Multicast Routing and Channel Assignment in Wireless Mesh Networks

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Abstract—**This paper studies the problem of multicast routing and channel assignment in multi-channel and multi-interface wireless mesh networks. The advantage of the wireless broadcast's nature is used to reduce interference and improve network throughput. The employed network model is first described. Next, a heuristic channel assignment algorithm that makes use of the wireless broadcast's advantage is presented. Simulation results reveal that the proposed heuristic algorithm can reduce interference and increase the network throughput in multi-channel multi-interface wireless mesh networks.**

Keywords- channel assignment; multi-channel; multi-interface; multicast routing; wireless mesh networks

I. INTRODUCTION

Wireless mesh networks (WMNs) have in recent years provided an alternative technology for last-mile broadband Internet access service. They have attracted much research interest because of their advantage of economical and fast deployment compared to the wired network, and numerous potential applications. A WMN comprises two types of node - mesh routers and mesh clients, as displayed in Fig. 1. Mesh routers are characterized by infrequent movement and everlasting power supply. They communicate with each other through wireless links and form a mesh backbone for the mesh clients. Some of the mesh routers serve as gateways through which nodes within the WMN can get access to the Internet.

One of the problems that need to be solved in WMNs is the limited network capacity due to the interference among links that transmit simultaneously. An effective approach to alleviate the interference is to allow the network to use multiple channels and equip each node with multiple interfaces. With appropriate channel assignment to the interfaces, interference can be greatly reduced.

Channels can be assigned to NICs in a static or dynamic manner. In the static mode [1-3], each NIC is bound to a particular channel, and this binding will last for a long period of time. In the dynamic mode [4], NICs are allowed to switch from one channel to another at a very fast time scale. While most research on channel assignment in WMNs assumed that traffic is sent using unicast transmission [1-4], channel assignment considering multicast transmissions has not been extensively studied [5, 6]. In this paper, we study the problem of multicast routing and channel assignment in multi-channel multi-channel wireless networks.

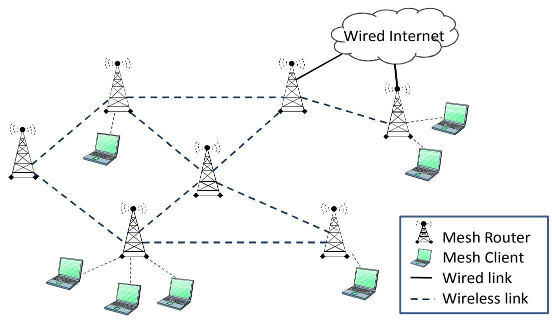

Fig. 1. An example of wireless mesh network that consists of several mesh routers and mesh clients.

Multicast is a communication form that sends data from a source node to a set of destination nodes in a way that uses network resources in an efficient manner. The authors in [7] claimed that the Steiner tree is not generally the minimal-cost multicast tree in WMNs. They proposed a new cost function to compute the minimal-cost multicast tree. The minimal-cost multicast tree is the tree that connects sources and receivers by issuing a minimum number of transmissions, rather than having a minimal edge cost. They also demonstrated that the problem of minimizing the cost of such a multicast tree in a wireless mesh network is NP-complete.

In this paper, we consider using static channel assignment for a set of multicast requests. Wireless broadcast advantage (WBA) [5, 8], which refers to transmissions from a node can be received by the neighbors within its communication range, is an important notion that is useful in multicast scenarios. We propose a heuristic algorithm that take WBA into account for the routing and channel assignment problem.

The rest of this paper is organized as follows. Section II presents our network model. Section III proposes a heuristic algorithm and describes the strategies of the routing phase and the channel assignment phase. Section IV explains the simulation results. The paper concludes in Section V.

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II. Wireless Mesh Network Model

A. Network Model

To simplify the model, the mesh clients in our network model are ignored. The wireless mesh network is represented by a directed graph $G(V, E)$ where V is the set of nodes corresponding to the set of mesh routers and E the set of bidirectional links. We assume that each mesh router is equipped with the same number of NICs. All channels are assumed to be orthogonal, i.e. they do not interfere with each other.

