Joint Topology Control and Routing Assignment for Wireless Mesh with Directional Antennas

Wangkit Wong   Xun Chen   Fei Long   S.-H. Gary Chan
Department of Computer Science and Engineering
The Hong Kong University of Science and Technology
Hong Kong, China
Email: {wwongaa,chenxun,feilong,gchan}@cse.ust.hk

***Abstract*—Using directional antennas in wireless mesh networks (termed DMesh in this paper) is attractive due to its longer coverage range and spatial separation between transmissions of the same channel. However, the connectivity in a DMesh is much lower than its omni-directional counterpart. This makes topology control (through beaming) a critical problem in DMesh. Because topology control coupled with routing decision, their joint optimization is critical to achieve the best performance. In this paper, we consider a multimedia DMesh with a certain traffic demand at each mesh router. We first formulate the joint topology control and routing assignment as an optimization problem and show that it is NP-hard. To address the problem, we propose a novel and efficient heuristic called TORA (Joint Topology Control and Routing Assignment), an ant-colony optimization algorithm which seeks to jointly optimize topology and routing for DMesh. Simulation results based on NS3 show that TORA performs substantially better in terms of loss rate, delay and throughput as compared with a recent scheme.**

I. Introduction

A wireless mesh network (WMN) is a multi-hop communication network made up of connected mesh routers providing Internet connectivity to end users. WMN has the advantages of low cost, ease of deployment and high reliability, and hence can be deployed to provide broadband access where wired infrastructure is difficult or economically infeasible to deploy [1], [2]. One of the key factors that affect the performance of WMNs is transmission interference. In traditional mesh using omni-directional antennas (termed omni-Mesh in this paper), links of the same channel within each other's power range interfere with each other. Due to the limited number of available non-overlapping channels (IEEE 802.11b only offers 3 non-overlapping channels [1]), reducing interference in an omni-Mesh is a challenging problem.

It has been well-known that directional antennas can reduce the interference of the network because they focus energy in only the intended direction [2]. They also enjoy longer transmission range, leading to shorter hops in the network. Because of better spatial separation of channels and longer communication range, applying directional antenna in WMN has aroused much interest recently. Recent studies have shown that wireless mesh designed with directional antennas, termed DMesh in this paper, can improve capacity significantly as compared with omni-Mesh.

In DMesh, each directional antenna often can only connect to one neighbor node (because the beam width of signal is narrow as compared with inter-node distance). Because the number of spatial directions of a node is limited (usually between two and eight), the connectivity of DMesh is lower than its omni-directional counterpart. Therefore, topology control (i.e., which routers should a router beams to) is an important issue in DMesh. Because mesh topology also affects routing decision, they need to be jointly optimized to achieve the best performance.

In this paper, we consider the joint optimization of topology control and routing assignment for a multimedia DMesh. In the network there is a gateway connected to the Internet. Each mesh router has a number of steerable beam directions, and has a certain (heterogeneous) Internet traffic demand from its end users (zero if it does not have local users and just forwards traffic). Two routers can communicate with each other only if they are within the beam coverage of each other.

In a DMesh, topology control is to select a sub-graph out of the reachability graph of the routers given the number of directional antennas at each router, while routing assignment is to find paths to minimize the link cost (we consider single-path routing due to its simplicity). Clearly, topology control and routing assignment are coupled, i.e., the decision of one affects the decision of the other. Because interference is greatly reduced with the use of directional antennas, we consider that the link cost is mainly due to the traffic it carries. The problem is then, given multimedia traffic requirements, how to jointly optimize network topology and routes for all routers so as to achieve a good overall loading in the links (i.e., the worst-case link cost from routers to gateway is minimized).

