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Bandwidth-Guaranteed Multicast in Multi-Channel Multi-Interface Wireless Mesh Networks

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***Abstract* – We consider multi-channel multi-interface wireless mesh networks with a schedule-based MAC protocol, where conflict-free transmission is ensured by requiring links assigned with the same channel and within the mutual interference range of each other to be active at different time slots. When a (point-to-multipoint) multicast call arrives, the call is accepted if a multicast distribution tree can be established for connecting the source node with all the receiving nodes, and with sufficient bandwidth reserved on each link. Otherwise, the call is rejected. To maximize the call acceptance rate, the multicast tree must be constructed judiciously upon each call arrival. Aiming at minimizing the carried load on the most-heavily loaded channel, and maximizing the residual capacity of the most heavily loaded node, an integer linear program (ILP) is formulated for multicast tree construction. Since solving ILP can be time-consuming, an efficient heuristic algorithm is then proposed. We compare the two tree construction algorithms by simulations. We found that both algorithms give comparable call acceptance rate, but the heuristic algorithm requires much shorter running time.**

***Keywords* –** multiple channels, multiple interfaces, wireless mesh network, multicast, broadcast.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) have emerged as a practical solution for the wireless extension of the broadband Internet. A WMN consists of stationary wireless mesh routers, which are connected to one another in a multi-hop manner to form a wireless backbone. End user mobile devices can connect to the wireless backbone via some mesh routers within their transmission range. With the increasing computational power of mobile devices in recent years, many multicast applications (e.g. video streaming) for wired networks are adopted by wireless networks [1], where efficient multicast algorithm is urgently needed to regulate the increased multicast traffic in the wireless backbone.

The broadcasting nature of wireless transmissions allows all neighbors to receive the same copy of data with the source node only transmitting once. This is known as wireless broadcast advantage [2]. On the other hand, the interference induced by a transmission can suppress the transmissions on other wireless links within its interference range, which severely limits the capacity of a wireless network. To improve the network capacity, mesh routers of WMNs can be equipped with multiple network interface cards (NICs) to allow parallel transmissions over multiple orthogonal channels [3-6]. This provides a new dimension to network resources management, and also makes the multicast routing in WMNs more challenging.

Many multicast protocols [7-15] have been proposed while focusing on a single multicast session in a wireless network. They differ in their design objectives. In [7, 8], the objective is to minimize the energy consumption of mobile ad hoc networks so as to maximize the network lifetime. For WMNs, mesh routers are usually installed at fixed locations with abundant AC power supply. In [9, 10], algorithms for finding multiple nearly-disjoint multicast trees for delivering the multiple descriptions of a video stream have been proposed. In [11, 12], the objective is to establish a single multicast tree with maximum throughput for a multicast session. A multicast tree with minimum number of transmissions was studied in [13]. In [14], low-latency multicast was achieved by using multiple transmission rates. Fairness of resource sharing was investigated in [15], and reliability was studied in [16-18].

In this paper, we consider dynamic multicast call arrivals, where each call is characterized by a pre-determined multicast group membership and a specific bandwidth requirement. We envision that multicast video streaming will be a killer application for WMNs. In order to ensure video quality, each streaming session should be provisioned with sufficient network bandwidth. We assume that each multicast streaming call arrives in real-time, and is associated with a source node (where the streaming server locates), a set of receiving nodes (where subscribers are attached to), and a specific bandwidth requirement. A call is accepted if a multicast distribution tree can be established for connecting the source node with all the receiving nodes, and with sufficient bandwidth reserved on each link. In order to maximize the call acceptance rate, the multicast tree must be judicially constructed upon each call arrival. In this paper, aiming at minimizing the carried load on both the most-heavily loaded channel and the most-heavily loaded node, an integer linear program (ILP) is first formulated for multicast tree construction. Since solving ILP can be time-consuming, an efficient heuristic algorithm is then proposed. The two tree construction algorithms are compared by simulations. We found that both algorithms give comparable call acceptance rate, but the heuristic algorithm requires much shorter running time.

