On the Performance of Expected Transmission Count (ETX) for Wireless Mesh Networks

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ABSTRACT

The Expected Transmission Count (ETX) metric is an advanced routing metric for finding high-throughput paths in multi-hop wireless networks. However, it has been determined that ETX is not immune to load sensitivity and route oscillations in a single radio environment. Route oscillations refer to the situation where packet transmission switches between two or more routes due to congestion. This has the effect of degrading performance of the network, as the routing protocol may select a non optimal path. In this paper we avoid the route oscillation problem using a route stabilization technique which forces data transmission on a fixed route. We implement this solution in a popular routing protocol, AODV, by disabling both error messages and periodic updating messages. Therefore, packet transmissions will stay on the routes initially found by AODV. ETX is compared with a widely used routing metric, HOPS, for reference purposes. We find ETX greatly improves initial route selection in AODV compared to HOPS in networks in which only single flows exists. For networks in which there are multiple simultaneous flows, ETX behaves similar to HOPS in initial route selection. Although the known cause of performance degradation is eliminated, the ETX metric still shows anomalous behavior. We determine that a major cause of the poor performance of ETX is additional collisions due to extra overhead. We propose a modified solution in which we repeatedly broadcast RREQ (Route Request) packets. Simulation results show that our modified solution improves ETX in the initial route selection in both single flows and multiple flows cases.

1. INTRODUCTION

In the past few years Wireless Mesh Networks (WMNs) have been shown as a promising technology to provide flexible and low-cost broadband network services. The unique characteristics of WMNs, such as the ability to dynamically self-organize and self-configure [1, 2], have been proven to be a powerful technology. Consequently, there is an increasing trend to use WMNs in different network applications. Among applications that utilize WMNs, an application architecture in which the client requests an action or service from the service provider, has attracted a great deal of attention. This kind of application can be applied for low-data rates, such as traffic light control signals in a traffic control network (TCN); or high-data rates, such as video streams (VS) from a service provider. The TCN using traditional wired connections has problems of high operating cost, inflexibility, and difficulty of installation at new sites. These problems can be overcome by replacing wired connections with WMNs. For video streams, WMNs can provide an effective way to provide connectivity between a remote service provider and clients [3].

One of the challenges for using WMNs in client-server applications is the provision of quality of service (QoS) guarantees, such as transmission reliability for low-data rate TCN and high throughput for high-load VS. There are several approaches that focus on QoS guarantees in WMNs, such as architecture optimization [4-6], protocol improvement [7-9] and advanced algorithm design [10-12]. Among these latter approaches, a popular technique is to develop advanced routing algorithms [13, 14] which help WMNs find optimal routes. The routing algorithm requires a route metric in order to establish and define the quality of the multiple links present in the network. Minimal Hop Count (HOPS) is currently the most widely used route metric. However, paths found by HOPS can have poor performance because they tend to include wireless links between distant nodes. These long wireless links can be slow or lossy leading to poor throughput [15].

Currently, the Expected Transmission Count (ETX) is one of the most favored routing metrics because it has good accuracy in determining link quality. ETX has been shown to improve network throughput, especially for long paths [16]. There is a large body literature comparing the performance of ETX with various routing metrics [15-18]. Most of this work claims that the performance of ETX is much better than the other routing metrics in static multi-hop WMNs. Specifically, Draves et al. [17] compared the performance of ETX with two link-quality metrics:

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per-hop Round Trip Time (RTT) and per-hop packet pair (PktPair). Draves et al. [17] claimed that ETX significantly outperforms RTT and PktPair because ETX is load independent and accordingly suffers little from the self-interference problem seen in RTT and PktPair. However, Yun [19] demonstrated the route oscillation behavior of ETX in WMNs test beds, showing that the ETX metric is not immune to load sensitivity. The load sensitivity of routing metrics can lead to route oscillations, during which packet transmission switches between different routes due to congestion. This has the effect of degrading performance of the network, as the routing protocol may select a non-optimal path [19].

One straightforward approach to solve the route oscillation problem in ETX is to make the routing protocol permanent on the initial routes it finds. The risk of this approach is that the initial routes might not be high quality routes. Sticking on a lossy route would cause poor network performance. Consequently, one critical factor for using route stabilization to solve the route oscillation problem in the context of ETX is whether the ETX metric can help determine a high quality initial route.

Our main goal in this paper is to evaluate the performance of ETX on finding high quality initial routes in two applications: TCN and VS, which represent low-data rate client-server applications and high-data rate client-server applications, respectively. To evaluate the performance of ETX, we compare the ETX and the HOPS metrics on the performance of AODV protocol [20].

The contributions of this paper are three-fold. First, we present detailed simulation results to show that in both low-data rate and high-data rate applications, the initial routes found by ETX have significantly higher performance in comparison with the initial routes found by HOPS when there is only one flow in the network. We also show that when multiple simultaneous flows are issued, ETX behaves similar to that of HOPS for the performance of the initial route. Second, our results show that using route stabilization to solve the route oscillation problem in the context of ETX is good for single flows but poor in the situation of multiple simultaneous flows. Finally, we propose a modified solution by repeatedly broadcasting RREQ (Route Request) packets. Simulation results show that our modified solution improves ETX in the initial route selection in both single flow and multiple simultaneous flows cases.

The rest of this paper is organized as follows. We describe related work in Section 2. Section 3 presents simulation results for low-data rate client-server applications. Section 4 presents simulation results for high-data rate client-server applications. In section 5, we propose a modified solution to address the problem of ETX for multiple simultaneous flows. Finally, Section 6 concludes this paper.

