A Study of Routing Algorithms in Wireless Mesh Networks

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Abstract

Wireless mesh networks (WMNs) are a special case of mobile ad-hoc networks where the nodes have relative fixed positions and communicate to the Internet through one or more gateways. While traditional ad-hoc routing algorithms, such as DSR and AODV, can be used in WMNs, their performance is typically less than ideal. The problem is that such algorithms make assumptions that are no longer true in WMNs, and those assumptions can have significant performance penalties in the WMN environment. This paper studies routing algorithms in wireless mesh networks, particularly diverse routing and fault-tolerant properties. Because of the stable positions of nodes, we propose using quasi-fixed routing. This is a multipath form of routing adopted from parallel computing that offers robustness and performance advantages over traditional ad-hoc routing protocols. We also comment on the need for power-controlled transmission, and discuss network-connectivity problems and gateway selection.

Introduction

With the widespread adoption of mobile devices such as laptop computers, cellular phones and PDAs, wireless access to the Internet has become an important demand. Wireless LANs have drawn considerable attention from both industry and academia. Various standards, especially the IEEE 802.11 suite, have been created, while others are still under debate. In the IEEE 802.11 standard, there are two wireless access modes: infrastructure mode and ad-hoc mode. In the former mode, the LAN has a centralized device, referred to as an access point, which is directly connected to Internet with wire (typically Ethernet twisted pair). It operates as a wireless interface that forwards Internet data packets to/from other stations. Many current academic papers and industry deployments assume that stations are within one hop radio transmission range of such an access point. In ad-hoc mode there is no centralized device. All stations, or nodes, operate in a peer-to-peer mode, and they compete for the shared wireless channel. In this way, they are able to communicate among the domain, but are unable to access outer networks.

In practical use, however, another scenario appears in which all users in a local area network try to connect to Internet, but some of them are beyond one hop transmission range of the access points. This happens when wireline Internet access is too expensive to deploy for various reasons, including low utilization or expense of cabling. For example, in existing buildings, cable deployment is the major portion of the cost for network setup. Similarly, in a conference there will be high utilization, but only for the period of the conference. The cost of deployment just for the conference is expensive. In such situations, the stations have relatively fixed positions (within one room, for example), and are required to forward others' packets in a peer-to-peer mode, while they communicate to Internet via access points. In such cases, the access point that is connected to the Internet is more frequently referred to as a gateway, and the network is called a wireless mesh network (WMN) [2] [6] [8].

In this paper we discuss the unique aspects of wireless mesh networks, and their differences from ad-hoc networks. In particular, we propose an algorithm for routing in such networks that is able to take advantage of the capabilities of such networks that are not present in ad-hoc networks. We provide some evidence that the approach we propose is likely to perform noticeably better than existing ad-hoc routing protocols.

This remainder of this paper is organized as follows. In Section II we introduce wireless mesh networks and our diverse-routing algorithm. We describe its advantages, and give evidence that it will be a superior approach. In Section III we study the power-aware network connectivity problem. Section IV briefly discusses the impact of gateway selection on network performance. Finally, in Section V, we conclude the paper.

Wireless Mesh Network and Diverse Routing

Wireless mesh networks have the potential to play a critical role as an alternative technology for last-mile broadband Internet access. They can be viewed as a special case of wireless multi-hop ad-hoc networks, in which each node operates both as a host and as a router. However, WMNs have a number of features that distinguish them from pure ad-hoc networks. First, the positions of different nodes of a WMN are relatively fixed. By relatively fixed position, we mean that, although the nodes may not be absolutely immobile, any change of position is limited within certain range. The implication of this is that routing paths can be created that are likely to be stable. This substantially reduces the need for routing packet overhead. Indeed, such routing packets are likely only needed at initialization and when traffic volume is sufficiently low that a node cannot be sure that its neighbour is still present, as opposed to having crashed. Second, unlike pure ad-hoc networks, where the traffic flows between arbitrary pairs of nodes, in WMN, all traffic is either to or from a designated gateway, which connects the wireless mesh network to the Internet. The relevance of this point is that the traffic may be split over multiple gateways, so as to reduce the load within any given portion of the network. Third, the nodes will typically have access to a power source, and so power consumption is not a critical issue. Finally, such systems can be created within a single domain of authority, and so many security issues present in ad hoc networks are no longer relevant.