To the best of our knowledge, the most related work is that in [19]. While establishing a multicast tree with bandwidth requirement, the proposed algorithm tries to maximize the remaining channel bandwidth for future calls by exploiting the link-rate diversity. But such an algorithm can only be applied to WMNs with a single-shared channel. In [6], we investigated the minimum-channel-utilization broadcast tree problem. In this paper, our focus is on the more general multicast scenario.

II. ILP FORMULATION OF MULTICAST TREE CONSTRUCTION

We assume a schedule-based MAC protocol, where the whole system works under a synchronized frame structure and conflict-free transmission is ensured by requiring links assigned with the same channel and within the mutual interference range to be active at different time slots. We model the WMN by a connectivity graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$, where $\boldsymbol{V}$ and $\boldsymbol{E}$ represent the set of static mesh routers/nodes and the set of unidirectional logical links, respectively. There is a logical (directed) link $(u, v) \in \boldsymbol{E}$ if u and v are within the transmission range of each other. We assume symmetric connectivity, such that link $(u, v) \in \boldsymbol{E}$ if and only if $(v, u) \in \boldsymbol{E}$. Each node $u \in \boldsymbol{V}$ is equipped with t_u half-duplex NICs, each of them can switch among orthogonal channels in the channel set $\boldsymbol{C}$. To capture the effect of interference, the *receiver conflict avoidance* interference model [20] is adopted, which only requires the receiver to be clear for receiving. The set of nodes within the interference range of node v is represented by $\boldsymbol{I_v}$.

Without loss of generality, we consider a WMN with some on-going calls in the network. Each call is characterized by a source node A, a set of receivers $\boldsymbol{R}$, and a specific bandwidth requirement F_T. We denote the bandwidth requirement as well as the loading in the network by time fractions. The time fraction of node u sending on link (u, v) using channel k is Y_{uv}^k. The total time fraction of node u sending on link (u, v) is $Y_{uv} = \sum_{k\in \boldsymbol{C}} Y_{uv}^k$. The total time fraction of node u sending on channel k is $B_u^k = \sum_{v\in \boldsymbol{V}} Y_{uv}^k$. If $m \in \boldsymbol{I_v}$, then the interference caused by node m as observed by node v on channel k is $n_{mv}^k = B_m^k$. If $m \notin \boldsymbol{I_v}$, $n_{mv}^k = 0$. Then the total interference as observed by node v on channel k (including node v) is $\sum_{m\in \boldsymbol{I_v}} n_{mv}^k$. We call it channel k utilization as observed by node v.

When a multicast call arrives, it is accepted if a multicast distribution tree can be established without re-routing the existing calls, and with sufficient bandwidth F_T reserved on each tree link. As call splitting over multiple channels is allowed, the time fraction to be reserved for the new call on a tree link (u, v) using channel k is f_{uv}^k, and the total time fraction reserved on link (u, v) is $\sum_{k\in \boldsymbol{C}} f_{uv}^k = F_T$. To maximize the call acceptance rate, multicast tree should be constructed with load balancing in mind because this will leave the maximum flexibility for accepting future calls.

To measure the load balancing performance, we define x as the maximum channel utilization in the network, and y as the minimum residual NIC capacity. They are given by

$$x = \max_{\forall v\in \boldsymbol{V}, \forall k\in \boldsymbol{C}} \left\{ \sum_{m\in \boldsymbol{I_v}} n_{mv}^k \right\} \quad \text{and} \tag{1}$$

$$y = \min_{\forall v\in \boldsymbol{V}, \forall (v,w)\in \boldsymbol{E}} \left\{ t_v - \sum_{k\in \boldsymbol{C}} \sum_{(u,v)\in \boldsymbol{E}} \left(f_{uv}^k + Y_{uv}^k \right) - \sum_{k\in \boldsymbol{C}} \left(f_{vw}^k + B_v^k \right) \right\}. \tag{2}$$