2. RELATED WORK

There are numerous routing metrics proposed for WMNs. For example, the Expected Transmission Time (ETT) [21], which was proposed as an improvement over ETX, considers the differences in link transmission rates. ETT of a link is the expected MAC layer duration for a successful transmission of a packet at the link. The weight of a path is the summation of the ETT's of the links on the path. By taking transmission rates into account, ETT significantly outperforms ETX in environments with different data rates. Both ETT and ETX perform badly in environments with multiple radios [21]. In contrast, the Weighted Cumulative ETT (WCETT) proposed by Draves et al. [21] is used only in multi-channel environments. WCETT reduces intra-flow interference by reducing the number of nodes on the path of a flow that transmit on the same channel. Based on Yang et al. [22], the drawbacks of WCETT are two-fold: 1) it does not explicitly consider the effects of inter-flow interference and accordingly WCETT may route flows to dense areas where congestion is more likely; 2) only algorithms with exponential complexity can calculate minimum weight paths based on this routing metric. In contrast with the above metrics, the metric AirTime [23] used by the IEEE 802.11s wireless mesh standard [23] provides the path selection protocol in a mesh network with an efficient radio aware path. It reflects the amount of channel resources consumed by transmitting the frame over a particular link.

Performance comparison of routing protocols using ETX and HOPS has been studied previously. The work of [15, 17, 19] is similar to our work in that they do comparison in a static ad hoc network. Douglas et al. [15] implemented ETX as a metric for two routing protocols: DSDV and DSR. Performance comparison between ETX and HOPS in [15] demonstrated that DSDV perform well with ETX. However, there is little benefit found from ETX when a DSR-based routing protocol is used. In contrast to [15], Draves et al. [17] measured four routing metrics: ETX, HOPS, RTT and PktPair, for different transmission patterns, such as varying bandwidth and different packet generation functions. They concluded that, in a static wireless network, ETX outperforms the other three metrics for DSR when using TCP transmission instead of UDP. Moreover, [17] showed that HOPS performs better than the other three metrics in a mobile network. The purpose of [17] was to prove ETX outperformed the other metrics in various scenarios. On the other hand, Draves et al. [17] claimed that one of the limitations in their study is they do not investigate the performance of multimedia traffic, such as packet loss and jitter with CBR datagram traffic. We try to address this issue.

There is a large body of literature addressing the route oscillation problem. For example, the experiments conducted in [19] showed that in the context of ETX there is high number of oscillations when traffic loads approaching maximum channel capacity. Basu et al. [24] described a solution to the route oscillation problem in I-BGP (Internal Border Gateway Protocol). The solution in [24] is a modification to the I-BGP protocol using route reflection. Elliott et al. [25] characterized the route oscillations problem in the Internet and proposed a method of forcing explicit withdrawals in BGP to reduce oscillations. Varadhan et al. [26] showed that there exist domain policies that cause BGP/IDRP (Border Gateway Protocol version 4 and the Inter-Domain Routing Protocol) to exhibit persistent oscillations. The persistent oscillations mean each domain repeatedly chooses a sequence of routes to a destination. Varadhan et al. [26] evaluated ways to prevent or avoid persistent oscillations in general topologies by analyzing the

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conditions for persistent route oscillations in a simple class of inter-domain topologies and policies.

3. EVALUATION IN LOW-DATA RATE WMNs

In this section, we evaluate the ETX metric via ns2 simulation [27]. ns2 is a discrete event-driven network simulator, which is a part of the VINT project developed at UC Berkeley and USC ISI with extensions from the MONARCH project at Carnegie Mellon University [28].

3.1 Simulation Setup

Our WMN consists of a wireless 5*5 grid of 25 nodes, in which the spacing of the grid is 200m as shown in Figure 1. A grid was chosen as the logical topology of the WMN due to its ability to create a fully connected mesh network and the possibility of creating a large variety of other topologies by selectively switching on particular nodes [18]. The wireless transmission range is 250m, and the propagation model is two-ray-ground. The interference range of the WMN is 356m which is as calculated in [29]. The diagonal nodes are at a distance of 283m. The diagonal spacing is smaller than the interference range and larger than the transmission range. Consequently, diagonal nodes are hidden nodes. The carrier sense range is 324m. The packet sizes of both test data and real data are 512 Bytes. The ETX probe packet size is 16 Bytes. Channel bandwidth is 11Mb/s for data packets, and 1Mb/s for control packets.

Each simulation in the specified scenario involves all route metrics. We run each scenario 100 times in order to ensure the results are consistent. An entire simulation consists of four phases. 1) At the start of simulation the routing software is reset, and then the sending node (node 0) transmits test data which is used to trigger the sending of ETX probes. This phase lasts for 40s. At the end of this phase, nodes in the WMN should know the stabilized ETX values associated with the links which connect nodes and their neighboring nodes. 2) In the next 2s, the sending nodes stop sending test data. The rest of the nodes will run out of packets buffered in their queues for the duration. All the buffers should be emptied at the end of this phase. 3) Then the sending node sends real data packets at a constant bit rate for 60s. 4) Finally, the sending node stops sending data packets and the rest of the nodes run out of packets buffered in their queues in the last 48s.

3.2 Scenario Setup

Before describing these scenarios, we first define the following terms.

