Hop-by-Hop Steering in Wireless lattice Networks with Reliable Bandwidth

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Abstract— **Wireless Mesh Network (WMN) has become an important edge network to provide Internet access to remote areas and wireless connections in a metropolitan scale. In this paper, we study the problem of identifying the maximum available bandwidth path, a fundamental issue in supporting quality-of-service in WMNs. Due to interference among links, bandwidth, a well-known bottleneck metric in wired networks, is neither concave nor additive in wireless networks. We propose a new path weight which captures the available path bandwidth information. We formally prove that our hop-by-hop routing protocol based on the new path weight satisfies the consistency and loop-freeness requirements. The consistency property guarantees that each node makes a proper packet forwarding decision, so that a data packet does traverse over the intended path. Our extensive simulation experiments also show that our proposed path weight outperforms existing path metrics in identifying high-throughput paths.**

Keywords— ***Wireless mesh networks, QoS routing, proactive hop-by-hop routing, distributed algorithm.***

Introduction

A wireless mesh network (WMN) consists of a large number of wireless nodes. The nodes form a wireless overlay to cover the service area while a few nodes are wired to the Internet. As part of the Internet, WMN has to support diversified multimedia applications for its users. It is essential to provide efficient Quality-of-Service (QoS) support in this kind of 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 additional rate a flow can push before saturating its path [2]. 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 available bandwidth path is also called widest path.

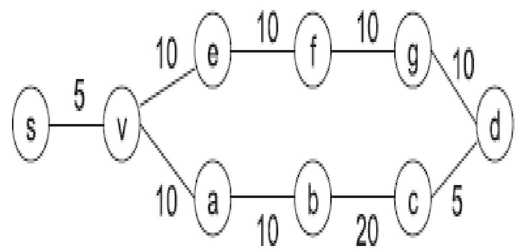


Fig.1.Example of Network Topology.

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

Intraflow interference

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 residual 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 violating the bandwidth guarantees of existing flows, the rate of this flow can be at most the available bandwidth of the link.

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 idle to avoid conflict. Intraflow interference complicates 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 individual links of the path. 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. Even though a source identifies a widest path to a destination, intermediate nodes on the widest path may not make a consistent packet forwarding decisions by using the

traditional destination-based hop-by-hop packet forwarding mechanism.

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 264 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. 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.

PRELIMENARIES

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 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.

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 {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. Denote fQ1; . . .;QKg as the maximal interference clique set of the network.

The work [25] introduces the following lemma.

Lemma 1. Denote f as a link flow vector, where f(e) is the aggregate data rate of the flow on link e. If f does not satisfy the following inequalities.

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

then f is not schedulable.

Lemma 1 gives the method to compute the theoretical available bandwidth of a path.

Given a p=<v_1,v_2,....v_h>, we first find the set of the maximal cliques {S1; S2; . . . ; SM} such that $S_m \cap p \neq \emptyset$ for all m =1,...,M.Denote fsum;m as the total current data rate of the flows on all the links of the maximal clique Sm 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 $k_m r \leq C - f_{sum,m}$for all m=1,...M.

The rationale behind this constraint is that the aggregate additional data rates on all links in the maximal clique Sm 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 mechanismto achieve the maximum available bandwidth.

In the following, we describe another mechanism to approximatelycompute the maximum available bandwidth of a path, and there exists a simple scheduling to achieve theestimated bandwidth.

Given a path p=<v_1,v_2,....v_h>, based on the currentflows on each link in the network, denote B(e) as theavailable bandwidth of link e,e. It means that if a newconnection only needs to go through link e, e can send atmost 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 Qp 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 Qp for path p. The available bandwidth of path p is estimated as follows [5], [6]:

$$B(p) = \min_{\mathbf{q} \in \mathbf{Q}_p} C_{\mathbf{q}}; \quad C_{\mathbf{q}} = \frac{1}{\sum_{l \in \mathbf{q}} \frac{1}{B(l)}}. \qquad (2)$$

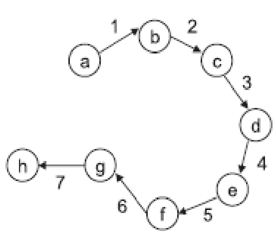
The rationale behind the formula is: transmissions on the links in a clique cannot be concurrent but occur in a serial manner. Thus, the time it takes $\sum_{l \in \mathbf{q}} \frac{1}{B(l)}$ for 1 Mbit data to traverse all the links in the clique q. Cq is thus the bandwidth available over the clique q.

The available bandwidth of the path is the bandwidth of the bottleneck clique. We refer readers to the references for further explanation.

