Routing and Channel Assignment for Multicast in Multi-Channel Multi-Radio Wireless Mesh Networks

Wen-Xiao Shi, Ke-Qiang Cui, and Yuan Chai
College of Communication Engineering, Jilin University, Changchun, 130012, China
Email: swx@jlu.edu.cn; {cuikq14, chaiyuan14}@mails.jlu.edu.cn

Abstract —Channel assignment assigns proper channels for interfaces, which helps dramatically reduce interference and improve network capacity. Routing selects proper paths for packet delivery, which can also help improve network capacity. In order to reduce computational complexity of joint multicast routing and channel assignment, multicast routing and channel assignment are regarded as two separate problems and solved sequentially in this paper. A scheme named Sequential BIP is proposed to obtain optimal solutions to multicast routing and channel assignment. Simulation results demonstrate its effectiveness and show that it can be used as benchmark to evaluate other schemes.

Index Terms—Multicast, routing, channel assignment, binary integer programming

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are multi-hop networks which can extend the coverage of wireless networks, with the advantages of fast deployment, low front cost and so on. They are potential techniques to build the next generation wireless communication systems [1]. Recent research on WMNs mainly focuses on Multi-Radio Multi-Channel (MRMC) WMNs which allow the networks to use multiple channels and equip each node with multiple radio interfaces [2].

Multicasting is a key service in WMNs, which can deliver information to a group of receivers simultaneously [3]. Routing and channel assignment are the most important issues to guarantee efficient multicast communications. Due to the differences between unicast and multicast in packet transmission mode and MAC layer processing manner, schemes proposed for unicast are not suitable for multicast communication. In this paper, we study the multicast routing and channel assignment problem in MRMC WMNs. In order to reduce computational complexity and provide optimal solution, multicast routing and channel assignment are regarded as two problems as most literatures do, and Binary Integer Programming (BIP) is formulated to solve them, respectively. We call this method Sequential BIP. The solution to it can be used as benchmark to evaluate the performance of other heuristic schemes.

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Corresponding author email: swx@jlu.edu.cn.
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The paper is organized as follows. We summarize the related works in Section 2. The BIP formulation for channel assignment and multicast routing is provided in Section 3. Its performance is evaluated by comparing with conventional schemes in Section 4. Finally we conclude our work and point out future research directions in Section 5.

II. RELATED WORKS

In general, multicast routing and channel assignment schemes in MRMC WMNs can roughly be classified into two types, i.e., Joint Multicast Routing and Channel Assignment (JMRCA) and Sequential Multicast Routing and Channel Assignment (SMRCA). JMRCA considers about the interaction between multicast routing and channel assignment and solves them as a whole, while SMRCA regards multicast routing and channel assignment as two problems and solves multicast routing problem first then channel assignment [4]. Due to its low computational complexity, SMRCA is adopted in most literatures published, and heuristic schemes are proposed to achieve near-optimal performance.

In [5], Multi-Channel Multicast (MCM) algorithm was proposed to fully exploit all available channels. The multicast routing process is conducted with the goal of minimizing the number of relay nodes and the hop count distance between multicast source and multicast receivers. The channel assignment process is conducted with the goal of minimizing interference between a node and its relay nodes. However, hidden channel problem may occur and random channel selection may not give the best performance. Minimum interference Multi-channel Multi-radio Multicast (M4) algorithm was proposed on the basis of MCM [6], but its goal is to balance the channel separations between a node and its neighbors instead of minimizing total interference.

Intelligent computational methods such as tabu search, genetic algorithm and stimulated annealing are utilized to solve the multicast routing and channel assignment problem [7]-[9]. They all aim at keeping network interference as small as possible. However, interference still exists among nodes at the same level and some channels are wasted. Also, only Orthogonal Channels (OCs) are utilized and the resulting co-channel interference prevents nodes from parallel transmissions.

BIP formulation was performed for multicast routing and channel assignment in [10] and [11]. The goal is to minimize total number of links and overall interference.

However, Wireless Broadcast Advantage (WBA) is not exploited and only OCs are utilized, which degrades network performance.

From the analysis above, the SMRCA problem has not been properly solved and the optimal solution to multicast routing and channel assignment has not been provided. The optimal solution can be used as benchmark to evaluate the performance of other heuristic schemes, and it is the goal of this paper.

III. Binary Integer Programming Formulation for Multicast Routing and Channel Assignment

$G(V, E)$ is a directed graph which represents MRMC WMNs, where V represents the set of nodes and E is the set of all edges. C is the set of all available channels which can be used by WMNs. Each node is configured with multiple radio interfaces, and these interfaces can be divided into input interfaces and output interfaces. Input interface is used by a node v to receive packets from its parent, and output interface is used to transmit data packets to its children. Corresponding links are called incoming links and outgoing links respectively.

