Protecting Multicast Sessions in Wireless Mesh Networks

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Abstract

To support reliable multicast routing in wireless mesh networks, it is important to protect multicast sessions against link or node failures. The issue of protecting multicast sessions in wireless mesh networks is a new problem to the best of our knowledge. In this paper, we propose a resilient forwarding mesh approach for protecting a multicast session in wireless mesh networks. Utilizing the wireless broadcast advantage, a resilient forwarding mesh effectively establishes two node disjoint paths for each source-destination pair. This allows a multicast session to be immune from any single link or intermediate node failure. We introduce four heuristic algorithms to obtain approximate solutions that seek to minimize the number of required broadcast transmissions. We evaluate the performance of these heuristic algorithms against the optimal resilient forwarding mesh (ORFM) obtained by solving an integer linear programming (ILP) formulation of the problem. Experimental results demonstrate that one of these heuristic algorithms, which we call the minimal disjoint mesh algorithm (MDM), performs sufficiently close to ORFM. Besides, we find that the resilient forwarding mesh approach provides efficient 1+1 protection [8] to the multicast session without incurring much additional overhead on a single minimal cost multicast tree.

1 Introduction

Recently, a lot of commercial application of wireless community networks have emerged. Wireless mesh network (WMN) is a promising technology for deploying wireless infrastructure to provide users always-on-line service anywhere anytime [1]. Compared with current generation wireless networks such as Wi-Fi or cellular networks which are single-hop, the wireless mesh networks disseminate data through multi-hop forwarding. Each node in wireless mesh networks not only receives but also forwards traffic to other nodes through a multihop wireless path. Compared with Wi-Fi or cellular networks, wireless mesh networks have some key advantages such as high speed, low interference, large service coverage, low up-front cost, fast deployment, easy maintenance, and robustness [3]. In the future, high-speed wireless meshes will enable a whole new range of exciting broadcast/multicast applications, such as IP-TV and video-on-demand (VOD) [2].

Much work has been done in developing multicast in wireless mesh networks and mobile ad hoc networks, some of which will be introduced in the next section. However, resilience for multicast sessions against node or link failures in wireless mesh networks is a new problem, to the best of the authors' knowledge. In this paper we propose an approach called resilient forwarding mesh (RFM) which is able to protect a multicast session in wireless mesh networks. We also propose four different heuristics to obtain near optimal solutions of RFM because we believe the problem of finding optimal RFM is NP-complete.

The rest of this paper is organized as follows. In Section 2, previous work related to our research is discussed. In Section 3, we give a formal definition of the concept of resilient forwarding mesh. In Section 4, we present the problem statement and the integer linear programming (ILP) formulation for computing the optimal RFM. Several heuristics are proposed to obtain the approximate solution of the optimal resilient forwarding mesh in Section 5. In Section 6, we discuss the results from experiments of different heuristic and optimal solution from ILP. Finally, we present our conclusions in Section 7.

2 Related Work

Mobile ad hoc networks (MANETs) share some common features with WMNs, such as wireless environment and multihop transmission. A lot of multicast routing protocols were specifically proposed for MANETs such as MAODV, ODMRP, NSMP, DCMP, *etc.* (see [6] and references therein). Nevertheless, they are not suitable for wireless mesh networks, since they mainly focus on the issue of handling the frequent topology changes due to node mobility and power limitation problem which are common in ad hoc networks. Moreover, because of the frequent topology changes, it is less likely to have an efficient mechanism that can be aware of the global network topology and thus difficult to get optimal multicast dissemination in the network scale. In contrast, the mesh routers in WMNs are generally stationary and without the limitation of power [5]. Therefore the frequent topology change is not a big concern of WMNs. As a consequence, the aim of protocols in WMNs is shifted from keeping path availability to finding high-throughput path. Therefore, the performance metrics for wireless mesh networks are delay, throughput, the number of broadcast transmissions rather than number of hops or energy efficiency.