In this paper, we address this joint optimization problem. We first formulate the problem and show that it is NP-hard. Using traffic load as a metric of link weights which captures load distribution in the network, we propose an efficient heuristic call TORA (Topology control and Routing Assignment) which jointly controls topology and assigns routes to mesh routers with traffic demands. TORA is an ant-based algorithm to find a degree-bound spanning tree which balances the network traffic load in links, and hence effectively eliminates the bottlenecks

This work was supported, in part, by the HKUST Special Research Fund Initiative (SRFI11EG15), Google Mobile 2014 and Faculty Research Awards, and HP Labs Innovation Research Program Award (HP11EG02).

978-1-4673-0921-9/12/$31.00 ©2012 IEEE

to achieve good performance. Simulation results confirm its performance with substantially lower loss rate and higher throughput as compared with another scheme.

The rest of the paper is organized as follows. We first discuss the related works in Section II. We then formulate the problem and prove its complexity in Section III. We present TORA, our ant-based approach for topology control and routing assignment in Section IV. In Section V, we present illustrative simulation results based on NS3. We conclude in Section VI.

II. Related works

Most of the work on DMesh focus on routing and channel assignment without considering topology control. The work in [3] formulates the routing and channel assignment (RCA) problem in DMesh as a Mixed Integer Programming (MIP) problem. The work in [2] structures the DMesh nodes as a tree according to which the channel assignment is done in the parent nodes. These works all assume that the link state or the topology of the DMesh is given. To the best of our knowledge, this work is the first one addressing the *joint topology control and routing assignment* of a DMesh with *traffic demands*.

Another body of work studies the topology control problem for omni-mesh [4]. An MST-based topology construction algorithm has been proposed in [5]. The work in [6] proposes an approximation algorithm to compute a minimum-degree spanning trees while maintaining the connectivity. The resultant topology is shown to achieve good overall performance in terms of power usage, reliability and interference. In [7], an ant colony heuristic is proposed to control topology in sensor network. It models link cost independent of traffic. A self-adaptive contention window adjustment algorithm for congestion control in WLAN is proposed in [8]. While these works are impressive, the results cannot be extended to DMesh with constraints in the number of directional antennas. Furthermore, they are on topology control instead of *joint* optimization of topology and routing. We also consider the more realistic case of link cost as a function of its aggregated traffic, and study how to construct a well-balanced topology to support heterogeneous traffic requirement of the nodes.

III. Problem Formulation and Complexity Analysis

A. Preliminaries

We consider a DMesh with a gateway which enables connectivity to the wired Internet. The mesh nodes only have traffic to the public Internet through the gateway. We show an example in Figure 1, which consists of six mesh nodes labeled from 1 to 6, one of which is gateway (Node 1). Users may be associated to any mesh node. There is a certain traffic rquirement in each node (zero if there is no users). The amount of traffic is given by a traffic demand vector, which may be obtained from averaging long-term traffic statistics of the network. There are a certain number of directional antennas in a router. Each of its antennas can be beamed to one of its neighbors to form a communication link. Dotted lines in the Figure indicate possible communication links. All links are bidirectional.

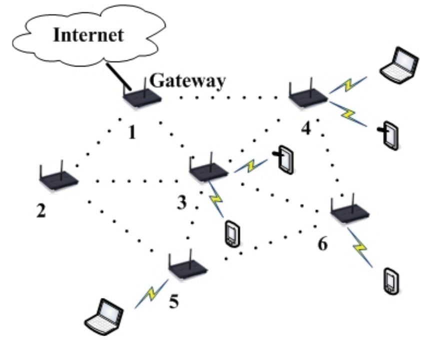

Fig. 1. A DMesh with six nodes as labeled. Some of them have traffic demand.

TABLE I
Important Symbols used in the paper.

