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"Identifying high throughput path in Wireless Mesh Networks with bandwidth Guarantees

Regan. R[1], Divya.K[2], Madheswari.R[3]
[1,2,3] Department of Computer Science and Engineering
University College of Engineering, Panruti
reganr85@gmail.com[1], [2]divyakasinathan7@gmail.com , [2]madeshwari2013@gmail.com

Abstract:-Wireless mesh networks (WMNs) have occurred as a key technology for next generation wireless networking. Because of their advantages over other wireless networks, WMNs are undergoing swift progress and inspiring numerous applications. To accelerate hop-by-hop routing, we develop a mechanism for calculating the available bandwidth of a path in a dispersed manner. Unfortunately, available bandwidth is not isotonic, the obligatory and appropriate property for reliable hop-by-hop routing. To solve the problem, we introduce an isotonic parameter that captures the available bandwidth metric so that packets can traverse the maximum bandwidth path consistently according to the routing tables constructed in the nodes along the path. To the best of our knowledge, our protocol is the first WMN hop-by-hop routing scheme that can identify bandwidth assured paths.

Index Terms—Wireless mesh networks, QoS routing, proactive hop-by-hop routing, distributed algorithm.

I.INTRODUCTION

With the proliferation of Internet, Wireless Mesh Networks (WMNs) have become a practical wireless solution for providing community broadband Internet gate services. These networks exhibit characteristics that are novel in the wireless context, and in many ways more similar to traditional wired networks [1]. In Infrastructure WMNs, Access Points (APs) provide internet access to Mesh Clients(MCs) by forwarding aggregated traffic to Mesh Routers(MRs), known as relays, in a multi-hop fashion until a Mesh Gateway (MG) is reached. MGs act as bridges between the wireless infrastructure and the Internet.

Other than the routing competence for gateway/bridge functions as in a probable wireless router, a mesh router contains additional routing functions to support mesh networking. Through multi-hop communications, the same coverage can be achieved by a mesh router with much lower transmission power. To further improve the flexibility of mesh networking, a mesh router is usually equipped with multiple wireless interfaces built on either the same or different wireless access technologies. Inspite of all these differences, mesh and conventional wireless routers are usually built based on a similar hardware platform. Mesh routers have minimal mobility and form the mesh backbone for mesh clients.

Thus, although mesh clients can also work as a router for mesh networking, the hardware platform and software for them can be much simpler than those for mesh routers. For example, communication protocols for mesh clients can be light-weight, gateway or bridge functions do not exist in mesh clients, only a single wireless edge is needed in a mesh client, and so on. In addition to mesh networking among mesh routers and mesh clients, the gateway/bridge functionalities in mesh routers enable the mixing of WMNs with various other networks. Conventional nodes fortified with wireless network interface cards (NICs) can connect directly to WMNs through wireless mesh routers. Customers without wireless NICs can access WMNs by connecting to wireless mesh routers through, for example, Ethernet. Thus, WMNs will greatly help users to be always-on-line anywhere, anytime. Consequently, instead of being another type of ad-hoc networking, WMNs spread the capabilities of ad-hoc networks. This feature brings many advantages to WMNs, such as low up-front cost, easy network maintenance, heftiness, reliable service coverage, etc.

Therefore, in addition to being widely accepted in the traditional application sectors of ad hoc networks,

To date, several companies have already realized then potential of this technology and offer wireless mesh networking products. A few test beds have been established in university research labs. However, for a WMN to be all it can be, considerable research efforts are still needed. For example, the available MAC and routing protocols are not scalable; throughput drops significantly as the number of nodes or hops in WMNs increases.