Wireless mesh networks are, as with pure ad hoc networks, easy to install. The setup cost for Internet service providers (ISPs) is only gateway installation and configuration. This makes WMNs a good choice compared to traditional directional antenna wireless access. Scalability is a second advantage for WMNs. When new subscribers activate their Internet connections, ISPs only need to perform an authentication process to decide whether to admit or deny. Nodes can be added one at a time, and the more nodes admitted, the more reliable the network, because a densely distributed network tends to maintain higher connectivity. Traditional directional antenna networks, on the other hand, suffer from poor scalability since, when a new subscriber is admitted, the antenna's direction has to be manually adjusted. Furthermore, if a new gateway is installed to alleviate heavy traffic, half of existing subscribers' antennae should be re-aimed to new gateway, putting a heavy cost on ISPs.

Ad-hoc network routing algorithms, such as AODV, DSR and many of their extensions, are complex because they need to deal with the possibility of highly mobile nodes. There has, therefore, been significant attention put on route discovery and maintenance. Although ad-hoc networks' routing algorithms can be directly applied in WMNs, the relatively stationary topology of WMNs suggests that we could develop much more simplified routing algorithms. Further, the traffic pattern in WMNs is such that alternate protocols are likely preferred.

The most commonly used topology for wireless mesh networks is a grid layout, due to the layout of buildings. Since each node would communicate with the gateway, it must do so either directly, if it is within the radio transmission range, or indirectly, which requires other nodes to forward packets. In order to minimize the collision probability, each node should adjust its power to a level that is able to reach its four direct neighbors, and no more. This, thus, forms a grid network. Therefore, we can adopt a quasi-xy-routing algorithm in WMN. Xy-routing is commonly used in mesh or torus topology parallel computers to avoid deadlock in wormhole routing [1]. In WMN with this grid topology, each node routes to its direct neighbours. For example, a node (x, y) in Fig. 1 has direct neighbors (x-1, y), (x+1, y), (x, y-1), (x, y+1). Each node performs packet forwarding for its neighbors to and from the gateway.

Packet delay is caused by various reasons, including collision resolution during packet forwarding, packet buffering, and different scheduling algorithms. However, the most critical cause is packet delay in WMN is path length. Under the same traffic intensity, a smaller number of hops would lead to less packet delay. For two nodes, S (x_S, y_S) and D (x_D, y_D), in a grid network, their shortest distance is given by:

$$d = | x_S - x_D | + | y_S - y_D | \qquad (1)$$

To minimize packet delay we wish to use the shortest path. However, this must be done in the context of minimizing collisions, since highly-contended paths that are shortest are not necessarily ideal [9]. We therefore propose a shortest-path load-balancing diverse routing protocol. Our protocol is as follows:

1. *if the next hop is a gateway, compete for transmission with it; else*
2. *determine neighbour nodes' load;*
3. *select a lightly-loaded path for next hop and transmit;*
4. *go to step 1.*

Step 2 enables the current node to acquire a picture of local network traffic. We presume this may be achieved by promiscuous snooping of the medium. While in a pure ad-hoc network the cost of such snooping may be too high, in terms of energy consumption, in the WMN context this should be quite feasible. Step 3 is then a simple matter of selecting the lightest-load node. There will, in general, be just two choices for any given destination, presuming that a shortest path route is desired. Alternately, the current node can skip step 2 and simply randomly alternate between the two choices (*e.g.* right or down in Fig. 1). In this manner our protocol achieves diverse routing. The number of paths available is then determined according to the following theorem.

Theorem 1: *For any two given node S (x_S, y_S) and D (x_D, y_D) in a wireless mesh network, there exists*

$$\binom{|x_S - x_D| + |y_S - y_D|}{|x_S - x_D|}$$

different routes that have distance d, given in Eq. 1.