Symbol	Meaning
r	Transmission range (m)
S	The set of source nodes
g	Gateway
$N(i)$	The set of neighbors of node i
I_i	Number of directional antennas node i has
H	Number of orthogonal channels
$D(i)$	Traffic demand of node i
c	Bandwidth of wireless links (kb/s)
f_{ij}	Flow on link $(i,\ j)$ (kb/s)
x_{ij}	Decision variable indicating whether link $(i,\ j)$ is used for transmission
τ_{ij}	Pheromone intensity on link $(i,\ j)$
$G(V,E)$	Reachability graph for router/node set V and edge set E

We model a DMesh as an undirected graph $G(V,E)$, where V is the set of mesh nodes with directional antennas and E is the set of links in the network. In the DMesh, each node is equipped with several directional antennas. The communication range of the directional antenna is denoted as r. For any $i, j \in V$, let $d(i,j)$ be the Euclidean distance between i and j; a link (i,j) exists if and only if $d(i,j) \leq r$. Vertex i and j are neighbors if they are in each other's communication range. The set of neighbors of vertex i is defined as $N(i)$. Each link $e \in E$ has a cost, which is defined as the congestion of the link. One typical cost function to measure link congestion when where is little interference is the queuing delay $\sigma/(c-f)$, where σ is a constant, c is link bandwidth and f is the traffic on the link.We show the important symbols used in this paper in Table I.

Node i has I_i directional radio transceivers (does not need to be equal), which can be tuned to a particular channel for transmission or reception of data. Each antenna can be steered to a specified direction. The wireless spectrum has H orthogonal channels. In order to minimize interference within a node, each radio of a node is assigned a unique channel. In

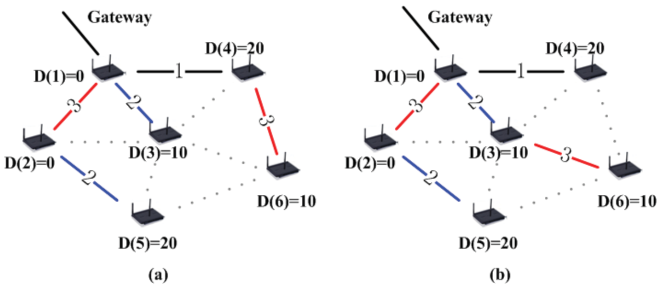

Fig. 2. Two possible schemes of topology control and routing assignment.

other words, no two radios of the same node are assigned the same channel; i.e., we consider that $I_i \le H$.

B. Problem Formulation

Given the connectivity graph G, topology control in DMesh is to decide which ones out of $N(i)$ neighbors that node i should beam the antenna to in order to form a topology. Clearly, the number of beamed neighbours must be no more than $\min(I_i, N(i))$. If the topology and routing are not designed properly, there may be congested links which affects network performance. Therefore, thei joint optimization is very important to the performance of the network.

Because of the use of directional antennas, link interference is greatly reduced. We hence consider that the major factor affecting the network performance is due to the traffic a link carries. We hence model the link cost as a function of its total traffic it carries (due to buffering, processing, etc.).

We show in in Figure 2 two possible topologies, and hence routings, given the network graph of Figure 1. All the routers have $I_i = 3$ interfaces. Mesh router i has traffic demand given by $D(i)$. Numbers labeled on links represent the channels used by links. Though both figures show balanced-tree configuration, their link loads are markedly different. In Figure 2(a), because the traffic from router 6 passes through router 4, the total traffic at router 4 is 30 units, which is quite high. This leads to high queuing delay of the link, and hence high cost. On the other hand, in Figure 2(b), the traffic demand is more uniformly distributed on each link. This leads to lower totoal cost. Obviously this topology and routing is better.