We assume that each NIC has the same transmission range and interference range, denoted by R_T and R_I, respectively. Let $dis(u, v)$ denotes the distance between node u and node v. There is a link connecting node u and node v if and only if $dis(u, v) \leq R_T$. Note that link (u, v) and link (v, u) here refer to the same link between node u and node v. The two end nodes of a link can communicate directly only if they have a common channel assigned to their interfaces.

B. Interference Model

In this sub-section, we first introduce the interference model based on those in [2, 3]. We then show through example on how the model should be modified to fit for multicast scenarios.

Each node is associated with an interference disk centered at the node with radius R_I. The use of interference disk was modeled in [2]. The node interferes with the nodes within the region of its interference disk that is assigned the same channel. For two links (u, v) and (u', v') to be able to transmit simultaneously without interfering each other, $dis(u, u')$, $dis(u, v')$, $dis(v, u')$, and $dis(v, v')$ should all be less than R_I. Usually, $R_I \geq R_T$. In this paper, we assume $R_I = 2 \cdot R_T$.

For each link $(u, v) \in E$, define its interference link set, denoted by $intf(u, v)$, as the set of links that are covered, including those that are partially covered, by the interference disk formed by nodes u and v. Let $intf\_ch(u, v)$ denote the set of links in $intf(u, v)$ that are assigned the same channel as link (u, v). For each link (u, v), the following constraint, call channel capacity constraint, must be satisfied.

$$C - \sum_{(u',v') \in intf\_ch(u,v)} x_{u',v'} \geq 0, \quad (1)$$

where xu,v denotes the aggregated load on link (u, v) and C the raw capacity of each channel.

The model described above is suitable for the unicast scenarios. However, this model cannot be directly used in multicast scenarios. In Fig. 2, assume that all links use the same channel. Two constant bit rate (CBR) multicast traffic are present in the network: request r_1 is sending with rate two from node 1 to node 2 and node 3; request r_2 is sending with rate three from node 7 to node 6 and node 8. The multicast trees for r_1 and r_2 are also shown in the figure. For r_1, the data sent from node 1 can be received simultaneously by node 0 and node 2, and node 0 then forwards the data received from node 1 to node 3. For r_2, the data sent from node 7 can be received simultaneously by node 6 and node 8. Since each transmission, whether received by one or more receivers, interferes with link (4, 5) only once, the total load of the links in the interference link set of link (4, 5) is 2 + 2 + 3 = 7, where the two 2s come from r_1 and the 3 comes from r_2. Therefore, the available capacity for link (4, 5) is max{C - 7, 0}.

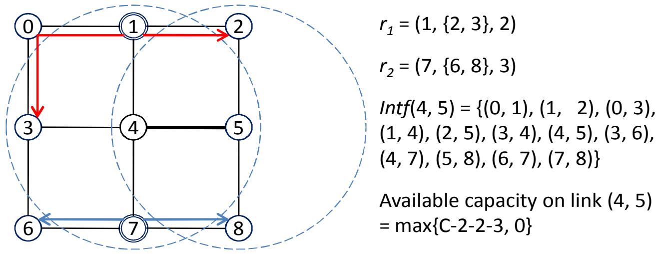


Fig. 2. An example illustrating calculation of residual capacity of a link in multicast scenario.

C. Problem Statement

First, a multicast request is defined. A multicast request r is denoted by $r = (s, \{d_1, d_2, \ldots\}, \rho)$, where s is source node and $\{d_1, d_2, \ldots\}$ is a set of destination nodes that the source s intends to share the same information with at a bit rate ρ. The problem we study is as follows. We are given a WMN $G(V, E)$, transmission and interference range of the NICs, number of NICs each node is equipped with, number of available channels, and a traffic profile which consists of a set of multicast requests that is to be routed on the network. The goal is to determine a static channel assignment to the links so that the maximum number of multicast requests in the given traffic profile can be satisfied. Note that a multicast request is successfully routed if and only if all destinations of the request can receive the data at the rate specified by the request.

III. A Heuristic Algorithm

In this section we propose a heuristic algorithm that consists of three stages. First, the routing problem is solved wherein a multicast tree is found for each multicast request in the given traffic profile. Second, from these multicast trees, we derive estimation of the saving of the link capacity when WBA is utilized in the traffic transmission. The third stage then assigns channels on the links based on the result from the second stage. Details of each stage are described in the following subsections.