Proof: We prove the theorem by induction. Without loss of generality, assume $x_S \le x_D$ and $y_S \le y_D$.

Step 1. From S (x_S, y_S) to (x_S, y_S+1), there is only one path; Likewise for S (x_S, y_S) to (x_S+1, y_S). The number of shortest paths between S (x_S, y_S) to (x_S+1, y_S+1) is 2, which is a summation of the above 2.

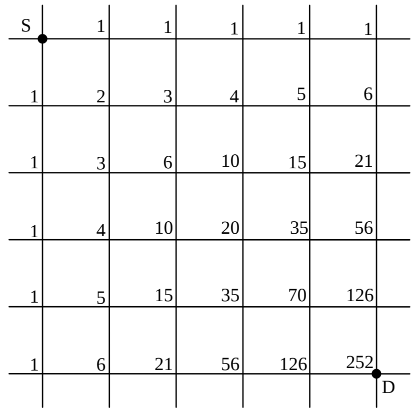

Fig. 1. Diverse Route Calculation.

Step 2. Suppose from S to T(x_T, y_T), the number of shortest paths is

$$\binom{x_T - x_S + y_T - y_S}{x_T - x_S}$$

Again, suppose $x_S \le x_T$ and $y_S \le y_T$.

Step 3. From S to (x_T+1, y_T), the number of shortest paths can be calculated recursively as

$$\frac{(x_T - x_S + 1 + y_T - y_S)!}{(x_T - x_S + 1)! \cdot (y_T - y_S)!}$$

From S to (x_T, y_T+1), the number of paths is

$$\frac{(x_T - x_S + y_T - y_S + 1)!}{(x_T - x_S)! \cdot (y_T - y_S + 1)!}$$

Therefore, from S to (x_T+1, y_T+1), the paths are a sum of the above two, because the paths must go through either (x_T+1, y_T) or (x_T, y_T+1). That is,

$$\frac{(x_T - x_S + y_T - y_S + 2)!}{(x_T - x_S + 1)! \cdot (y_T - y_S + 1)!}$$

which is

$$\binom{x_T - x_S + 1 + y_T - y_S + 1}{x_T - x_S + 1}$$

$\square$.

The question then arises as to how useful our approach would be. Jones [9] has performed extensive experiments in multipath WMN routing algorithms, using source-based routing. In particular, his work demonstrated the following. First, single-flow multipath routing to/from separate gateways can improve the performance by up to a factor of two over single-path routing, as is used in AODV and DSR. Second, in grid networks of 10*10 nodes, with sources and destinations selected randomly, using multipath routing aggregate throughput increased by between 5% and 61%, with an average increase of 27%. This indicates that the multipath routing can improve the performance of grid networks. We expect that our approach will yield better results than Jones because we dynamically adjust the path on route, based on current load.

Apart from routing issues, many researchers are concerned with scheduling algorithms in WMN [4] [5]. Jakubczak *et al.* [3] observed that nodes close to a gateway tend to have better chance for transmission when competing for the shared wireless channel with others that are further away from the gateway. Both

Jakubczak *et al.* [3] and Munawar [7] offer scheduling algorithms that achieve both fairness and high throughput.

Fault Tolerance in Wireless Mesh Network

In the previous section, we discuss routing issues for wireless mesh networks. For a relatively stationary topology, it is easy to find a route from an individual node to a gateway, as compared to ad-hoc network routing. This section addresses the route-maintenance problem.

In ad-hoc networks, route failure is mainly caused by node mobility or power-off. Most routing algorithms would produce a route-error message, and trigger re-routing. In wireless mesh networks, where nodes tend not to move, route failure is most probably caused by power-off or system failure. Under this circumstance, we may re-route with another diverse path. Note that for stations on the boundary of a mesh network, we do not need to strictly follow the shortest-distance diverse path. If a node's only adjacent neighbor fails, the node becomes an island. We would then increase its power level so that it can reach other neighbors. This scenario is illustrated in Fig. 2.

