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A new routing metric for wireless mesh networks

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DEDICATION

I would like to dedicate this thesis to my mother, father and my sister for all their love and support. I would also thank my friends for their guidance and encouragement without which I would not have been able to successfully complete this work.

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ABSTRACT

In Wireless Mesh Networks the main goal is to achieve the best possible quality and efficiency of data transmission between source and destination nodes. To achieve such transmission, a routing algorithm should select better paths by taking the quality of wireless links into account. Simple path selection based on minimal hop count often leads to poor performance due to the fact that paths with low hop count often have higher packet loss rates. Better paths can be obtained by characterizing the actual quality of wireless link. A number of link quality aware routing metrics such as Expected Transmission Count (ETX), Expected Transmission Time (ETT), Weighted Cumulative Expected Transmission Time (WCETT), Metric of Interference and Channel Switching (MIC), Interference Aware Metric (iAWARE) etc have been explored. This study highlights some shortcomings of these routing metrics and proposes the design of a novel metric called ETX- 3 hop, which addresses the discussed weaknesses and works more efficiently under various link quality conditions. ETX-3hop consists of a more accurate method to measure the link quality and a path metric that better captures the quality of a path. The performance of the ETX-3hop metric is compared against the original ETX with different path metrics. In extensive simulations, ETX-3hop metric outperforms the original ETX metric in terms of network throughput.

CHAPTER 1. INTRODUCTION

1.1 Overview of Wireless Mesh Networks

Wireless Mesh Networks (WMNs) are an emerging technology and are making significant progress in the field of wireless networks in recent years. Mesh networks are capable of rapid deployment and reconfiguration and this gives them advantages like low up-front cost, easy network maintenance, robustness, and reliable service coverage (1). Typically WMNs consist of mesh routers and mesh clients where each node can operate both as host and router. Mesh routers generally have minimal mobility in a mesh network and form the backbone of WMNs. The clients could be either stationary or mobile and can form self organized ad hoc networks which can access services by relaying requests to wireless backbone network. Mesh routers are generally equipped with multiple wireless interfaces to improve flexibility while mesh clients usually have only a single wireless interface. Based on functionality of nodes, WMNs can be classified into three categories: Infrastructure backbone, client backbone and hybrid WMNs. In Infrastructure WMNs, the mesh routers form a mesh of self-configuring and self-healing links among themselves and provide an infrastructure for the clients that connect to them. The network consists of access links to the end-users and mesh relay links between mesh routers to form the packet transport backbone. This type of network enables integration of WMNs with existing wireless networks, through gateway/bridge functionalities in mesh routers. In client WMNs, client nodes form peer-to-peer mesh network among themselves. The client nodes perform routing and configuration as well as providing wireless access to end user applications. Hybrid WMNs are a combination of both the above types of WMNs and are expected to be the best choice in the next generation WMNs.

Based on their unique characteristics, WMNs have a wide range of applications. The WMNs provide support for applications that are not possible with other existing wireless networks such as cellular networks, wireless sensor networks, ad hoc networks etc. The potential applications include wireless broadband services, community networking, instant surveillance systems, high speed metropolitan area networks, intelligent transportation

systems, transient networks in convention centers, and disaster recovery and back-haul service for large-scale wireless sensor networks.

Routing protocols are at the heart of Wireless Mesh Networks and control the formation, configuration and maintenance of topology of the network. Owing to their common features, routing protocols developed for ad-hoc networks are applicable for WMNs. Some of the commonly used routing protocols in WMNs are Dynamic Source Routing (DSR) (2) and Ad-hoc on-demand distance vector (AODV) (3) routing. However, design of new routing protocols for WMNs is still an active research topic as new performance metrics need to be discovered and utilized to improve performance of routing protocols. They need to address issues of scalability and the difference in requirements for power efficiency and mobility in Ad-hoc and WMNs. An optimal routing protocol for WMNs must capture the following features: Performance Metrics/Routing Metrics, Fault Tolerance, Load Balancing and Adaptive support for both Mesh clients and routers (4) .

Recently, a lot of research effort has been focused on multi-radio wireless mesh networks (5) (6). Due to the relatively low cost of commodity wireless hardware such as radio interfaces based on IEEE 802.11 standards, it is now feasible to include multiple radios on a single node. By operating these interfaces on orthogonal channels, the capacity of a Mesh Router can be significantly increased, and overcomes the limitation of half duplex operation of single-radio nodes. However, routing protocols must be designed to take advantage of the availability of multiple interfaces efficiently.

1.2 Contribution of this work

In this work, we focus on design of good routing metric for routing protocols in WMNs. In WMNs, a routing protocol provides one or more network paths over which packets can be routed to the destination. The routing protocol computes such paths to meet criteria such as minimum delay, maximum data rate, minimum path length etc. A routing metric that accurately captures quality of network links and thus aids in meeting such criteria is central to computation of good quality paths. In this work, we proposed a new routing metric called ETX-3 hop and compared it with the existing ETX routing metric.

The proposed ETX-3 hop metric has the following advantages:

1. ETX- 3 hop metric estimates the link quality more accurately when compared to other existing routing metrics.

2. The path metric of ETX- 3 hop chooses a high throughput path when compared to other metrics.

1.3 Outline of this work

The rest of this thesis is organized as follows. We start with an overview of the existing routing metrics, their advantages and disadvantages in chapter 2. In chapter 3 we discuss the motivation for proposing the new ETX- 3 hop metric and then describe the functioning of this metric. In chapter 4 we present the comparative simulation results of ETX- 3hop and the other three ETX based metrics. We evaluate our ETX- 3hop under various scenarios and metrics. We end the thesis by providing conclusions from our work and outlining future work in chapter 5.

CHAPTER 2. RELATED WORK ON ROUTING IN WIRELESS MESH NETWORKS

2.1 Characteristics of Routing Metrics

As mentioned earlier, a good routing metric must accurately capture the quality of network links and aid in computation of good quality paths. Key components that can be utilized to compose a routing metric for mesh networks are: Number of hops, Link Capacity, Link Quality and Channel Diversity. Below we describe some of the desirable characteristics of a good routing metric for WMNs, that is, some of the criteria routing metric needs to address. (7)

2.1.1 Interference

Interference in a mesh network can be of three types

- Intra-flow Interference: Intra-flow interference occurs when the radios of two or more links of a single path or flow operate on the same channel and can be reduced by increasing channel diversity. i.e. by selecting non-overlapping channels for adjacent hops of a path. Interference range of a node is typically bigger than a single hop and hence links on same channel in a multi-hop path can still interfere with each other and not just restricted to immediate neighbors.

- Inter-Flow Interference: Inter-flow interference is the interference caused by other flows that are operating on the same channels and are competing for the medium. Inter-flow interference is harder to control than intra-flow interference, due to the involvement of multiple flows and routes.

- External Interference: External interference occurs when a link experiences interference outside of the control of any node in the network. Here, we have two kinds of external interference: Controlled Interference, where other nodes external to the network use networking technologies that overlap with those used by the network, and Uncontrolled Interference, which is caused by any other source of radio signals emitted in the same frequency range, but not participating in the same MAC protocol.

2.1.2 Locality of Information

Some metrics require information such as channels used on previous hops of a path, or other metrics observed on other nodes of the networks, such as packet delivery rate or noise levels. This non-local information can be part of routing metric and can be used to make more optimal routing decisions.

2.1.3 Load Balancing

The ability of a metric to balance load and provide fairer usage of the networks distributed resources. This is a very important consideration especially when there is concentration of traffic at the Internet Gateways in mesh networks.

2.1.4 Agility

The agility of a metric refers to its ability to respond quickly and efficiently to changes in the network in terms of topology or load. In order for a metric to be considered agile, the rate at which measurements are taken should be higher than the rate of change in the network.

2.1.5 Isotonicity

The isotonic property of a routing metric means that a metric should ensure that the order of weights of two paths is preserved if they are appended or prefixed by a common third path. Isotonicity is the necessary and sufficient condition of a routing metric for the existence of efficient algorithms to find minimal weight paths, such as Bellman-Ford (8) or Dijkstra's algorithm.

2.1.6 Throughput

In general, a metric should be able to select routes with greater throughput consistently.

2.2 Routing Metrics

In this section, we describe various existing routing metrics, their advantages, drawbacks and issues regarding implementation if any. We also discuss whether the metric is practical i.e. whether the metric is easy to implement or not.

2.2.1 Hop Count

Hop count is the traditional routing metric used in most of the common routing protocols like AODV, DSR, DSDV designed for multi-hop wireless networks. It finds paths with shortest number of hops

Advantages:

1. In scenarios of high mobility, hop-count can outperform other load dependent metrics. This is mostly a result of the metric's agility.

2. It is also a metric with high stability and further has the isotonicity property, which allows minimum weight paths to be found efficiently.

Drawbacks:

1. This metric treats all links in the network to be alike.

2. It does not account for link load, link capacity, channel diversity and interference experienced by the links.

3. It can often result in paths which have high loss ratio and poor performance.

4. It may choose paths with low throughput and poor medium utilization, as slower links take more time to send packets.

Implementation Evaluation:

Out of all the routing metrics for Wireless Mesh Networks, Hop Count can be easily implemented as the routing protocol simply needs to increment the count of the number of hops and chose a path with less number of hops, but its drawbacks outweigh this advantage.

2.2.2 Expected Transmission Count (ETX)

Expected Transmission count ETX (9) is defined as the number of transmissions required to successfully deliver a packet over a wireless link. The ETX of a path is defined as sum of ETX of each link along the path.

ETX is measured in link of a real network by

$$ETX = 1/(Df * Dr)$$

where Df is the forward delivery ratio, Dr is the reverse delivery ratio. The delivery ratios Df and Dr are measured by broadcasting dedicated link probe packets of a fixed size every average period (a typical value is 1 second) from each node to its neighbors.

Advantages:

1. ETX is based on delivery ratios, which directly affects throughput and accounts for the effects of link loss ratios and asymmetry in the loss ratio in both directions of each link.

2. It favors paths with higher throughput and lower number of hops as longer paths have lower throughput due to intra-flow interference.

3. ETX deals with inter-flow interference indirectly. As ETX measures link-layer losses, the links with a high level of interference will have a higher packet loss rate and therefore higher ETX value.