A. Construction of Multicast Trees

We use Ruiz's algorithm [7] to yield these multicast trees with a minimum number of transmissions. More specifically, Ruiz's algorithm is individually executed for each multicast request in the give traffic profile. A multicast request thus has a multicast tree which represents the actual routing the traffic will be sent on. For the time being, these multicast trees are used in the next stage to estimate the load on the links of the network. For a multicast request r, the corresponding multicast tree is denoted by $t(r)$.

B. Estimatating Saving of the Link Capacity

To clarify the notation in our presentation, we use arc (u, v) when the direction from u to v is concerned.

In this stage, each link and arc in the network is made associative with a set of values which represent different traffic loads on the link and the arc. Examples are used to illustrate the calculation of these values. We note here that for each value associated to a link, the value is the summation of the corresponding values on its two opposite-direction arcs.

1) Original Load: Original load of a link/arc represents the estimated load on the link/arc, assuming that WBA is not utilized in the transmission, i.e., all transmissions are unicast. Load of a link (u, v) comprises load on arc (u, v) and arc (v, u). Load on arc (u, v) is the sum of the load contributed by all the requests whose multicast tree contains arc (u, v). Fig. 3(a) shows a network of four nodes. Assume that each link in the graph is assigned the same channel. Two multicast requests, r_1 = (A, {B, C}, 300) and r_2 = (B, {A, D}, 200) and their corresponding multicast trees are also shown in the figure. The loads contributed by r_1 on arc (A, C) and arc (A, B) are both 300. The expected load contributed by r_2 on arc (B, A) and arc (B, D) are both 200. Consequently, the load of link (A, B), i.e., the sum of the expected loads on arc (A, B) and arc (B, A) is 300 + 200 = 500.

2) WBA Load: Contrary to the original load, WBA load of a link/arc is calculated assuming that WBA is utilized in transmission. Estimation of link load therefore needs to incorporate such WBA effect. For a multicast request r and a node v in multicast tree $t(r)$, let $A(v, t(r))$ denote the set of arcs in $t(r)$ incident from node v. The load contributed by r on each arc $\in A(v, t(r))$ is calculated by $\rho_r / |A(v, t(r))|$. The formula quantifies the WBA effect shared by the arcs that are involved in the transmission.

The example above is again used and the results are show in Fig. 3(b). For node A, instead of having two transmissions to send identical data to its neighbors, B and C, it now only requires one transmission. For the traffic generated by node A for r_1, the loads of the two arcs, (A, B) and (A, C), are now both transformed from 300 to 300/2=150. For r_2 on node B, the same method is applied and the WBA loads on arc (B, A) and (B, D) are both 100. The WBA load of link (A, B), is therefore 150 + 100 = 250.

3) Saving Load: Saving load of a link/arc is derived by subtracting its WBA load from its original load. Saving load of a link/arc represents the possible saving of the capacity when WBA is utilized in transmission. The same example is again used in Fig. 3(c). Each link's original load, which is derived in Fig. 3(a), minus its WBA load, which is derived in Fig. 3(b), equals its saving load. Consider link (A, B) for example. Its original load and WBA load is 500 and 250, respectively. Therefore, saving load of link (A, B) is 500 - 250 = 250.

C. Channel assignment

In this stage, channels are assigned to the links in order. This stage contains two sub-stages. The first is called node-based channel assignment and the second link-based channel assignment. Note that a valid channel assignment must satisfy the NIC constraint. That is, for each node, the number of channels used by the node must be equal or less than the number of NICs the node is equipped with.