Table I. Definition of variables

t_v	number of NICs at node v
r_u	equals to 1 if node u is a root, 0 otherwise
e_{uv}	equals to 1 if link (u, v) is on tree, 0 otherwise
s_u	voltage value assigned to node u (for loop prevention)
f_{uv}^k	time fraction assigned to link (u, v) for carrying the new call on channel k
n_{mv}^k	interference caused by node m as observed by node v on channel k
Y_{uv}^k	existing total time fraction for link (u, v) to be active on channel k
B_u^k	existing total time fraction for node u to transmit on channel k
F_T	bandwidth required (in time fraction) by the new call
A	denotes the root/source of the new multicast tree
α	a small constant (e.g. 0.0001)

From (1), the maximum channel utilization x is the utilization of the most congested channel in the network as observed by some node. By having x minimized, the loading on different *channels* (as perceived by different nodes) will be better balanced. On the other hand, channels can have spare room for a new call but a node may not have sufficient NIC capacity to carry the call. To this end, we also want to maximize y, the minimum residual NIC capacity at a node. In (2), t_v is the number of NICs at node v, and the first and second summation terms on the right hand side represent node v's total ingress and egress load, respectively.

We thus propose to denote the cost of constructing a multicast tree by $(x - \beta y)$, where β denotes the relative importance of x and y, and its value can be obtained empirically. To find the best multicast tree for accommodating a new call, we would like to find a multicast tree that can minimize the cost $(x - \beta y)$. Note that $(x - \beta y)$ can be negative. The above multicast tree construction problem can be solved by the following ILP, where the notations involved are summarized in Table I.

Objective:

$$\text{minimize } \{x - \beta y\} \tag{3}$$

Subject to

$$\sum_{u\in \boldsymbol{V}} r_u = 1 \tag{4}$$

$$r_A = 1, \qquad A \in \boldsymbol{V} \tag{5}$$

$$\sum_{(u,v)\in \boldsymbol{E}} e_{uv} = 1, \qquad \forall v \in \boldsymbol{R} \tag{6}$$

$$\sum_{(u,v)\in \boldsymbol{E}} e_{uv} \le 1 - r_v, \qquad \forall v \in \boldsymbol{V} \setminus \boldsymbol{R} \tag{7}$$

$$\sum_{(u,v)\in \boldsymbol{E}} e_{uv} \ge e_{vw} - r_v, \qquad \forall (v,w) \in \boldsymbol{E}, v \in \boldsymbol{V} \setminus \boldsymbol{R} \tag{8}$$

$$\sum_{w\in \boldsymbol{V}} e_{vw} \ge e_{uv}, \qquad \forall (u,v) \in \boldsymbol{E}, v \in \boldsymbol{V} \setminus \boldsymbol{R} \tag{9}$$

$$e_{uv} + e_{vu} \le 1, \qquad \forall (u,v) \in \boldsymbol{E} \tag{10}$$

$$s_v - s_u \ge \alpha e_{uv} - (1 - e_{uv}), \qquad \forall (u,v) \in \boldsymbol{E} \tag{11}$$

$$f_{uv}^k \le e_{uv}, \qquad \forall (u,v) \in \boldsymbol{E}, \forall k \in \boldsymbol{C} \tag{12}$$

$$\sum_{k\in \boldsymbol{C}} f_{uv}^k \ge e_{uv} \cdot F_T, \qquad \forall (u,v) \in \boldsymbol{E} \tag{13}$$

$$f_{uv}^k - f_{uw}^k \le 2 - e_{uv} - e_{uw}, \quad \forall (u,v),(u,w) \in \boldsymbol{E}, \forall k \in \boldsymbol{C} \tag{14}$$

$$\sum_{k\in \boldsymbol{C}} \sum_{(u,v)\in \boldsymbol{E}} \left(f_{uv}^k + Y_{uv}^k \right) + \sum_{k\in \boldsymbol{C}} \left(f_{vw}^k + B_v^k \right) \le t_v, \forall v \in \boldsymbol{V}, \forall (v,w) \in \boldsymbol{E} \tag{15}$$