There are also some research on multicast in WMNs. Ruiz et al. [12], Chou et al. [4, 5] and Qadir et al. [9, 10] all study multicast tree in wireless mesh networks using the *wireless broadcast advantage* [18], which means that in the wireless environment, when a node needs to forward a multicast packet to some of its neighbor nodes, it merely requires one single broadcast transmission to reach all the nodes within its transmission range. In [12], the authors formulated the minimal cost multicast tree problem in terms of minimizing the number of broadcast transmissions in single rate scenario. Two algorithms are presented to compute the approximate optimal solution because the problem is NP-complete. Chou et al. [4, 5] and Qadir et al. [9, 10] studied minimizing broadcast latency in multi-rate wireless mesh networks. They presented a number of algorithms for achieving low latency multicast in wireless mesh using wireless broadcast advantage and multi-rate nature of radio. However, neither of them has taken the resilience problem into consideration.

Wireless mesh networks are typically used as wireless backbones. However, the nature of instability of radio makes wireless communication links between nodes prone to failure. In addition, hardware failure, channel error or interference are also likely to cause nodes to fail. Therefore resilience against node or link failures is an important issue for supporting reliable multicast routing in wireless mesh networks. Disjoint paths between source and destinations is a classical protection scheme against link or node failure [11]. Link disjoint paths are parallel routes which do not have any link in common. Similarly, node-disjoint paths are parallel routes which do not have any node in common except the source and the destination. The disjoint paths make traffic from the source to the destination delivered simultaneously on both paths. Therefore in case a single link or node failure in one of the paths, there is an unaffected path to guarantee the data delivery. Srinivas et al.[16] and Shpungin et al.[14] have proposed algorithms to compute node-disjoint paths in mobile ad hoc networks. Both of them are concerned in unicast scenario and the metric is minimizing energy consumption. They are not suitable for our work because of two aspects. Firstly, in infrastructure wireless mesh networks, energy efficiency is not of great concern because the mesh routers always connect to the power outlets. Our objective of performing multicasts in WMNs is to minimize the number of transmissions. Secondly, their works focus on unicast but not multicast. The optimal solution of multicast is not simple sum of several optimal solutions of unicast. Besides, in multicast scenario, the wireless broadcast advantage has to be taken into consideration since it is very likely that one node might have multiple neighbors which are either multicast receivers or multicast forwarding nodes.

In [15], Singhal et al. proposed a multicast session protection scheme called optimal path-pair (OPP) to address the need of multicast resilience in wired mesh networks. However, our previous research [20] shows that OPP does not suit for wireless mesh networks because OPP, which is designed for wired networks, does not take wireless broadcast advantage into consideration. [19] proposed a resilient and opportunistic routing solution for mesh networks which is called ROMER, which ensured resilience agains link loss and node failure. However, ROMER is designed for unicast therefore it cannot be used in multicast scenario. To the best of our knowledge, there is no research on resilience problem in multicast of wireless mesh networks.

3 Resilient Forwarding Mesh

We propose a resilient forwarding mesh approach to protect a multicast session in wireless mesh networks. A resilient forwarding mesh is defined to be a set of multihop wireless paths that has the following property. For each source-destination pair in the multicast session, the resilient forwarding mesh contains at least two node-disjoint paths that connect the source and the destination in parallel and concurrently. The reason we prefer node disjoint paths but not link disjoint paths is that in wireless scenario both link and node are prone to failure. In this way, any single link or intermediate node failure in the forwarding mesh will not disrupt the multicast session.