We formulate joint topology control and routing assignment as an optimization problem. In order to achieve a good overall loading in all the links (so as to minimize bottleneck links), we seek to minimize the worst-case link cost. The gateway is denoted as $g \in V$. For each ordered pair (u, v), we define a binary variable $x_{uv} \in \{0, 1\}$ which indicates whether link (u, v) is chosen to form the topology or not. We further let f_{uv} be the aggregated traffic flow on link (u, v). Since the traffic flows into one node must equal to the traffic flowing out of the node, we must have the following flow conservation for $i \in V \backslash \{g\}$:

$$\sum_{v:(i,v)\in E} f_{iv} x_{iv} - \sum_{u:(u,i)\in E} f_{ui} x_{ui} = D(i). \tag{1}$$

For the gateway g (which is a sink), we need

$$\sum_{v:(g,v)\in E} f_{gv} x_{gv} - \sum_{u:(u,g)\in E} f_{ug} x_{ug} = -\sum_{i\in V} D(i). \tag{2}$$

We further require

$$\sum_{v\in V} x_{iv} = 1, \ \forall i \in V \backslash \{g\}, \tag{3}$$

which simply means that each router must have one out-going link, i.e., single path routing.

In order not to use more antennas than a router has and not to cover more nodes than a node has, we need the following degree constraints:

$$\sum_{v:(i,v)\in E} x_{iv} + \sum_{u:(u,i)\in E} x_{ui} \le \min(I_i, N(i)), \ \forall i \in V. \tag{4}$$

Subject to the above Constraints (1) to (4)), we seek to minimize the bottleneck in the network, i.e., minimize the worst-case link cost:

$$\min \max_{(u,v)\in E} \frac{\sigma}{c - f_{uv}} x_{uv}, \tag{5}$$

where c is the bandwidth of link (u, v). The optimization problem is hence equivalent to finding a degree-bound minimum-cost spanning tree where the cost is the highest link cost.

C. NP-hard Proof

We show in this section that finding an optimal solution to the above optimization problem is NP-hard. We prove that by showing that the well-known NP-hard partition problem can be reduced to our problem.

Recall the partition problem: Let P be a set of integers. Let $sum(P)$ be the sum of numbers in the set P. The partition problem is to find an optimal partition to divide P into two subsets P_1 and P_2 such that the difference of $sum(P_1)$ and $sum(P_2)$ is minimized.

The partition problem can be reduced to our optimization problem.

Similar to [9], we construct the following graph: Create a node labeled g representing the gateway of our problem, a node labeled P_1 and a node labeled P_2. For every integer of value t, create a node with traffic demand t to the gateway. Connect each node with two links of infinite capacity, one link is connected to nodes P_1 and the other is connected to P_2. Then connect P_1 and P_2 to gateway g.

Given the graph just defined, our problem is to find a tree connecting all nodes such that the difference of aggregated traffic on link (P_1, g) and link (P_2, g) is minimized. Obviously, if we find an optimal solution to our problem, the optimal partition can also be found. Therefore our problem is as hard as the partition problem.

IV. TORA: Joint Topology Control and Routing Algorithm

Due to the NP-hard nature of our problem, we propose an efficient heuristic to address it. Our heuristic, called TORA, is based on ant-colony algorithm. In this section, we first briefly review ant colony algorithm in Section IV-A, and then describe TORA in details in Section IV-B. Note that TORA is orthogonal to any channel assignment scheme. When a solution is obtained, any channel assignment approach can be used to choose channel for each antenna.

A. Review of Ant-Colony Algorithm

Ant colony algorithm is a bionic algorithm first proposed by M. Dorigo. It simulates the ants' behavior of seeking good paths.

The researchers of the ants observe that ant colony has the ability to find the best path (for example the shortest path) between their caves and food sources. The ant colony achieves this by releasing pheromone on the path they passed by. Ants choose the path that has dense pheromone with high probability. After finding the food, they come back in the same path according to the pheromone left on it. Consequently, the ants who find better paths will release more pheromone on the paths than the ants who find worse paths over a certain period of time.

Under the above positive feed-back or reinforcement mechanism, the density of pheromone of better paths will increase. As time goes by, almost every ant chooses the best path.

B. TORA Details

Given graph $G = (V, E)$ and traffic demand $D(i)$, let S represent the set of source routers which have non-zero traffic demand. Then ant-colony algorithm helps to find a degree-bound spanning tree that minimizes the largest link load.