4. ETX is isotonic and therefore allows efficient calculation of minimum weight and loop-free paths.

Drawbacks:

1. It is a routing metric for single-channel multi hop wireless network.

2. It only captures link loss ratio ignoring the interference experienced by the links which has a significant impact on the link quality and the data rate at which packets are transmitted over each link.

3. It does not consider differences in transmission rates.

4. As the transmission rate of probe packets is typically low, it does not accurately reflect loss rate of actual traffic.

5. As it does not consider load of the link, it will route through heavily loaded nodes leading to unbalanced resource usage.

6. ETX does not discriminate between same channel paths and channel-diverse paths. So, it makes no attempt to minimize intra flow interference.

7. In highly mobile single radio environments, ETX shows poor agility due to long time window over which it is obtained.

Implementation Evaluation:

As ETX is based on delivery ratios, each node remembers the number of probe packets received by that node from each of its neighbors. Once this information is obtained, the ETX metric for all the links from that node to its neighbors is calculated. The ETX of a route is the sum of the link metrics. Though this is not as simple as Hop Count metric, it is practical and can be implemented.

2.2.3 Expected Transmission Time (ETT)

The Expected transmission time (ETT) (10) metric is an extension of ETX which takes into account packet size and link bandwidth. ETT is expected time to successfully transmit a packet at the MAC layer and is defined for a single link as

$$ETT = ETX * S/B$$

S denotes the average size of packet and B denotes current link bandwidth.

ETT path metric is obtained by adding up all the ETT values of individual links in the path.

Advantages:

1. It can increase the throughput of path by measuring the link capacities and would increase the overall performance of the network

2. ETT is isotonic

Drawbacks:

1. ETT retains many disadvantages of ETX.

2. ETT does not consider link load explicitly due to which it cannot avoid routing traffic through already heavily loaded nodes and links.

3. ETT is not designed for multi radio networks so it does not minimize intra-flow interference.

Implementation Evaluation:

To Calculate ETT, we need to know the forward and reverse loss rates and bandwidth of each link. Implementation section of ETX mentions how to calculate the forward and reverse loss rates. The problem of determining the bandwidth is more complex. Several algorithms such as RBAR (11) and OAR (12) have been proposed. Draves et al (10) measures the bandwidth using a technique of packet pairs (13). Each node sends two back-to-back probe

packets to each of its neighbors every minute. The first probe packet is small (137 bytes), while the second probe packet is large (1137 bytes). The neighbor measures the time difference between the receipt of the first and the second packet and communicates the value back to the sender. The sender takes the minimum of 10 consecutive samples and then estimates the bandwidth by dividing the size of the second probe packet by the minimum sample. Note that this estimate is not very accurate, since it ignores several factors that affect packet delivery time (10). So there is an additional overhead in calculating the bandwidth in ETT when compared to that of ETX.

2.2.4 Weighted Cumulative Expected transmission Time (WCETT)

Weighted Cumulative Expected transmission Time (WCETT) (10) is an extension over ETT. The WCETT metric of a path p is defined as follows:

$$\text{WCETT(p)} = (1-\alpha) \sum_{\text{link } l \square p} \text{ETT}_l + \alpha^* \max_{1 \leq j \leq k} X_j$$

X_j is the sum of ETT values of links that are on channel j in a system that has orthogonal channels and α is a tunable parameter within the bounds $0 \leq \alpha \leq 1$, which allows controlling preference over path lengths versus channel diversity. In the above equation, k specifies the total number of different channels used in a path. The first term is summation of the individual link ETTs, and therefore favors shorter and high quality paths. The second term in the equation is summation of ETT of all links of a given channel and takes maximum over all channels. So, this gives higher value for a path with larger number of links operating on same channel i.e. it favors channel diversity and low intra flow interference.

Advantages:

1. WCETT effectively considers intra-flow interference into account and selects channel diversified paths.

2. It retains all the advantages of ETT except isotonicity.

3. It manages to improve the performance of multi-radio, multi-rate wireless networks when compared to simpler metrics such as ETT, ETX and hop count.

4. The two weighted components tuned by α of WCETT substitutes the simple summation of ETT and attempt to strike a balance between throughput and delay.

Drawbacks:

1. WCETT simply considers the number of links operating on the same channel and their respective ETTs but does not consider the relative location of these links. It assumes all links of a path operating on same channel interfere which can lead to selection of non-optimal paths.

2. Because of the second term, WCETT is not isotonic. If a metric is not isotonic, then it is very difficult to use with link state routing protocols.

3. WCETT does not explicitly consider the effect of interflow interference. Due to this, it may establish routes which suffer from high levels of interference.

Implementation Evaluation:

To calculate WCETT, we need to know the ETT values and we have to choose the value for the tunable parameter α. The issues regarding calculating ETT values are mentioned in the section 2.2.3.

2.2.5 Metric of interference and channel switching (MIC)

Metric of interference and channel switching (MIC) (14) is designed to support load balanced routing and to consider intra-flow and inter-flow interference, in addition to being isotonic. MIC for a path p is defined as follows:

$$MIC(p) = 1/(N * min(ETT)_{link}) * \sum_{i \in p} IRU_l + \sum_{node\ I \in p} CSC_i$$

Where N is the number of nodes in the network and min(ETT) is the smallest ETT in the network. The two components of MIC, IRU (Interference-aware Resource Usage) and CSC (Channel Switching Cost) are defined as follows.

$$IRU_l = ETT_l * N_l$$

$$CSC_i = w1 \ If \ CH(prev(i)) \neq CH(i)$$

$$CSC_i = w2 \ If \ CH(prev(i)) = CH(i) , 0 \le w1 \le w2$$

N_l is the set of neighbors that interfere with transmissions on line i. CH(i) represents channel assigned for node i's transmission and prev(i) represents the previous hop of node i along path p.

Advantages:

1. MIC takes both inter-flow interference, intra-flow interference and it can be made isotonic if it is decomposed into virtual nodes while applying minimum weight path finding algorithms such as Dijkstra's algorithm.

Drawbacks:

1. The overhead required to maintain update information of the ETT for each link can significantly affect the network performance depending on traffic loads.

2. This metric assumes that all links located in the collision domain of a particular link contributes to same level of interference and counts the amount of interference on a link only by the position of interfering nodes no matter whether they are involved in any transmission simultaneously with that link or not.

3. The second component CSC captures intra-flow interference only in two consecutive links.

Implementation Evaluation:

To Calculate MIC, we need to calculate IRU component and CSC component. Considering IRU component, it depends on ETT and N_l. We have already discussed how to calculate ETT in section 2.2.3. An important implementation issue of IRU is the estimation of N_l. Since mesh networks are static, existing research results have shown that it is possible to measure whether two nodes are in each other's interference range at the time when the network is established. Yang Yaling et. al (15) discusses the estimation of N_l as follows:

"A simple measurement technique proposed by Agarwal et. al (16) exploits the fact that if two nodes are in each other's interference range, their carrier-sensing mechanisms prevent them from transmitting simultaneously. Therefore, if the two nodes start to broadcast consecutive packets at the same time, the transmission rate of each of the nodes should be much smaller than the transmission rate if only one node is broadcasting. Hence, by simply measuring the broadcasting rates of two nodes, it can be determined if the two nodes are in each other's interference range".

The CSC component just assigns weight to a link based on the channel used by the previous link. So this component can be implemented easily.

As a whole, N_l value is hard to obtain so this is the bottleneck to implement MIC metric.

2.2.6 Load Aware Expected Transmission Time (LAETT)

The two main goals of LAETT (17) are to provide a path which satisfies the bandwidth request of the flow and to leave room for future requests by balancing the load across the network. It combines wireless access characteristics and load estimates. It consists of an adaptation of ETT metric

$$ETT_{ij} = ETX_{ij} * S/B_{ij}$$

ETX_{ij}=Expected transmission count on link (i,j)

S =Packet size

B_{ij}= Effective bit rate

$B_{ij} = B_i/\tau_{ij}$

B_i =Transmission rate of node i

τ_{ij} =Link quality factor

$\tau_{ij} = 1$ when the link of good quality when the transmission quality degrades, τ_{ij} increases and B_{ij} decreases.

To consider load balancing, remaining capacity (RC_i) on each node is introduced and it is given by

$$RC_i = B_i - \sum_{k=1}^{N}(f_{ik*} \tau_{ij})$$

f_{ik} are the transmission rates of the N_i current flows that traverse node i. The cost of a flow on remaining capacity is weighted by factor ik: good quality transmissions use fewer resources than bad quality ones. The packet pair algorithm can be used to estimate the available bandwidth on a link which provides τ_{ij} .

We define $LAETT_{ij}$ by:

$$LAETT_{ij} = ETX_{ij} *(S/((RC_i + RC_j)/ 2\tau_{ij}))$$

The second factor captures the remaining capacity at both end nodes. When two paths have same cumulative weight in terms of ETX, LAETT metric favors the one with the most remaining capacity.

Advantages:

1. LAETT is a load aware isotonic routing scheme that uses weighted shortest path routing to balance the load across the network.

2. It captures link quality and traffic load.

Drawbacks:

1. It does not consider intra flow interference and does not explicitly consider inter flow interference.

Implementation Evaluation:

To calculate LAETT, we need to obtain ETT, Effective bit rate (B_{ij}), Transmission rate (B_i), Link quality factor (τ_{ij}) and remaining capacity (RC_i). Aiache et. al (17) uses packet-pair algorithm to estimate the available bandwidth on a link, which gives τ_{ij}. It may also be obtained from the air interface. The remaining capacity (RC_i) computation further requires knowledge of the link quality, available bandwidth on the link (provided by packet-pair) which can be obtained from the air interface through the sending/receiving bitrates. For air interfaces that use the Demand Assignment Multiple Access-Time Division Multiple Access (DAMA-TDMA) technique such as WiMAX (18), the remaining capacity can be obtained from layer 2 in terms of free slots and completed by information on the used modulation schemes.

As a whole, calculating Effective bit rate (B_{ij}), Transmission rate (B_i), Link quality factor (τ_{ij}) and remaining capacity (RC_i) is very hard to obtain.

2.2.7 Exclusive Expected Transmission Time (EETT)

Exclusive Expected Transmission Time (EETT) (19) is a novel interference aware routing metric which selects multi-channel routes with least interference to maximize end to end throughput. It is used to give better evaluation of a multichannel path. For any given l, Interference set (IS) is defined as the set of links that interfere with it. A links interference set also includes the link itself. The link l's EETT is defines as

$$EETT_l = \sum_{link\, i \in IS(l)} ETT_i$$

IS(l)= Interference set of link l. The path weight is defined as the sum of EETT's of all links on the path.