$$n_{mv}^k \ge f_{mn}^k + B_m^k, \quad \forall v \in \boldsymbol{V}, \forall m \in \boldsymbol{I}_v, \ \forall k \in \boldsymbol{C}, \ (m,n) \in \boldsymbol{E} \tag{16}$$

$$f_{uv}^k + B_u^k + \sum_{m\in \boldsymbol{I}_v, m\ne u} n_{mv}^k \le 1, \qquad \forall (u,v) \in \boldsymbol{E}, \forall k \in \boldsymbol{C} \tag{17}$$

$$x \ge \sum_{m\in \boldsymbol{I}_v} n_{mv}^k, \qquad \forall v \in \boldsymbol{V}, \forall k \in \boldsymbol{C} \tag{18}$$

$$y \le t_v - \sum_{k\in \boldsymbol{C}} \sum_{(u,v)\in \boldsymbol{E}} \left(f_{uv}^k + Y_{uv}^k \right) - \sum_{k\in \boldsymbol{C}} \left(f_{vw}^k + B_v^k \right), \forall v \in \boldsymbol{V}, \forall (v,w) \in \boldsymbol{E} \tag{19}$$

Constraints (4)-(11) restrict the routing decision to a tree topology. In particular, (4) and (5) specify that there is only one root at source node A. Constraint (6) ensures that there is one ingress link to each receiver of the multicast group. Constraint (7) specifies that an ingress link for non-member nodes (i.e.

neither root nor receiver) is not necessary. However, as required by (8), if there is an outgoing link from any non-member node, then there must be an ingress link to it. Similarly in (9), a non-member node without an outgoing link should not have an ingress link. Constraint (10) limits the tree links to be unidirectional, and (11) prevents the formation of routing loop.

Then channels and transmissions are assigned using time fractions according to constraints (12)-(17). By (12) and (13), time fractions are assigned to the tree links only, and are bounded by the bandwidth requirement F_T. The property of wireless broadcast advantage (WBA) is enforced by (14), where all neighbors receive the same data with the source transmitting once. Oversubscription of NICs is prevented by (15), and the interference generated by node *m* on channel *k* as observed by node *v* is defined by (16). Due to WBA, transmissions on all outgoing links of a node are treated as a single transmission. By (17), the total assigned time fractions within the interference region should not be greater than 1, which is also a necessary and sufficient condition for the time fractions to be schedulable [5].

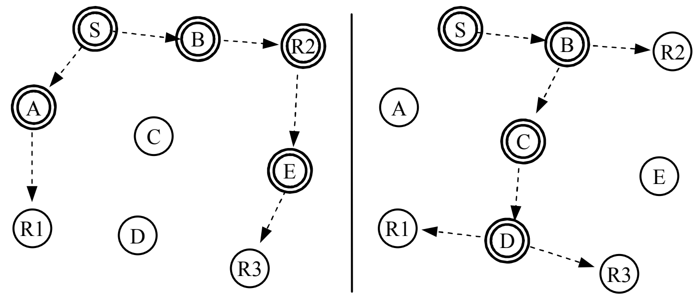
When a multicast call arrives, the above ILP is solved. If a solution is found, a feasible transmission schedule always exists and can be found using graph-coloring algorithms [5]. In this paper, a perfect scheduler for finding the transmission schedule is assumed.

III. Efficient Heuristic Algorithm for Multicast Tree Construction

Solving the ILP-based algorithm can be too slow for real-time call admission. A heuristic algorithm, called largest coverage shortest-path first, is designed in this section. Consider the example in Fig. 1. When a multicast call arrives at node S (then S becomes the source/root) with receivers R1, R2, R3 and a bandwidth requirement F_T, a simple screening test is performed to determine if any multicast group member(s) will be oversubscribed. If yes, the call is rejected right away. Otherwise, a multicast tree rooted at S is to be built.