Thus, existing protocols need to be enriched or re-invented for WMNs. Researchers have started to revisit the protocol design of existing wireless networks, especially of IEEE 802.11 networks, ad hoc networks, and wireless sensor networks, from the perception of wireless mesh networking. Industrial standards groups, such as IEEE 802.11, IEEE 802.15, and IEEE 802.16, are all actively working on new specifications for WMNs. In this article we present a survey of recent advances in protocols and algorithms for WMNs. Our aim is to provide a better understanding of research challenges of this emerging technology. The rest of this article is organized as follows. The network architectures of WMNs are first presented, with an objective to highlight the characteristics of WMNs and the critical factors influencing protocol design. The mesh routers form a mesh of self-configuring, self-healing links among themselves. With gateway functionality, mesh routers can be connected to the Internet. This approach, also referred to as *infrastructure meshing* provides a backbone for conventional clients and enables integration of WMNs with enduring wireless networks, through gateway/bridge functionalities in mesh routers. Conventional clients with an Ethernet interface can be connected to mesh routers via Ethernet links. For conventional clients with the same radio technologies as mesh routers, they can directly communicate with mesh routers. If different radio technologies are used, clients must communicate with their base stations that have ethernet connections to mesh routers.

In addition to mesh networking among mesh routers and mesh clients, the gateway/bridge functionalities in mesh routers enable the integration of WMNs with various other networks. Seeking the path with the maximum available bandwidth is one of the fundamental issues for supporting QoS in the wireless mesh networks. The available path bandwidth is defined as the maximum added rate a flow can push before saturating its path Therefore, if the traffic rate of a new flow on a path is no greater than the available bandwidth of this path, accepting the new traffic will not violate the bandwidth guaranteed of the existing flows. This paper focuses on the problem of identifying the maximum available bandwidth path from a source to a destination, which is also called the Maximum Bandwidth Problem (MBP). MBP is a subproblem of the Bandwidth-Constrained Routing Problem (BCRP), the problem of identifying a path with at least a given amount of available bandwidth [3]. In the literatures, maximum offered bandwidth path is also called widest path. Finding the widest path between the source and the destination in wireless networks is very challenging due to the wireless transmission interference. Generally speaking, there are two types of interference: interflow interference and intraflow interference [2], [4]. Interflow interference refers to the situation that the resource available for a flow is affected by the presence of other flows.

In other words, the interflow interference affects the amount of lasting channel resources on each link that can be allocated for a new flow.The work in [5] gives how to estimate the available bandwidth (residual channel resources) of each link. It means that if the link has to carry another 1-hop flow without mocking the bandwidth guarantees of existing flows, the rate of this flow can be at most the available bandwidth of the link. On the other hand, intraflow interference refers to the scenario where when a data packet is being transmitted on a link along a path, some link along the path has to remain sleepy to avoid conflict. Intraflow interference dodges the process of developing hop-by-hop routing protocol for finding widest paths. Considering intraflow interference, the works in [2] and [6] present a formula to compute the available bandwidth of a path with the knowledge of the available bandwidth on precise links of the path.

II. RELATED WORKS

To identify the widest path, many researchers develop new path weights, and the path with the minimum/maximum weight is assumed to be the maximum available bandwidth path. In [9] and [10], the expected transmission count (ETX) metric was proposed. The ETX of a link is the anticipated number of data transmissions required to send a packet over that link, which is estimated by proactively sending a dedicated link probe packet periodically. The ETX of a path is the sum of the ETX metrics of all links on this path. It is the earliest link metric developed and many other metrics are extended from it [11]. ETT [12] is an improved version of ETX that also considers the effect of packet size and raw data rate on the links because of the use of multiple channels. In this paper, we consider the single-channel wireless mesh networks, and assume that the raw data rates of all the links are the same, as well as all the packets are of the same size. In this case, ETT is the same as ETX. Several other metrics, such as iAWARE [13], IRU [14], and CATT[15], are all extended from ETT. iAWARE is the ETT metric adjusted based on the number of the interference links and the existing traffic load on the interference links. IRU is the ETT metric weighted with the number of the interference links, while CATT extends IRU by considering the effect of packet size and raw data rate on the links because of the use of multiple channels. Some existing QoS routing protocols operate with the knowledge of the available bandwidth of each link [2], [4], [6], [16], [17], [18], [19]. These works study how to compute the available bandwidth of a path based on the available bandwidth of each link on this path. Liu and Liao [17] give a new link metric which is the available bandwidth of the link divided by the number of interference links of this link. The path bandwidth is thus defined as the minimum value of the new metrics of all the links on this path. In the mechanism described in [18], the available bandwidth of a path is the minimum bandwidth among the links on the path divided by 2, 3, or 4, depended on the number of hops on the path. Such formula cannot reflect the exact path bandwidth. The path selection processes in [4], [19], [20], [21], and [22] assume the bandwidth requirement of a connection request is known.

