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**Publication details:**
13th International conference on telecommunications, Proceedings
9729836841 (ISBN)

**Event details:**
13th International conference on telecommunications
Funchal, Madeira island, Portugal

**Publication Date:**
2006

**DOI:**
https://doi.org/10.26190/unsworks/379

# Resilient Multicasting 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. In this paper, we propose a resilient forwarding mesh approach for protecting a multicast session. 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. An integer linear programming (ILP) formulation is presented to find the optimal resilient forwarding mesh (ORFM) that minimizes the number of broadcast transmissions. In comparison with the existing optimal path-pair (OPP) approach proposed in [1] for wired mesh networks, our experimental results demonstrate that ORFM outperforms OPP in wireless scenarios.**

## I. Introduction

Wireless mesh networking has recently become a popular technology for deploying wireless backbones [2]. Unlike traditional wireless networks such as Wi-Fi or cellular networks, the networking infrastructure of wireless mesh networks is decentralized. Each node in wireless mesh networks not only receives but also forwards traffic to other nodes through a multihop wireless path. Compared with their counterparts, wireless mesh networks manifest several key advantages such as high speeds, 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) [4].

Various multicast routing protocols have been proposed for wired IP networks (see [5] and references therein). However, they can not be directly used in wireless mesh networks, since they are not able to utilize the *wireless broadcast advantage* [6] inherent with wireless media. 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 which can reach all nodes within its transmission range. This is distinct from the requirement of packet duplication and separate transmission to each corresponding node in the wired environment. For a multicast session composed of one single source and multiple destinations, Ruiz *et al.* [7] observed that the minimal cost multicast tree established in wired IP networks (i.e. to minimize the overall edge cost) is in general not comparable to the one established in wireless mesh networks in terms of the number of broadcast transmissions.

On the other hand, in the wireless domain, there are also numerous multicast routing protocols specifically proposed for mobile ad hoc networks (see [8] and references therein). Nevertheless, they are not suitable to be used in wireless mesh networks either, since they mainly focus on the issue of handling the frequent topology change due to node mobility that is common in ad hoc networks. Moreover, because of the frequent topology change, it is less likely to have an efficient mechanism that can be aware of the global network topology and thus can compute the minimal cost multicast tree which minimizes the number of broadcast transmissions required to establish the tree. In contrast, nodes in wireless mesh networks, in particular the mesh routers, are generally stationary, and are usually not limited by power [9]. Therefore, the performance metrics for wireless mesh networks are delay, throughput, the number of broadcast transmissions rather than energy efficiency. The problem of efficiently performing broadcast/multicast in wireless mesh networks has been considered in a few recent papers. The work in [9] and [10] studied minimizing broadcast latency in multi-rate wireless mesh networks. Ruiz *et al.* [7] formulated the minimal cost multicast tree problem in terms of minimizing the number of broadcast transmissions required to send a packet from the single source to all the destinations in a multicast session. They showed that such a problem is NP-complete.

Our specific interest in this paper is to consider an extended version of the minimal cost multicast tree problem that is coupled with certain resilience property for multicast trees in wireless mesh networks. This is due to the concern that the nature of instability of radio makes wireless communication links between nodes prone to failure. In addition, hardware failure or interference makes nodes themselves prone to failure. Given the fact that wireless mesh networks are typically used as wireless backbones, resilience against link or node failures is therefore an important issue for supporting reliable multicast routing in wireless mesh networks.

In order to protect the connection within a source-destination pair, a classical path protection scheme is to provide two link (node) disjoint paths between the source and the destination [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. In case of any single link (intermediate node) failure, link (node) disjoint paths guarantee that only one of the paths is subjected to connection disruption. If traffic from the source to the destination is delivered simultaneously on both paths, the destination node can switch automatically to the unaffected path, thus making the path restoration simple and fast.