We know that minimizing channel utilization facilitates load balancing. Intuitively, channel utilization can be minimized if the number of sending nodes in a multicast tree is minimized. To minimize the number of sending nodes, a simple way is to construct a shortest-path tree, by iteratively adding the receiver with the next shortest-path to the tree. Refer to Fig. 1(a). To construct a shortest-path tree rooted at S, R1 is added via the 2-hop shortest-path S-A-R1. Then R2 is added via S-B-R2. Finally, R3 is added to R2 via R2-E-R3. The resulting multicast tree requires five sending nodes. It is, however, not as efficient as the tree shown in Fig. 1(b), which only requires four sending nodes. The tree in Fig. 1(b) is constructed based on the concept of *largest coverage shortest-path first* and is detailed below.

Let $\boldsymbol{Z}$ be the set of on-tree nodes. At the beginning of multicast tree construction, $\boldsymbol{Z}$ only consists of the root S. An on-tree node that sends packet to other on-tree nodes is a sending node. In Fig. 1(a), node R3 is an on-tree node but not a sending node. Unlike the shortest-path tree construction, we propose to add the largest coverage shortest-path first. For a given path, its coverage is defined as the number of not-yet-on-tree receivers that can be covered by the transmission of some nodes along the path.



(a) Shortest-path tree (b) Largest coverage shortest-path tree

Fig. 1. Tree construction strategy (A double-circle indicates a sending node.)

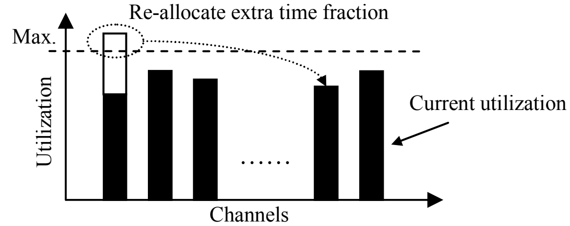


Fig. 2. Transmission assignment strategy

To find the largest coverage shortest-path, we first count the number of not-yet-on-tree receivers that are covered by any non-sending node *v*, denoted by *N*(*v*). (Note that if a receiver is covered by a sending node, this receiver is already on-tree.) In Fig. 1(b), *N*(S)=0, *N*(A)=1, *N*(B)=1, *N*(C)=0, *N*(D)=2, *N*(E)=2, *N*(R1)=0, *N*(R2)=0 and *N*(R3)=0. Then nodes with the largest *N*(*v*), i.e. D and E in this case, become the candidate nodes.

For each candidate node, we find all the possible shortest-paths from the current tree (i.e. nodes in $\boldsymbol{Z}$) to it. In Fig. 1(b), there are three shortest-paths to node D: P1=S-A-R1-D, P2=S-A-C-D and P3=S-B-C-D. Among them, the most efficient path is identified as the one that covers the most not-yet-on-tree receivers. From Fig. 1(b), *N*(P1)=2, *N*(P2)=2 and *N*(P3)=3. Therefore, S-B-C-D is the most efficient path to D. Similarly, the most efficient path to E is S-A-C-E.

When the set of candidate paths (i.e. S-B-C-D and S-A-C-E) are identified, we tentatively assign transmission to each of them to observe the cost involved. Transmissions are assigned to the nodes along a path sequentially (downstream). In order to minimize channel utilization (as well as channel switching overhead), we add the requested load (F_T) to the least utilized channel first. If the selected channel does not have enough capacity, then the outstanding demand will be allocated to the second least utilized channel as shown in Fig. 2. When assigning a time fraction to a node, it should not violate (15) and (17). If the candidate path involves some sending node(s) (of the current request), no further transmission assignment to it is required as it has already been assigned.

The cost of assigning a candidate path is measured by the resulting $(x - \beta y)$ value, as that in (3). As we have argued in Section II, $(x - \beta y)$ is a good measure of load balancing performance. Among all the candidate paths, the one with the least *cost* will be added to the tree. Suppose the path S-B-C-D yields a smaller cost, then the nodes along the path (B, C, D) are put into $\boldsymbol{Z}$, and nodes (S, B, C, D) become sending nodes. The covered receivers (R1, R2, R3) are also put into $\boldsymbol{Z}$. The algorithm repeats until all receivers are covered.