Advantages:

1. As this metric builds over ETT, it has all the advantages of ETT.

2. It effectively considers intra-flow interference and indirectly considers inter-flow interference

3. EETT is isotonic.

Drawbacks:

1.   EETT of link l represents the busy degree of the channel used by link l. It is the worst case estimation of transmission time for passing link l.

Implementation Evaluation:

To calculate EETT, we need to calculate ETT and Interference Set (IS) for each link. We have already discussed how to calculate ETT in the section 2.2.3. Weirong Jiang et. al (19) does not mention how they calculate the Interference Set (IS) . So implementing EETT is very tough.

2.2.8 Interference Load Aware metric (ILA)

Interference Load Aware (ILA) (20) metric is built over MIC metric. It is composed of two components: Metric of channel interference (MTI) and channel switching cost (CSC). CSC component is same as that in MIC metric.

MTI metric is defined as follows

$$MTI_i(C) = ETT_{ij}(C) * AIL_{ij}(C); \ N_l(C) \neq 0$$

$$MTI_i(C) = ETT_{ij}(C); \ N_l(C) = 0$$

AIL_{ij} = Average load of neighbors that may interfere with transmission between nodes i and j over channel C.

$$AIL_{ij}(C) = \sum_{Nl} (IL_{ij}(C)/N_l(C)), \ N_L(C) = N_i(C) \ U \ N_j(C)$$

$IL_{ij}(C)$ = (Interfering load) is the load of interfering neighbors.

$N_l(C)$ = Set of interfering nodes of neighbors i and j

The path weight function is as follows

$$ILA(p) = \alpha * \sum_{link \ I \ \square \ p} MTI_i + \sum_{node \ I \ \square \ p} CSC_i$$

To balance the difference of magnitude of the two components (MTI and CSC), scaling factor _is applied

to MTI metric α is given as

$$(1/ \alpha) = min(ETT) * min(AIL); \ N_i(C) \neq 0$$

$$(1/ \alpha) = min(ETT); \ N_i(C) = 0$$

where min(ETT) and min(AIL) is the smallest ETT and average load in the network. The important implementation issue of the metric is estimation of load of interfering neighbors (21).

Advantages:

1. This metric addresses the aforementioned limitations of existing metrics such as hop count, ETX, ETT, WCETT, MIC for Wireless mesh networks.

2. This routing metric finds paths with less congestion, low level of interference, low packet drop ratio and high data rate.

3. ILA calculates interflow interference by considering the amount of traffic generated by interfering neighbors which is drawback of MIC.

Drawbacks:

1. The second component CSC captures intra-flow interference only in two consecutive links.

Implementation Evaluation:

To Calculate ILA, we need to calculate MTI component and CSC component. The implementation of CSC component is already discussed in section 2.2.5. To calculate MTI component, we need to obtain ETT, AIL_{ij} and $N_{l.}$. Devu Manikantan et. al (20) does not specify how to calculate the AIL_{ij} and N_l components of the ILA metric. So implementing ILA metric is very tough.

2.2.9 Interference Aware metric (iAWARE)

iAWARE (22) is the first routing metric for multi radio WMN to factor in both interflow and intra flow interference and characterized by the physical interference model. The iAWARE metric is defined as follows:

$$iAWARE(p) = (1-\alpha) * \sum_{i=1}^{n} iAWARE_i + \alpha * \max_{1 \leq j \leq k} X_j$$

X_j is same as in WCETT. The iAWARE value of a link j is defined as follows:

$$iAWARE_j = ETT_j / IR_j$$

IR_j =Interference ratio for a link j is the value between two nodes u and v. It is defined as follows.

$$IRj = \min (IR_j(u), IR_j(V))$$

Interference ratio (IR) value for a link j is the value between two nodes u and v. It is defined as follows.

$$IR_i(u) = SINR_i(U) / SNRi(U)$$

$SINR_i(U)$ is the signal to interference noise ratio and $SNR_i(U)$ is the signal to noise ratio at node U for link i.

Advantages:

1. iAWARE captures the effect of variation in link loss ratio, differences in transmission rate as well as inter-flow and intra -flow interference.

2. iAWARE retains many of the properties of WCETT with the exception of its handling of inter-flow interference measurements. It directly measures the average interference generated by neighboring nodes.

3. The introduction of SINR is a great breakthrough for inter-flow interference routing compared with other ETX based metric like MIC, ETX, WCETT etc.

Drawbacks:

1. iAWARE is a non-isotonic routing metric.

2. When a link has higher IR_j that ETT_j , the $iAWARE_j$ metric will have a lower value. This will result in the $iAWARE_j$ metric choosing a path with lower ETT but higher interference. The drawback of this metric is that it gives more weight to ETT compared to interference of the link.

Implementation Evaluation:

To calculate iAWARE metric for a link, we need to obtain ETT and Interference Ratio (IR) values for each link. Interference Ratio (IR) in turn needs Signal to Interference and Noise Ratio (SINR) and Signal to Noise Ratio (SNR) values for each link. To measure SINR and SNR values, there are some models proposed in the literature like Protocol Interference Model (23) (24) and Physical Interference Model (23). Anand et. al (22) uses the physical

interference model to capture the interference experienced by links in the network. Obtaining SINR and SNR values need a lot of computations and are very complicated to implement.

2.3 Routing Protocols for Wireless Mesh Networks

In this section, we describe three different routing protocols in which routing metrics are incorporated in wireless mesh networks to find best possible paths (25).

2.3.1 Destination Source-Routing Protocol (DSR)

DSR (2) is an on-demand routing protocol that is based on concept of source routing. In source routing algorithm, each data packet contains complete routing information to reach its destination. Nodes are required to maintain route caches that contain source routes of which the node is aware. There are two major phases in DSR; the route discovery and route maintenance. For route discovery, the source node broadcasts a route request message which contains the address of the destination, along with source nodes address and a unique identification number. Every node which receives this packet checks if it has route information to destination. If not, it appends its own address to route record of the packet and forwards the packet to its neighbors. A route reply is generated if the route request reaches either the destination itself or an intermediate node which has route information to the destination. DSR has route cache to maintain route information to the destination. Route maintenance is done through the use of route error packets and acknowledgments. Main disadvantage of DSR is it has increased traffic overhead as it contains complete route information in each of its data packet. This degrades DSRs routing performance.

2.3.2 Destination Sequence Distance Vector Routing Protocol (DSDV)

DSDV (26) is a proactive unicast routing protocol based on classical Bellman-Ford (8) routing mechanism. Every node in the network has a routing table which contains information on all possible destinations within the network. Sequence numbers are used to distinguish stale routes from fresh ones. To maintain consistency, routing table updates are periodically transmitted throughout the network. If two updates have same sequence number,

the path with smaller metric is used in order to optimize the path. DSDV protocol only supports bi-directional links.

2.3.3 Ad-hoc On-demand Distance Vector Routing Protocol (AODV)

AODV (3) is a reactive on-demand routing protocol which builds on both DSR and DSDV. AODV is an improvement on DSDV as it minimizes the number of required broadcasts by creating routes on demand basis. It is also an improvement on DSR as a node only needs to maintain routing information about the source and destination as well as next hop, thereby largely cuts back the traffic overhead. The process of route discovery is similar to DSR. Route request (RREQ) packets are broadcasted for route discovery while route reply (RREP) packets are used when active routes towards destination are found. HELLO messages are broadcasted periodically from each node to its neighbors, informing them about their existence.

CHAPTER 3. THE PROPOSED ETX- 3 HOP METRIC

In the previous chapter we have discussed about various existing routing metrics. In this work we propose a new metric called ETX- 3 Hop which is based on original ETX metric. We chose to improve original ETX metric because it is the basis for all the other routing metrics such as ETT, WCETT, MIC, LAETT, EETT, ILA, iAWARE etc. All the routing metrics which we have discussed in the section 2.2 of previous chapter are based on original ETX. Moreover, ETX is very easy to implement when compared to other routing metrics, therefore it is practical.

3.1 Drawbacks of Original ETX

Original ETX metric has some of the drawbacks which we tried to overcome in ETX- 3 hop metric.

Firstly, original ETX metric uses 134 byte probe packets to estimate the link loss ratios. However, the loss ratios experienced by data packets of other sizes may differ from the original ETX estimate. The estimates which ETX metric will provide are only suitable for 134 byte data packets (i.e. data packets of very small size). When we use data packets of other sizes such as 512 bytes and/or 1024 bytes then ETX metric does not choose the most efficient route.

Secondly, each node broadcasts the probe packets to its neighbors in original ETX metric, due to which the transmission rates of these probe packets is very low i.e. the probe packets are transmitted at the base rate which does not accurately reflect the loss rate of actual traffic.

Thirdly, the ETX of a route is the sum of all the ETX values of all the links present in that particular path. Generally for a particular path, the bottleneck link (the link which has lowest delivery ratio) dictates the link quality of that particular path. For example, if a path 'A' having 3 hops has a link of ETX value 4 and all the ETX values of other links in the path have ETX value 1 and consider another path 'B' which has 7 hops where each link has ETX value of 1 then we can say that the ETX path metric chooses the path A as the summation of link metrics for path A comes to be 6 where as that of path B comes to be 7. But when we

simulated this we found that the throughput from path B is more than that of path A which contradicts what ETX has predicted.

Lastly, ETX only uses single packet size measurements (134 byte probe packets) even to measure the delivery ratio of ACK packets. ACK packets are generally 38 bytes in total, including all 802.11b overhead while ETX uses 134 byte probe packets to measure it due to which ETX tends to overestimate the number of required transmissions as it underestimates the ACK delivery ratio for each link. These above drawbacks are properly taken care of in ETX- 3 hop metric which we have proposed.