The metric proposed in [4] is based on the bandwidth requirement of a certain request. The protocol in [19] checks the local available bandwidth of each node to determine whether it can satisfy the bandwidth requirement. Some works [20], [21], [22] consider the TDMA-based MAC model and discuss how to assign the available time slots on each link for a new flow in order to satisfy the bandwidth requirement of the new flow. Former studies [2], [6], [16], [23], [24], [25], [26] discuss how to estimate the available bandwidth of a given path. They all apply the clique-based path bandwidth computation method. Zhai and Fang [23], Jia et al. [24], Kordialam and Nandagopal [25] give the formula to compute the exact available bandwidth of a path, which cannot be solved in polynomial-time, because the problem is NP-complete in nature [23], [26]. Even though we can find the available bandwidth of a given path, it is not easy to identify a schedule that achieves that bandwidth since the scheduling problem is also NP-complete [22]. In other words, finding the available bandwidth on any kind of MAC model is NPcomplete [3]. The works in [2] and [6] developed another formula to approximately compute the available bandwidth of a path. We will show that the bandwidth calculated by this formula can be easily achieved. In other words, we can find a simple scheduling mechanism to achieve the bandwidth calculated by the formula in [2] and [6].

However, all these works do not consider the problem of providing bandwidth guarantees. Given a request with the bandwidth requirement, we cannot determine whether the best path selected by using these proposed metrics can support the request. In fact, packet loss based metrics such as ETX and its extensions do not always provide correct information for identifying high throughput paths [10]. The authors in [10] develop a centralized mechanism to compute the available bandwidth of a path and this metric performs better than other loss-based metrics compared.Much attention has been paid to the problem of finding routes with bandwidth concerned in wireless ad hoc networks [15]-[21]. The works in [15, 16, 17] consider the effect of the interference of wireless communications, and their works are all based on the TDMA channel model. The choice of MAC would affect the overall bandwidth utilization of the network, and different QoS routing schemes should be adopted for different MAC protocols. [18]-[21] study QoS routing in 802.11 wireless networks. The mechanisms in [18, 19, 22] are based on the AODV protocol, which is a reactive approach.However, a feasible path may not be identified even if it does exist in the network. The work in [21] proposes a polynomial-time routing algorithm that considers bandwidth requirements. This algorithm requires a FIFO scheduling policy, in which all the packets contending the common channel are prioritized based on their arrival time where the highest priority packet seizes the channel first. Ref. [20] also considers how to find the path that provides the maximum bandwidth. We mentioned earlier that if a node just advertises one path to its neighbors, its neighbors may not be able to identify the maximum available bandwidth path. In [20], each node keeps multiple paths to a destination so as to increase the probability of finding the best path from each node to a destination. All of these mechanisms are not distributed in nature and cannot be used directly in a hop-by-hop manner. A heuristic method for computing the maximum bandwidth path was proposed in [23]. In this work, the bandwidth of a link is defined as the minimum of the bandwidth for all links which interfere with this link, and the bandwidth of a path is defined as the minimum of the bandwidth for all links on this path. We can easily develop a hop-by-hop routing protocol by using this method. However, this method cannot guarantee that the found path can satisfy a certain bandwidth requirement. To the best of our knowledge, we are the first to develop a hop-by-hop routing protocol with bandwidth guarantees.