In [1], Singhal *et al.* proposed a multicast session protection scheme called *path-pair* to address the need of multicast resilience in wired mesh networks. A path-pair essentially finds two link disjoint paths for each source-destination pair in the multicast session, thus protecting the session against any single link failure. Singhal *et al.* presented an integer linear programming (ILP) formulation, which we shall call optimal path-pair (OPP) in this paper, that can be used to find the minimal cost path-pair. Because of the nature of the wired environment, OPP aims at computing the optimal path-pair that minimizes the overall edge cost. However, as we have discussed, it is important to observe 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 due to the inherent broadcast capability of wireless media. Clearly, OPP is not able to utilize this broadcast advantage. This makes the optimal path-pair obtained by OPP in general a sub-optimal solution if its cost is measured in wireless mesh networks using the metric of the number of broadcast transmissions.

We propose in this paper an approach called *resilient forwarding mesh* which is more efficient to protect a multicast session in wireless mesh networks. A resilient forwarding mesh is computed in such a way that each source-destination pair in the multicast session is connected by two node disjoint paths. Notice that we consider node disjoint paths in this context since we believe that in wireless mesh networks both links and nodes are prone to failure. We shall see that, by utilizing the broadcast advantage of wireless media, such a set of node disjoint paths for each source-destination pair, if can be found, effectively protects the multicast session against any single intermediate node failure as well as any single link failure without much significantly increase the overall cost (i.e. the number of broadcast transmissions). We present an ILP formulation, which we shall name optimal resilient forwarding mesh (ORFM) in this paper, that can be used to find the minimal cost resilient forwarding mesh. For the purpose of performance comparison between OPP and ORFM, we have modified the OPP formulation presented in [1] to find node disjoint paths for the optimal path-pair.

The rest of this paper is organized as follows. In Section II, we first give a formal definition of the concept of resilient forwarding mesh. We then illustrate through a small network topology how the broadcast advantage of wireless media can be exploited to reduce the number of broadcast transmissions required for a resilient forwarding mesh. We demonstrate that OPP leads to sub-optimal solutions in wireless scenarios. In Section III, we present the problem statement and ILP formulation for ORFM. In Section IV, we verify the performance gain of ORFM over OPP using a large network topology. Finally, we present our conclusions in Section V.

## II. 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. This way, any single link or intermediate node failure in the forwarding mesh will not disrupt the multicast session.

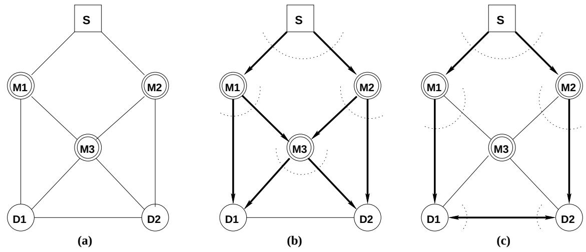


Fig. 1. Illustration of resilient forwarding mesh: (a) Network topology; (b) Optimal solution; (c) Suboptimal solution.

The concept of resilient forwarding mesh can be best 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 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 $(S \rightarrow M_1 \rightarrow M_3 \rightarrow D_2)$.

If we consider the same topology in the wired environment, and assume that the cost of each edge to be one hop, the solution of Fig. 1(b) would demand an overall edge cost of eight hops in this case. OPP, on the other hand, finds the optimal path-pair as shown in Fig. 1(c) which requires a less overall edge cost of six hops only. Such a set of multihop paths again constitutes a resilient forwarding mesh in the case of the wireless environment. However, to realize such a forwarding mesh, we now require the multicast packet to be further broadcast from both $D_1$ and $D_2$ rather than from $M_3$. This solution is suboptimal since it requires totally five broadcast transmissions, as compared with four broadcast transmissions resulted from the solution of Fig. 1(b). In fact, it is not difficult to find that the solution of Fig. 1(b) represents the optimal resilient forwarding mesh for this particular small topology.