The algorithm of TORA is shown in Algorithm 1. It consists of multiple iterations. Let τ_{ij} be the pheromone intensity on link (i, j). Before the first iteration, pheromone of each link is initialized to τ_{ij}^0. The pheromone evaporates with rate ρ. In each iteration, Algorithm 2 is used to search for a spanning tree. It accomplishes the search by sending $|S|$ ants from $|S|$ source routers to the gateway. Since all ants stop at the gateway, they together find a degree-constrained spanning tree, where the tree cost is given by the maximum link cost of the tree. We always record the best spanning tree, denoted as $minTree$, generated and update the pheromone of each link after every M iterations.

In order to enhance pheromone on links of the best tree and evaporate pheromone on links are not in the best one. We update pheromone according to

$$\tau_{ij} = (1 - \rho)\tau_{ij} + \rho\Delta\tau_{ij}, \tag{6}$$

where

$$\Delta\tau_{ij} = \begin{cases} 1/cost(minTree), & \text{if } (i, j) \in \text{minTree}; \\ 0, & \text{otherwise.} \end{cases}$$

We use $optTree$ to store the tree of the best cost found so far. The terminating condition is true if the best cost tree has not been updated within a certain number of iterations or a maximum number of iterations has been reached.

We show in Algorithm 2 how ants search for a spanning tree. $|S|$ ants are sent from source routers. In order to find a spanning tree, an ant in our algorithm only solves a part of the whole problem. Therefore, each ant moves from one node to another at each step to search for a path from the source to gateway. Each ant maintains a node list called $Visited$ in order not to visit the same node twice. In the algorithm, T is a set of the edges representing a routing tree, and V is the set of nodes visited by the ant. V should contain all nodes once the spanning trees is found. Index i represents the current position of the ant, while index j represents the next node to be visited by the ant. An ant at position i chooses j as its next hop with a certain probability. We follow the previous work [10] to use the following transition probability:

$$p_{i,j} = \frac{\tau_{ij}(\eta_{ij})^\beta}{\sum_{k \in N(i)} \tau_{ik}\eta_{ik}^\beta}, \tag{7}$$

where $\eta_{ij} = 1/l_j$ and l_j is the hop count of the shortest path from j to the gateway. This is a local heuristic for choosing the next hop closer to gateway. Recall that τ is the pheromone level. In each M iterations, Pheromone on the best tree links will be enhanced. Therefore, choosing next hop with probability that proportional to τ can be seen as a global heuristic.

Function $cd(i)$ is used to check if the degree bound of node i is satisfied. If the current ant chooses node i as its next hop and the degree of node i still satisfies the bound, $cd(i) = 1$; otherwise $cd(i) = 0$. $N'(i)$ is the set of possible next hops for the ant at node i. At some stage, Algorithm 2 may return a tree that violates the bandwidth constraints of some links. In this situation, we simply drop the tree and search for another one.

Algorithm 1 TORA

```
minTree = ∅, optTree = ∅;
while stopping condition not met do
   if cost(minTree) ≤ cost(optTree) then
      optTree ← minTree;
   end if
   Trees = ∅;
   T ← antExplore;
   Trees ← Trees ⋃ T;
   minTree ← arg min_{T∈Trees} cost(T)
   if i mod M == 0 then
      for each (i, j) ∈ E do
         τ_ij ← (1 − ρ)τ_ij + ρΔτ_ij
      end for
   end if
end while
return optTree
```

V. Illustrative Simulation Results

In this section, we present illustrative simulation results to show the performance of TORA. We first describe simulation environment and metrics. Then, we compare TORA with another scheme.