1) *Link quality*: Link quality refers to the degree to which a link successfully delivers packets. A high-quality link should successfully deliver a packet with a high probability. ETX measures the link quality by computing the product of delivery ratios in both directions of the link. A link with a high product of delivery ratios suggests that it is a high-quality link. In contrast, HOPS does not take the link quality issue into account at all.
2) *Lossy node*: Lossy node refers to a node which is artificially set to have an incoming loss ratio. Packets directed to a lossy node would be dropped by the node with a predefined probability.

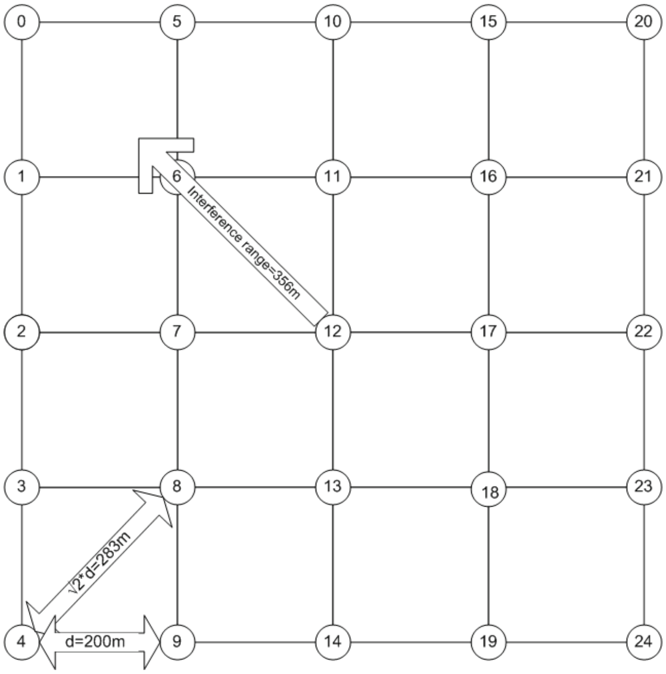

Figure 1. The WMN as a wireless 5*5 grid of 25 nodes.

3) *Lossy link*: Links associated with lossy nodes are defined as lossy links. The reason for this is packets on these links directed to the lossy nodes would be dropped.
4) *Path*: A path connects a source and a destination, which cannot talk to each other directly, by a chain of nodes. A multi-hop path consists of a number of links.

To conduct simulations, we set up four scenarios based on the topology shown in Figure 1.

- Scenario A has four lossy nodes which all have a 50% loss ratio. The four lossy nodes are nodes 6, 8, 16 and 18. There is only one communicating node pair in Scenario A, which is from node 0 to node 24. The use of Scenario A is to validate our ETX implementation. Scenario A is similar to the scenarios used in previous works [15, 17, 19].

- Scenario B is used to simulate multiple server-to-client traffic. There is one source and twenty-four sinks. Node 0 acts as a server and transmits packets to the rest of the nodes simultaneously. Packets are sent as CBR traffic over UDP. The number of lossy nodes, the loss ratios of lossy nodes, and the positions of the lossy nodes are set randomly. The number of lossy nodes is uniformly distributed between 0 and 12. The loss ratios of lossy nodes are uniformly distributed between 0 and 1.

- Scenario C has no lossy nodes. There is only one data flow from node 0 to node 24. The lack of lossy nodes leads the link quality of each link in the WMN to be the same.

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- Scenario D is a replication of Scenario B, except that there are no lossy nodes in this scenario.

3.3 Analysis of Results

We compared ETX and HOPS in low-data rate WMNs in the four scenarios. By measuring the average packet loss ratio of single flows and the average packet loss ratio of the overall flows in the four scenarios, we can find out which routing metric is suitable for this kind of low-data rate WMN. The average packet loss ratios of the overall flows in network in the four scenarios are shown in Table 1 and 2. Note that Scenario A and Scenario C use two data rates of 1pkt/s and 20pkts/s, whereas Scenario B and Scenario D use one data rate of 1pkt/s.

Table 1: Average packet loss ratio of overall flows in the four scenarios when using AODV with HOPS.

AODV with HOPS	Lossy links			No Lossy links		
	Scenario A		Scenario B	Scenario C		Scenario D
	1pkt/s	20pkts/s	1pkt/s	1pkt/s	20pkts/s	1pkt/s
Average packet loss ratio	0.036101	0.070531	0.167774	0.000000	0.000051	0.001541
MAX loss ratio	0.155172	0.195286	0.972973	0.000000	0.001695	0.003451
MIN loss ratio	0.000000	0.000000	0.000279	0.000000	0.000000	0.001355

Table 2: Average packet loss ratio of overall flows in the four scenarios when using AODV with ETX.

AODV with ETX	Lossy links			No Lossy links		
	Scenario A		Scenario B	Scenario C		Scenario D
	1pkt/s	20pkts/s	1pkt/s	1pkt/s	20pkts/s	1pkt/s
Average packet loss ratio	0.013997	0.011880	0.149954	0.000000	0.000093	0.001593
MAX loss ratio	0.166667	0.195286	0.836177	0.000000	0.003373	0.003451
MIN loss ratio	0.000000	0.000000	0.001375	0.000000	0.000000	0.001355

3.3.1 Observations from Scenario A

Scenario A is used to validate our ETX implementation. The expectations in Scenario A are: 1) ETX should choose routes that avoid lossy links. 2) The average packet loss ratio of the paths found by AODV using ETX should be much smaller than using HOPS. As shown in Table 1 and 2, the average packet loss ratios of the paths found by AODV using ETX are much smaller than using HOPS. This result fulfills the second expectation. To check out whether ETX chose routes without lossy links, we explore the average packet loss ratio. As shown in Figure 2, we find most runs of ETX[1] have loss ratios close to 0, which means that most of the time ETX chooses routes with no lossy links. In contrast, most runs of HOPS have loss ratios larger than 0. Consequently, the use of HOPS will leads to routes that consists of some lossy links.