In the next section, we shall provide an ILP formulation of the ORFM problem, which can be used to compute the optimal resilient forwarding mesh for larger and more complex topologies.

## III. 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 from node $i$ to node $j$ in $G$ indicates that node $j$ is within the transmission range of node $i$. 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. The ORFM problem is mathematically formulated as follows.

- **Given:**
  - A directed graph $G = (V, E)$ representing a wireless mesh network topology.
  - A multicast session $S = \{s, D\}$, where $s$ is the source node, and $D$ is the set of $k$ destination nodes.
- **Variables:**
  - Boolean variable $P^d_{mn}$ is equal to one if the link between nodes $m$ and $n$ is used for the $P$ route from the source node $s$ to the destination node $d$, $d \in D$. Otherwise, it is equal to zero.
  - Boolean variable $B^d_{mn}$ is equal to one if the link between nodes $m$ and $n$ is used for the $B$ route from the source node $s$ to the destination node $d$, $d \in D$. Otherwise, it is equal to zero.
  - Boolean variable $X^d_m$ is equal to one if node $m$, $m \neq d$, is used for the $P$ route from the source node $s$ to the destination node $d$, $d \in D$. Otherwise, it is equal to zero.
  - Boolean variable $Y^d_m$ is equal to one if node $m$, $m \neq d$, is used for the $B$ route from the source node $s$ to the destination node $d$, $d \in D$. Otherwise, it is equal to zero.
  - Boolean variable $Z_m$ is equal to one if node $m$, is used for the resilient forwarding mesh and is a broadcasting node. Otherwise, it is equal to zero.
- **Objective:**
  - Minimize the total number of broadcast transmissions required for the resilient forwarding mesh:

$$Minimize: \quad \sum_{m:m\in V} Z_m \tag{1}$$

- **Constraints:**

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

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

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

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

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

$$\sum_{n:(n,m)\in E} P^d_{nm} = X^d_m, \quad \forall d \in D,\ \forall m \in V - d \tag{7}$$

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

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

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

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

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

$$\sum_{n:(n,m)\in E} B^d_{nm} = Y^d_m, \quad \forall d \in D,\ \forall m \in V - d \tag{13}$$

$$X^d_m + Y^d_m \leq 1, \quad \forall m \in V \tag{14}$$

$$\sum_{d:d\in D} (X^d_m + Y^d_m) \geq Z_m, \quad \forall m \in V \tag{15}$$

$$\sum_{d:d\in D} (X^d_m + Y^d_m) \leq 2 \cdot k \cdot Z_m, \quad \forall m \in V \tag{16}$$

- **Explanation of constraints:** These constraints guarantee to create two node disjoint paths for each source-destination pair in the multicast session. Equations (2) and (3) ensure that for the $P$ route to each particular destination node, the source has one outgoing flow and zero incoming flow. Equations (4) and (5) ensure that for the $P$ route to 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 a node (which is neither the source node nor the destination node). Equations (8) to (13) similarly define the set of constraints for the $B$ route of 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. Equations (15) and (16) restrict that a node be counted only once if the node is used by any $P$ or $B$ route as a broadcasting node.

## IV. Experimental Results and Analysis

The ILP formulation for ORFM as well as OPP (presented in [1]) can be solved by CPLEX. This allows us to compare the performance between ORFM and OPP using a large network topology of 14 nodes as shown in Fig.2 (see next page). In our experiment, for each multicast session of size $M$, ranging from 3 to 11, we randomly select $M$ different nodes, one of which is set as the source node and others are for the destination nodes. We use CPLEX to obtain the resilient forwarding mesh found by ORFM and OPP, and we calculate the number of broadcast transmissions required for the corresponding solutions. For

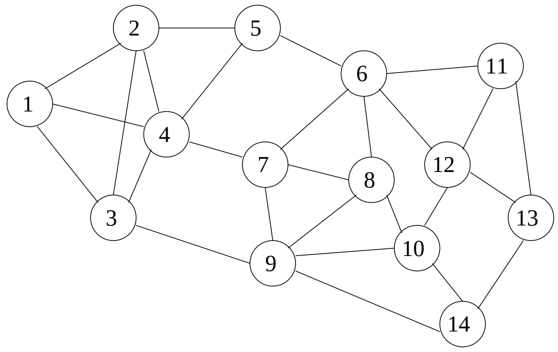


Fig. 2. A large network topology.