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III. PRELIMINARIES

In this section, we give the overview of the clique-based method for computing the available path bandwidth. Lots of the existing works [2], [6], [23], [24], [25], [26], [27], [28] apply the link conflict graph (or conflict graph for short) to reflect the interference relationship between links. A link in the wireless network becomes a node in the link conflict graph. If two links in the wireless network interfere with each other, we put a link between the corresponding nodes in the link conflict graph. We use an example in [23] to illustrate the link conflict graph. Fig. 2a shows a five-link chain topology. The numbers on the links are the ids of the links. The link conflict graph of the network is shown in Fig. 2b. Links 1 and 2 interfere with each other since node b cannot send and receive simultaneously. Links 1 and 3 interfere with each other since the signal from c is strong enough to interfere the reception at b. Therefore, there are links between 1 and 2 as well as 1 and 3 in the conflict graph. Assume that links 1 and 4 do not interfere because the signal from d cannot affect b in successfully receiving the signal from a. Then, there is no link between 1 and 4 in Fig. 2b.

An interference clique is the set of links which interfere with each other. In the conflict graph, the corresponding nodes of these links form a complete subgraph. In Fig. 2b, {1, 2}, {1, 3}, {1, 2, 3}, and {3, 4, 5} are interference cliques. A maximal interference clique is a complete subgraph that is not contained in any other complete subgraph. For instance, {1, 2, 3} and {3, 4, 5} are maximal cliques while {1, 2} and {1, 3} are not maximal cliques. In this work, we consider single-channel single-rate wireless networks, and so the original capacity of each link is the same, denoted by C. By finding all the maximal cliques, the maximum available bandwidth of path p can be found.However, finding all maximal cliques is NP-complete [23], [26]. Moreover, it is difficult to find a scheduling mechanism to achieve the maximum available bandwidth. In the following, we describe another mechanism to approximately compute the maximum available bandwidth of a path, and there exists a simple scheduling to achieve the estimated bandwidth. The available bandwidth of the path is the bandwidth of the bottleneck clique.

IV. PROPOSED SYSTEM

In this section, we first present our path selection mechanism. It is based on the distance-vector mechanism. We give the necessary and sufficient condition to determine whether a path is not worthwhile to be advertised. We then describe our new isotonic path weight. We show that the routing protocol based on this new path weight satisfies the optimality requirement. Afterward, we present our hop-by-hop packet forwarding mechanism which satisfies the consistency requirement. We apply to estimate the available bandwidth of a path. To simplify our discussion, in the rest of our paper, we use “available bandwidth” instead of “estimated available bandwidth” when the context is clear. On the other hand, “widest path” refers to the path that has the maximum estimated available bandwidth.

A. Path Selection

We would like to develop a distance-vector based mechanism.In the traditional distance-vector mechanism, a node only has to advertise the information of its own best path to its neighbors. Each neighbor can then identify its own best path. We mentioned that if a node only advertises the widest path from its own perspective, its neighbors may not be able to find the widest path. Infact,the abovetwochallenges mean that a correctrouting protocol should satisfy the optimality requirement and consistency requirement To illustrate, consider the network in Fig. 1 where the number of each link is the available bandwidth on the link.

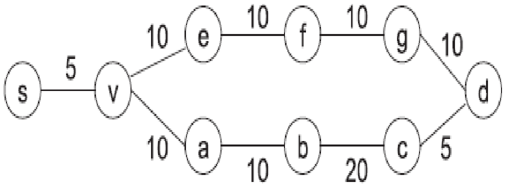

Fig. 1. An example of network topology.

In order to assure that the widest path from each node to a destination can be identified, a trivial way is to advertise all the possible paths to a destination. This is definitely too expensive. On the other hand, as long as we advertise every path which is a subpath of a widest path (e.g., <v, a, b, c, d> is a subpath of the widest path of <s, v, a, b, c, d>), we allow every node to identify its own widest path. Thus, to reduce the overhead, we should not advertise those paths that would not be a subpath of any widest path. In this section, we study the sufficient and necessary condition for a node to determine whether a path must not be the subpath of any maximum bandwidth path.