3.3.2 Observations from Scenario B

The characteristic of scenario B is that even if the lower layers support high bandwidths, the channel capacity for each flow is much smaller compared to the channel bandwidth. Node 0 sends traffic to the rest of nodes at the rate of 4.096 kb/s. This bit rate is much smaller than the maximum channel capacity for each flow and meets the requirements of low-data rate. As shown in Table 1 and 2, the average packet loss ratios of the overall flows of HOPS and ETX are 16.7% and 15% respectively. Figure 3 shows that most flows of ETX have similar average packet loss ratio compared to the flows of HOPS.

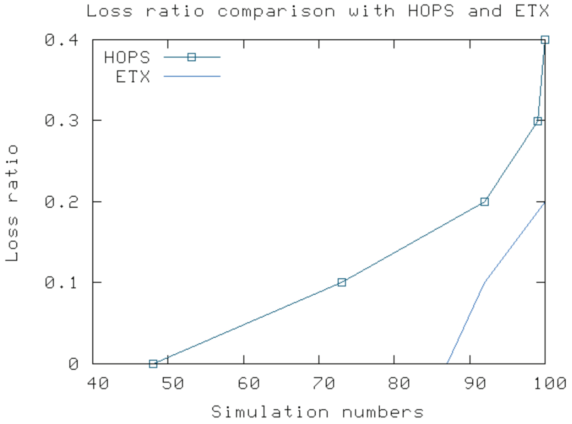

Figure 2. Loss ratio comparison with HOPS and ETX in Scenario A.

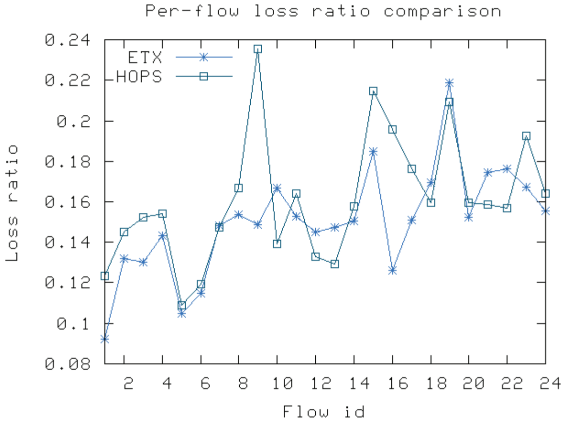

Figure 3. Loss ratio comparison for different flows in Scenario B.

3.3.3 Observations from Scenario C

Since there are no lossy links and less interference in this scenario, both ETX and HOPS are expected to have less packet loss. The average packet loss ratios of HOPS and ETX shown in Table 1 and 2 confirm our expectation.

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[1] By the terminology "of ETX", "the ETX", etc, in this paper we mean the use of the ETX metric within AODV (likewise for HOPS).

3.3.4 Observations from Scenario D

The use of Scenario D is to determine whether ETX and HOPS suffer interference via simultaneous traffic flows and how this affects the performance of packet loss ratio. We find the average loss ratios of HOPS and ETX are similar to those shown in Table 1 and 2.

3.3.5 Conclusions

The gains in the performance that ETX can provide depend on whether there are different link quality links in the network. When links have similar qualities, the initial routes found by ETX are the same as the initial routes found by HOPS. We confirm that the overhead of ETX would not affect the decision of route selection under low-data rate. The ETX metric shows significantly better performance than the HOPS metric only when the network has different link qualities and only when single flows are present.

We find there is little gain from ETX in a lossy WMN when multiple simultaneous flows are launched, as shown in Scenario B. This is due to simultaneous flows introducing inter-flow interference. While the loss measurements used by ETX are not significantly affected by the interference, the RREQ packets with superior ETX metrics may collide due to high inter-flow interference. Through deliveries of the RREQ packets with inferior ETX metrics, routes including lossy links could be established.

4. EVALUATION IN HIGH-DATA RATE WMNs

In this section, we evaluate the ETX metric for high-data rate client-server applications, such as video stream transmissions. In contrast to Section 3, the key performance metric evaluated in this section is the per-flow throughput. Simulation results of the HOPS metric are used as a baseline to evaluate the performance of the ETX metric. There are several factors which could affect the performance of the ETX and HOPS routing metrics in the client-server applications, such as inter-flow interference, heavy workload and lossy links. We start our simulations in a relatively simple scenario in which there is only one factor, and then move the simulations to complex scenarios with several factors. These scenarios are similar to those of Section 3 but with minor changes.

4.1 Simulation Setup

Parameters in the simulations are the same as those in Section 3, except for packet size and per-flow data rate. For the video stream used in the simulations, we select the H.264 codec [30] which possesses an efficient video compression. The resolution is 176*144 pixels and the frame size is 792 Bytes, which are in accordance with level 1.1 in the H.264 standard. We use a range of data rates to evaluate the performance of the ETX and HOPS routing metrics. In the Scenarios E and G, in which there is only one flow in the network, data rates are steadily increased in 100kb/s intervals from 0.2 Mb/s to 1 Mb/s. In the Scenarios F and H, in which the server launches flows to every other node, data rates are steadily increased in 6kb/s intervals until the throughput reaches the saturation point.

4.2 Scenario Setup

Four scenarios, Scenarios E, F, G and H, are similar to those used in Section 3.