3.2 Design of ETX- 3Hop

Considering the first case in section 3.1, we did simulation tests to check which probe packet size to choose. The new probe packets size should be such that it accurately estimates the link cost for both small data packet sizes as well as for large data packet sizes. The figure 1 shows the topology we have considered for this simulation. The figure 1 also mentions the delivery ratios of all the links. In this topology we used ETX metric to choose the best route from node 1 to node 7 using probe packet sizes 134 bytes, 512 bytes, 1024 bytes and 2048 bytes in the figures 2, 3, 4 and 5 respectively. The route chosen by 134 byte probe packets is 1-3-7. The route chosen by 512 byte probe packet is 1-4-6-7 and that with 1024 and 2048 byte probe packets is 1-2-4-6-7. Now using the path 1-4-6-7 (the route chosen by using 512 byte probe packet) we have done simulation tests for data packets of various sizes, say 134 bytes, 512 bytes, 1024 bytes and 2048 bytes and found that the throughput is comparable to those paths which would have been chosen if those respective data packet sizes are used as probes. So due to this reason we decided upon using 512 bytes as the probe packet size instead of using 134 bytes.
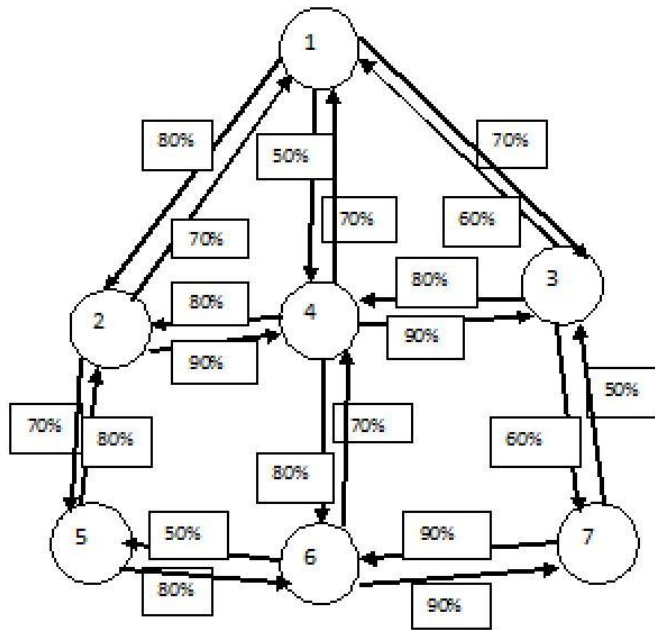
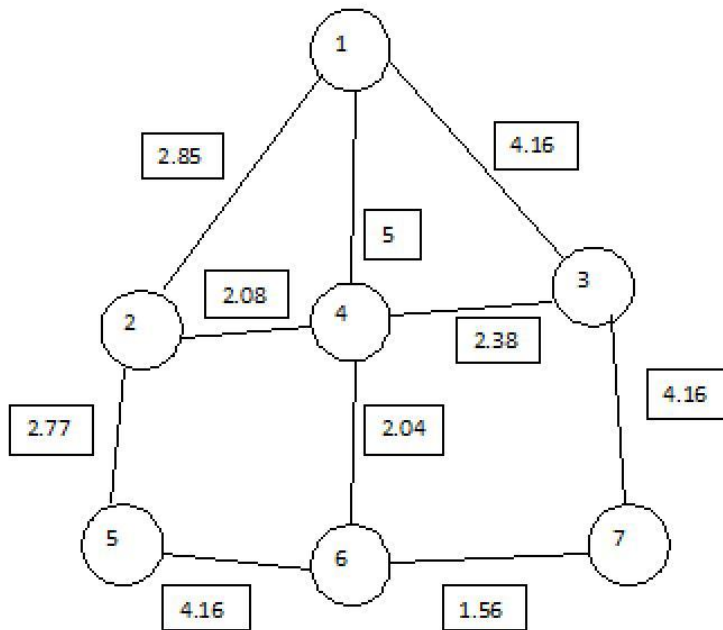Figure 1 Forward and Backward Delivery ratios of the network topology

Figure 2 ETX values of all links with 134 byte probe packets
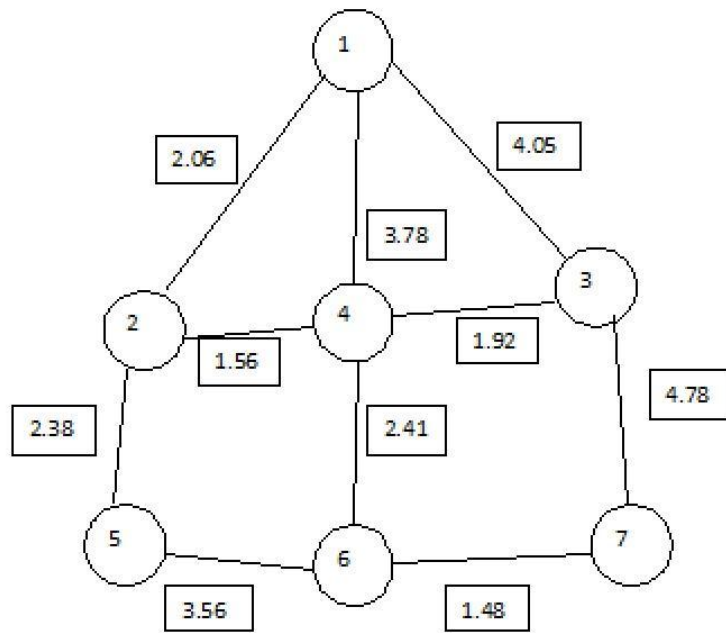
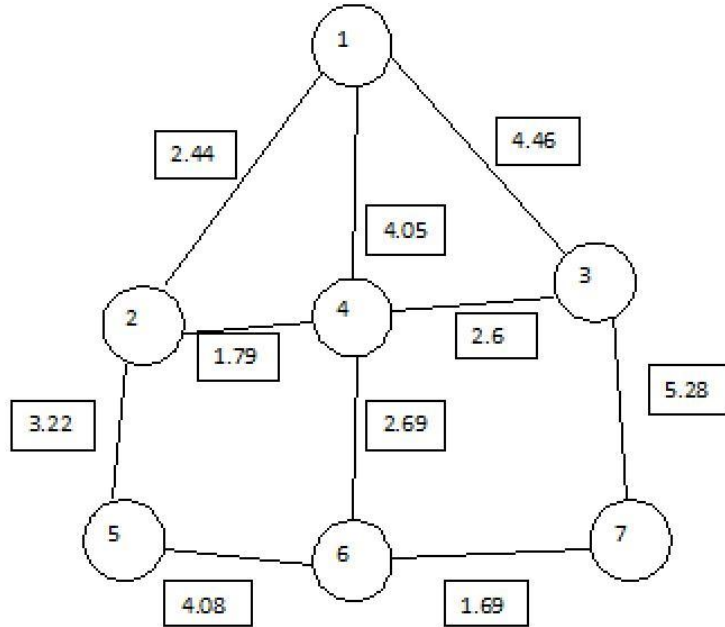Figure 3 ETX values of all links with 512 byte probe packets

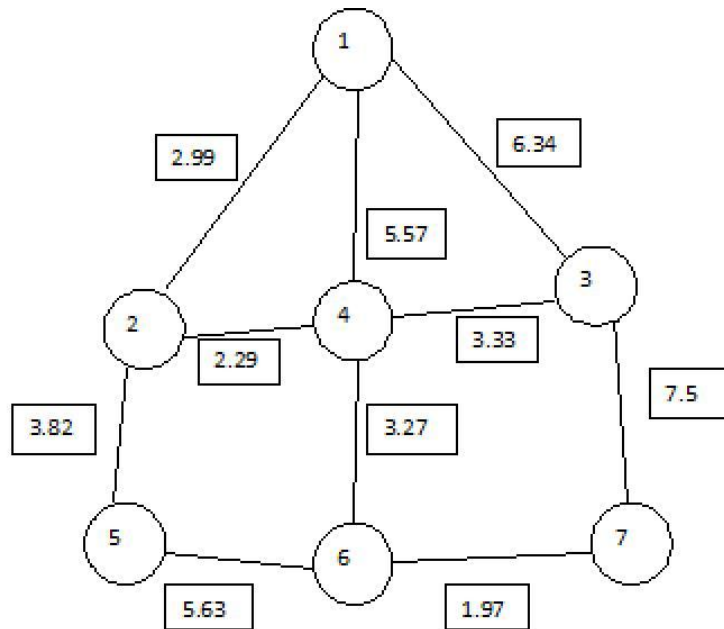Figure 4 The ETV values of all links with 1024 byte probe packets

Figure 5 The ETX values of all links with 2048 byte probe packets

In the second case of section 3.1, the original ETX metric broadcasts the probe packets. These probe packets are small and are sent at the lowest possible data rate due to which original ETX may not reflect the same loss rate as that of the data packets sent at higher rates. So we tried to overcome this drawback by unicasting the probe packets instead of broadcasting them. Each node in the graph sends unicast probe packets of size 512 bytes to its neighbors with maximum possible data rate instead of sending them at the lowest possible data rate. Though this would increase the overhead when compared to the ETX metric but it would accurately measure the link quality when compared to that of the original ETX metric.

Considering the third case of section 3.1, we have done an experiment to check the dependency of number of hops on the throughput. In this experiment we used two cases mentioned in figures 6 and 7. In figure 6, we used all perfect links and used different data rates (6 Mbps, 8 Mbps and 10 Mbps) and checked how the throughput depends as the number of hops increased. We did the same with all the links having delivery rate 80% in figure7.
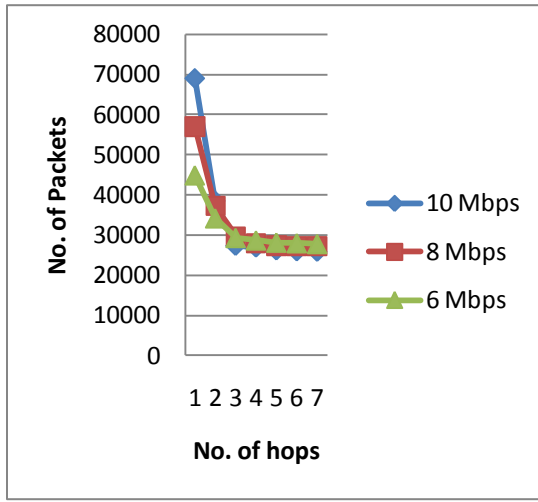
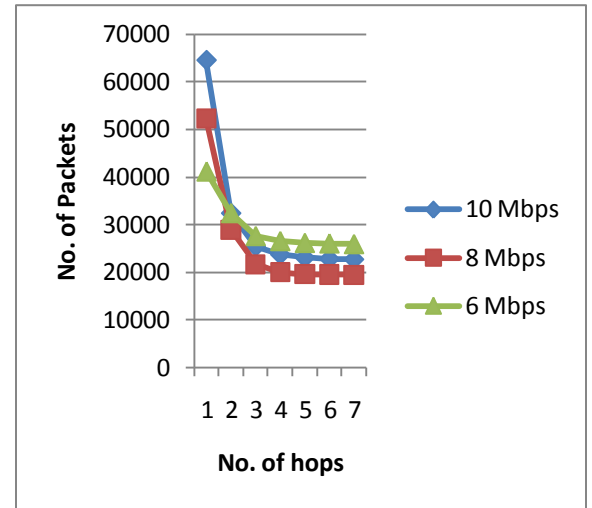Figure 6 Graph where all the links are perfect (100 % delivery ratio)

Figure 7 Graph where all the links have 80% deliveryratio

As we can see from the figures 6 and 7 that the throughput decreases till the hop count reaches 3 and from then on it is almost constant in both the cases. This is because of less intra flow interference between any two links which are separated by three hops. From this we have come to a conclusion that throughput inversely depends on number of hops only when the number of hops is less or equal to 3. If the number of hops is greater than 3 the throughput decrease is very minute. We have included this in the ETX-3 hop metric we proposed. Instead of summing up all the ETX values of all the links in the path we select a 3 hop segment from the path which has the highest ETX value (the value obtained by summing up the ETX values of all the three links in the segment). This is clearly explained using an example below.