Algorithm 2 antExplore

$T = \oslash$, $V = \oslash$;
for each $s \in S$ **do**
  $Visited = \{s\}$
  $i \leftarrow s$;
  while $i! = g$ AND $i \notin V$ **do**
    $V = V \bigcup \{i\}$;
    for each $j \in N(i)$ **do**
      if $cd(j) = 1$ AND $j \notin Visited$ **then**
        $N'(i) \leftarrow N'(i) \bigcup \{j\}$;
      end if
    end for
    for each $j \in N'(i)$ **do**
      choose l as the next hop with probability $p_{i,j} \leftarrow \tau_{ij}(\eta_{ij})^{\beta} / (\sum_{k \in N'(i)} \tau_{ik}(\eta_{ik})^{\beta})$;
      if j is chosen **then**
        add (i, j) to T;
        $Visited \leftarrow Visited \bigcup \{j\}$;
        $T \leftarrow T \bigcup (i, j)$;
        $i \leftarrow j$;
        break;
      end if
    end for
  end while
end for
return T

A. Simulation Environment and Metrics

We study TORA performance using NS-3 simulation. In our simulation, 25 mesh nodes are randomly deployed into an area of size 2000m $\times$ 2000m. Unless otherwise stated, we use the following baseline parameters: $r = 700$m, $H = 3$, $I_i = 3$, $c = 12(Mbps)$, the total number of flows is 10, and traffic rate per flow is 1.5 Mbps. UDP traffic is generated according to normal distribution, while TCP traffic is CBR traffic. The source routers of traffic flows and the node locations are randomly assigned. The parameters used in TORA are as follows: $\sigma = 0.1$, $\beta = 2$, $M = 100$, $\rho = 0.1$, and $\tau_{ij}^{0} = 0.1$. The TORA algorithm terminates if the best-cost tree is not updated for $3 \times M$ iterations or the algorithm has run for $10,000$ iterations.

The performance metrics we are interested in are:

- *Loss rate (UDP)*: It is the loss rate of the UDP flows given a certain traffic per flow. We are interested in the distribution and average.
- *Delay (UDP)*: It is the end-to-end delay of the successfully received packets. We are interested in its average and distribution.
- *Throughput (TCP)*: It is the aggregated throughput of the TCP flows. We are interested in the system throughput and distribution.

To the best of our knowledge, this is the first piece of work on joint topology control and routing with given traffic demand for DMesh. In the absence of previous work, we compare TORA with a routing scheme described in [11]. The work also uses a spanning tree to solve the topology control and routing problem, by forming a degree-constrained shortest path first tree. We label this scheme as SPF.

B. Illustrative Results

We plot the loss rate versus the traffic load per flow in Figure 3. The loss rate increases with the traffic rate because higher traffic load leads to higher congestion and higher chance of interference. TORA substantially performs better than SPF. This is because TORA uniformly distributes traffic over the network. It can efficiently reduces the probability of congestion, hence reduces loss rate. Besides, TORA tends to eliminate long source to gateway paths, which also helps to reduce loss rate. In contrast, SPF simply minimizes hop counts without considering traffic demand. The loss rate of it increases drastically.

We compare the cumulative distribution function (CDF) of UDP loss rate in Figure 4. The cumulative percentile of TORA is higher than SPF, which means that TORA has substantially lower loss rate. By minimizing the worst-case link congestion of the topology, TORA can actually reduce the number of nodes suffering from high loss rate.

Figure 5 shows the average end-to-end delay versus the traffic load per flow. The end to end delay is increasing with the traffic load. While delay in SPF increases sharply with traffic load, TORA manages to maintain relatively low average delay. The reason is obvious: Due to traffic dynamics, the peak traffic can be very heavy. Packet will queue up on congested links. To capture this factor, TORA uses queuing model to model link cost. This model penalizes links with heavy traffic load in topology construction, thus leads to a link-load balanced tree topology. As the traffic load reaches some value, the increase in delay starts to slow down. This is because the packet loss rate will be high when the traffic load goes up too much.