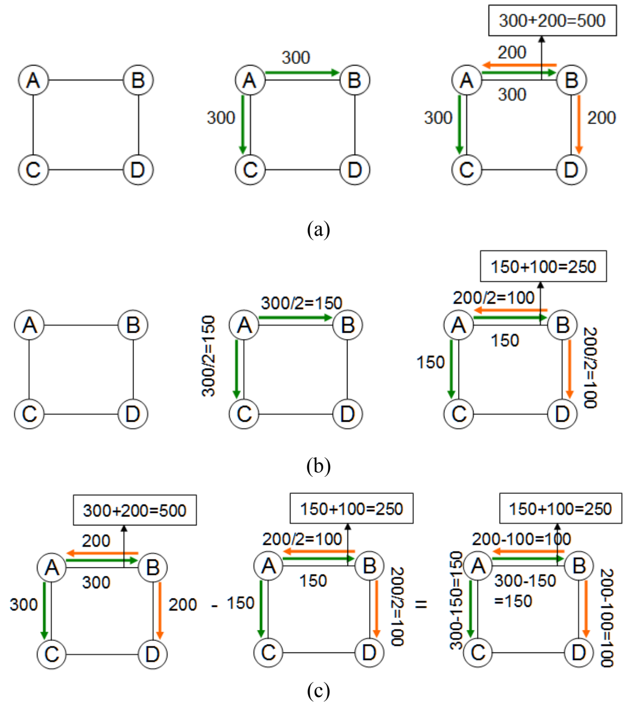


Fig. 3. An example illustrating the calculation of the three types of loads. (a) Original load. (b) WBA load. (c) Saving load.

1) Node-based Channel assignment

Intuitively, links incident on a node which has larger transmission efficiency, i.e., a large amount of traffic is intended to be received by most of its neighbors, may deserve higher priority to be assigned a less interfered channel. This sub-stage is called node-based channel assignment because we need to search for nodes that can utilize WBA efficiently. These nodes are called WBA nodes.

The various load values associated to the links/arcs in Section III.B are utilized to help identifying WBA nodes. A criterion, called saving ratio, of an arc is defined to be the saving load of the arc to the WBA load of the arc. We qualify an arc to be a WBA arc if its saving ratio is greater than a threshold, and a node having more than two WBA arcs incident from it as a WBA node. In this paper, the threshold for expected saving link ration is set to 0.5.

The WBA nodes then go through following procedure. The output of the procedure is the channel assignment to some of the links on the network. Let the set of WBA nodes be S.

Step 1: Select the node that has the most WBA arcs from S. Let this node be node x and remove x from S.

Step 2: Let $A(x)$ be the WBA arcs incident from x. If any *arc* in $A(x)$ has been assigned a channel, then drop node x and go to step 1.

Step 3: Remove the arc in $A(x)$, if any, with the smallest saving ratios until the sum of WBA load in $A(x)$ is less than the capacity of the channel. If the number of x's remaining WBA arcs, $|A(x)|$, do not exceed two, x is discarded and go step 5.

Step 4: Search the least loaded channel within the union of interference link sets of the links in $A(x)$ and assign it to the links in $A(x)$.

Step 5: If $S \neq \emptyset$, go step 1. Otherwise, finish.

2) Link-based Channel assignment

After node-based channel assignment, there remains some links in the network that have not been assigned any channel. Thus, this sub-stage proceeds with a link-based channel assignment.

Let H *be* the set of links that have not been assigned a channel. The number of NICs of a node u that has not been assigned a channel is denoted $anic(u)$. The steps are as follows.

Step 1: Select the link that has the largest WBA load from H. Let this link be l, and the end nodes of this link be node u and node v. Remove l from H.

Step 2:

case 1: $anic(u) > 0$ and $anic(v) > 0$

Both nodes have available NICs that are not bound to any channel. Assign the least load channel to this link and set the NIC correctly.

case 2: $anic(u) = 0$ and $anic(v) = 0$

If there is any common channel on u and v, assign the least loaded channel to link l. Otherwise, the ripple-effect of channel changing occurs, which is dealt with in the next paragraph.

case 3: ($anic(u) > 0$ and $anic(v) = 0$) or ($anic(u) = 0$ and $anic(v) > 0$)

For the former case, assign the least loaded channel from those channels of node v to link l and node u. The latter case is similar to the former case.

Step 3: If $H \neq \emptyset$, go step 1. Otherwise, finish.

Ripple-effect occurs when assigning a channel to a link results in the violation of NIC constraint on either end nodes of the link, which would force the neighboring links to change their channel, and so on. Let CL be the set of channels that is assigned to node u and node v. Let WL be the set of channels that is assigned to WBA nodes described in Section III.C.1. The following procedure aims to reduce interference and protect the channel assignment already conducted in Section III.C.1 from being changed.