Due to the high computational complexity of solving joint multicast routing and channel assignment problem, we regard multicast routing and channel assignment as two sub-problems and formulate BIP to solve them sequentially, which guarantees the optimal solution for each sub-problem. The output of multicast routing process is regarded as input to the channel assignment process. These two problems are formulated with the goal of minimizing total number of interfaces consumed and minimizing overall interference, respectively. The formulation details are given below.

A. BIP Formulation for Multicast Routing Problem

The variables which will be used in the formulation process of the multicast routing problem are listed in Table I.

The optimal multicast routing problem is formulated with the goal of minimizing total resource consumption, here resource means node interfaces. If WBA can be fully utilized, minimizing total number of node interfaces consumed equals to minimizing total number of transmissions, which can help to save bandwidth. BIP can be formulated with the objective (1) and constraints from (2) to (8).

Objective

$$\text{Minimize } TotalRadio \tag{1}$$

s.t.

$$\sum_{u\in V} l_{uw} \le 1, \quad v \in V \setminus (S, MR) \tag{2}$$

$$\begin{cases} \sum_{uv\in E} l_{uv} \ge l_{vw} \\ \sum_{vw\in E} l_{vw} \ge l_{uv} \end{cases} \quad v \in V \setminus (S, MR), \quad u \in V, w \in V \tag{3}$$

$$\sum_{u\in V} l_{uv} = 0, \quad v \in S \tag{4}$$

$$\sum_{w\in V} l_{vw} \ge 1, \quad v \in S \tag{5}$$

$$\sum_{u\in V} l_{uv} = 1, \quad v \in MR \tag{6}$$

$$l_{uv} + l_{vu} \le 1 \quad uv \in E \tag{7}$$

$$h_v - h_u \ge \beta \times l_{uv} - (1 - l_{uv}) \tag{8}$$

S is the multicast source and MR means the set of multicast receivers; β is a small constant, such as 0.001; h_v is the level of node v, which is defined by the hop count distance from the source. Constraints (2) and (3) are the interface constraints for node except multicast source and multicast receivers, that is, the number of its incoming link should be at most one, and if it has an incoming link, then it definitely has outgoing links, and vice versa. Constraints (4) and (5) ensure that multicast source should have no incoming link and at least one outgoing link. Constraint (6) ensures all multicast receivers should have just one incoming link. Constraint (7) ensures all links on the tree to be unidirectional. Constraint (8) prevents the occurrence of routing loop on the tree.

TABLE I: VARIABLE DEFINITION FOR MULTICAST ROUTING PROCESS

Variable	Definition
l_{uv} $u \in V, v \in V$	a binary variable determines whether link uv is involved in the multicast tree
$Radio_{In}(v)$ and $Radio_{Out}(v)$	two binary variables determine whether the input interface/ output interface of node v is occupied respectively $Radio_{In}(v) = \begin{cases} 1 & if \sum_{u\in V} l_{uv} \ge 1 \\ 0 & else \end{cases}$ $Radio_{Out}(v) = \begin{cases} 1 & if \sum_{w\in V} l_{vw} \ge 1 \\ 0 & else \end{cases}$
$TotalRadio$	A non-negative variable determines total number of interfaces consumed by the multicast tree $TotalRadio = \sum_{v\in V} Radio_{In}(v) + Radio_{Out}(v)$

B. BIP Formulation for Channel Assignment Problem

The variables which will be used in the formulation process of the channel assignment problem are listed in Table II.

For each link in WMNs, at most one channel should be assigned to it.

$$\sum_{c\in C} a_{uv}(c) = l_{uv}, \quad uv \in E \tag{9}$$

Sibling links should be assigned with the same channel to exploit WBA in the channel assignment process.

$$|a_{uv}(c) - a_{uw}(c)| \le 2 - l_{uv} - l_{uw} \tag{10}$$

The objective in Equation (11) together with the above two constraints formulate standard BIP.