We plot UDP average loss rate versus number of orthogonal channels in Figure 6. As the number of channel increases, we can achieve lower loss rate, because channel diversity helps to reduce interference between links. The decrease of loss rate, however, diminishes and flats off as channel number increases to a certain point equal to the number of directional antennas in each node. This expected due to the spacial separation of channel reuse in DMesh. The figure also shows that the number of orthogonal channels should not be too few as compared with the number of antennas due to co-channel interference at the nodes.

Figure 7 shows TCP throughput versus traffic load given different schemes. As the traffic demand increases, SPF shows its lower performance and reaches capacity limit much earlier than TORA. This is because without considering heterogeneous traffic demand, traffic from different source routers in SPF might be aggregated to one link. The link will become a bottleneck of the network. In contrast, TORA manages to minimize the worst-case link load.

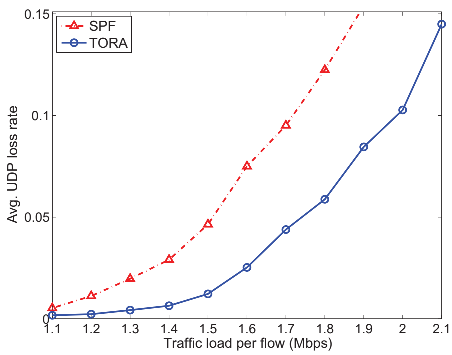

Fig. 3. UDP loss rate comparison.

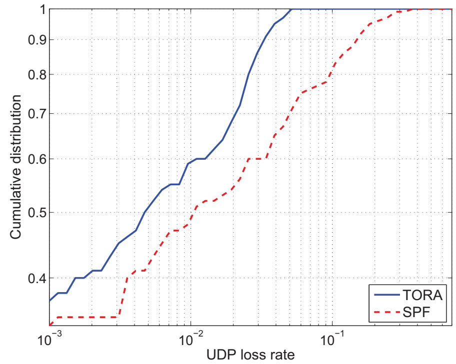

Fig. 4. Cumulative percentile versus loss rate.

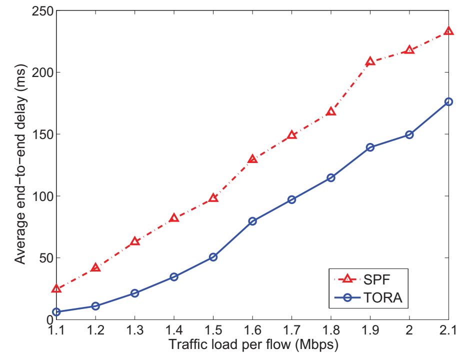

Fig. 5. UDP average end-to-end delay comparison.

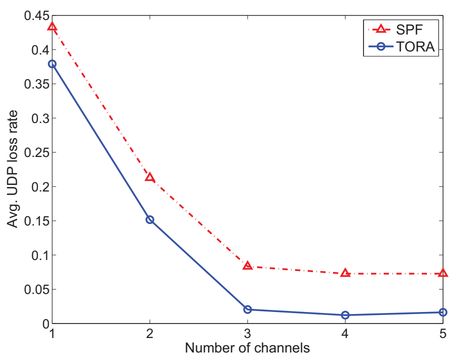

Fig. 6. Loss rate versus number of channels.

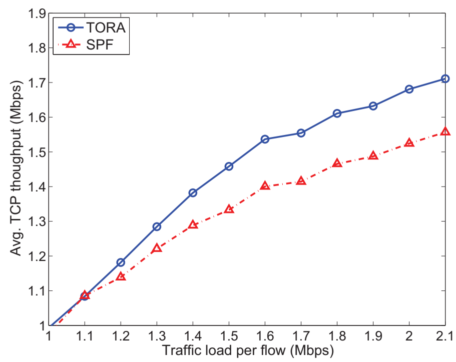

Fig. 7. TCP throughput comparison.