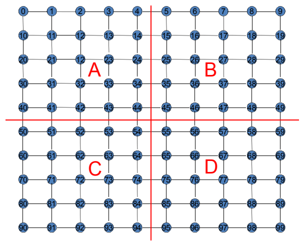


Fig. 4. 10x10 grid network topology with 4 regions

Step 1: Select the least loaded channel from $CL \backslash WL$ if $CL \backslash WL$!= $\emptyset$; Otherwise, select the least loaded channel from CL. Denote this channel w.

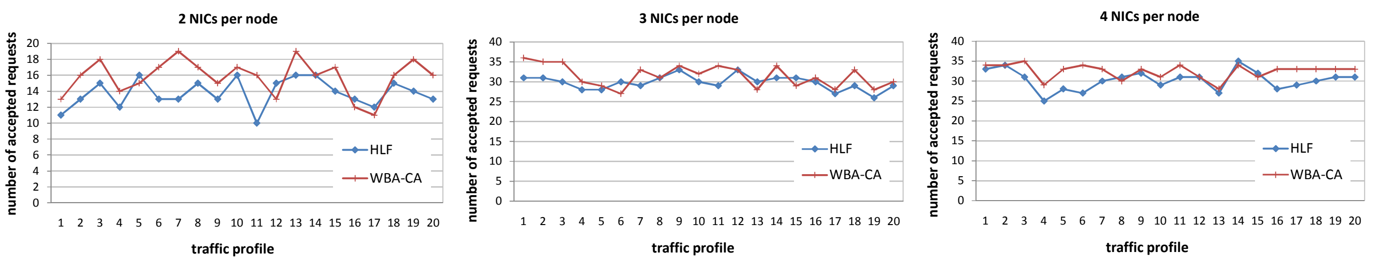
Step 2: If channel w is on node u, then select a channel w' from node v. Do the same thing if channel w is on node v. Assign channel w to link l.

Step 3: Recursively change the channel of the links that are assigned channel w' and connected to the links that have just been changed, to channel w, until no NIC constraint is violated.

IV. SIMULATION RESULTS

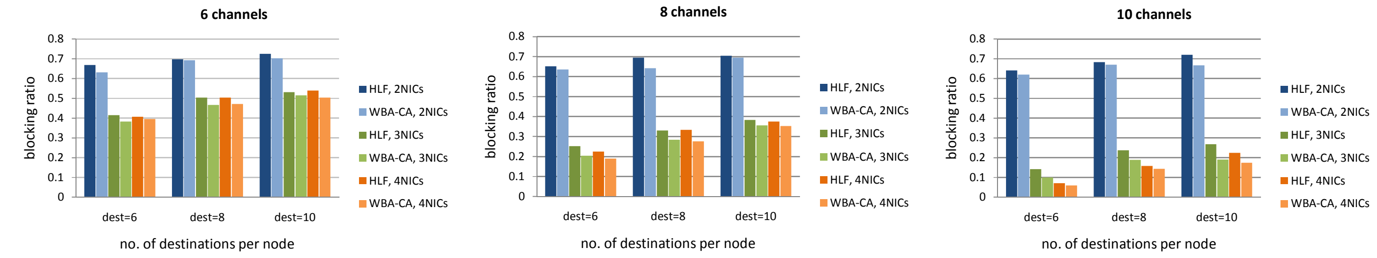
In the simulations, a full 10×10 grid topology with 100 nodes is used, as shown in Fig. 4. The transmission range is set such that each node can communicate with its one-hop away neighbor nodes. The interference range is set such that each node interferes with those nodes that are away from it by two hops. All the channels are assumed to be non-interfering with each other and each link in the network can be assigned only one channel. The capacity of each link is 3590Kbps.

In each simulation scenario, the traffic rate of all multicast requests is 200Kbps and 45 requests will be generated. The source node and the destination nodes of each multicast request are chosen randomly by the following rules. First, the grid topology is divided into four regions as shown in Fig. 4. For each multicast request, the source node is randomly chosen from region A or region B. If the source node is in region A, the corresponding destination nodes will be located in region C. Similarly, the destination nodes will be located in region D if the corresponding source node is located in region B. By generating traffic in this way, it can be expected that local heavy congestion is more likely to be in regions C and D. For each simulation run, the number of destination nodes in each multicast request is the same. Six, eight, and ten destination nodes will be tested to simulate different congestion levels.



