Hop- by-Hop Routing in Wireless Mesh Networks with Bandwidth Guarantees

P.Rajani[1], P.K.Sahu2
1.M.Tech Scholar,Department of Computer Science and Engineering,
Aditya Institute of Technology and Management,Tekkali-532 201,Srikakulam(dt),A.P.,India.
E-mail:rajanipatri545@gmail.com
2. Associate Professor ,Department of Computer Scince and Engineering,
Aditya Institute of Technology andManagement,Tekkali-532 201,Srikakulam(dt),A.P.,India.
E- mail- promod_sahu@yahoo.com

Abstract—Remote Mesh Network (WMN) has turned into a vital edge system to give Internet access to remote regions and remote associations in a metropolitan scale. In this paper, we contemplate the issue of distinguishing the greatest accessible transfer speed way, a basic issue in supporting nature of-administration in Wmns. Because of impedance among connections, transmission capacity, a well-known bottleneck metric in wired systems, is not curved or added substance in remote systems. We propose another way weight which catches the accessible way data transfer capacity data. We formally demonstrate that our jump by-bounce steering convention focused around the new way weight fulfills the consistency and circle freeness necessities. The consistency property ensures that every hub settles on a legitimate bundle sending choice, so that an information parcel does navigate over the expected way. Our broad recreation explores likewise demonstrate that our proposed way weight beats existing way measurements in recognizing high-throughput ways.

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

1. INTRODUCTION

Wireless mesh network (WMN) includes numerous wifi nodes. The nodes form a radio overlay to pay the support region although a number of nodes tend to be “cable “to the World wide web. As part of the World wide web, WMN has to service varied hiburan applications because of its users. It is important to supply effective Quality-of-Service (QoS) service within this type of cpa networks [1]. Trying to find the path while using maximum offered bandwidth is among the fundamental issues intended for promoting QoS inside wifi mesh cpa networks. The offered path bandwidth pertains to the utmost additional charge a flow can push previous to saturating it's path [2]. As a result, if your targeted visitors charge of your new flow with a path isn't any in excess of the offered bandwidth with this path, receiving the brand new targeted visitors won't violate the bandwidth guaranteed in the present streams. These specific papers targets on the condition associated with identifying the utmost offered bandwidth path from a supplier to some location, that's also called the Optimum Bandwidth Trouble (MBP). MBP is often a sub problem in the Bandwidth-Constrained Routing Trouble (BCRP), the condition associated with identifying a path together with at the very least confirmed quantity of offered bandwidth [3]. From the literatures, maximum offered bandwidth path is also referred to as broadest path. Within these papers, all of us use these conditions interchangeably.

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 describes the situation which the reference available for a new stream is affected by your occurrence associated with some other flows. Quite simply, your interflow interference affects the quantity of left over route re-sources in each website link which can be allocated for the fresh stream. The job throughout [5] offers the way to calculate your offered bandwidth (residual route resources) of website link. This means if the url has got to have yet another 1-hop stream without violating your bandwidth helps ensure associated with present flows, your charge of this stream is usually at your offered bandwidth from the website link. Alternatively, intraflow interference describes your situation where by every time a facts packet has been carried using a website link together a new course, some website link along the course has got to remain nonproductive in order to avoid clash. Intraflow interference complicates the method associated with developing hop-by-hop course-plotting standard protocol pertaining to discovering largest pathways. Unfortunately, finding widest path in a hop-by-hop manner is still not solved. The unique structure of the path bandwidth computation formula introduces two challenges described below:

1. Some nodes may not find the widest path if only the available bandwidth is used as the routing metric.
2. Despite the fact that a beginning hub locates a largest way to a goal, moderate hubs on the amplest way may not settle on a steady bundle sending choices by utilizing the conventional end of the line based jump by-bounce parcel sending system.

For example, in Fig. 1, according to the formula in [2] and [6] (will be described in detailed later), the upper path from v to d has a larger available bandwidth than the lower path from v to d. Nevertheless, by the formula in [2] and [6], the lower path from s to d is better in terms of available bandwidth. According to the traditional distance vector protocol, node v just advertises the upper path information to its neighbors, so that node s cannot obtain the widest path from itself to d. Even s identifies the lower path to d which has the larger available bandwidth, the problem is not solved. When node v receives the data packet from s, it will forward the packet to e but not to a by using the traditional destination-based hop-by-hop routing, since the upper path from v to d has the larger available bandwidth. That is, the data packet actually does not traverse on the widest path from s to d.