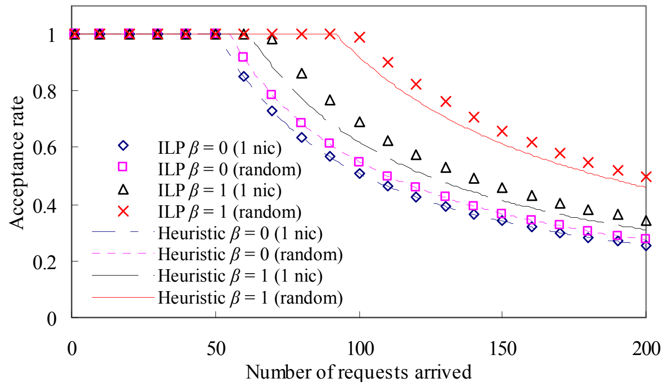


Fig. 3. Impact of residual NIC capacity.

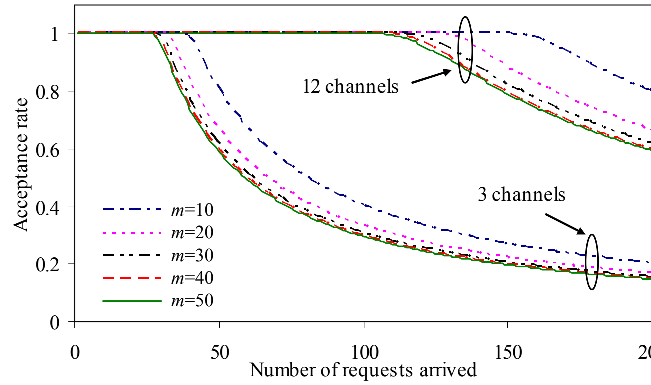


Fig. 5. Multicast in dense 50-node random network with 3 NICs/node

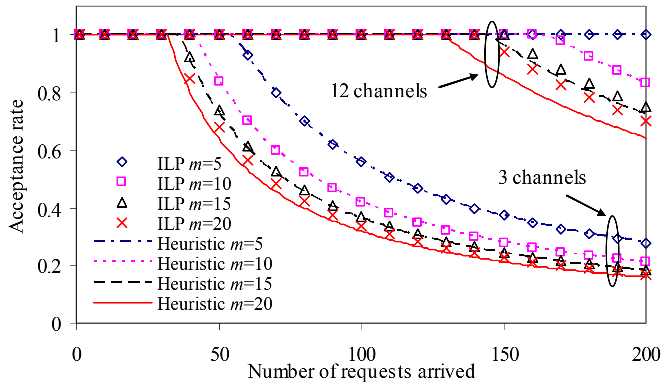


Fig. 4. Multicast in 4x5 gird network with 3 NICs/node

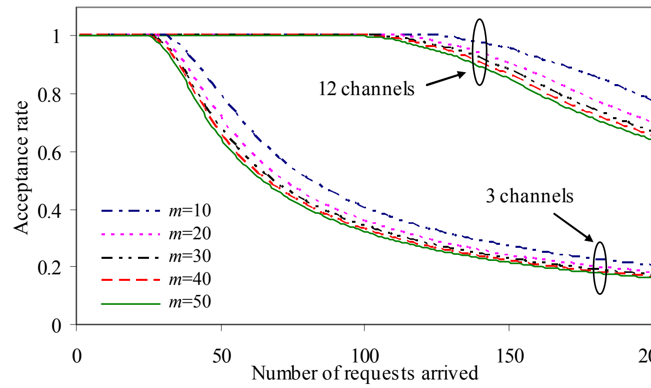


Fig. 6. Multicast in sparse 50-node random network with 3 NICs/node

IV. PERFORMANCE EVALUATIONS

We study and compare the performance of the ILP-based tree construction algorithm and the heuristic algorithm by simulations in this section. The ILP is solved by CPLEX. Two types of network topologies are simulated, grid and random. The wireless transmission range and interference range are set to 250m and 500m, respectively. The number of orthogonal channels and number of NICs per node vary. Two hundred multicast calls for each multicast group size are randomly generated, each with a bandwidth requirement of 0.01 (in terms of time fraction). Each data point in Figs. 3-6 is obtained by averaging over 20 independent samples.