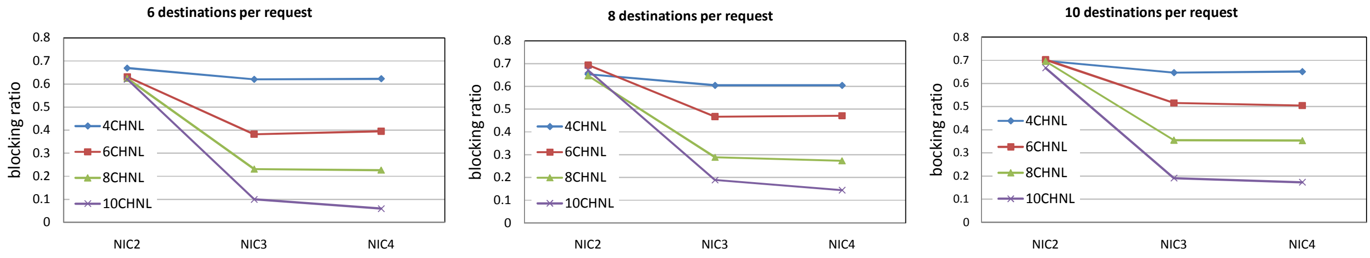
(a) (b) (c)

Fig. 5. Number of accepted requests in the network that has 8 channels and each multicast request contains 8 destinations. Different numbers of NICs per node are tested. (a) 2 NICs per node. (b) 3 NICs per node. (c) 4 NICs per node.



(a) (b) (c)

Fig 6. Comparison of WBA-CA and HLF in the network with different number of available channels. (a) 6 channels. (b) 8 channels. (c) 10 channels.



(a) (b) (c)

Fig. 7. Blocking ratio under various network scenario using WBA-CA. (a) 6 destinations per node. (b) 8 destinations per node. (c) 10 destinations per node.

For comparison, a heavy-load-first channel assignment algorithm is implemented which simply assigns channels to the links in decreasing order of their original link load. We denote this algorithm, which does not utilize WBA, HLF and the algorithm proposed in section III, which utilize WBA, is denoted WBA-CA (WBA channel assignment).

Figure 5 compares the number of requests accepted using the two algorithms. Number of channels is fixed at eight. The number of NICs per node is set to two, three, and four in Fig. 5(a), (b) and (c), respectively. Each scenario is executed 20 times. Generally, WBA-CA has greater traffic throughput than HLF. It can also be observed that the network configuration with larger number of NICs per node performs better than those with less number of NICs per node. In the figure, some traffic profiles shows that the proposed algorithm underperforms HLF. This is caused by the ripple-effect of channel changing, which destroys the channel assignment of the WBA nodes and increases the number of links that uses the same channel.

Figure 6 compares the average blocking ratio of WBA-CA with HLF. The X-axis represents the number of destinations per request. It reveals that the WBA-CA has a lower blocking ratio in all cases than that HLF. Finally, as the number of destinations per request increases, the blocking ratio also increases.

Figure 7 presents the effect of different number of NICs per node and different number of channels available to the network. A huge performance gain is obtained when the number of NICs per node increases from two to three. However, there is only a slight performance improvement as the number of NICs per node increases from three to four. It also reveals that a larger number of available channels improve performance.

V. CONCLUSIONS

This work studies the problem of multicast routing and channel assignment using wireless broadcast advantage in multi-channel and multi-interface wireless mesh networks. A heuristic algorithm that assigns channels to links and nodes according to three load graphs is developed. The three load graphs are obtained from the Ruiz's minimum number of transmissions multicast tree of each multicast request. They help to identify the WBA nodes and detect interference between links, increasing the effect of the wireless broadcast advantage and reducing the interference.

The simulation results reveal that the proposed algorithm exhibits performance improvements over the heavy-load-first channel assignment approach. Simulations indicate that the number of NICs affects the available bandwidth of a wireless mesh network, and the heuristic algorithm exhibits a huge performance gain if the number of NICs is increased from two to three but only a slight performance gain if the number of NICs is increased from three to four. The simulations also reveal that a larger number of channels available for a wireless mesh network correspond to better performance gain of the proposed heuristic.

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