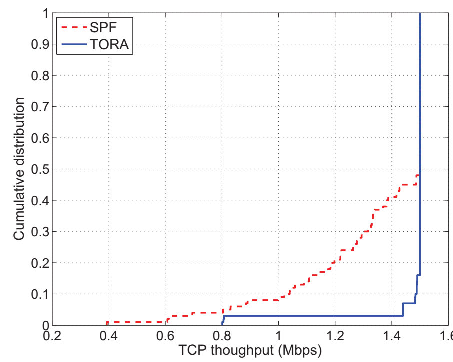

Fig. 8. Cumulative percentile versus throughput.

We show the distribution of TCP throughput in Figure 8. Clearly, much fewer nodes in TORA suffer from low throughput than SPF. Significantly more nodes in TORA meets their traffic requirements. The figure also shows that TORA achieves much better throughput fairness.

VI. Conclusion

The performance of DMesh (wireless mesh with directional attennas) largely depends on the topology control and routing assignment. Because topology control and routing assignment are inter-dependent decisions, in this paper we have addressed their joint optimization to achieve good overall link loading (by minimizing the worst-case link cost due to its aggregate traffic).

We have considered a multimedia DMesh with flow requirements in nodes. We first formulate the joint optimization problem and show that it is NP-hard. We propose TORA, a joint topology control and routing assignment based on ant-colony algorithm. TORA is novel, simple and efficient. Our simulation results based on NS3 show that it achieves much lower packet UDP loss rate and much higher TCP throughput as compared with a recent scheme.

References

[1] I. Akyildiz and X. Wang, "A survey on wireless mesh networks," *IEEE Communications Magazine*, vol. 43, no. 9, pp. S23 – S30, Sep. 2005.

[2] S. Das, H. Pucha, D. Koutsonikolas, Y. Hu, and D. Peroulis, "Dmesh: Incorporating practical directional antennas in multichannel wireless mesh networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 2028 –2039, nov. 2006.

[3] W. Zhou, X. Chen, and D. Qiao, "Practical routing and channel assignment scheme for mesh networks with directional antennas," in *IEEE International Conference on Communications, 2008. ICC '08.*, may 2008, pp. 3181 –3187.

[4] X. Wu, S.-H. G. Chan, B. Mukherjee, and B. Bhargava, "MADF: Mobile-assisted data forwarding in wireless data networks," *Journal of Communications and Networks*, vol. 6, no. 3, pp. 216–225, Sep. 2004.

[5] N. Li, J. Hou, and L. Sha, "Design and analysis of an MST-based topology control algorithm," in *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. IEEE Societies*, vol. 3, march-3 april 2003, pp. 1702 – 1712 vol.3.

[6] U. Kumar, H. Gupta, and S. Das, "A topology control approach to using directional antennas in wireless mesh networks," in *IEEE International Conference on Communications, 2006. ICC '06.*, vol. 9, june 2006, pp. 4083 –4088.

[7] G. Singh, S. Das, S. Gosavi, and S. Pujar, "Ant colony algorithms for steiner trees: An application to routing in sensor networks," *Recent developments in biologically inspired computing*, p. 181, 2005.

[8] Q. Pang, S. Liew, J. Lee, and S. Chan, "A TCP-like adaptive contention window scheme for WLAN," in *2004 IEEE International Conference on Communications*, vol. 6. IEEE, 2004, pp. 3723–3727.

[9] D. Lorenz, A. Orda, D. Raz, and Y. Shavitt, "How good can IP routing be," *DIMACS Rep*, vol. 17, 2001.

[10] M. Dorigo and L. Gambardella, "Ant colony system: a cooperative learning approach to the traveling salesman problem," *IEEE Transactions on Evolutionary Computation*, vol. 1, no. 1, pp. 53–66, apr 1997.

[11] O. Incel and B. Krishnamachari, "Enhancing the data collection rate of tree-based aggregation in wireless sensor networks," in *5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2008. SECON'08.* IEEE, 2008, pp. 569–577.