We first introduce some notations. The bandwidth of the link from a to b is B(a, b). Given a path p=<v1,v2,...,vh>,let WB(p)=B(p), FB(p)=B(v1,v2), TB(p)=WB(<v1,v2,v3>), and HB(p) = WB(<v1, v2, v3, v4). In other words, WB(p) is the bandwidth of the whole path, FB(p) is the bandwidth on the first link, TB(p) is the bandwidth of the subpath composed of the first two links, and HB(p) is the bandwidth of the subpath composed of the first three links. We further denote the concatenation of paths p1 and p2 as p1 EXOR p2.

B. Isotonic Path Weight

In this section, we introduce our new isotonic path weight, while the next section describes how we use the path weight to construct routing tables. The isotonicity property of a path weight is the necessary and sufficient condition for developing a routing protocol satisfying the optimality and consistency requirements. Left-isotonicity The quadruplet (S, EXOR, ῶ, ≥) is left-isotonic if w(a)≥w(b) implies w(c EXOR a) ≥ w(c EXOR b), for all a, b, c € S, where S is a set of paths, EXOR is the path concatenation operation, w is a function which maps a path to a weight, and is ≥ the order relation. Given two paths p1 and p2 from a node s to d, assume that p1 is better than p2 by comparing their weights. If the path weight used is left-isotonic, Definition 2 tells us that, given any path p` from a node v to s, p`EXOR p1 must be better than p`EXOR p2. Now, we present the proposed left-isotonic path weight, called composite available bandwidth (CAB).

C. Table Construction and Optimality

The isotonicity property of the proposed path weight allows us to develop a routing protocol that can identify the maximum bandwidth path from each node to each destination. In particular, it tells us whether a path is worthwhile to be advertised, meaning whether a path is a potential subpath of a widest path. In our routing protocol, if a node finds a new nondominated path, it will advertise this pathinformation to its neighbors. We call the packet carrying the path information the route packet. For each nondominated path p from s to d, s advertises the tuple (s, d, NF(p), NS(p), NT(p)) to its neighbors in a route packet. NF(p), NS(p), and NT(p) are the next hop, the second next hop, and the third next hop on p from s, respectively. Based on the information contained in a route packet, each node knows the information about the first four hops of a path identified. This information is necessary for consistent routing.

Each node keeps two tables: distance table and routing table. Node s puts all the non-dominated paths advertised by its neighbors in its distance table. It keeps all the non-dominated paths found by s itself in its routing table. When s receives an advertisement (u, d,NF(p), NS(p),NT(p)) from u which represents a non-dominated path p from u to d, s removes all the locally recorded paths from u to d which are dominated by p. Denote p` as the path from s to d which is one-hop extended from p.

By comparing ῶ (p`) with the CABs of the paths from s to d in the routing table, s can determine whether p` is a non-dominated path and remove the paths that are dominated by p`. If p` is a nondominated path, s generates an advertisement (s, d, u, NF(p), NS(p)).

It illustrates the distance table of node a in Fig. 6b.Based on its distance table, a knows that there are two nondominated paths from b to destination d. Path <b, v, e, d> has a CAB of (60, 11 , 60,11 , 6, 10) and path <b, v, c, d>`s CAB is (5, 5, 20 3 , 10). Based on the two non-dominated paths from b to d, a finds two non-dominated paths from itself to d and puts the information in the routing table. Table 2 illustrates the routing table of a. NU(p) denotes the fourth next hop on p. For each path p, the source keeps the subpath of the first four hops on p. NF(p) is the neighbor that sent the nondominated path to a. NS(p), NT(p), and NU(p) are the NF(p`), NS(p`), and NT(p`), respectively, where p` is the nondominated path used to construct p.