The concept of resilient forwarding mesh is illustrated using a small network topology as shown in Fig. 1(a). In this topology, we have one source node (marked by S), three intermediate nodes (marked by M_1, M_2 and M_3), and two destination nodes (marked by D_1 and D_2). Since both M_1 and M_2 are within the transmission range of S, due to the wireless broadcast advantage of wireless media, only one broadcast transmission from S is sufficient to reach both M_1 and M_2. Subsequently, the multicast packet can be further broadcast from M_1 to both D_1 and M_3, from M_2 to

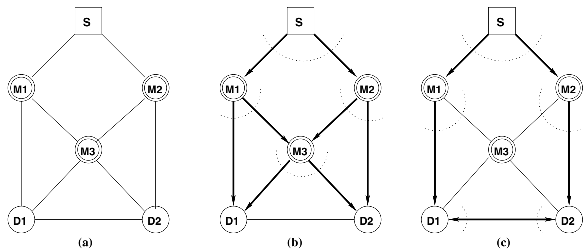

Figure 1. Illustration of resilient forwarding mesh: (a) Network topology; (b) Optimal solution; (c) Suboptimal solution.

both D_2 and M_3, and from M_3 to both D_1 and D_2. Clearly, such a sequence of four broadcast transmissions constitutes a resilient forwarding mesh that contains exactly two node-disjoint paths for each source-destination pair. In particular, as shown in Fig. 1(b), $\{S, D_1\}$ is connected by both $(S \rightarrow M_1 \rightarrow D_1)$ and $(S \rightarrow M_2 \rightarrow M_3 \rightarrow D_1)$, while $\{S, D_2\}$ is connected by both $(S \rightarrow M_2 \rightarrow D_2)$ and $(S \rightarrow M_1 \rightarrow M_3 \rightarrow D_2)$. Fig. 1(c) shows an alternative solution of the resilient forwarding mesh for this topology. In this case, $\{S, D_1\}$ is connected by both $(S \rightarrow M_1 \rightarrow D_1)$ and $(S \rightarrow M_2 \rightarrow D_2 \rightarrow D_1)$, while $\{S, D_2\}$ is connected by both $(S \rightarrow M_2 \rightarrow D_2)$ and $(S \rightarrow M_1 \rightarrow D_1 \rightarrow D_2)$. Nevertheless, this latter solution requires the multicast packet to be further broadcast from both D_1 and D_2 rather than from M_3. Consequently, it requires totally five broadcast transmissions, as compared with four broadcast transmissions resulted from the solution of Fig. 1(b).

In this paper, we define the optimal resilient forwarding mesh (ORFM) as the resilient forwarding mesh that requires the minimal number of broadcast transmissions. Since it is known from [12] that the problem of finding the minimal cost multicast tree (with no resilience capability) in wireless mesh networks is NP-complete, we believe that the problem of finding the ORFM to protect multicast sessions in wireless mesh networks is also NP-complete. It needs to be pointed out that, a special case of the ORFM problem with only one destination, i.e. to protect a unicast session with two node-disjoint paths, can be solved in polynomial time using Suurballe's algorithm [17]. Suurballe's algorithm finds a node-disjoint path pair with minimal link cost in polynomial time for a unicast session in wired networks. Since two node-disjoint paths do not share any common intermediate node, the number of broadcasting nodes (which is equivalent to the number of broadcast transmissions) involved in a resilient forwarding mesh equals to the number of links minus one. It is due to this fact that we can solve the special unicast case of the ORFM problem in polynomial time using Suurballe's algorithm by setting the link cost as one.

In the next section, we shall provide an ILP formulation of the ORFM problem, which can be used to compute ORFM solutions to protect multicast sessions in larger and more complex topologies.

4 Problem Statement and Formulation

Consider a wireless mesh network topology in the form of a directed graph $G = (V, E)$, where V is the set of nodes and E is the set of edges connecting the nodes. A directed edge (m, n) from node m to node n in G indicates that node n is within the transmission range of node m. We assume that a multicast session consists of one source node marked by s and a set D of k destination nodes. We wish to find an optimal resilient forwarding mesh so that each source-destination pair is connected by two node-disjoint paths while the total number of broadcast transmissions is minimized. We recall that if two parallel routes are node disjoint, any single intermediate node failure that affects one route will not affect the other route. For convenience of description, we shall refer to one of such two parallel routes as the P route and the other as the B route.