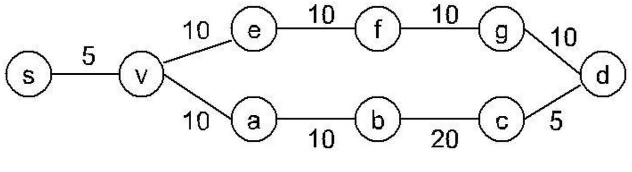


Fig. 1.An example of network topology

In fact, the above two challenges mean that a correct routing protocol should satisfy the optimality requirement and consistency requirement. The key for designing such routing protocol is to develop an isotonic routing metric. Interested readers can refer to [7] and [8] for the detailed discussion.

In this work, we study how to perform routing in the 802.11-based WMNs and make the following contributions.

We propose a new path weight that captures the concept of available bandwidth. We give the mechanism to compare two paths based on the new path weight. We formally prove that the proposed path weight is left-isotonic.

We describe how to construct the routing table and distance table, and we develop a hop-by-hop packet forwarding scheme. We formally prove that our routing protocol satisfies the optimality and consistency requirements.

Finally, we implement our routing protocol based on the DSDV protocol in the NS2 simulator. The extensive simulation experiments demonstrate that our routing protocol outperforms the existing routing protocols for finding the maximum available bandwidth paths.

The rest of the paper is organized as follows: After describing the related works in Section 2, we explain how to compute the available bandwidth on a path in Section 3. Section 4 describes our hop-by-hop routing protocol in details, and Section 5 presents our extensive simulation results. We finally conclude our paper in Section 6.

2. 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 predicted 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.

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 NP-complete [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]. In this work, we will apply the mechanism in [2] and [6] to estimate the available bandwidth of a given path. Although a formula is developed in [2] and [6], the authors did not provide a packet forwarding mechanism to assure that the data packet traverses over the estimated widest path from the source to the destination. Our main goal is to develop a practical routing protocol that allows packets to go through the estimated widest path.

QoS support in multihop wireless networks has been studied from the cross-layer design perspectives. Zhang and Zhang [1] give a comprehensive review for the current study on the cross-layer paradigm for QoS support in multihop wireless networks. Contrary to the cross-layer mechanism, our protocol performs over the practical 802.11 MAC protocol, and so our routing protocol can be easily incorporated in the current wireless devices.

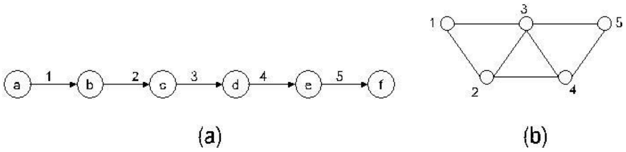


Fig. 2.Illustration for interference model.(a) The original graph, (b) The conflict graph.

3. 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 sub graph. In Fig. 2b, {1, 2}, {1, 3}, {1, 2, 3}, and {3, 4, 5} are interference cliques. A maximal interference clique is a complete sub graph that is not contained in any other complete sub graph. 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. Denote fQ$_1$;. . .; Q$_K$g as the maximal interference clique set of the network. The work [25] introduces the following lemma.

Lemma 1.Denotes a link flow vector, wherefðeÞis the aggregate data rate of the flow on link e. If f does not satisfy the following inequalities then f is not schedulable.

$$\sum_{e\in Q_k} f(e) \le C, \quad \forall k, \tag{1}$$

Lemma 1 gives the method to compute the theoretical available bandwidth of a path. Given a path p=<v$_1$;v$_2$, . . . ,v$_h$>, we first find the set of the maximal cliques {S$_1$; S$_2$; . . . ; S$_M$ }such thatS$_m$ ∩ p 6¼ _for all m = 1, . . . , M.Denote $f_{sum,m}$ as the total current data rate of the flows on all the links of the maximal clique S_m and $|S_m \cap p| = k_m$. Equation (1) implies that the maximum additional data rate r on path p should satisfy the condition that $k_m r \le C - f_{sum,m}$ for all m=1,. . ., M. The rationale behind this constraint is that the aggregate additional data rates on all links in the maximal clique S_m should be less than $C-f_{sum,m}$ in order to avoid conflict. 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.

Given a path p=<v_1; v_2;. . .; v_h>, based on the current flows on each link in the network, denote B(e) as the available bandwidth of link e. It means that if a new connection only needs to go through link e, e can send at most B(e) Kbits amount of information in a second without affecting existing flows. The work in [5] described how to obtain B(e), and the following discussion assumes B(e) is known. Note that the bit error rate of a link is considered in the link estimator, and thus the available bandwidth of each link becomes the expected available link bandwidth [23]. Denote Q_p as the set of the maximal cliques containing only the links on p. Generally speaking, if two links on apath interfere with each other, all the links between them along the path conflict with each other [23]. This implies that it is easy to find Q_p for path p. The available bandwidth of path p is estimated as follows [5], [6]:

Applying the hop count to approximate the distance will introduce some error for computing the estimated available path bandwidth. An example in [23] illustrates this situation. In Fig. 3, if node a is in the interference range of g, then link 1 interferes with 7. Assume that each link has the same available bandwidth B, the available bandwidth of this path is actually $^{2}{}_{7}$B, while it is computed as $^{1}{}_{3}$B by using (2). Jia et al. [23] calls p a detour route, and other paths are called direct routes. Similar to [6], [18], [22], and [23], we do not consider detour routes when computing the available path bandwidth.