- Scenario E has no lossy links and only one server-to-client transmission. More specifically, the sever node 0 sends data to the client node 24 at an increasing data rate. Data rate is steadily increased in 100kb/s intervals until throughput reaches the saturation point. In this scenario, the only factor that could affect the performance of the routing metrics is the increasing data rate. There is no difference in link quality in the network. ETX should perform similarly to HOPS. However, we suspect the ETX probe packet overhead might affect throughput when the data rate is increasing. The use of this scenario is to check the effect of ETX overhead on throughput when the data rate is increasing.

- Scenario F has no lossy links and the sever node 0 launches server-to-client transmission to every other node simultaneously. Unlike Scenario E, inter-flow interference is introduced here.

- Scenario G has a few lossy links and one server-to-client data transmission. The lossy links are randomly distributed.

- Scenario H has some lossy links and multiple simultaneous flows. We divide the Scenario H into two cases: S1 and S2. S1 is a relatively simpler situation in which the positions of lossy links are predefined as shown in Figure 4. Because the lossy link locations are known in advance, the routes found by ETX can be deduced before simulations, so that the results from S1 can be used as a baseline for S2. In S2 the number of lossy links, the positions of lossy links, and the packet loss ratios of the lossy links are chosen randomly. The resutls from these two cases are expected to be the same.

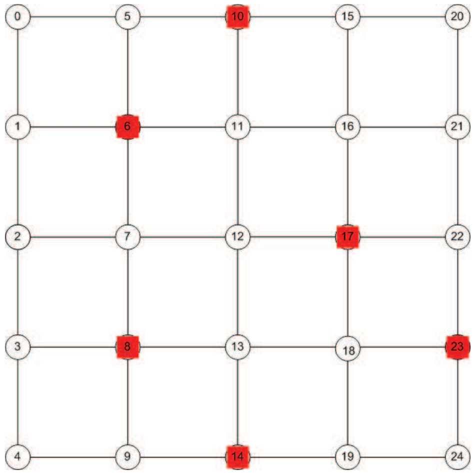

Figure 4. Schematic drawing of S1 in Scenario H; the nodes in dark are lossy nodes, which have incoming packet loss ratios uniformly distributed between 0 and 1.

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4.3 Analysis of Results

In the Scenarios E and F, each link in the network has the same link quality. Consequently, the ETX metric is expected to behave the same as the HOPS metric. Results from Scenarios E and F can be used as a baseline for Scenarios G and H.

4.3.1 Observations from Scenario E

Figure 5 provides throughput comparison between ETX and HOPS for increasing data rates. The ETX curve is essentially coincident with the HOPS curve when the bit rate is smaller than 0.6 Mb/s. Moreover, the saturated throughput using ETX is almost the same as the saturated throughput using HOPS. This phenomenon fulfills our expectation that ETX should work similar to the HOPS when there is no difference in link qualities.

When the bit rate is larger than the maximum load that the system can carry (0.6 Mb/s), the throughput using either ETX or HOPS decreases. This is due to network congestion caused by heavy traffic load. The throughput of ETX decreases faster than that of HOPS. This is because when the network becomes heavily loaded the ETX probe packets intensify the congestion problem. Nodes in a grid topology can have at least one hidden node and at most four hidden nodes. Collisions caused by the ETX probe packets sent by the hidden nodes further exacerbate the problem. The resulting packet retransmission and backoff in 802.11 DCF would decrease network throughput.

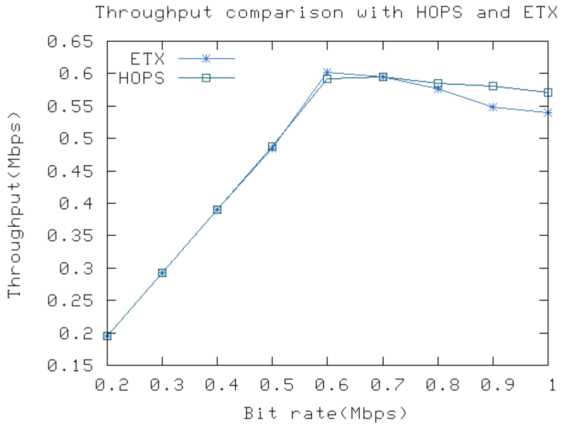

Figure 5. Throughput versus increasing bit rate of the video stream from node 0 to node 24 in Scenario E.

4.3.2 Observations from Scenario F

The use of Scenario F is to find out the performance of ETX under the circumstance of high inter-flow interference. Receivers in the grid topology are symmetrically placed as shown in Figure 6. Nodes are distributed at the two sides of the solid line. Consequently, nodes can be categorized into fourteen groups (G1-G14) based on their locations. Each group is different from the other groups in terms of their minimum path length to server and number of neighbors. For example, G1 has a minimum path length of 1 hop and 3 neighboring nodes while G4 has a minimum path length of 4 hops and 2 neighboring nodes. The throughput of the flows in the same node group should be the same.

We examine throughput of flows from different groups that belong to the top, center and bottom parts of the network. We find that all flows show similar results. As shown in Figure 7, the ETX curve essentially coincides with the HOPS curve when the bit rate is smaller than 0.042 Mb/s. When per-flow bit rate is larger than 0.042 Mb/s, both the ETX curve and the HOPS curve decrease. The ETX curve decreases faster than the HOPS curve because ETX probe packets consume bandwidth and cause collisions, which exacerbate congestion and high interference. This phenomenon is accordance with observations from the Scenario E.