Let P^d_{mn} denote a boolean variable, where P^d_{mn} is equal to one if the link between nodes m and n is used in the P route for the destination node d, $d \in D$. Let B^d_{mn} denote a boolean variable, where B^d_{mn} is equal to one if the link between nodes m and n is used in the B route for the destination node d, $d \in D$. Let X^d_m denote a boolean variable, where X^d_m is equal to one if the P route for the destination node d, $d \in D$, passes through node m, $m \in V - \{s, d\}$. Let Y^d_m denote a boolean variable, where Y^d_m is equal to one if the B route for the destination node d, $d \in D$, passes through node m, $m \in V - \{s, d\}$. Let Z_m denote a boolean variable, where Z_m is equal to one if node m, $m \in V - \{s\}$, is used in the resilient forwarding mesh as a broadcasting node.

Given the above notation, the ORFM problem is mathematically formulated as follows:

$$Minimize \qquad 1 + \sum_{m \in V - \{s\}} Z_m \tag{1}$$

subject to

$$\sum_{n:(s,n) \in E} P^d_{sn} = 1, \quad \forall d \in D \tag{2}$$

$$\sum_{n:(n,s) \in E} P^d_{ns} = 0, \quad \forall d \in D \tag{3}$$

$$\sum_{n:(d,n) \in E} P^d_{dn} = 0, \quad \forall d \in D \tag{4}$$

$$\sum_{n:(n,d)\in E} P_{nd}^d = 1, \quad \forall d \in D \tag{5}$$

$$\sum_{n:(m,n)\in E} P_{mn}^d = X_m^d, \quad \forall d \in D, \forall m \in V - \{s,d\} \tag{6}$$

$$\sum_{n:(n,m)\in E} P_{nm}^d = X_m^d, \quad \forall d \in D, \forall m \in V - \{s,d\} \tag{7}$$

$$\sum_{n:(s,n)\in E} B_{sn}^d = 1, \quad \forall d \in D \tag{8}$$

$$\sum_{n:(n,s)\in E} B_{ns}^d = 0, \quad \forall d \in D \tag{9}$$

$$\sum_{n:(d,n)\in E} B_{dn}^d = 0, \quad \forall d \in D \tag{10}$$

$$\sum_{n:(n,d)\in E} B_{nd}^d = 1, \quad \forall d \in D \tag{11}$$

$$\sum_{n:(m,n)\in E} B_{mn}^d = Y_m^d, \quad \forall d \in D, \forall m \in V - \{s,d\} \tag{12}$$

$$\sum_{n:(n,m)\in E} B_{nm}^d = Y_m^d, \quad \forall d \in D, \forall m \in V - \{s,d\} \tag{13}$$

$$X_m^d + Y_m^d \leq 1, \quad \forall d \in D, \forall m \in V - \{s,d\} \tag{14}$$

$$P_{sd}^d + B_{sd}^d \leq 1, \forall d \in D, (s,d) \in E \tag{15}$$

$$\sum_{d\in D, d\neq m} (X_m^d + Y_m^d) \geq Z_m, \quad \forall m \in V - \{s\} \tag{16}$$

$$\sum_{d\in D, d\neq m} (X_m^d + Y_m^d) \leq 2 \cdot k \cdot Z_m, \quad \forall m \in V - \{s\} \tag{17}$$

The objective function presented in (1) considers the fact that the source node itself must be used in the resilient forwarding mesh as a broadcasting node. The constraints provided in equations (2) to (17) guarantee that two node disjoint paths are created for each source-destination pair in the multicast session. Specifically, equations (2) and (3) ensure that in the P route for each particular destination node, the source has one outgoing flow and zero incoming flow. Equations (4) and (5) ensure that in the P route for each particular destination node, the destination node itself has one incoming flow and zero outgoing flow. Equations (6) and (7) determine for each particular destination node whether its P route passes through an intermediate node (which is neither the source node nor the destination node). If so, the intermediate node must have exactly one incoming flow and one outgoing flow. Equations (8) to (13) similarly define the set of constraints of the B route for each source-destination pair. Equation (14) enforces the node-disjoint constraint, which ensures that there is no node in common within any pair of disjoint paths. In case if a link exists between the source and a destination node, equation (15) makes sure that such a link is not used in both the P route and the B route for the corresponding destination node. Equations (16) and (17) restrict that a node be counted only once if the node is used by any P or B route as a broadcasting node.