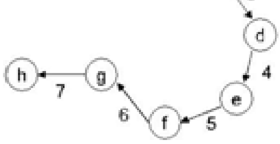
Both the conflict graphs in Figs. 2b and 3 assume r¼1, which is not the TRCA interference model we are using in this paper. In Fig. 2a, under the TRCA model, when a sends data to b, d is not allowed to transmit since it is in the interference range of b. This means that links 1 and 4 interfere with each other under the TRCA interference model. Then, each maximal clique contains four consecutive links. Based on the link bandwidth values in Example 1, if we apply the TRCA interference model, the estimated available band-

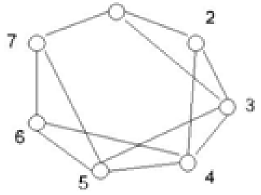
width of path <a; b; c; d; e> is ð$_{50}{}^{1}$þ$_{100}{}^{1}$þ$_{25}{}^{1}$þ$_{20}{}^{1}$Þ$^{-1}$¼$\frac{25}{3}$, — —
which is less than the available bandwidth calculated in Example 1. Given a path p¼<v_1; v_2;. . .; v_h>, let BðkÞ be the estimated available bandwidth on the link between v_k and $v_{kþ1}$. Under the TRCA interference model, the formula for estimating the available bandwidth of path p is as follows [6]:

$$B(p) = \min\nolimits_{1 \le k \le h-4} C_k,$$

$$C_k = \left(\frac{1}{B(k)} + \frac{1}{B(k+1)} + \frac{1}{B(k+2)} + \frac{1}{B(k+3)}\right)^{-1}. \qquad (3)$$

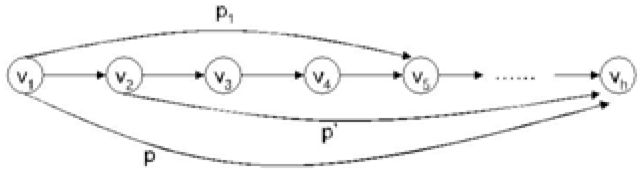
Given path p¼<v_1; v_2;. . .; v_h>, let p^0¼<v_2;. . .; v_h> and p_1 ¼ <v_1; v_2; v_3; v_4; v_5>, as illustrated in Fig. 4. We can easily verify that B(p)=min{B(p_1); B(p^0)}. This formula allows the estimated path bandwidth to be computed in a hop-by-hop manner. Although the works in [2], [6], and [16] apply this mechanism to compute the path bandwidth, no work has been found to propose an efficient path selection mechanism which satisfies the optimality requirement. That is, no existing protocol can provide the performance guarantee for finding the maximum available bandwidth path by using (3).





MESH NETWORK WITH BANDWIDTH GUARANTEES

Original graph conflict graph
Fig.3.an example in(23)



HOP-BY-HOP ROUTING WIRELESS

Fig .4.path bandwidth commutation in a hop-by-hop manner

In the following discussion, we assume that the interference range for each node is the same, which is modeled as 2-hop count. In practice, the interference range for different node may be different. The following discussion focuses on introducing a new way to design a routing metric with the isotonic property. We will not mention the case that the interference ranges are different for different nodes due to the space limitation. Actually, our protocol can be easily extended for this case.

4. QOS ROUTING PROTOCOL

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 [7], [8]. Afterward, we present our hop-by-hop packet forwarding mechanism which satisfies the consistency requirement. We apply (3) 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.

4.1 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. In Section 1, 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. To illustrate, consider the network in Fig. 1 where the number of each link is the available bandwidth on the link.
Theorem 2.Our routing protocol satisfies the optimality requirement.

Proof. We now prove that each node v_1 must find the maximum bandwidth path to destination v_n, denoted by
<v_1; v_2, . . . ,v_n>. Suppose that the widest path between $v_1$and v_n is unique, we now prove that each on-path node v_i must advertise the information of the sub path<v_i, . . . , v_n>to v_{i_1}, where i = 2, . . . , n - 1, by induction.

As the basic step, since v_{n_1} is a direct neighbor of v_n, it must advertise the information of path <v_{n_1}; v_n> to v_{n-2}.