Objective

$$\text{Minimize } \textit{TotalInterference} \tag{11}$$

TABLE II: VARIABLE DEFINITION FOR CHANNEL ASSIGNMENT PROCESS

Variable	Definition
$a_{uv}(c)$ $c \in C$, $u \in V$, $v \in V$	a binary variable determines whether channel c is assigned to link uv
$IsInterfer(u, v, c_1, m, n, c_2)$	a binary variable determines whether interference occurs between link uv on channel c_1 and link mn on channel c_2
$InterferLink(u, v, c_1)$ $c_1 \in C$, $u \in V$, $v \in V$	a non-negative variable determines the number of links which interfere with link uv on channel c_1
$InterferLink(u,v,c_1) = a_{uv}(c_1) \times \sum_{c_2 \in C} \sum_{mn \in E \cap m \neq u} (l_{mn} \times a_{mn}(c_2) \times IsInterfer(u,v,c_1,m,n,c_2))$	
$TotalInterference$	a non-negative variable represents overall interference
$TotalInterference = \dfrac{\sum_{u \in V} \sum_{v \in V} \sum_{c_1 \in C} InterferLink(u,v,c_1)}{2}$	

C. Complexity Analysis of BIP Formulation

The computation complexity of BIP is the sum of multicast routing and channel assignment complexity.

For the first part, the worst case is that the multicast receiver has the largest hop count from the gateway and the number of neighbors is V-1. The computation complexity is $O(M \times |V|^L)$, where M is the scale of multicast group, and V is the total number of nodes. L here is the largest hop count to the gateway, which is the largest level of nodes in the network. If the network topology is certain, L is a constant value.

For the second part, because each link can be allocated any channel in set C, the computation complexity is $O(C^N)$, where N is the number of links which need to be allocated channels. In the worst case, all links in the network need to be allocated and the value of N is $|E|$. The total complexity is $O(M \times |V|^L)+O(C^N)=O(C^N)$. Since links composing multicast tree are a part of all links in the network, the real implementation complexity is much lower. At the same time, the same channel should be assigned for sibling links, so the power exponent of the complexity will decrease sharply.

IV. SIMULATION ANALYSIS AND PERFORMANCE EVALUATION

We evaluate Sequential BIP by comparing it with other schemes published in both grid and random WMNs with 30 nodes. Our experiments are carried out using Matlab and network simulator (NS-3.19). We also modify NS to support multi-channel multi-radio and partially overlapped channels. The performance comparisons are conducted according to metrics including network interference, number of interfaces occupied, multicast throughput and average end-to-end delay, and their definitions can be found in [12].

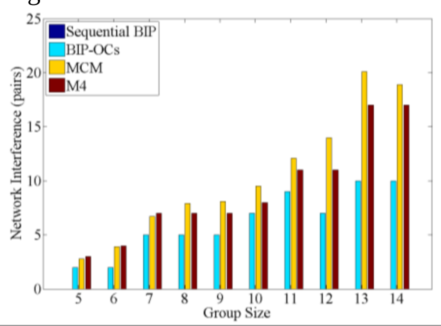
Sequential BIP is compared with MCM, M4 and BIP-OCs. Here BIP-OCs is obtained by substituting all 11 available channels in Sequential BIP with 3 OCs. Performance evaluation of Tabu search [7], Generic algorithm [8], Stimulated annealing [9], Cross-layer BIP [10] and Layered BIP [11] is not provided, as they are non-optimal channel assignment schemes designed for WMNs using OCs. In this paper, we use BIP-OCs to represent the optimal multicast routing and channel assignment result that can be gained by OCs WMNs. No matter in grid topology or random topology, gateway is always located at the center of WMNs. Multicast receivers are randomly chosen from all mesh routers except for the gateway. The gateway sends out data packets with constant bit rate. Each mesh router is equipped with 2 radios, and omni-directional antennas are used to send and receive packets. All 11 channels in IEEE 802.11b are available for channel assignment, and 1Mbps system bandwidth is used for multicast data transmission. The packet sending rate of the multicast source is set to 200packets/s to simulate heavy load, and the multicast group size changes from 5 to 14. The main simulation parameters are shown in Table III. The simulation results are also shown below.

TABLE III: SIMULATION PARAMETERS

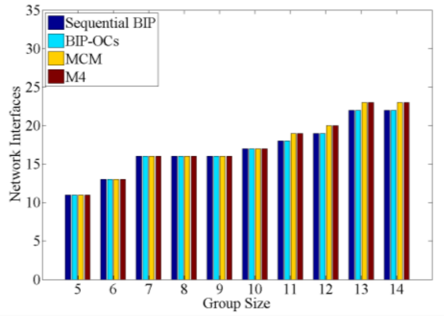
Simulation parameters	Values
Simulation time	30s
Number of channels	11
MAC layer technology	IEEE 802.11b
Data transmission rate	1Mbps
Traffic type	Constant bit rate (UDP)
Packet size	512 Bytes
Transmission range	250m
Interference range	550m
Antenna	Omni-directional