5 Heuristic Algorithms

While the ILP formulation presented in the previous section can be used to compute the optimal solution of the ORFM problem, for large size network topologies, it is known that no efficient methods exist that can solve such an ILP model in a reasonable amount of time. In this section, we propose four heuristic algorithms that can be used to find approximate solutions of the ORFM problem in polynomial time. Note that the first two algorithms are tree-based protection schemes, and the last two algorithms are path-based protection schemes. The following notation is used in all the four algorithms. Notation specific to each individual algorithm will be described later in the corresponding subsections.

- As before, the network is denoted by $G = (V, E)$ as a directed graph, where V is the set of nodes. E is the set of directed links between nodes, and l is the notation of a directed link.
- D is the set of multicast destination nodes.
- The cost of each directed link l between nodes is denoted as $C(l)$, and is initialized to one.
- FN is the set of forwarding nodes which compose the RFM. In the initiation phase, FN is set to empty. When a node is determined to be a forwarding node, it will be put into FN. Since each forwarding node only forwards once for the same data, the number of transmissions equals to the number of forwarding nodes plus one, where the "plus one" transmission comes from the source.
- PT and BT denote the multicast trees from source to all multicast destinations (The context of PT and BT is similar to P and B in Section 4).
- P and B denotes the paths from source to a multicast destination.
- $InterNode(X)$ is a function of X which returns the set of intermediate nodes in X from source to destination. Here the X could be a tree (P or B) or a path (PT or BT).
- $OutFlow(x)$ is a function of node x which returns the set of directed links from node x to all of its neighbors.

Algorithm 1 Node-Disjoint Tree (NDT)

Given: $G = (V, E)$; $D = \{d_1, ..., d_j\}$
for all $l \in E$ **do**
  $C(l) \leftarrow 1$
end for
$FN \leftarrow \phi$
Build minimal multicast tree PT in V for D using Greedy-based heuristic algorithm in [12]
$FN \leftarrow FN \bigcup InterNode(PT)$
$V = V - FN$
Build another minimal multicast tree TB in V for D
$FN \leftarrow FN \bigcup InterNode(BT)$

Algorithm 2 Revised Node-Disjoint Tree (RNDT)

Given: $G = (V, E)$; $D = \{d_1, ..., d_j\}$
for all $l \in E$ **do**
  $C(l) \leftarrow 1$
end for
$FN \leftarrow \phi$
Build minimal multicast tree PT in V for D using Greedy-based heuristic algorithm in [12]
$FN \leftarrow FN \bigcup InterNode(PT)$
for all $n \in InterNode(PT)$ **do**
  for all $l \in OutFlow(n)$ **do** $C(l) \leftarrow 0$
end for
for all $d \in D$ **do**
  $P \leftarrow \phi$; $B \leftarrow \phi$
  $P \leftarrow$ the path from source to d in PT
  $V' \leftarrow V - InterNode(P)$, $G' = (V', E)$
  Find a shortest path $B(d)$ from source to d in V' using Dijkstra's algorithm [8] with new link cost C
  for all $n \in InterNode(B)$ **do**
    for all $l \in OutFlow(n)$ **do** $C(l) \leftarrow 0$
  end for
  $FN \leftarrow FN \bigcup InterNode(B)$
end for

5.1 Node-Disjoint Tree algorithm (NDT)

The first heuristic which is called Node-Disjoint Tree Algorithm (NDT) is described as Algorithm 1. The main idea of NDT is to find two node-disjoint trees for all destinations. The first step is building a multicast tree PT with minimal number of transmissions using the Greedy-based heuristic algorithm in [12]. We then remove all intermediate nodes of PT from the node set V and find a new minimal multicast tree BT in the new V. Since tree PT and BT do not have any common node except the source, they are node-disjoint. All intermediate nodes of PT and BT are put into FN composed forwarding nodes of resilient forwarding mesh.