For the inductive step, assume that v_k advertises the information of path <v_k,. . ., v_n> to v_{k_1}. If v_{k_1} does not advertise path p_1=<v_{k_1},v_k,. . ., v_n> to v_{k_2}, there must exist a path p_2=<v_{k_1}, g_1, g_2,. . ., g_m, v_n> which

dominatesp$_1$. We thus have. Denote p=<v_1; . . . ; v_{k_1}>. By Theorem 1 and Definition 2, we have

. This means p - $p_2$has larger available bandwidth than path <v_1;. . .; v_n>, which implies that <v_1;. . .; v_n> is not the maximum bandwidth path, which leads to contradiction.

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 [7].

```
Procedure QoS Update of Node s
/*
receives advertisement $(u, d, \mathrm{NF}(p), \mathrm{NS}(p), \mathrm{NT}(p), \vec{\omega}(p))$
for each path p1 from u to d in the distance table of s do
    if $\textbf{if } \vec{\omega}(p) \succ \vec{\omega}(p_1)$ then
        Remove p1 from the distance table
        $p' \leftarrow <s, u> \oplus p$
        Calculate $\vec{\omega}(p')$ using (7)
        for each path p2 from s to d in the routing table of s do
            if $\vec{\omega}(p') \succ \vec{\omega}(p_2)$ then
                Remove p2 from the routing table
            else
                if $\vec{\omega}(p_2) \succeq \vec{\omega}(p')$ then
                    return
        Add ðs; d; u;NFðpÞ; NSðpÞ;NTðpÞ;~!ðp0ÞÞ in the routing table
        Advertise ðs; d; u;NFðpÞ; NSðpÞ;~!ðp0ÞÞ
```

4.2 *Packet Forwarding and Consistency*

Suppose that node s wants to transmit traffic to d along the widest path p=<s; v_1,. . ., v_n, d>. Then, each node v_i on this path should make the consistent decision so that the traffic does travel along p. However, as mentioned earlier in Example 2, the widest path from v_i to d may not be a subpath on p. If v_i 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.

For example, assume that node s in Fig. 6b wants to send a packet to d. In the previous section, we know that there is one entry $(s, d, a, b, v, c, (\frac{20}{7}, \frac{10}{3}, 5, 10))$ in the routing table of s. By looking up the routing table, the Routing Field <a; b; v; c> will be put in the packet. The packet is sent to the next hop a. When a receives the data packet from s, it knows that the packet should traverse over subpath <a; b; v; c>. Thus, it locates the path p where NF(p)=b and NS(p)=v and NT(p)= c in its routing table. Table 2 shows that the nextfour hop of the path going through <a, b, v, c> is NU(p)=d. Then, it updates the Routing Field to <b, v, c, d> and sends it to b. We can see that the data packet does traverse over the widest path from s to d in this example.

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 character-istics of a hop-by-hop packet routing mechanism [7], and is a distributed packet forwarding scheme.

5. PERFORMANCE EVALUATION

In this section, we conduct the simulation experiments under NS2 [30] to investigate the performance of our routing protocol for finding the maximum available bandwidth path. We compare our proposed path weight, Composite AvailableBandwidth, with some existing path weights.

5.1 *Routing Metrics*

The earliest metric proposed for finding the maximum available bandwidth path is ETX [10]. The ETX metric of each link l is defined as ETX_l =1/p_l , where p_l denotes the packet loss probability on link l at the MAC layer. p_l is estimated by proactively broadcasting the dedicated link probe packets. Couto et al. [10] give the details on how to calculate p_l. In our simulation, we completely follow the instructions presented in [10] to compute p_l. As we consider single-channel networks in this work, we would not compare with metrics that are developed for the multi-channel situation, such as ETT [12]. Another metric we compare is the Interference-aware Resource Usage (IRU) proposed in [14], which is defined as IRU_l¼ETX_jN$_l$j, where N_l consists of the neighbors whose transmission interfere with the transmission on link l. Because we assume all data packets have the same size and all the links have the same raw data rate, the performance of IRU is the same as the performance of the CATT metric proposed in [15].

5.2 *Simulation Settings*

Unless otherwise stated, the simulation experiment setup is as follows: The MAC layer protocol is IEEE 802.11 with RTS/ CTS. The radio transmission range and the carrier-sensing range (interference range) are 250 and 550 m, respectively. The bandwidth of the wireless channel is 1 Mbps. All the traffics are CBR flows with the packet size of 1,000 Bytes. The bit error rate of each channel is zero.

In order to simulate different link available bandwidths, we generate some background traffic which takes up the capacities of the links by randomly deploying some one-hop flows in the network. The data rates of the one-hop flows follow the uniform distribution Uð1;20Þ Kbps. After accept-ing all these one-hop flows, the available bandwidth of each link is different. Each destination then initiates the path computation process to compute the best paths from all the other nodes to itself in the network. When a node receives a connection to a destination, it has the widest path to the destination kept in its routing table. We then randomly select a pair of nodes which are not direct neighbors. A CBR traffic is then established between this pair of nodes. This traffic is called a new flow or a multihop flow to differentiate with the existing background one-hop flows.