Consider the path in figure 8 which has 5 hops. The link metrics are mentioned on the links in figure below. Now we have 3 sub paths having 3 hops each. The sub paths and their summation of ETX link metric are as listed in Table 1.
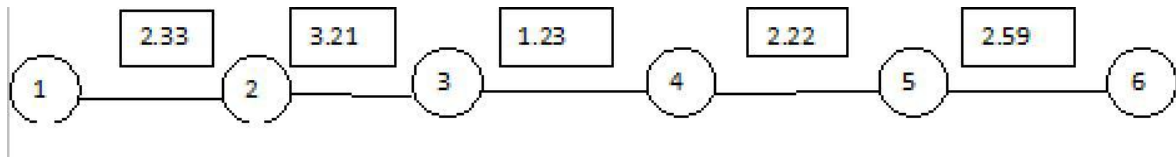
Figure 8 A Network Topology with ETX values of all the links

Table 1 Sub paths having 3 hops in Figure 8 and their ETX link metrics

Sub paths having 3 hops each	ETX link metric value for the subpath
1-2-3-4	6.77
2-3-4-5	6.66
3-4-5-6	6.04

Out of the ETX values of these three sub paths from Table 1, the ETX metric for 1-2-3-4 sub path is maximum(6.77) so it will be the path metric for the path 1-2-3-4-5-6. In this way we can calculate the path metric for the route using ETX-3 hop metric.

Considering the example mentioned previously in the page 19 of this work, the path metric of ETX-3 hop would chose path B instead of path A (as the ETX-3hop path metric value for path A is 6 while that of path B is 3).

Considering the last case, the original ETX metric uses 134 byte probe packets even for the ACK packets. This would over estimate the number of transmissions needed to send a data packet from source to destination because it underestimates the ACK delivery ratio for each link. We tried to overcome this in ETX-3 hop metric by using 38 byte ACK probe packets. Now there are two types of probe packet sizes in ETX-3 hop metric. The 512 byte probe packets are used to measure the data packet delivery ratio and the 38 byte probe packets are used to measure the ACK packet delivery ratio.

Let us discuss how we measure the original ETX based on the network shown in figure 9. Node 1 sends 10 probe packets of size 134 bytes to node 2, one probe packet per second for 10 seconds. Let us assume that node 2 receives only 8 such probe packets sent by node 1. Now node 2 also sends 10 probe packets, one every second for 10 seconds of size 134 bytes and node 1 receives 7 such probe packets from node 2. Now the forward delivery ratio is

Df= 8/10 = 0.8 Dr = 7/10 = 0.7

The ETX metric for the link based on original ETX = 1/ (0.8*0.7) = 1.79

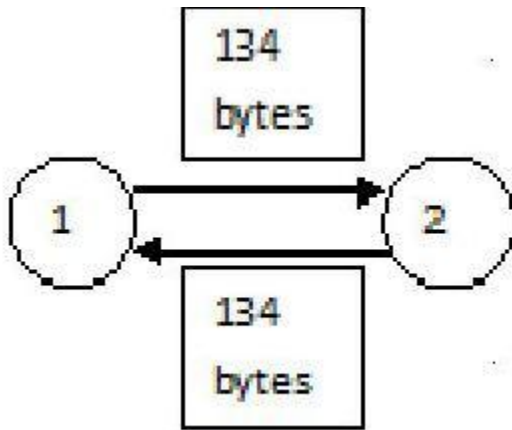So the link metric based on original ETX in figure 9 is 1.79

Figure 9 Node 1 sends 134 byte probe packets to Node 2. In return Node 2 sends 134 byte probe packets to Node 1.
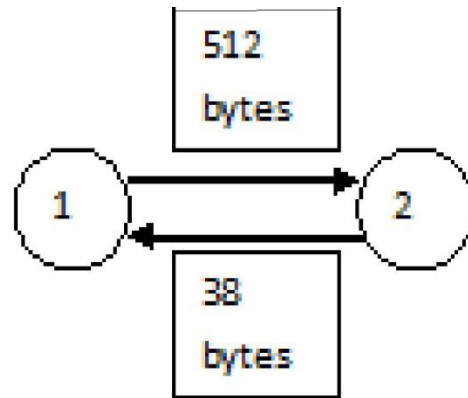
Figure 10 Node 1 sends 512 byte probe packets to Node 2. In return Node 2 sends 38 byte probe packets to Node 1.

We discuss how to measure the link metric based on ETX-3 hop on the same network shown in figure 10 where we use different probe packet sizes. First let us measure the link metric using ETX-3 hop for the directed link from node 1 to node 2. Here node 1 sends 10 probe packets of size 512 bytes to node 2, one packet every second for 10 seconds. Let us assume that node 2 receives 8 out of the 10 probe packets. Now node 2 sends 10 probe packets of size 38 bytes to node 1, one packet a second for 10 seconds. Let us assume that node 1 receives 9 out of 10 probe packets .Now the link metric for the directed link from 1 to 2 is as follows:

Df = 8/10 = 0.8 and Dr = 9/10 = 0.9

The ETX-3hop metric for the directed link from 1 to 2 = 1/ (0.8*0.9) = 1.39

Let us measure the link metric using ETX-3 hop for the directed link from 2 to 1 shown in figure 10. Here we send 10 probe packets of size 512 bytes, one every second from node 2 to node 1. Let us assume that node 1 receives 7 out of 10 probe packets. Now the node 1 sends 10 probe packets of size 38 bytes, one probe per second to node 2 and let's assume node 2 receives 8 out of 10 such probes.

Now the link metric for the directed link from node 2 to node 1 is as follows:

Df= 7/10= 0.7 and Dr = 8/10 = 0.8

The ETX-3hop metric for the directed link from node 2 to node 1 = 1/ (0.7*0.8) = 1.79.

Based on this example we can conclude if we use original ETX metric the link cost from node 1 to node 2 is same as that from node 2 to node 1 i.e. 1.79 in both the directions, whereas if we use the ETX-3 hop metric the link cost from node 1 to node 2 is 1.39 where as that from node 2 to node 1 is 1.79. Moreover, the original ETX metric uses the same 134 byte probe packets to estimate the link quality for ACK packets also which is not the case with ETX-3 hop metric.

3.2.1 ETX-3 hop Metric

ETX- 3 hop is similar to ETX as it is defined as the number of transmissions required to successfully deliver a packet over wireless link. The ETX-3 hop of a path is defined as the maximum value of ETX values of all three hop sub paths in the path. If two paths have the same ETX path metric (this can be a case when the bottleneck three hop sub path is shared by both the paths) then choose the path having less number of hops. Pf be the packet loss probability in forward direction and Pr is the packet loss probability in the reverse direction. Let P denote the probability that the packet transmission from node x to node y in a link is not successful.

P = 1-(1-Pf)(1-Pr)

The expected number of transmissions to successfully deliver a packet in 1 hop can be expressed as ETX-3 hop = 1/ (1-P).

ETX-3 hop is measured in link of a real network by ETX-3 hop = 1/ (Df*Dr),

Where Df= forward delivery ratio (1-Pf)

Dr = reverse delivery ratio (1-Pr).

The delivery ratios Df and Dr are measured by sending unicast probe packets of size 512 bytes in the forward direction and probe packets of size 38 bytes in the reverse direction. Every pair of nodes has two directional links between them. The probe packets are transmitted at an average period τ (one second in this implementation). Every node remembers the probes it receives during the last w seconds (ten seconds in out implementation), allowing it to calculate the delivery ratio from the sender at any time t as:

$$r(t) = count(t\text{-}w, t)/(w/\tau)$$

count(t-w, t) is the number of probes received during the window w and w/ τ is the number of probes that should have been received. Calculation of the link's ETX-3hop value requires both Df and Dr.

3.2.2 Advantages of ETX-3hop metric

1. It uses 512 byte probe packets in the forward direction and 38 byte probe packets in the backward direction (for ACK packets) which makes it more accurate when compared to other metrics such as ETX, ETT etc where only a fixed size probe packets(134 bytes) is used in both backward and forward directions.

2. It unicasts probe packets which can be transmitted at highest possible transmission rate where as ETX, ETT and other link quality metrics broadcast probe packets at the base rate which would go through even when the link is highly congested as the probe packets are sent at the base rate.

3. The path metric of ETX-3 hop considers only the maximum ETX-3 hop value of the three hop sub path in a particular path rather than summing up all the ETX-3hop values of all the links present in the path. By doing this ETX-3 hop favors paths which are free from congestion rather than favoring those paths which have lower number of hops but suffer from high congestion.

4. Like ETX, ETX-3hop is also based on delivery ratios which directly affects the throughput and accounts for the effects of link loss ratios and asymmetry in the loss ratio in both directions of each link.

5. It also deals with inter flow interference and intra flow interference indirectly. As ETX-3 hop measures link layer losses, the links with a high level of interference will have a higher packet loss rate and therefore have higher ETX-3 hop value.