A. Results in Grid WMNs

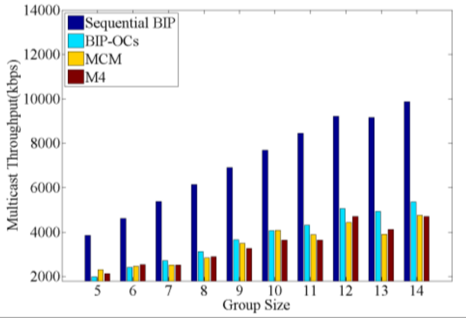
In 5×6 30-node grid topology, each vertex is deployed with a mesh router, and each edge denotes a wireless link. The grid step is set to 250m, which is the distance between adjacent nodes. This means that a node can communicate with its neighbors except the diagonal nodes. We measure the network interference, number of interfaces occupied, multicast throughput and average end-to-end delay of these schemes, and the results are given in Fig. 1.



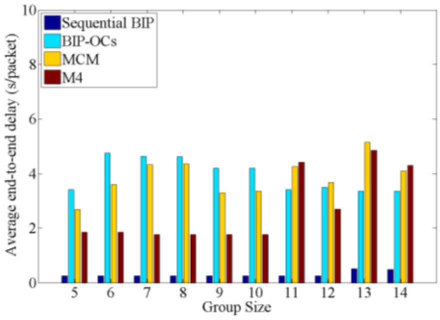
(a)



(b)



(c)



(d)

Fig. 1. Comparison results in 30-node grid WMNs

From Fig. 1 (a) and Fig. 1 (b), we can see that the network interference of Sequential BIP keeps at 0 when multicast group size changes, and it means that Sequential BIP can achieve optimal multicast tree construction and channel assignment. Multicast data transmissions can be performed without interfering with each other. BIP-OCs builds the same multicast tree as Sequential BIP, thus the number of interfaces occupied of BIP-OCs is the same as Sequential BIP no matter how large the multicast group size is. However, the limited number of OCs limits the possibility to assign different channels for adjacent transmissions, therefore the competition for channel access results in network interference. When the multicast group size is not more than 10, MCM and M4 can achieve optimal multicast tree construction, but they occupy more node interfaces when the multicast size is larger than 10. MCM and M4 brings in heavy interference, and the reasons are listed below: MCM only considers about the channel assignment of one-hop neighbors and the resulting hidden channel problem introduces more interference; Random channel selection cannot provide the best performance when several channels all satisfy the minimum interference requirement. M4 aims at minimizing channel separations between a node and its one-hop and two-hop neighbors, but it cannot lead to minimum interference.

From Fig. 1 (c) and Fig. 1 (d), we can obtain the following observations:

1) For Sequential BIP, its multicast throughput proportionally increases as the multicast group enlarges, and the reason is: Sequential BIP can achieve interference-free data transmissions, and all packets can be delivered without loss. Packets do not need to wait in the buffer queue, thus the average end-to-end delay is very small and can be neglected.

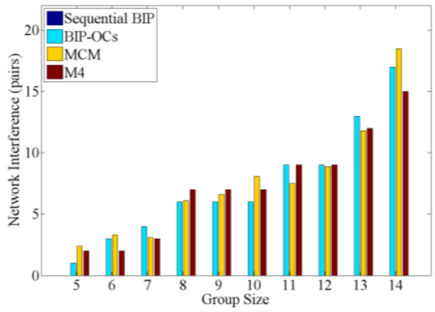
2) M4 can result in higher multicast throughput than MCM in some cases while in other cases not, and the random channel selection of MCM leads to above results.

Their average end-to-end delay increases as multicast group size gets larger.

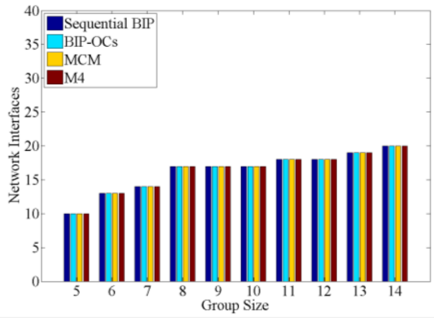
3) The limited number of available channels limits the performance of BIP-OCs. Its multicast throughput is between Sequential BIP and MCM, and packets spend long time to reach destinations, therefore its average end-to-end delay is large.