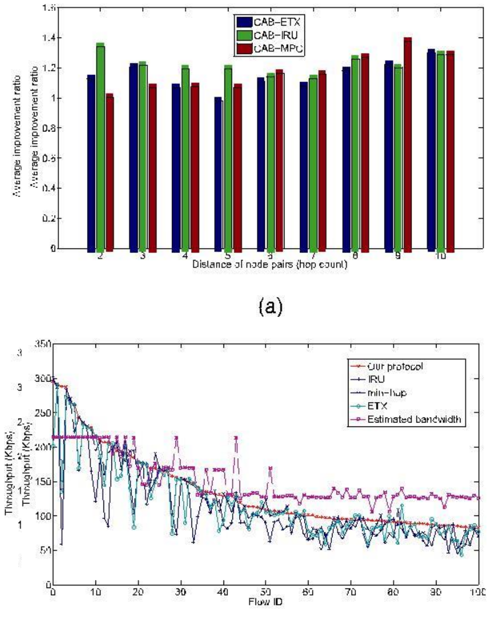
When the traffic rate of the multihop flow is larger than the actual available bandwidth of the best path, accepting the new flow will violate the bandwidth guarantees of the existing flows. In our simulation, in order to reserve enough bandwidth resources for the existing flows, we always let an existing flow have a higher priority to use a link that a node always transmits the higher priority packet before a lower priority one. We set the buffer size of each node to be 50 packets.

To understand whether the priority mechanism works, we study the throughput of the existing flows before and after a new flow is introduced. For example, in one instance of the simulation, we randomly deploy 200 one-hop flows in the network, where there are around 400 links in total. The total throughput of these one-hop flows is 4.1882 Mbps. We then select a pair of nodes that are farthest apart in terms of hop count in the network. We apply our algorithm to find the widest path between this node pair, and push a flow of 300 Kbps, which is much larger than the available band-width, on this path. We measured the total throughput of the existing flows again and it is 4.1730

Mbps, while the throughput of the multihop flow is 62.385 Kbps. We can see that the new flow does not take up the capacity meant to be allocated for the existing flows. It means that we can almost fairly measure the actual throughput of the best paths found by the different algorithms under the condition that the bandwidth guarantee of the existing flows is not violated.

5.3 Simulation Results

In our simulation experiments, the random network topology was generated by the "setdest" tool provided in the NS2 simulator. We define the distance between two nodes as the minimum hop-count between them. For each possible node pair distance in a network, we randomly select some node pairs. For each node pair, our protocol (CAB), IRU, ETX, and the minimum hop count may find different paths between the node pair. Our protocol can also give an estimation for the available bandwidth of its own widest path. We then establish a new flow on the paths found by the algorithms, one at a time, to measure the throughput of the paths. The new flow has a data rate much larger than the available bandwidth of our widest path, so that we can obtain the maximum throughput supported by the path without violating the bandwidth guaranteed for the existing flows. We compare the throughput of the paths found by the different protocols to evaluate the perfor-mances of the different protocols for finding the maximum available bandwidth path. Denote B_{CAB}, B_{MPC}, B_{ETX}, B_{IRU} as the average throughput of the paths found by applying the CAB, minimum hop count, ETX, and IRU metrics, respectively. $\frac{{}^{B}\mathrm{CAB}}{{}^{B}\mathrm{MPC}}$, $\frac{{}^{B}\mathrm{CAB}}{{}^{B}\mathrm{ETX}}$, and $\frac{\mathrm{BCAB}}{{}^{B}\mathrm{IRU}}$ are called the improvement ratios of our new metric (CAB) with the minimum hop count, ETX, and IRU, respectively. The larger the improvement ratio, the better our new metric.



(a)

(b)

Fig. 7.100-node in 1,450m*1,450m. (a) Average improvement ratios, (b) Throughput of flows.

5.4 Simulation Results for Scenario 1

We first deploy 100 nodes in a 1,450m*1,450m square (denoted by TOP1). There are about 400 bidirectional links in the network. We randomly select 100 links and deploy the existing one-hop flows on them. We define the distance of a node pair as the minimum hop count between them. We randomly select 20 node pairs such that each node pair has the same distance. In this topology, we consider the distance of node pair from 2 to 10, and there are totally 120 multihop flows. Fig. 7a shows the average improvement ratios of our metrics with the existing metrics as a function of the distance of node pair. We can observe that almost all of the improvement ratios are larger than 1, which implies that our metric works the best for finding the high throughput path. We randomly select 100 multihop flows and investigate the throughput of individual flow produced by the different protocols. Fig. 7b shows the simulation results of the flows which are sorted according to the throughput of our protocol. This figure also shows the gap between the practical throughput and the estimated available bandwidth.