5.2 Revised Node-Disjoint Tree algorithm (RNDT)

The second heuristic Revised Node-Disjoint Tree (RNDT) algorithm is a revised version of NDT. In NDT algorithm, when all intermediate nodes of PT are removed from V, it is unlikely to find another multicast tree successfully. Besides, it also cannot utilize the wireless broadcast advantage of some nodes in the tree already for BT. Rather than finding another tree by removing all intermediate nodes of the first tree, the RNDT utilizes the intermediate nodes of the multicast tree to find node-disjoint path. After a minimal multicast tree PT has been found, RNDT puts the intermediate nodes of PT into FN and sets the cost of all out-flow links of all intermediate nodes of PT as zero. The reason of updating the cost of all out-flow links of the intermediate nodes of PT as zero is that when a node is selected as a forwarding node, if there are other neighbors interested in the multicast session, no additional transmission is needed because of the wireless broadcast advantage. For each destination node, RNDT repeatedly does: (1) finding a shortest path B from source which is node-disjoint to the path in PT from source, using Dijkstra's algorithm [8]. (2) updating the cost of all out-flow links of intermediate nodes in B as zero. All intermediate nodes in PT and B are put into FN acting as forwarder of resilient forwarding mesh.

All node-disjoint paths B can constitute a new tree BT. Although PT and BT may not be node-disjoint tree, the paths between the source to any multicast destination in PT and BT are node-disjoint. Therefore this heuristic can protect the multicast session effectively against any node or link failure.

5.3 Shared Disjoint Mesh algorithm (SDM)

The Shared Disjoint Mesh algorithm (SDM) and the following Minimal Disjoint Mesh algorithm (MDM) use different approach to generate resilient forwarding mesh. Both of them compute node-disjoint path pair for each destination node in turn. The aim of both approaches is to make the node-disjoint path pair of each destination share common intermediate node as much as possible.

In order to find forwarding nodes for RFM, SDM does the following steps for each destination node repeatedly: (1) find a shortest path P from source to the destination; (2) remove all intermediate nodes of P from V, and find another shortest path B which is node-disjoint to P; (3) put all intermediate node into FN, and update the cost of all out-flow links of those intermediate nodes as zero. The "zero updating" is also used for utilizing wireless broadcast advantage

Algorithm 3 Shared Disjoint Mesh (SDM)

Given: $G = (V, E)$; $D = \{d_1, ..., d_j\}$
for all $l \in E$ **do**
  $C(l) \leftarrow 1$
end for
$FN \leftarrow \phi$
for all $d \in D$ **do**
  $P \leftarrow \phi$; $B \leftarrow \phi$
  Find a shortest path P from source to d using link cost C
  $V' \leftarrow V - InterNode(P)$, $G' = (V', E)$
  Find a shortest path $B(d)$ from source using link cost C
  for all $n \in (InterNode(P) \bigcup InterNode(B))$ **do**
    for all $l \in OutFlow(n)$ **do** $C(l) \leftarrow 0$
  end for
  $FN \leftarrow FN \bigcup InterNode(P) \bigcup InterNode(B)$
end for

because after the nodes are selected as a forwarding node, if other destinations wish to utilize some of these nodes as forwarding nodes, no additional transmission is needed. Since in SDM algorithm RFM is composed by all node-disjoint path pairs, it can also protect any node or link failure successfully.