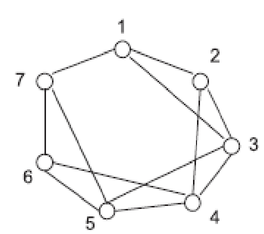
Example 1. Let B(1), B(2), B(3), and B(4) of the networking be 50, 100, 25, and 20 Mbps, respectively, as in the example provided in [2]. There are two maximal cliques on path <a; b; c; d; e> and they are {1, 2, 3} and {2, 3, 4}. $C_{\{1,2,3\}} = (\frac{1}{50} + \frac{1}{100} + \frac{1}{25})^{-1} = \frac{100}{7}$ and $C_{\{1,2,3\}} = (\frac{1}{50} + \frac{1}{100} + \frac{1}{25})^{-1} = 10$. The estimated available bandwidth of path <a; b; c; d; e> is min$\left\{\frac{100}{7}, 10\right\} = 10Mbs$.

We are going to show that we can find a simple scheduling mechanism to achieve B(p) computed by Fig.3.First, it is not difficult to find all the maximal cliques Qp containing only the links on path p. Let B(p) be the transmission data rate of link e. It takes Pe2q1B(p) time for all links in a clique q to sequentially transmit 1 unit of data.We let all the links on path p, which do not interfere with each other, to transmit concurrently. The total time for each link on p to transmit 1 unit of data is $max_{q \in Qp} = \{\sum e \in q1/Be \ \}$. We use an example to show the conclusion. Following [23], if two links on path p interfere with each other, all links between them (include both the links) interfere with each other. Without loss of generality, assume Qp contains two maximal cliques

In this example, two cliques contain the different number of links, in order to consider a generic scenario. If the total time for each link in q1 to transmit 1 unit of data is larger than that in q2, the time for link e0 to transmit 1 unit of data is larger than the total time for e3 and e4 to transmit 1 unit of data. Since link e0 does not interfere with e3 or e4, when link e0 transmits, either e3 or e4 can transmit.



Original Graph



Conflict Graph

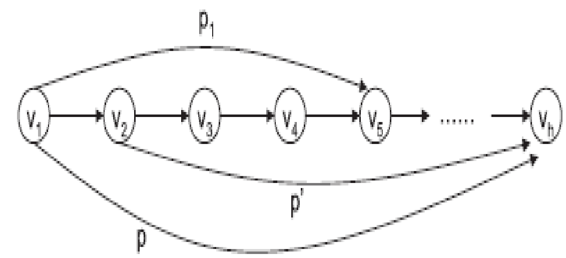


Fig.2. Path bandwidth computation in a hop-by-hop manner

Thus, when e0 completes transmitting 1 unit of data, both e3 and e4 have completed transmitting 1 unit of data. Therefore, the total time for each link on p to transmit 1 unit of data is the total time for q1 to transmit 1 unit of data.The above discussion implies that the path bandwidth calculated by Fig.3. can be achieved. In other words, Fig.3. gives an underestimation for the available path bandwidth.The size of a maximal clique depends on how many links interfere with each other, which depends on theinterference model adopted in the network.

Due to the popularity of the 802.11 technology, we develop our work based on this MAC protocol. Both the two-way handshake DATA/ACK and the four-way handshake RTS/CTS/ DATA/ACK of 802.11 require the receiver of a data packet to send an ACK back to the sender of the data packet.

Therefore, for a packet transmission to be successful, both the sender and the receiver should not be interfered by other nodes. a is interfered by another node b if a is within the interference range of b. In other words, the transmissions on links are successful at the same time if and only if both s and d are outside the interference ranges of u and v.

This model is referred as the bidirectional transmission model [23] and the Transmitter-Receiver Conflict Avoidance (TRCA) interference model [25] in the literatures, and is adopted by many existing works [3], [4], [27], [28]. (Fig. 2b is NOT constructed based on the TRCA model.

We will come back to this later in this section.) Following [6], we define the transmission range of a node to be one hop, while the interference range to be r hops.

To simplify our discussion, we set r ¼ 2 [6].

It is worth noting that our results can be extended to any value of r. Moreover, our mechanism also works, after extension, on other commonly used interference models, such as the protocol model [28], in which as long as the receiver is free from interference, the transmission is regarded as successful.

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.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 7B, while it is computed as 1/3B by using Fig.3. 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 assume r ¼ 1,which is not the TRCA interference model we are using in this paper. 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 bandwidthof path <a; b; c; d; e> is $\left\{\frac{1}{50}+\frac{1}{100}+\frac{1}{25}+\frac{1}{20}\right\} = 25/23$, which is less than the available bandwidth calculated.

$$B(p) = \min_{1\le k\le h-4} C_k,$$
$$C_k = \left(\frac{1}{B(k)}+\frac{1}{B(k+1)}+\frac{1}{B(k+2)}+\frac{1}{B(k+3)}\right)^{-1}. \quad (3)$$

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 Fig.4.1 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.