CHAPTER 4. SIMULATION RESULTS

4.1 Simulation Setup

For simulation the Qualnet Simulator 5.0.1 is used. The network of 13 static nodes placed in a 500m×500m area shown in figure 11 is the topology considered for simulation. The figure 11 also mentions the delivery ratios of the links between the nodes. It is assumed that nodes are placed in the area with many large reflectors e.g. walls, trees, and buildings, where the sender and the receiver are not in line of sight of each other. The Two Ray propagation and the Rayleigh fading model are used in simulation. The radio propagation range is 100m and the channel data rate is auto rate fallback. Each node had one 802.11b radio channel.

We have compared four metrics by simulating them on a 13 node network using Qualnet Simulator 5.0.1. The four metrics we compared are as follows:

a) Original ETX-$\sum$ -The ETX metric proposed in De Couto et al (9)(this metric uses broadcast probe packets of size 134 bytes) where the ETX of a route is the sum of the original ETX for each link in the route.

b) Original ETX-3 hop - This metric uses the original ETX proposed in De Couto et al (9) but the path metric is different from the original one. Here the path metric is the maximum of original ETX values of all the three hop segments present in the path.

c) ETX-$\sum$ - This metric uses the ETX metric proposed in this work (i.e. it uses unicast probe packets of 512 bytes in the forward direction and 38 bytes in the backward direction). The path metric is the sum of the ETX for each link in the route.

d) ETX-3 hop - This is the actual metric discussed in this work. It uses unicast probe packets of size 512 bytes in the forward direction and 38 bytes in the backward direction. Here the path metric is the maximum of ETX values of all the three hop paths present in the route.

Let us consider the 13 node network in figure 12 and 13 both the topologies are same but the link metrics on figure 12 are based on original ETX whereas figure 12 is based on ETX metric discussed in this work). We used static routing to send the probe packets from a node

to its neighboring nodes to calculate the link metric and then based on the link metrics we sent the data packets from source to destination for 30 seconds.

Original ETX-∑ and original ETX-3 hop metrics are based on the figure 12 as both are based on original ETX where 134 byte probe packets are transmitted between two neighboring nodes. So we have only one link between two neighboring nodes.

ETX-∑ and ETX-3 hop metrics are based on Figure 13 as both are based on the ETX metric discussed in this work where 512 byte and 38 byte probe packets are unicasted between two neighboring nodes.
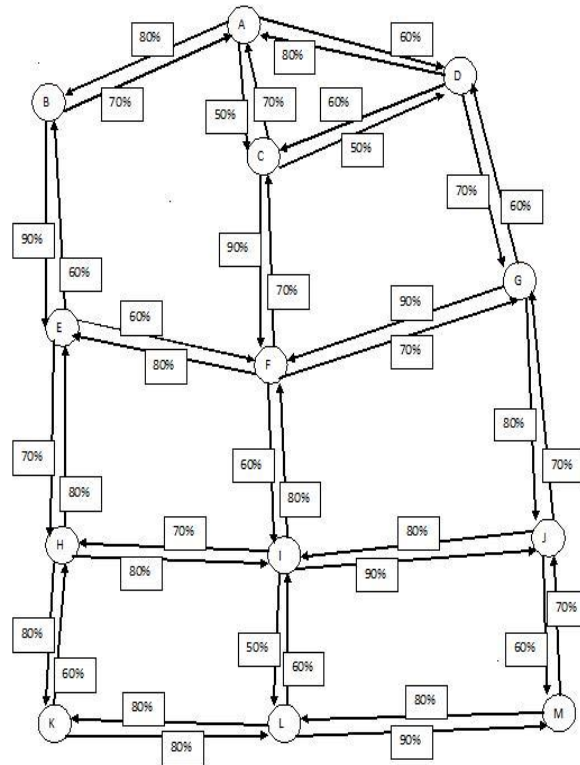

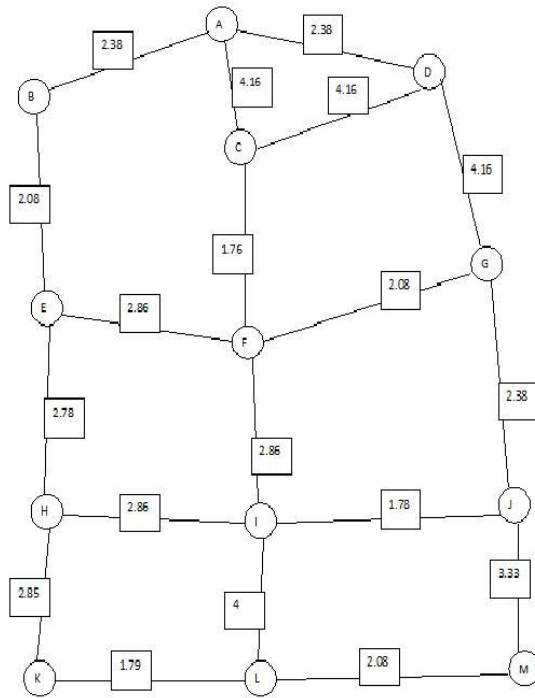Figure 11 Topology with delivery ratios mentioned on the links

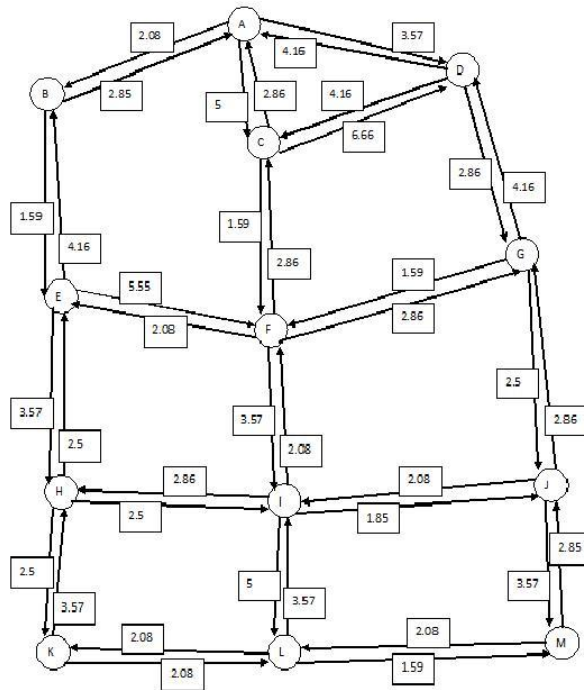Figure 12 ETX values on each link using 134 byte probe packets

Figure 13 Topology with ETX-3 hop values on each link based on the 512 byte probe packets in forward direction and 38 byte probe packets in the reverse direction

Based on the figures 12 and 13, we have considered a set of source and destination pairs and compared all the performance of all the four metrics discussed above. The set of source and destination pairs are as follows: A-M, A-L, D-K, B-J, C-K, G-H, M-A, L-A, K-D, J-B, K-C, and H-G. The figures 14 - 25 below show the throughput performance comparison of all the three metrics for the above mentioned 12 sets of source-destination pairs. The paths taken by each metric is also mentioned in the tables 2- 13 respectively.

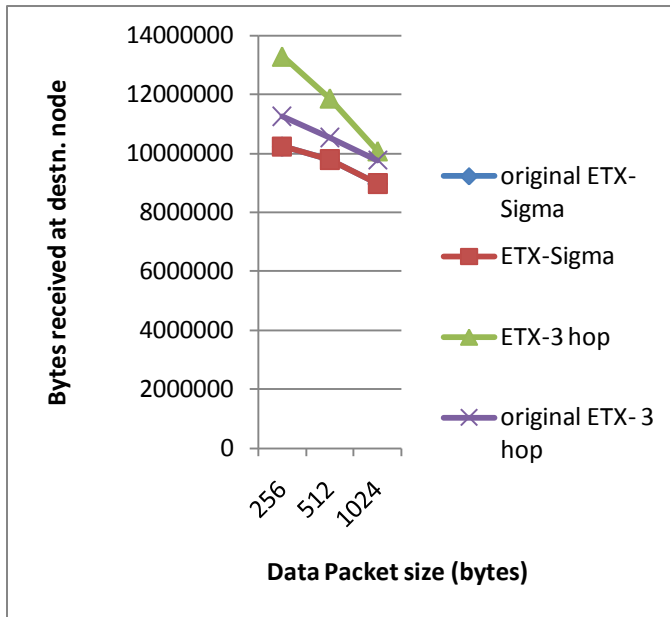Table 2 Paths chosen by various routing metrics for Source Destination Pair A-M

Routing Metric	Path chosen
Original ETX- Sigma	ADGJM
ETX-Sigma	ADGJM
ETX- 3 hop	ABEHIJM
Original ETX- 3 hop	ABEHKLM

Figure 14 Source Destination Pair: A-M

Table 3 Paths chosen by various routing metrics for the Source Destination pair M-A

Routing Metric	Path chosen
Original ETX- Sigma	MJGDA
ETX- Sigma	MJIFCA
ETX- 3 hop	MJIFCA
Original ETX- 3 hop	MLKHEBA
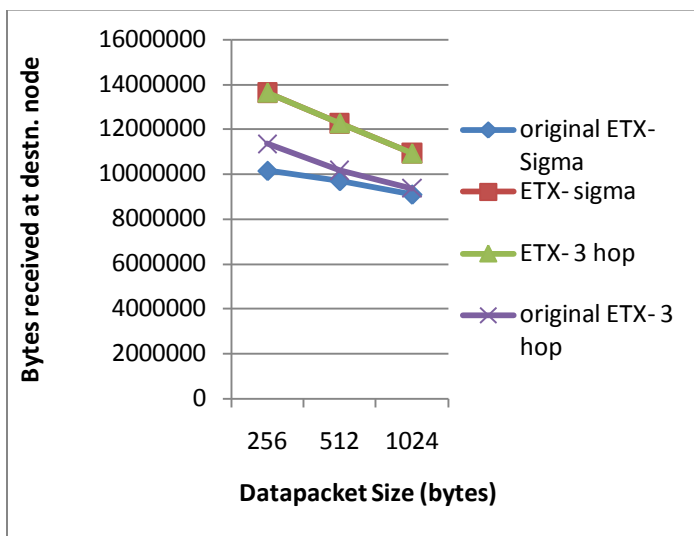
Figure 15 Source Destination Pair: M-A

Table 4 Paths chosen by various routing metrics for the Source Destination pair A-L