We first analyze the differences among different proto-cols. We can observe that ETX and IRU do not work well in some cases. For instance, the practical throughputs of flow ID 3 delivered by ETX and IRU are much less than that of our metric. Without considering the bit error rate of each channel, the packet loss probability can reflect the traffic load on each link to a certain degree. However, the path ETX or IRU is simply computed by summing the ETXs or IRUs of all the links on a path. Such calculation method causes ETX and IRU prefer the short path to the long path, such that ETX or IRU may select a low available bandwidth path. Although the practical throughput of the existing metric is higher than that of our metric for some particular flows, the difference is small. Therefore, our metric is relatively more efficient for finding the high-throughput path.

We now investigate why there is a difference between the practical throughput and the estimated available band-width. Fig. 7b shows that the practical throughput may be more than or less than the estimated one. First, according to [5] and the discussion in Section 3, our work develops an underestimate of the true available bandwidth. However, thetheoretical studies do not take into account of packet overheads and collisions in the MAC layer, which reduce the actual throughput in a real network. For example, we have measured the actual throughput of a four-node network where the distance between neighbor nodes is the same as the transmission range. The theoretical throughput is 250 Kbps but the actual is only 200 Kbps. We believe networks of larger scale would experience even more serious collisions. Another factor that leads to the practical throughput is less than the theoretical throughput is the assumption on interference range. We assume 2-hop interference but situations like Fig. 3 can happen. The practical throughput is thus smaller than the estimated path bandwidth. Our simulation results show that our approach gives an overestimation for almost all of the flows with large hop-count distance. By (3), path bandwidth is independent on the hop-count distance of the path. However, the longer the path, the larger the collision probability. Thus, the hop-count distance affects the practical throughput of a path. That is why (3) is likely to overestimate the bandwidth of a path with large distance.

5.5 Simulation Results for Scenarios 2 and 3

As the performance of our routing protocol depends on the background traffic, we change the background traffic in TOP1 to evaluate the performance of the routing protocols. In scenario 2, we let the data rates of the existing flows follow Uð1;30ÞKbps, and Fig. 8 shows the simulation experiments. In scenario 3, we let 150 links carry the existing flows, while the data rates of the existing flows still follow Uð1;20ÞKbps, and Fig. 9 shows the simulation results. As the background traffic load in scenario 2 increases, the available bandwidth for each flow may be lower than that in scenario 1. Comparing Figs. 7b and 8b, we can observe that the average throughput of our protocol in scenario 2 is lower than that in scenario 1. From Fig. 8a, we can observe that the average improvement ratio of our protocol to the min-hop count is very high when the distance of node pair is 6, 7, and 9. As the min-hop count does not consider the traffic load on each link, it is probably that the min-hop path has very lower available bandwidth. Therefore, considering the current traffic load information is very important for finding the high-throughput path. Generally, Figs. 7a, 8a, and 9a show that our protocol works the best for finding the high-throughput path with the different background traffic loads.

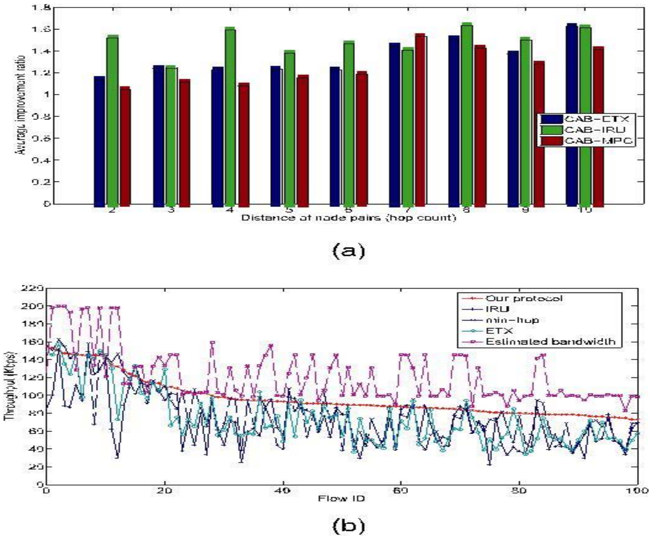
5.6 Simulation Results for Scenarios 4 and 5

We now study the effect of network topology. We deploy 100 nodes in a 1,000 m*1,000m square (denoted by TOP2) and deploy 200 nodes in a 2,000 m*2,000m square (denoted by TOP3). We randomly select select 100 and 230 links in TOP2 and TOP3, respectively, to carry background one-hop flows. Figs. 10 and 11 show the simulation results under both the network topologies. In TOP2, the maximum distance of node pair is 6, and the network is very dense. Fig. 10a shows that for a certain distance of node pair (say,6), the average improvement ratio in TOP2 is probably higher than that in TOP1. The average improvement ratio also depends on the network nopology. If there are many alternative paths between a node pair, there are lots of choices for our metric. On the other hand, if there is only one path between a node pair, we believe that any metric produces the same throughput. In network with larger node degree or larger number of nodes, there are many alternatives paths between a node pair, so that the difference among the different routing metrics is more significant. That is why the performance improvement of our protocol in TOP2 and TOP3 is more significant than that in TOP1. Figs. 10b and 11b show the practical throughput of individual flow in TOP2 and TOP3, respectively. Both figures show that our approach probably over estimates the pat bandwidth.