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 neighbours. Each neighbour 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 neighbours may not be able to find the widest path. To illustrate, consider the network where the number of each link is the available bandwidth on the link.

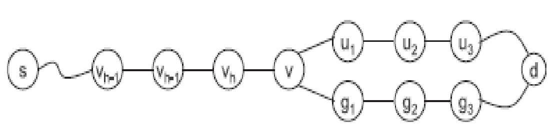


Fig.3. Illustration for path comparision.

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 threshold (say 10 percent), the node will 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 [29].

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 entries have the same sequence number, our path comparison is used to determine which path should be kept.

Due to the delay of the route update propagation, it is possible that route information kept in some nodes is inconsistent. For instance, the widest path kept in the routing table may not be the widest anymore. Routing loops may occur as well.

The situations are referred as inconsistency due to transient route updates, which is different from the definition used in [7].

In [7] and this paper, we consider whether packets can be routed on the computed widest path when the routing tables are stable. How to avoid loops when routing tables change is an important but difficult problem, and is outside the scope of this paper.

We refer readers to [29] for the techniques to reduce route update inconsistencies in the distance-vector protocolwhich can be applied in our mechanism as well.

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 Available Bandwidth, with some existing path weights.

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 ETXl ¼ 1 pl , where pl denotes the packet loss probability on link l at the MAC layer. pl is estimated by proactively broadcasting the dedicated link probe packets. Couto et al. [10] give the details on how to calculate pl. In our simulation, we completely follow the instructions presented in [10] to compute pl. As we consider single-channel networks in this work, we would not compare with metrics that are developed for the multichannel situation, such as ETT [12].

Another metric we compare is the Interference-aware Resource Usage (IRU) proposed in [14], which is defined as IRUl ¼ ETX jNlj, where Nl 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].

Simulation SettingsUnless 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.

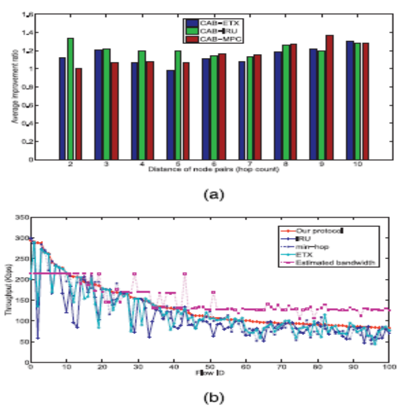


Fig.4. 100 node in 1,450m*1,450m. (a) Average improvement ratios, (b) Troughput of flows

After accepting 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 bandwidth, 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.

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 performances of the different protocols for finding the maximum available bandwidth path. Denote BCAB, BMPC, BETX, BIRU as the average throughput of the paths found by applying the CAB, minimum hop count, ETX, and IRU metrics, respectively. BCAB , BCAB BETX , and BCAB BIRU 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.

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 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.

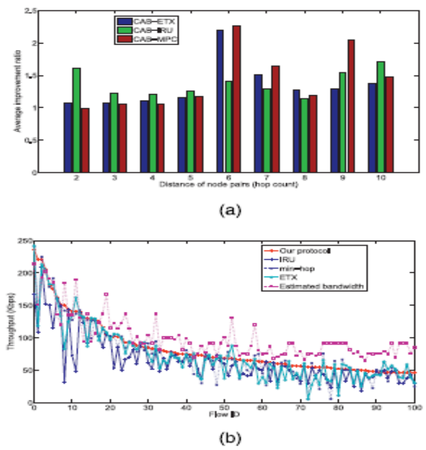


Fig.5. 100-node in 1,450m*1,450m with exiting flows following U(1,30)Kbps.
(a) Average improvement ratios, (b) Throughput of flows.

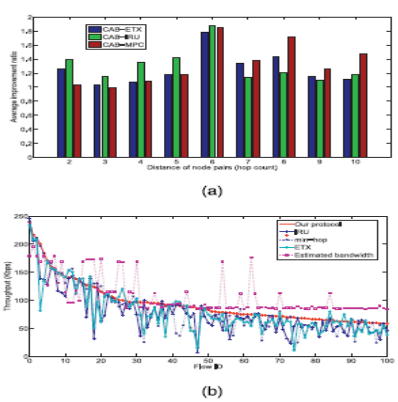


Fig .6 100-node in 1,450m*1,450m with 150 exiting flows. (a) Average improvement ratios, (b) Throughput of flows.