We have proved that our routing protocol satisfies the optimality requirement, meaning a node can definitely identify a widest path to every destination through advertisement from its neighbors. However, it is not sufficient to ensure a packet does traverse over the widest path. We need a consistent hop-by-hop packet forwarding mechanism to send a packet along the intended route of the sender. The consistency property also ensures loop-free routing. Some existing QoS routing protocols operate with the knowledge of the available bandwidth of each link.

```
Procedure QoS_ Update of Node s
/*
S receives advertisement(u, d, NF(p), NS(p), NT(p), $\tilde{\omega}(p)$)
*/
for each path p1 from u to d in the distance table of s do
    if $\tilde{\omega}(p) > \tilde{\omega}(p1)$ then
        Remove p1 from the distance table
p` ← <s, u> EXOR p
Calculate $\tilde{\omega}$ (p`) using (7)
for each path p2 from s to d in the routing table of s do
    if $\tilde{\omega}(p`) > \tilde{\omega}(p2)$ then
        Remove p2 from the routing table
    else
        if $\tilde{\omega}(p2) > \tilde{\omega}(p`)$ then
            return
Add (s, d, u,NF(p), NS(p), NT(p), $\tilde{\omega}(p`)$) in the routing table
Advertise (s, d, u;NF(p), NS(p), $\tilde{\omega}(p`)$)
```

D. Packet Forwarding and Consistency

Suppose that node s wants to transmit traffic to d along the widest path p = <s, v1,…,vn, d>. Then, each node vi on this path should make the consistent decision so that the traffic does travel along p. However, as mentioned earlier in Example, the widest path from vi to d may not be a subpath on p. If vi selects the next hop according to its widest path to d, the traffic may not be sent along the best path from s to d. In this section, we present the consistent hop-by-hop packet forwarding mechanism.

In a traditional hop-by-hop routing protocol, a packet carries the destination of the packet, and when a node receives a packet, it looks up the next hop by the destination only. In our mechanism, apart from the destination, a packet also carries a Routing Field which specifies the next four hops the packet should traverse. When a node receives this packet, it identifies the path based on the information in the Routing Field. It updates the Routing Field and sends it to the next hop.

In our packet forwarding mechanism, each intermediate node determines the fourth next hop but not the next hop as in the traditional mechanism. Our packet forwarding mechanism still requires each intermediate node to make route decision based on its routing table. Besides, only the information of the first few hops of a path is kept in the routing table in each node and the routing field in a packet. Therefore, our mechanism possesses the same characteristics of a hop-by-hop packet routing mechanism, and is a distributed packet forwarding scheme.

We can see that the space complexity and the advertisement complexity of our routing protocol are directly related to the number of nondominated paths from each node to each destination. Denote A as the average number of the neighbors of each node. Since there is only one non dominated path going through the same first three links, the maximum number of nondominated paths from each node to a destination is O(A3). Therefore, our mechanism is a polynomial-time routing algorithm for computing the maximum throughput path.

Note that the consistency discussed in the above assumes that each node has the accurate state information about its neighbors. Route update may also cause inconsistency, as discussed later. However, such inconsistency is independent on which routing metric or what kind of the packet forwarding mechanism is applied, while it is completely due to the delay of the route update propagation. Therefore, such inconsistency exists in all distributed routing protocols.

E. Route Update

After the network accepts a new flow or releases an existing connection, the local available bandwidth of each node will change, and thus the widest path from a source to a destination may be different. When the change of the local available bandwidth of a node is larger than a advertise the new information to its neighbors. After receiving the new bandwidth information, the available bandwidth of a path to a destination may be changed. Although the node is static, the network state information changes very often. Therefore, our routing protocol applies the route update mechanism in DSDV . Based on DSDV, each routing entry is tagged with a sequence number which is originated by the destination, so that nodes can quickly distinguish stale routes from the new ones. Each node periodically transmits updates and transmits updates immediately when significant new route information is available. Given two route entries from a source to a destination, the source always selects the one the larger sequence number, which is newer, to be kept in the routing table. Only if two entrieshave the same sequence number, our path comparison is used to determine which path should be kept.

V. CONCLUSION

In this paper, we studied the maximum available bandwidth path problem, which is a ultimate issue to upkeep quality-of-service in wireless mesh networks. The main impact of our work is a new left-isotonic path weight which captures the existing path bandwidth information. The left-isotonicity property of our proposed path weight aids us to develop a proactive hop-by-hop routing protocol, and we formally proved that our protocol satisfies the optimality and consistency requirements. Based on the available path bandwidth information, a source can immediately determine some infeasible connection requests with the high bandwidth requirement.

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