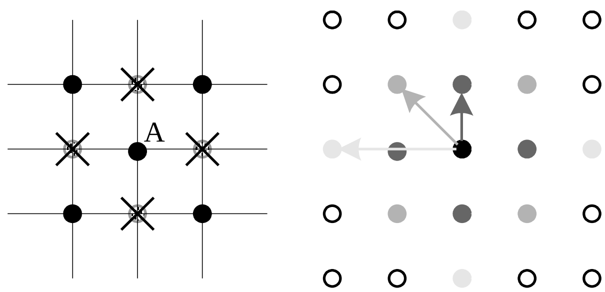

Fig. 2. Island node A and its different power levels.

Our scheme is to keep the power level as low as possible. Although a higher power level can reach a longer distance, and thus require fewer hops, it will also lead to more interference with other nodes, increasing the collision probability. In an extreme situation, where each node can hear every other node, a lot of collision will happen, and will have to be resolved with a much longer back-off time, especially in heavy-traffic situations. There is always a trade-off between network capacity and throughput [4]. Therefore, we try to keep the power to a low level. When the gateway is not the performance bottleneck, multiple packet-forwarding paths with fewer collisions can improve network throughput.

However, if a station is unable to reach other nodes, it will have to increase its power level to find some neighbours. In the same way, if a node joins the network, it will first look for its neighbors. Some island nodes might restore their power upon a new node's appearance, which could connect them to gateway in a normal mesh. How to find an alternative path during network failure is critical in wireless mesh networks.

Gateway's Effect on Performance

Due to the traffic pattern, most of the data packets are to or from designated gateway. As such, it is difficult or impossible to balance the load between nodes close to gateway and other nodes. With diverse routing, we have tried to balance the load among different routing paths to the gateway in order to avoid interference. Further, we presume nodes can use multi gateways. Finally, we note that placement of gateways at different positions in the mesh can have a direct effect on network throughput. For example, in Fig. 1, a gateway at a corner, rather than at the center, will more likely result in a higher delay and lower throughput for the mesh.

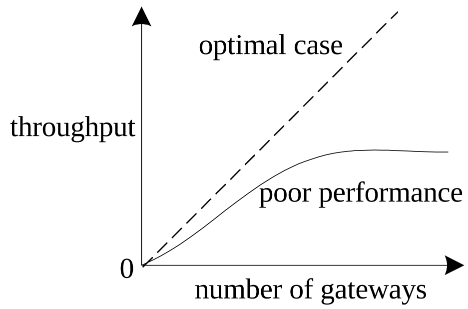

Fig. 3. Throughput should increase with number of gateways.

When traffic increases to certain amount that the existing gateways cannot handle any more, adding new gateways in mesh network could greatly alleviate congestion. For example, in a conference center when several conferences are held simultaneously, the organizers might place additional gateways to meet the increasing Internet traffic. In this situation, maintaining a balanced load among all gateways is important. The throughput of a load-balanced network would ideally grow linearly with the increment of gateway numbers.

Specifically, we propose to build some intelligent gateways that can perform virtual private network (VPN) functions. Because of the simplified routing issue, nodes might be able to use a local address, say, (x, y), to route Internet packets, and the packets are encapsulated at intelligent gateway and forwarded by other nodes. This would further allow multiple WMN subscribers to share limited number of IP addresses, if gateways can do address conversion.

Conclusion

Wireless mesh networks are a special case of ad-hoc networks. Since they are easy to setup and maintain, and have good scalability, WMNs are potentially a popular wireless-access method for hospitals, hotels, and conference centers. This paper studies routing algorithms for wireless mesh networks, using diverse routing, which addresses load-balancing and fault-tolerance problems. The gateway's effect on network performance is also discussed.

Future research is needed to integrate routing and scheduling algorithms and study wireless mesh network's performance. The number of gateways and their placement are also significant open problem, with network topology having a great impact on the final results. Particularly, in most papers, symmetric traffic is assumed. That is, all the nodes have similar traffic intensity. This is not the case in most applications, where most users' bandwidth demand is small, while a small portion of users have large bulk- or streaming-data transmission. A measurement study on wireless network's traffic model is needed.

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