We randomly select 100 multihop flows and investigate the throughput of individual flow produced by the different protocols. Fig.5(b) shows the simulation results of the flows whichare 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 protocols. 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 highthroughput path. We now investigate why there is a difference between the practical throughput and the estimated available bandwidth.First, according to [5] and the discussion in Section 3, our work develops an underestimate of the true available bandwidth.

However, the theoretical 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.6 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 Fig.6, path bandwidth is independent on the hop-count distance of the path.

However, the longer the path, the larger the collision probability.

Thus, the hopcount distance affects the practical throughput of a path. That is why Fig.6 is likely to overestimate the bandwidth of a path with large distance.

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; 30Þ Kbps, and ws the simulation experiments.

In scenario 3, we let 150 links carry the existing flows, while the data rates of the existing flows still follow; 20Þ Kbps 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.We can observe that the average throughput of our protocol in scenario 2 is lower than that in scenario 1.

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 our protocol works the best for finding the high-throughput path with the different background traffic loads.

Simulation Results for Scenarios 4 and 5

We now study the effect of network topology. We deploy 100 nodes in a 1,000 m*1,000 m square (denoted by TOP2) and deploy 200 nodes in a 2,000 m*2,000 m square (denoted by TOP3).

We randomly select 100 and 230 links in TOP2 and TOP3, respectively, to carry background one-hop flows The average improvement ratio also depends on the network topology. If there are many alternative paths between a node pair, there are lots of choices for our metric.

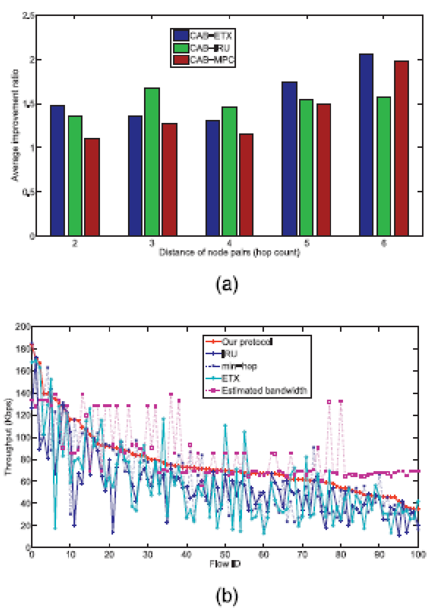


Fig. 7. 100-node in 1,000m*1,000m. (a) Average improvement ratios, (b) Throughput of flows.

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 alternative 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.

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 With shadowing propagation model, the interference range cannot be simply represented by the distance. 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 shows the throughputs of 100 individual flows and the estimated path bandwidth calculated by our approach. With the shadowing model, a clique in Qp of Fig.3. is likely to contain three links but not four, such that Fig.6 should underestimate the path bandwidth from the theoretical perspective.

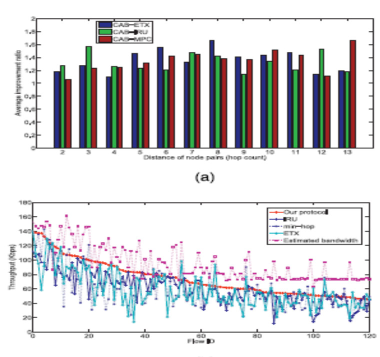


Fig.8. 200-node in 2,000m*2,000m. (a) Average improvement ratios, (b) Throughput of flows.

However, with the effect of the collision caused by the 802.11 protocol, our simulation results show that Fig.4.1 still gives the overestimate for most of the paths. In conclusion, our extensive simulation results show that the proposed metric, CAB, performs better for finding the high-throughput path than the existing metrics.

On one hand, our approach theoretically gives an underestimation for path bandwidth.

On the other hand, our simulation results show that our approach probably gives an overestimation for path bandwidth in practice.

This implies that if a source accepts a request with the bandwidth requirement larger than the maximum estimated end-to-end available bandwidth, probably, no path can support this connection, and so the source should reject this request in order to guarantee the available bandwidth allocated for the existing flows.

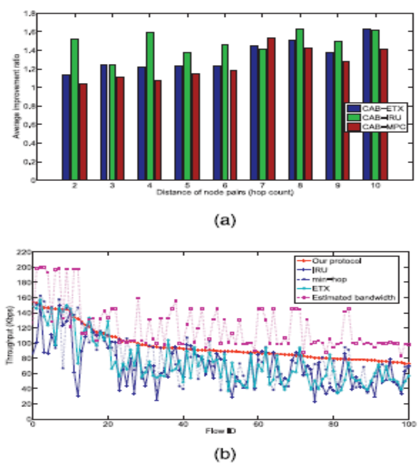


Fig. 9. 100-node in 145m*145m with shadowing model. (a) Average improvement ratios, (b) Throughput of flows.

CONCLUSION

In this paper, we studied the maximum available bandwidth 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.

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