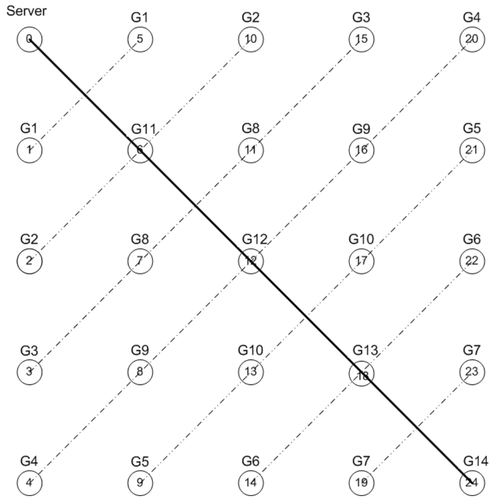

Figure 6. Node groups in the Scenario F. Nodes with the same label are in the same group.

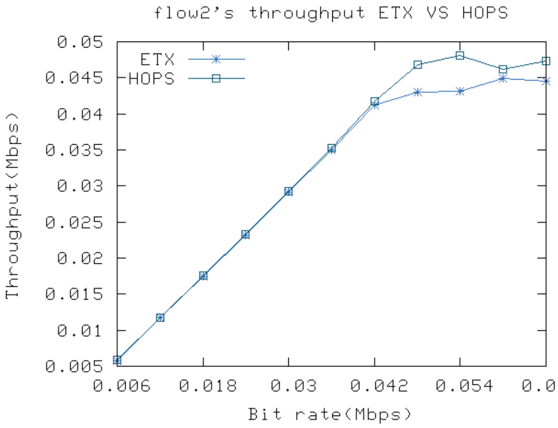

Figure 7. Throughput comparison at flow 2 (flow from server to node 2).

4.3.3 Observations from Scenario G

As shown in Figure 8, ETX shows significantly higher throughput than HOPS at every data rate. This result confirms ETX's improvement over HOPS. In contrast with the observations in Scenario E, in which ETX throughput decreases faster than HOPS throughput at high-data rates, in Scenario G ETX throughput is much higher than HOPS throughput even when the data rate is

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very high. This result confirms that the probe packet overhead is small.

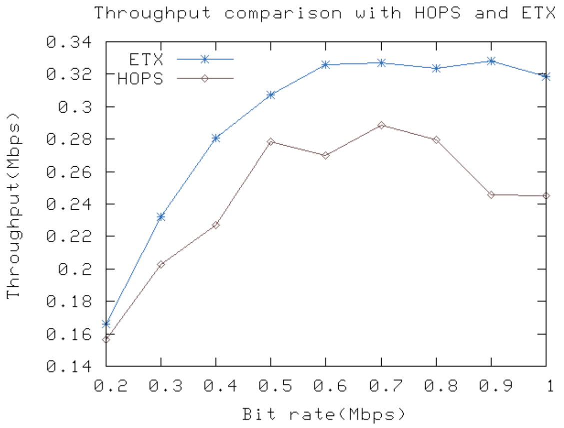

Figure 8. Throughput versus increasing bit rate of the video stream from node 0 to node 24 in Scenario G. ETX shows higher throughput than HOPS at each data rate.

4.3.4 Observations from Scenario H

As shown in Figure 4, the lossy node IDs in S1 (nodes 6, 8, 10, 14, 17 and 23) are fixed. It is meaningless to study the throughput of the flows 6, 8, 10, 14, 17 and 23; because the receiver nodes are lossy nodes. Packets destined to these lossy nodes are dropped according to the predefined incoming packet loss ratios of these nodes. The rest of nodes, which do not have incoming packet loss ratio, are classified into three groups as shown in Table 3. Observations at the nodes in the same group should be similar.

Table 3: Node groups in S1 of the Scenario H

Group	Node ID in the Group	Characteristics of the Group
Group 1	1, 2, 3, 4 and 5	HOPS and ETX should choose the same routes to these nodes.
Group 2	7, 9, 12, 13, 18, 19 and 24	The route selected by ETX has the same path length as the routes selected by HOPS.
Group 3	11, 15, 16, 20, 21 and 22	The route selected by ETX has longer path length compared to the routes selected by HOPS.

For nodes in Group 1, ETX should choose the same routes as HOPS to these nodes. Take node 3 as an example, the route to node 3 with the shortest hop count that HOPS would choose is nodes 0 → 1 → 2 →3. On the other hand, the route with the best ETX metric is the same route, nodes 0 → 1 → 2 →3. Consequently, the throughput of flow 3 using ETX should be the same as the throughput using HOPS. The other nodes in Group 1 should do the same as node 3. As shown in Figure 9, the ETX throughput curve of flow 3 is essentially coincident with the HOPS throughput curve. This is in accordance with our expectation that ETX should deliver similar results to HOPS for the nodes in Group 1.

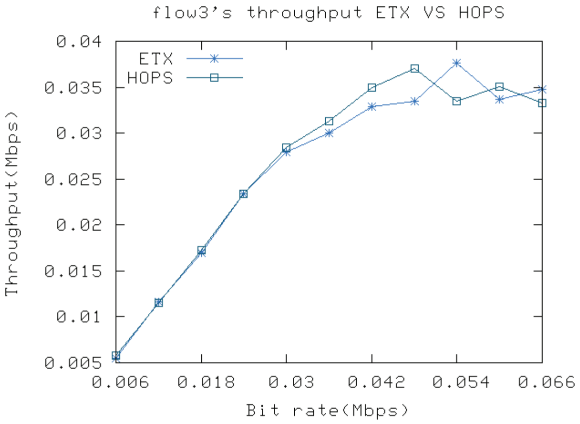

Figure 9. Throughput comparison at flow 3 in the S1 of the Scenario H.