5.4 Minimal Disjoint Mesh algorithm (MDM)

Algorithm 4 Minimal Disjoint Mesh (MDM)

Given: $G = (V, E)$; $D = \{d_1, ..., d_j\}$
for all $l \in E$ **do**
  $C(l) \leftarrow 1$
end for
$FN \leftarrow \phi$
for all $d \in D$ **do**
  $PP \leftarrow \phi$
  Find a minimal node-disjoint path-pair PP from source to d using link cost C by Suurballe's algorithm[17]
  for all $n \in InterNode(PP)$ **do**
    for all $l \in OutFlow(n)$ **do** $C(l) \leftarrow 0$
  end for
  $FN \leftarrow FN \bigcup InterNode(PP)$
end for

Minimal Disjoint Mesh algorithm (MDM) improves SDM in the way of building the node-disjoint path pair. Instead of finding two node-disjoint paths sequentially, MDM uses Suurballe's algorithm [17] to find node-disjoint path pair with minimal cost at the same time. Although SDM could find shortest path for each destination, the total cost of two node-disjoint path might not be optimal. The other parts of MDM is exactly as same as the SDM.

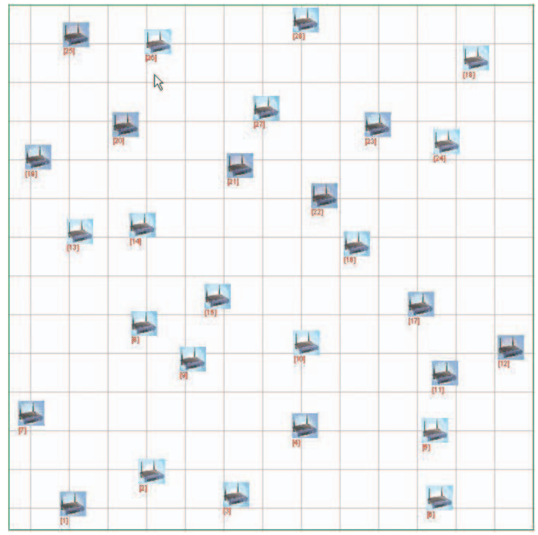

Figure 2. A large network topology.

6 Experimental Results and Analysis

In order to compare the performance of the various protection schemes proposed in Section 5, we generate a sample network shown in Figure2 using Qualnet [13] for the experiments. There are 28 nodes uniformly distributed across the networks. For each multicast group size M, ranging from 1 to 25, we randomly pick one node as source node and other M nodes as destination nodes. Then we use the four different heuristics to establish connection from source to the destinations in the network. We also use CPLEX [7] to obtain the optimal solution of RFM for the multicast group. In order to compare the overhead of the resilient forwarding mesh against single multicast tree, we calculate the cost of multicast tree which is realized by Greedy-based heuristic algorithm [12] and optimal multicast tree in terms of minimum number of transmissions by ILP in CPLEX. For each M, we repeat the experiment for 50 runs, each of which uses a randomly selected set of nodes as the multicast session members.

Figure 3 plots the average number of broadcast transmissions required for the various resilient forwarding mesh solutions found by different heuristics and the optimal RFM by CPLEX in our experiment. Although we could solve the ILP for a moderate-size network (tens of nodes), when calculating an optimal solution for a large group size, the running time on CPLEX may be huge (several tens of minutes). Therefore, we do the ILP calculation for session size only from 1 to 10. In Figure 3, we observe that for all M, the