We first consider a 4x5 grid network with grid length set to 200m. Fig. 3 shows the call acceptance rate of using the two proposed tree construction algorithms under broadcast call arrivals. There are 12 orthogonal channels, and each node is randomly equipped with 1 to 5 NICs. For comparison, a grid network with 1 NIC/node is also simulated. From Fig. 3, there are two important observations. First, it is important to jointly consider both channel utilization and residual NIC capacity in tree construction. With 1-NIC/node, up to 100 calls can be accepted with β in (3) set to 1 (i.e. both channel utilization and NIC utilization are considered), whereas only 50 calls can be accepted with $\beta = 0$ (i.e. only channel utilization is considered). This is because without considering the residual NIC capacity, a heavily loaded node will still be selected as a forwarding node. Once the NIC capacity of a node is fully occupied, no more call can be accepted. Second, the performance of the proposed heuristic tree construction algorithm is comparable to the ILP algorithm, especially when $\beta = 0$. The improvement of using $\beta = 1$ in the heuristic algorithm is less than that in the ILP. This is because the *path-based* selection provides less flexibility in selecting individual node with more residual NIC capacity. Note that we have studied the performance of using different values of β. We found that $\beta = 1$ gives good performance in most cases. In the following simulations, we only consider $\beta = 1$.

For the same 4x5 grid network, Fig. 4 shows the performance of multicast calls with different multicast group sizes (denoted by m). We set the number of NICs/node to 3 and vary the number of orthogonal channels from 3 to 12. As expected, more calls can be accepted by having more channels in the network and with smaller multicast group size. With 12 channels, all 200 multicast calls with group size m=5 can be accepted. Again, we can see that the heuristic algorithm provides a comparable performance as that of the ILP algorithm.

Figs. 5 and 6 show the performance of heuristic tree construction algorithm in both dense and sparse random networks. Since it takes too long to solve the ILP with these settings, ILP results are not presented. In a dense random network, 50 nodes are randomly placed within an area of 1000x1000m^2, whereas an area of 2000x2000m^2 is used for a sparse random network. From the figures, we can see that dense networks enable a higher call acceptance rate than the sparse networks. This is because in dense networks, more nodes can be covered by a transmission, and thus fewer transmissions are required to reach all the group members. In contrast, transmission in a sparse network tends to be less efficient as it covers fewer nodes. Besides, the number of shortest-paths between a node pair is also much smaller in a sparse network. As a result, multiple calls may pass through the same (or part of) shortest-path, depleting the network resources at the bottleneck link very quickly.

Another observation is that the performance gap between dense networks and sparse networks is reduced as the multicast group size increases. This is because larger group size tends to spread out the multicast traffic more evenly over the network. This implies a larger flexibility on selecting nodes with more residual NIC capacity to be the forwarding nodes.

It should be noted that although the transmission assignment strategy in our multicast heuristic algorithm allows traffic splitting over different channels, splitting does not happen in all the above simulations. This is because the bandwidth request of each call is set to 0.01 time fraction, this amount is small enough to fill in all capacity of a channel. In contrast, the algorithm in [6] splits every transmission (even as small as 0.01) over the channels. The induced channel switching overhead can be very high.

VI. Conclusion

In this paper, we have studied the bandwidth-guaranteed multicast routing for multi-channel multi-interface wireless mesh networks. To maximize the call acceptance rate, two multicast tree construction algorithms have been designed for call admission. They have the same objective of minimizing the carried load on both the most-heavily loaded channel and the most-heavily loaded node. Intuitively, this leaves more rooms for accepting future calls and thus the call acceptance rate can be maximized. Specifically, the first algorithm is based on ILP and the second one is an efficient heuristic. We found that both algorithms yield comparable call acceptance rate, but the heuristic algorithm has a much shorter running time than the ILP-based algorithm.

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