TABLE I
AN EXAMPLE OF ORFM

| Pair | $P$ route | $B$ route |
|---|---|---|
| {1, 6} | (1 → 3 → 9 → 8 → 6) | (1 → 4 → 7 → 6) |
| {1, 7} | (1 → 4 → 7) | (1 → 3 → 9 → 8 → 7) |
| {1, 9} | (1 → 3 → 9) | (1 → 4 → 7 → 9) |
| {1, 10} | (1 → 3 → 9 → 10) | (1 → 4 → 7 → 8 → 10) |

each $M$, we repeat the experiment for 15 runs, each of which uses a randomly selected set of nodes as the session members.

Results from the experiment have verified that ORFM consistently finds a valid optimal resilient forwarding mesh in each of the test cases. We demonstrate the validity of ORFM by showing an example where node 1 is set as the source node, and nodes 6, 7, 9 and 10 are set as the destination nodes. For this particular multicast session, the optimal resilient forwarding mesh found by ORFM is given in Table I. Clearly, for each source-destination pair, the $P$ route and the $B$ route are node disjoint, and both connects the source node and the destination node. It only requires a total number of six broadcast transmissions for such a multicast session with four destination nodes.

Figure 3 plots the average number of broadcast transmissions required for the various resilient forwarding mesh solutions found by ORFM and OPP in our experiment. For all $M$, we observe that ORFM outperforms OPP. Interestingly, in cases of small size sessions, the difference between ORFM and OPP is slight. For example, when there are two destination nodes (i.e. $M = 3$) in the multicast session, the average number of broadcast transmissions are 7.2 and 7.4 for ORFM and OPP, respectively. 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 are less likely to share common intermediate nodes, which makes it less able to utilize the *wireless broadcast advantage* to reduce the number of broadcast transmissions. However, when the session size increases, the destination nodes are more likely to be close to each other, which makes it more possible for ORFM to find routes that share common intermediate nodes to fully utilize the *wireless broadcast advantage*.

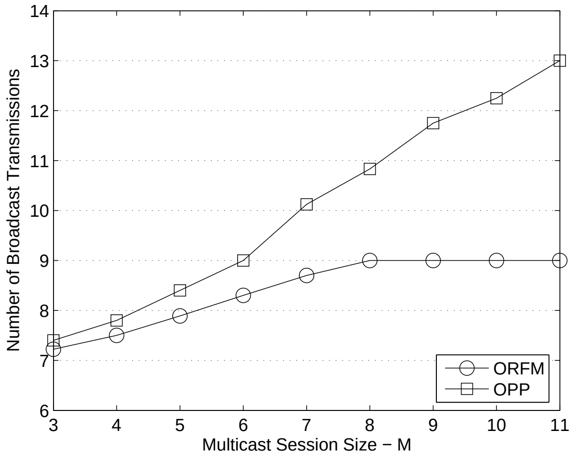


Fig. 3. Performance comparison between ORFM and OPP.

## V. CONCLUSION

In this paper, we have proposed a resilient forwarding mesh approach to effectively protect multicast sessions in wireless mesh networks against single node or link failures. We have presented an ILP formulation that can be used to find the optimal resilient forwarding mesh which fully utilizes the wireless broadcast advantage and thus minimizes the number of required broadcast transmissions.

## ACKNOWLEDGMENTS

This project is supported by Australian Research Council (ARC) Discovery Grant DP0664791.

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