For nodes in Group 2, the route selected by ETX has the same path length as the route selected by HOPS. Take node 9 as an example, ETX would choose nodes 0 → 1 → 2 → 3 → 4 → 9 as a route, while HOPS has many routes to choose with the same path length as the route selected by ETX, such as nodes 0 → 5 → 6 → 7 → 8 → 9. For routes with the same hop count, HOPS randomly uses one of them to deliver packets, and consequently the lossy links might be included in the route. In contrast, ETX selects a route without lossy links. Consequently, our expectation for the nodes in Group 2 is that ETX finds routes with significantly higher throughput compared to HOPS. Figure 10 is the throughput comparison at flow 9. From this figure, we find an unexpected phenomenon that ETX does not make a significant improvement in throughput compared to HOPS. The same phenomenon can be observed at the other nodes in Group 2, such as flow 24 shown in Figure 11.

For nodes in Group 3, the route selected by ETX has a longer path length compared to the routes selected by HOPS. Take node 11 as an example, ETX would choose nodes 0 → 1 → 2 → 7 → 12 → 11 as a route, while HOPS would choose a shorter route, such as nodes 0 → 5 → 10 → 11, or nodes 0 → 5 → 6 → 11, or nodes 0 → 1 → 6 → 11. No matter which route HOPS might choose; it must include one lossy node, either node 6 or node 10. Consequently, even though ETX chooses a longer path, the throughput of the path found by ETX should be much higher compared to the path found by HOPS.

Figure 12 shows that ETX behaves basically the same as HOPS. This result does not match our expectation that ETX should have much higher throughput than HOPS. The same phenomenon can be observed at the other nodes in Group 3, such as flow 21 shown in Figure 13.

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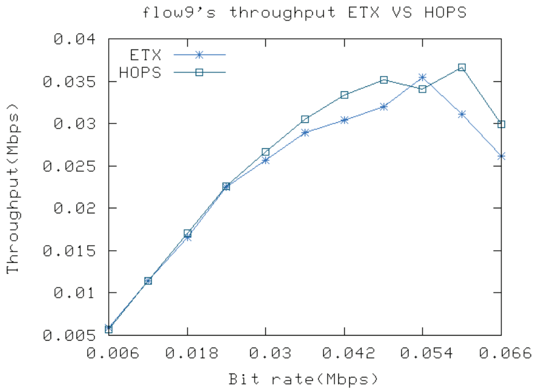

Figure 10. Throughput comparison at flow 9 in S1 of Scenario H.

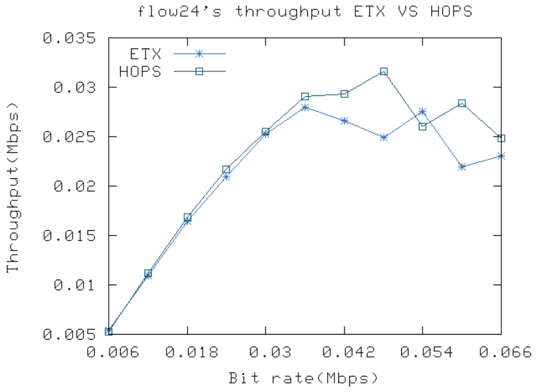

Figure 11. Throughput comparison at flow 24 in S1 of Scenario H.

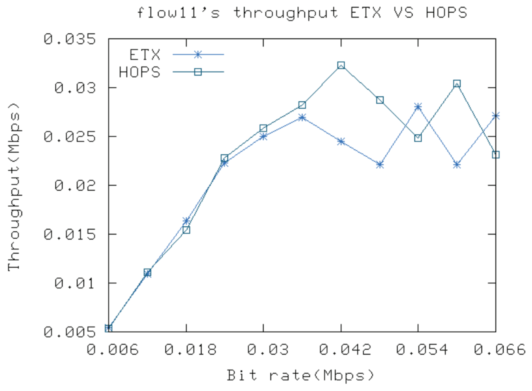

Figure 12. Throughput comparison at flow 11 in S1 of Scenario H.

Observations of the three node groups in S1 show that ETX does not outperform HOPS in Scenario H. Moreover, the throughput of some flows using ETX is lower than the throughput using HOPS. In S2, the lossy links are randomly chosen. The results from S2 are consistent with the observations from S1, in which ETX does not outperform HOPS.

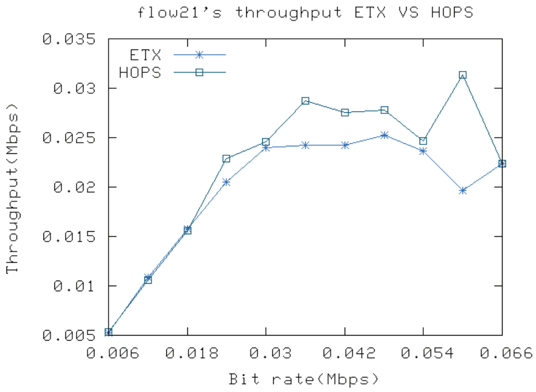

Figure 13. Throughput comparison at flow 21 in S1 of Scenario H.