5.7 Simulation Results with Shadowing Model

In the previous simulation, we apply the two-ray ground propagation model, which is widely used in the existing works [2], [5], [6] for the long-range communication. We would like to use log-normal shadowing propagation model provided in NS2 to evaluate the performance of our protocol. The default transmission range in NS2 by applying shadowing model is about 20 m, and the work in [31] also applies the shadowing model for short-range communication. Our simulation experiments use the "threshold" tool in NS2 to calculate Rx Threshold (power threshold to correctly receive data) and CS Threshold (power threshold to sense transmission) so that the transmission range is 25 m while the carrier-sensing range is 55 m. The default value is used for other parameters. We deploy 100 nodes in a 145m*145m square. We randomly select 100 links to carry background flows.

With shadowing propagation model, the interference range cannot be simply represented by the distance. Fig. 12a shows the average improvement ratios for the different distance of node pair. Generally speaking, the simulation results show our protocol works better than the existing protocols. Therefore, our protocol works well under different propagation models. Fig. 12b shows the through-puts of 100 individual flows and the estimated path bandwidth calculated by our approach. With the shadow-ing model, a clique in Q_p of (2) is likely to contain three links but not four, such that (3) should underestimate the



(a)

(b)

Fig.12.100-node in 145 m*145 with shadowing Model.(a) averageimprovement (b)throughput of flows

6.CONCLUSION

In this paper, we studied the maximum available band-width path problem, which is a fundamental issue to support quality-of-service in wireless mesh networks. The main contribution of our work is a new left-isotonic path weight which captures the available path bandwidth information. The left-isotonicity property of our proposed path weight facilitates 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. We tested the performance of our protocol under different scenarios.

7.REFERENCES

[1] Q. Zhang and Y.-Q. Zhang, "*Cross-Layer Design for QoS Support in Multihop Wireless Networks*," Proc. IEEE, vol. 96, no. 1, pp. 234-244, Jan. 2008.

[2] T. Salonidis, M. Garetto, A. Saha, and E. Knightly, "*Identifying High Throughput Paths in 802.11 Mesh Networks: A Model-Based Approach*," Proc. IEEE Int'l Conf. Network Protocols (ICNP '07), pp. 21-30, Oct. 2007.

[3] C.-Y. Chiu, Y.-L. Kuo, E. Wu, and G.-H. Chen, "*Bandwidth-Constrained Routing Problem in Wireless Ad Hoc Networks*," IEEE Trans. Parallel and Distributed Systems, vol. 19, no. 1, pp. 4-14,Jan. 2008.

[4] J. Tang, G. Xue, and W. Zhang, "*Interference-Aware Topology Control and QoS Routing in Multi-Channel Wireless Mesh Networks*," Proc. ACM MobiHoc, pp. 68-77, May 2005.

[5] Y. Yang and R. Kravets, "*Contention-Aware Admission Control for Ad Hoc Networks*," IEEE Trans. Mobile Computing, vol. 4, no. 4, pp. 363-377, Apr. 2009.

[6] H. Li, Y. Cheng, C. Zhou, and W. Zhuang, "*Minimizing End-to-End Delay: A Novel Routing Metric for Multi-Radio Wireless Mesh Networks*," Proc. IEEE INFOCOM, pp. 46-53, Apr. 2009.

[7] Y. Yang and J. Wang, "*Design Guidelines for Routing Metrics in Multihop Wireless Networks*," Proc. IEEE INFOCOM, pp. 2288-2296, Apr. 2008.

[8] J.L. Sobrinho, "*Algebra and Algorithms for QoS Path Computa-tion and Hop-by-Hop Routing in the Internet*," Proc. IEEEINFOCOM, pp. 727-735, Apr. 2001.

[9] R. Draves, J. Padhye, and B. Zill, "*Comparison of Routing Metrics for Static Multi-Hop Wireless Networks*," Proc. ACM SIGCOMM, pp. 133-144, Sept. 2004.

[10] D. Couto, D. Aguayo, J. Bicket, and R. Morris, "*A High-Throughput Path Metric for Multi-Hop Wireless Routing*," Proc.ACM MobiCom, pp. 134-146, Sept. 2003.