Routing Metric	Path chosen
Original ETX- Sigma	ABEHKL
ETX- Sigma	ABEHKL
ETX- 3 hop	ABEHKL
Original ETX- 3 hop	ABEHKL
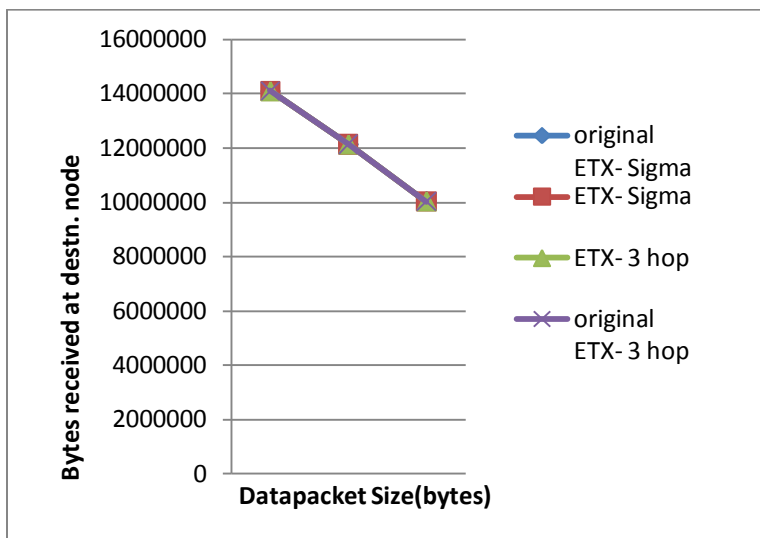
Figure 16 Source Destination Pair: A-L

Table 5 Paths chosen by various routing metrics for the Source Destination pair L-A

Routing Metric	Path chosen
Original ETX- Sigma	LKHEBA
ETX- Sigma	LIFCA
ETX- 3 hop	LMJGFCA
Original ETX- 3 hop	LKHEBA
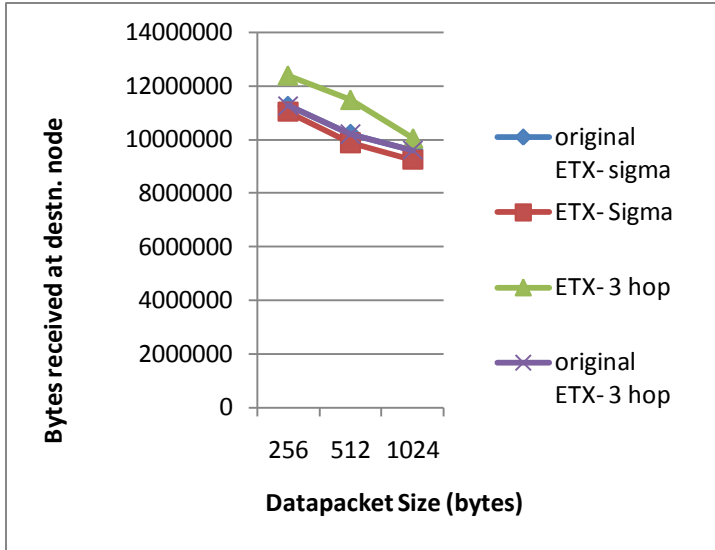
Figure 17 Source Destination Pair: L-A

Table 6 Paths chosen by various routing metrics for the Source Destination pair D-K

Routing Metric	Path chosen
Original ETX- Sigma	DABEHK
ETX- Sigma	DABEHK, DCFEHK
ETX- 3 hop	DABEHK
Original ETX- 3 hop	DABEHK
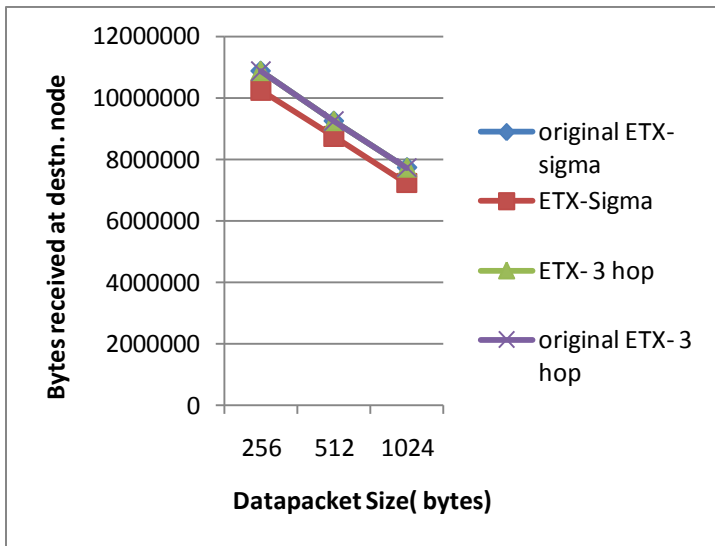
Figure 18 Source Destination Pair: D-K

Table 7 Paths chosen by various routing metrics for the Source Destination pair K-D
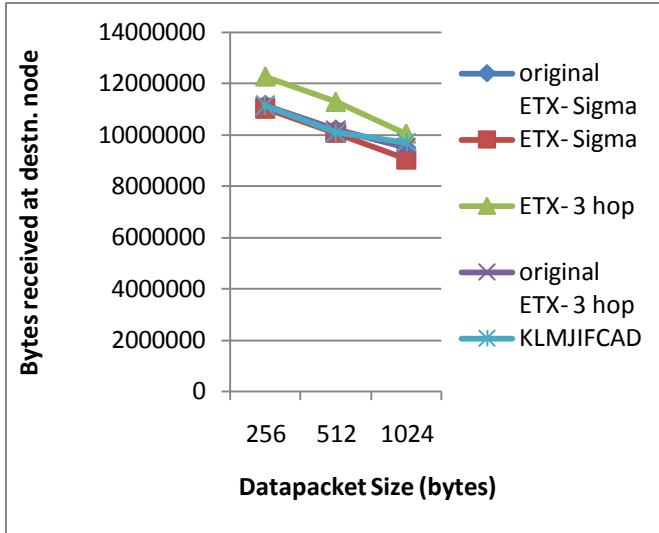
Figure 19 Source Destination Pair K-D

Routing Metric	Path chosen
Original ETX- Sigma	KHEBAD
ETX- Sigma	KLMJGD
ETX- 3 hop	KLIFCAD, KHIFCAD, KLMJIFCAD, KLMJGFCAD
Original ETX- 3 hop	KHEBAD

Table 8 Path chosen by various routing metrics for source destination pair D-K

Figure 20 Source Destination Pair: B-J

Routing Metric	Path chosen
Original ETX- Sigma	BEFGJ
ETX- Sigma	BEHIJ
ETX- 3 hop	BEHIJ
Original ETX- 3 hop	BEFEJ

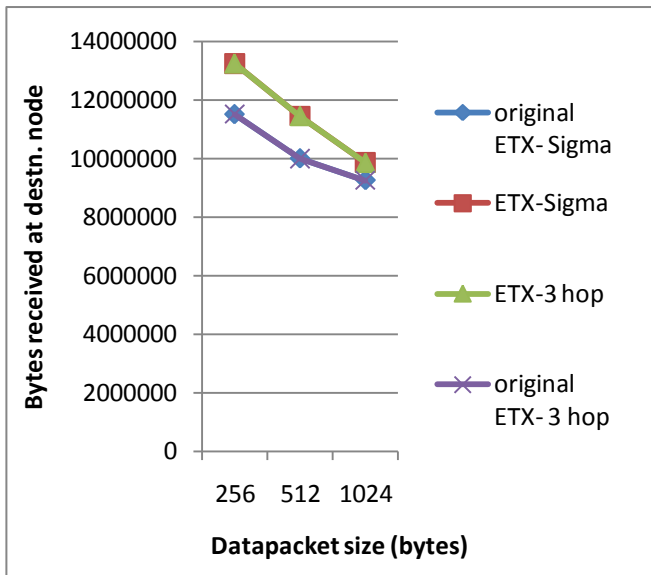Table 9 Paths chosen by various routing metrics for the Source Destination pair J-B

Routing Metric	Path chosen
Original ETX- Sigma	JGFEB
ETX- Sigma	JGFEB
ETX- 3 hop	JGFEB
Original ETX- 3 hop	JGFEB
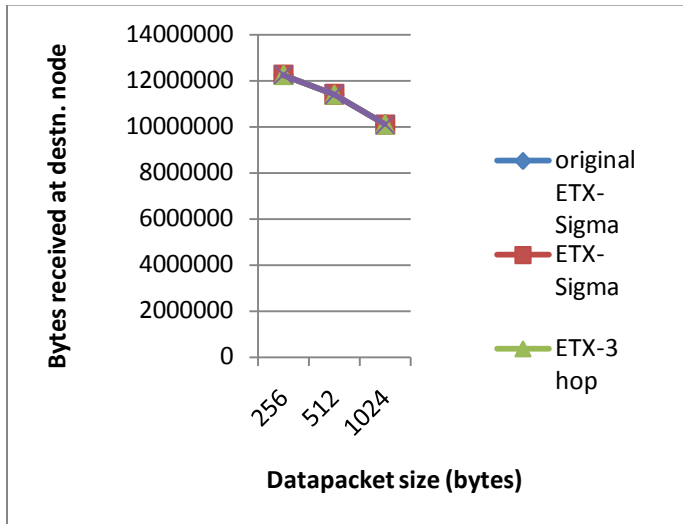
Figure 21 Source Destination Pair: J-B

Table 10 Paths chosen by various routing metrics for the Source Destination pair C-K

Routing Metric	Path chosen
Original ETX- Sigma	CFEHK
ETX- Sigma	CFEHK
ETX- 3 hop	CABEHK
Original ETX- 3 hop	CFEHK
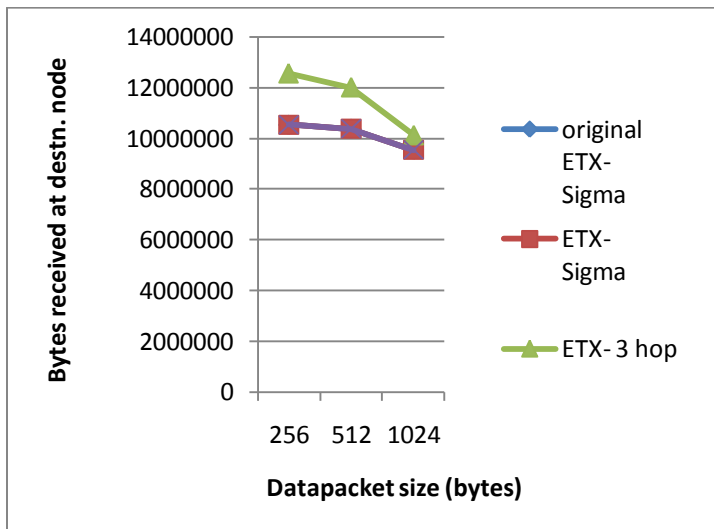
Figure 22 Source Destination Pair: C-K