Observations from Scenario H show that in this scenario ETX does not outperform HOPS. This is unexpected because link qualities differ from each other in the network of Scenario B. The paths found by the ETX metric should include links with high qualities and the path found by the ETX metric should have higher throughput in comparison with the path found by the HOPS metric. The reason for this unexpected phenomenon is that in Scenario B, ETX actually selects paths with lossy links. Take node 9 as an example, as shown in Figure 4. There is only one route without lossy links directed to node 9: nodes 0 → 1 → 2 → 3 → 4 → 9. The RREQ packet broadcast on this route has the superior metric compared to the RREQ packets which are sent on the other routes such as nodes 0 → 5 → 6 → 7 → 8 → 9. However, since 802.11b broadcasts are vulnerable to collisions from hidden nodes, the RREQ packet sent on the high quality route, nodes 0 → 1 → 2 → 3 → 4 → 9, might collide and dropped. On receiving the RREQ packet sent on the paths with lossy links, node 9 would reply a RREP in response to the received RREQ packet. In doing so, a path destined to node 9 would be established that contains lossy links.

5. DISCUSSION

As shown in Section 3 and Section 4, the ETX metric behaves the same as the HOPS metric when multiple simultaneous flows exist (when flows proceed using routes found initially). The reason for this is because the initial routes found by ETX can include lossy links. In this section, we provide a solution to address this problem. We first describe the design and implementation of the solution. Next, we re-run simulations in Scenario H, and utilize the simulation results to validate our solution.

As we described previously, the reason that initial routes found by ETX include lossy links is because the RREQ packets that arrive from the non-lossy routes can experience collisions. Since the 802.11 DCF does not retransmit broadcast packets, the destination node would not be aware of the no-lossy route. If the collided RREQ packets could be retransmitted and subsequently received by the destination node, the destination node can discover no lossy route. Based on this idea, we work out a low cost solution in which each node repeatedly broadcasts the same RREQ packets ten times. Then, the neighboring nodes can receive at least one

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RREQ packet. By repeatedly broadcasting RREQ packets, each RREQ packet can be delivered successfully.

It is probable that a node would receive the same RREQ packet many times. To ignore the duplicated RREQ packets, we make each node rebroadcast the RREQ packets with higher sequence number (or better metric) compared to the RREQ packets broadcast previously.

By making each node repeatedly broadcast RREQ packets, the destination node would most likely receive RREQ packets from all possible routes. After comparing route metrics contained in these RREQ packets, the destination node would answer the RREQ packet with the best route metric by unicasting a route reply (RREP). On receiving the route reply, the source node would recognize the route which contains no lossy nodes.

To validate our solution, we re-run simulations in Scenario H. The reason for using Scenario H is because the ETX metric behaves similar to the HOPS metric in initial route selection in this scenario. After adopting our solution, we expect to see significant gain from ETX in comparison with HOPS. To facilitate analysis, we use the S1 of Scenario H, in which lossy nodes are fixed in the positions as shown in Figure 4.

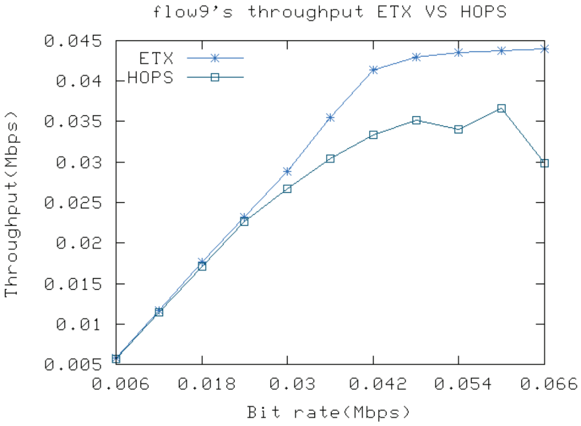

Figure 14. Throughput comparison at flow 9 using the improved routing protocol.

Figure 14 shows the average throughput comparison between ETX and HOPS at flow 9 for a range of data rates. As shown in this figure, the initial routes found by ETX have significantly higher throughput than the initial routes found by HOPS. Moreover, by investigating the ns2 trace file we find that for flow 9, ETX chooses the no lossy node path: 0 → 1 → 2 → 3 → 4 → 9 at every data rate. This observation fulfills our expectation that ETX behaves much better than HOPS when our solution is used.

Our solution has several obvious advantages. Firstly, it is easy to be implemented in either test bed or simulators. Secondly, the cost of repeatedly broadcasting RREQ packets is small compared to the gains that ETX provides. In our simulations, the size of the RREQ packets is 792 bits. Repeatedly broadcasting RREQ packets for ten times would introduce additional workload, which is 792 * (10 – 1) = 7128 bits. This additional workload is very small compared to channel capacity, which is 1 Mb/s.

The downside of this solution is that the route setup phase takes a long time. Due to CSMA/CA used in 802.11 DCF, when nodes sense the channel busy they will freeze the CW (Contention Window) counting down process and wait until the media is idle for a DIFS. Thus additional RREQ packets cause the route setup period to become longer.

6. CONCLUSIONS

We have examined the performance metrics of ETX and HOPS in the context of route stabilization. Our results are based on simulations in a range of scenarios using a 25-node grid based network topology. The results show that for ETX, solving route oscillations via route stabilization is only useful in the single flows case. This is due to the fact that in the multiple flow case, the broadcast packets have a higher possibility of collision. Consequently, two of the important broadcast packets in AODV/ETX, namely ETX probe packets and the RREQ packets, have high probability of collision. Our modified solution, of repeatedly broadcasting RREQ packets, allows ETX to be useful in the initial route selection for both single flows and multiple flows cases. Note we have carried out other simulations on a larger grid (10 * 10 grid) which result in similar results to those reported here.

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