[11] M. Campista, D. Passos, P. Esposito, I. Moraes, C. Albuquerque, D. Saade, M. Rubinstein, L. Costa, and O. Duarte, "*Routing Metrics and Protocols for Wireless Mesh Networks*," IEEENetwork, vol. 22, no. 1, pp. 6-12, Jan. 2002.

[12] R. Draves, J. Padhye, and B. Zill, "*Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks*," Proc. ACM SIGCOMM, pp. 114-128, Oct. 2004.

[13] A.P. Subramanian, M.M. Buddkihot, and S. Miller, "*Interference Aware Routing in Multi-Radio Wireless Mesh Networks*," Proc.Second IEEE Workshop Wireless Mesh Networks (WiMesh '06), pp. 55-63, Sept. 2006.

[14] Y. Yang, J. Wang, and R. Kravets, "*Designing Routing Metrics for Mesh Networks*," Proc. IEEE Workshop Wireless Mesh Networks(WiMesh '05), Sept. 2005.

[15] M. Genetzakis and V.A. Siris, "*A Contention-Aware Routing Metric for Multi-Rate Multi-Radio Mesh Networks*," Proc. FifthAnn. IEEE Comm. Soc. Conf. Sensor, Mesh and Ad Hoc Comm. and Networks (SECON '08), pp. 242-250, 2008.

[16] H. Li, Y. Cheng, and C. Zhou, "*Multi-Hop Effective Bandwidth Based Routing in Multi-Radio Wireless Mesh Networks*," Proc.IEEE Global Telecomm. Conf. (GlobeCom '08), pp. 1-5, Nov. 2008.

[17] T. Liu and W. Liao, "*Interference-Aware QoS Routing for Multi-Rate Multi-Radio Multi-Channel IEEE 802.11 Wireless Mesh Networks*," IEEE Trans. Wireless Networks, vol. 8, no. 1, pp. 166-175, Jan. 2009.

[18] L. Chen and W.B. Heinzelman, "*QoS-Aware Routing Based on Bandwidth Estimation for Mobile Ad Hoc Networks*," IEEE J. Selected Areas in Comm., vol. 23, no. 3, pp. 561-572, Mar. 2005.

[19] Q. Xue and A. Ganz, "*Ad Hoc QoS On-Demand Routing (AQOR) in Mobile Ad Hoc Networks*," J. Parallel and Distributed Computing, vol. 63, pp. 154-165, 2003.

[20] W. Liao, Y. Tseng, and K. Shih, "*A TDMA-Based Bandwidth Reservation Protocol for QoS Routing in a Wireless Mobile Ad Hoc Networks*," Proc. IEEE Int'l Conf. Comm. (ICC '02), pp. 3186-3190, Apr. 2002.

[21] K. Shih, C. Chang, Y. Chen, and T. Chuang, "*Dynamic Bandwidth Allocation for QoS Routing on TDMA-Based Mobile Ad Hoc Networks*," Computer Comm., vol. 29, pp. 1316-1329, 2006.

[22] C. Zhu and M.S. Corson, "*QoS Routing for Mobile Ad Hoc Networks*," Proc. IEEE INFOCOM, pp. 958-967, June 2002.

[23] H. Zhai and Y. Fang, "*Impact of Routing Metrics on Path*

[24] *Capacity in Multirate and Multihop Wireless Ad Hoc Networks*," Proc. 14thIEEE Int'l Conf. Network Protocols (ICNP '06), pp. 86-95, Nov. 2006.

[25] Z. Jia, R. Gupta, J. Walrand, and P. Varaiya, "*Bandwidth Guaranteed Routing for Ad-Hoc Networks with Interference Consideration*," Proc. IEEE Symp. Computers and Comm., pp. 3-9, 2005.

[26] M. Kordialam and T. Nandagopal, "*The Effect of Interference on the Capacity of Multi-Hop Wireless Networks*," Proc. IEEE Symp.Information Theory, pp. 470-470, June 2004.

[27] X. Cheng, P. Mohapatra, S.-J. Lee, and S. Banerjee, "*MARIA: Interference-Aware Admission Control and QoS Routing in Wireless Mesh Networks*," Proc. IEEE Int'l Conf. Comm. (ICC '08), 2865-2870, May 2008.

[28] M. Kodialam and T. Nandagopal, "*Characterizing the Capacity Region in Multi-Radio Multi-Channel Wireless Mesh Networks*," Proc. ACM MobiCom, pp. 73-87, Aug. 2005.

[29] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, "*Impact of Interference on Multi-Hop Wireless Network Performance*," Proc.ACM MobiCom, pp. 66-80, 2003.

[30] C.E. Perkins and P. Bhagwat, "*Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers*," Proc. ACM SIGCOMM, pp. 234-244, Aug. 1994.

.