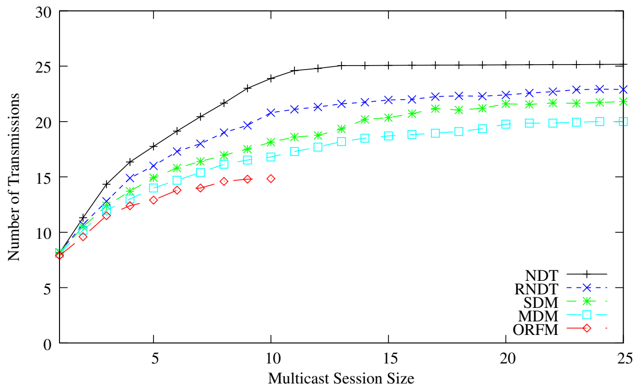

Figure 3. Performance comparison between different heuristics and ORFM

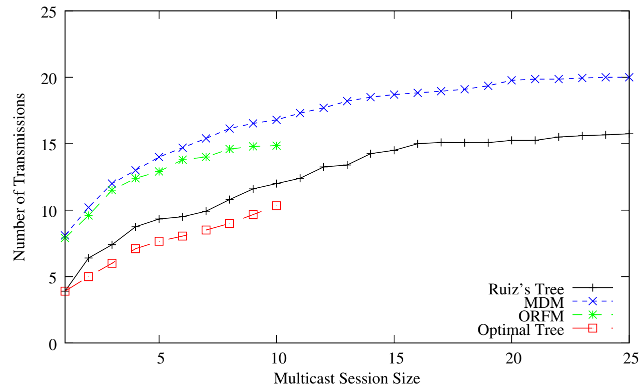

Figure 4. Overhead comparison between RFM and Tree

performance of four heuristics, from the worst to the best, are NDT, RNDT, SDM and MDM. As expected, RNDT outperforms NDT because RNDT can utilize the wireless broadcast advantages when finding node-disjoint paths for each destination. Since MDM uses Suurballe's algorithm to find optimal node-disjoint paths pair, the number of transmissions MDM needs is less than SDM. Observe that SDM constantly needs less transmissions to establish RFM than RNDT in all session size. This is because after establishing multicast tree PT in RNDT, only a part of intermediate nodes in PT can be used for node-disjoint paths by wireless broadcast advantages. The experiments show that MDM is closest to ORFM obtained by CPLEX. The biggest gap between MDM and ORFM is less than 2 transmissions when the multicast group size is 10.

Because RFM finds a pair of node-disjoint paths for each destination, it offers "1+1" protection [8] to the multicast session. If RFM needs too many additional transmissions to provide resilience to a single multicast tree, it will reduce the throughput of the network. Figure 4 shows the overhead needed by MDM, ORFM, Greedy-based heuristic algorithm for multicast tree [12] and optimal non-protected tree obtained by CPLEX. Observe that when the session size is small (i.e. $M < 5$), the number of transmissions MDM needs is about twice of Ruiz's tree. However, when the group size increases, there is no big increase of additional transmissions on MDM. In large group size case (i.e. $M > 15$), MDM always needs about five more transmissions, which is less than one third more transmissions than Ruiz's tree. This is because that, if the session size is small, the destination nodes are likely to scatter in the network and hence far from each other. As a result, node-disjoint paths for different source-destination pairs is less likely to share common intermediate nodes, which makes it less able to utilize the wireless broadcast advantage to reduce the number of transmissions. While the session size increases, the destination nodes are more likely to be close to each other, which makes it more possible for MDM to find the disjoint paths that share more common intermediate nodes utilizing wireless broadcast advantage.

7 Conclusion and Future Work

We consider resilience of multicast against node or link failure, which is a new problem in wireless mesh networks to the best of our knowledge. In this paper, we propose a resilient forwarding mesh (RFM) approach for protecting a multicast session utilizing the wireless broadcast advantage. The problem of finding an optimal RFM is believed to be NP-complete. We propose four polynomial time heuristics to protect multicast session effectively and efficiently. One heuristic called minimal disjoint mesh algorithm (MDM) outperforms all other algorithms in terms of number of transmissions. It is also close to the optimal solution obtained by Integer Linear Program (ILP) in CPLEX. Besides, a resilient forwarding mesh can provide "1+1" protection to the multicast session with limited additional overhead towards a single multicast tree.

Currently our heuristics of RFM are based in centralized scheme. Ongoing work seeks to find RFM in a distributed scheme which will be more appealing for wireless environment.

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