louisiana State University in 2003. He was a research fellow at Oak Ridge National Laboratory during 2003–2006 and an associate professor at University of Memphis during 2006–2015. He is currently a professor at New Jersey Institute of Technology. His research interests include big data, parallel and distributed computing, machine learning, high-performance networking, sensor networks, and cyber security.

*Received: February 16, 2020; Accepted: June 23, 2020.*