B. Results in Random WMNs

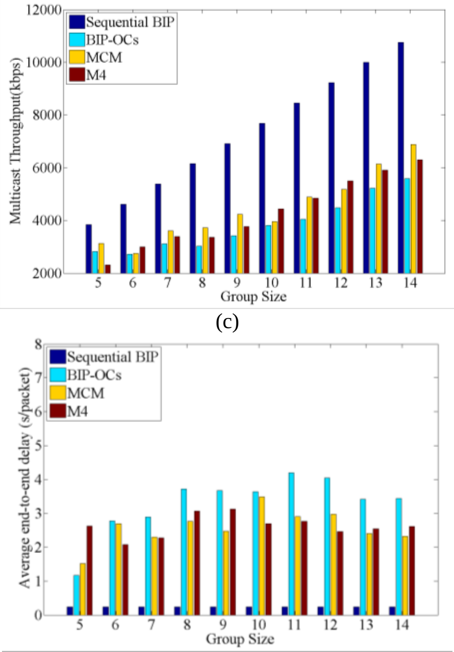
A random WMNs topology is generated using the following method. A square region with the area of 1000m×1000m is specified first which has the width [0, 1000m] on the *x* axis and the height of [0, 1000m] on the *y* axis. Then 30 nodes are generated and the position (*x*, *y*) of each node is randomly specified within the square area. If the distance between two nodes falls into the transmission range, we add a link between them. Finally, we check whether the generated topology is connected or not. If not, the above process repeats until the network connectivity is satisfied. Fig. 2 shows the comparison results in terms of network interference, number of interfaces occupied, multicast throughput and average end-to-end delay.



(a)



(b)



(c)

(d)

Fig. 2. Comparison results in 30-node random WMNs

From Fig. 2 (a) and Fig. 2 (b), we can see all these schemes have the same number of interfaces occupied. Due to the node distribution feature of random topology, the number of available routes between source and multicast receivers is less, thus all schemes deliver packets through the same paths, i.e., they build the same multicast trees. However, their channel assignment is different, which results in different network interference. Sequential BIP can still achieve low-interference data transmission. BIP-OCs, MCM and M4 have similar network interference which gets larger as the multicast group size increases.

As regard to multicast throughput and average end-to-end delay, see Fig. 2 (c) and Fig. 2 (d), these schemes exhibit similar trend as in grid topology, but their performance improves when compared to grid topology except Sequential BIP. They achieve optimal multicast tree construction, and in the channel assignment process, due to the shorter path length between source and multicast receivers, the number of links which need to be assigned with channels gets fewer, therefore channel assignment can find solutions with less interference.

All above simulation results demonstrate that our proposed Sequential BIP can achieve optimal performance and can be used as benchmark to evaluate other schemes.

V. Conclusions

In this paper, we study the multicast routing and channel assignment problem in MRMC WMNs. In order to reduce the computational complexity, multicast routing and channel assignment are processed as two problems. BIP formulation is conducted for these problems and the optimal solutions for both of them are obtained. Simulation results demonstrate the effectiveness of the proposed Sequential BIP, and its solutions can be used to evaluate other schemes.

Channel assignment for multicast is performed under single multicast flow scenario in this paper, where a single multicast tree should be built and only multicast intra-flow interference should be considered. Actually, there are multiple concurrent multicast flows and unicast flows in realistic network environment. As our future work, we will study the multicast routing and channel assignment problem under the coexistence of unicast flows and multiple multicast flows scenario and maximize throughput of the whole WMNs.

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Wenxiao Shi was born in Heilongjiang Province, China, in 1960. He received the B.S. degree in communication engineering from Changchun Institute of Posts and Telecommunications, Changchun, China in 1983, the M.S. degree in electrical engineering from Harbin Institute of Technology, Harbin, China in 1991, and the Ph.D. degree in communication and information systems from Jilin University, Changchun, China in 2006. Since 2000, he has been with the College of Communication Engineering, Jilin University, Changchun, China, where he is currently a Professor. His research interests include radio resource management, access control and load balance of heterogeneous wireless networks, wireless mesh networks, and free space optical communication, etc.

Keqiang Cui was born in Heilongjiang Province, China, in 1990. He received his B.S. degree in Communication Engineering from Jilin University, China in 2014. He is currently a M.S. student in the same university by postgraduate recommendation. He has been devoted to researching on multicast in wireless mesh networks. His current research interests include routing and channel assignment.

Yuan Chai was born in Heilongjiang Province, China, in 1991. She received her B.S. degree in Communication Engineering from Jilin University, China in 2014. She is currently a M.S. student in the same university by postgraduate recommendation. She has been devoted to researching on protocol design for wireless networks. Her current research interests include routing adapted to network state and resource management in wireless mesh networks.