Table 11 Paths chosen by various routing metrics for the Source Destination pair K-C

Routing Metric	Path chosen
Original ETX- Sigma	KHEFC
ETX- Sigma	KLIFC
ETX- 3 hop	KHIFC
Original ETX- 3 hop	KHEFC

Figure 23 Source Destination Pair: K-C

Table 12 Paths chosen by various routing metrics for the Source Destination pair G-H

Routing Metric	Path chosen
Original ETX- Sigma	GJIH
ETX- Sigma	GFEH
ETX- 3 hop	GFEH
Original ETX- 3 hop	GJIH

Figure 24 Source Destination Pair: G-H

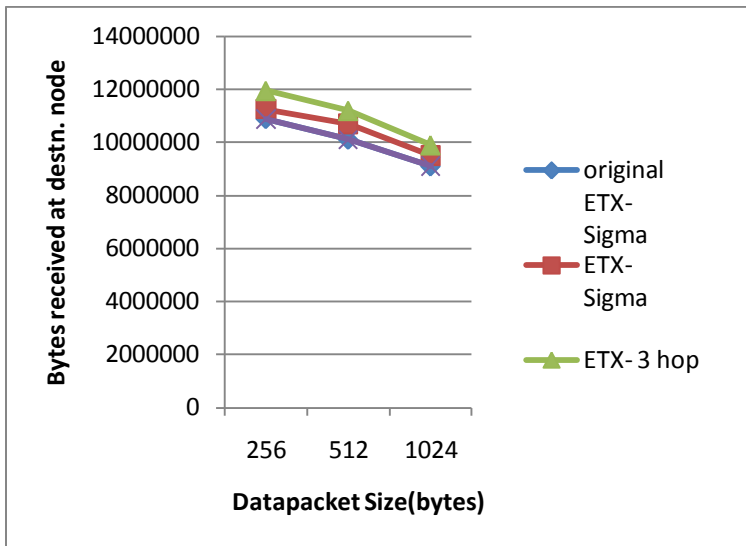Table 13 Paths chosen by various routing metrics for the Source Destination pair H-G

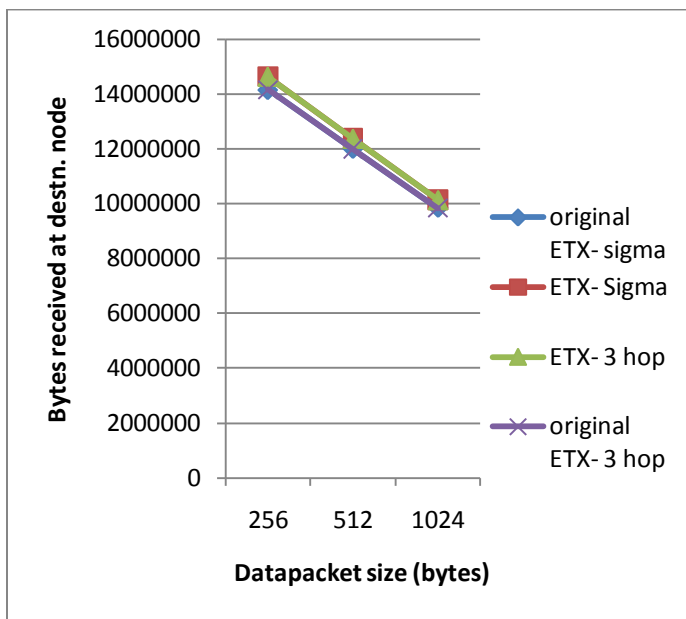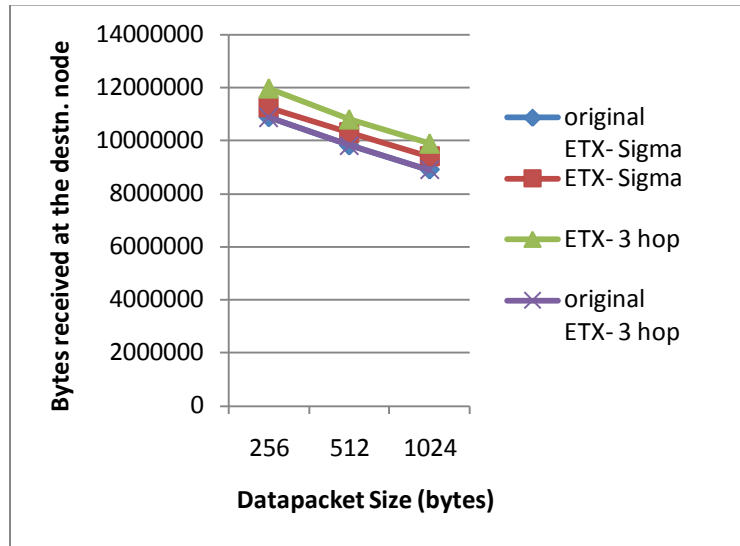Figure 25 Source Destination Pair: H-G

Routing Metric	Path chosen
Original ETX- Sigma	HIFG
ETX- Sigma	HEFG
ETX- 3 hop	HIJG
Original ETX- 3 hop	HIFG

4.2 Simulation Results

From all the figures we can conclude that either ETX-3hop is better than the other metrics or it is as good as the other metrics. From the figures 14, 15, 17, 18, 19, 20, 22, 23, 25 we can observe that ETX-3hop chooses a more efficient path than the path chosen by the other metrics .Where as in 16, 24, 21 all the metrics choose the same path so the throughput of all the metrics is equal. From all the above figures we can say that ETX-3 hop is always better than the other three metrics or in some cases it is as good as the other metrics. After ETX-3 hop the next best metric is original ETX-3hop. Except in figures 23 and 25, original ETX-3hop is better than the original ETX and ETX-∑ .We cannot conclude which metric is best among original ETX and ETX-∑ as in some cases original ETX scores over ETX-∑ and in some cases ETX-∑ scores over original ETX. Considering the paths chosen by the four different metrics we can conclude that original ETX-3 op and ETX-3 hop tend to chose longer paths when compared to the other two as the path metric (3 hop component) does not restrict them to choose a short path as we have already proved that throughput of a path does not depend on the number of hops one the path has more than 3 hops. There is one important

result in figure 19 which is worth mentioning. We can observe that by using ETX-3 hop metric for the source destination pair D-K, we get four different paths having the same ETX-3 hop path metric. They are KLIFCAD, KHIFCAD, KLMJIFCAD, and KLMJGFCAD. We can observe that all the four paths have the last 3 hops in common which is the bottleneck and which decides on the ETX-3 hop metric. As I have already discussed in the ETX-3 hop metric, if we have more than one path which has the same ETX-3hop path metric then we choose the path which has less number of hops. In this way we can say that though ETX-3hop does not restrict the paths based on the number of hops (as the paths chosen by ETX-3 hop generally have more hops than those chosen by original ETX and ETX-∑) but once it has more than one path having the same ETX-3 hop path metric then it chooses the path having the less number of hops.

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

This work introduces a new metric for multi- hop wireless networks, called ETX- 3 hop. Route selection using ETX-3 hop accounts for link loss ratios, the asymmetry of the loss ratios in the two directions of each link, the reduction of throughput due to interference among the successive hops of a route. It accurately measures the link loss ratios when compared to the original ETX based metrics as the probe packets are not sent at the base rate. The path metric of ETX- 3 hop considers only the three consecutive bottleneck links than taking into account all the ETX- 3 hop link metrics as the former accurately measures the path metric rather than the latter. The simulation results show that the ETX- 3 hop metric finds routes with significantly higher throughputs than the other ETX based metrics with which it is compared.

Several aspects of ETX- 3 hop metric can be improved in future. In our metric we have considered 512 bytes as the size of probe packets. 512 byte probe packets is more effective than having 134 byte, 256 byte or 1024 byte probe packets, but actual data packets can be of any size. It would have been even more accurate if the probe packets are of same size as that of data packets. In future we can use probe packet size which is based on the last few data packets sent.

In ETX- 3 hop metric we have only considered one parameter for computing the weight of link. In future research different parameters for choosing a link weight should be considered such as consumption of power, average delay etc.

We can also incorporate our metric in passive estimation of ETX. When data flows through the links, end nodes across a link can estimate the packet loss through periodic reports of received packets. This information can be fetched from the link layer if cross layer information flow is possible. Passive estimates of ETX would be much accurate than that done by probing. Active probing should be done for idle links for which we can use ETX- 3 hop. In future, we will also study more thoroughly the efficiency of existing approaches in terms of support for channel diversity and how to include it in our ETX- 3 hop metric.

BIBLIOGRAPHY

1. Miguel Elias M. Campista, Pedro Miguel Esposito, Igor M. Moraes, Luis Henrique M.K. Costa, Otto Carlos M. B. Duarte. Routing Metrics and Protocols for Wireless Mesh Networks. *Network, IEEE*, 22(1):6-12, 2008

2. Maltz, David B. Johnson and David A. Dynamic Source Routing in AdHoc Wireless Networks. *In Imielinski and Korth, editors, Mobile Computing, volume 353. Kluwer Academic Publishers,* 1996

3. Royer, E.M. Perkins, C.E. An Implementation Study of AODV Routing Protocol. In *Wireless Communications and Networking Conference, 2000. WCNC,* pages 1003 - 1008 vol.3 IEEE 2000.

4. Yaling Yang, Jun Wang**.** Design Guidelines for Routing Metrics in Multihop Wireless Networks. In *IEEE INFOCOM - The 27th Conference on Computer Communications*, pages 1615-1623. IEEE. 2008

5. Manolis Genetzakis, Vasilios A. Siris. Contention-Aware Routing Metric for Multi-Rate Multi-Radio Mesh Networks In *5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, pages 242-250. IEEE. 2008

6. Hongkun Li, Yu Cheng, Chi Zhou, Weihua Zhuang**.** Minimizing End-to-End Delay: A Novel Routing Metric for Multi-Radio Wireless Mesh Networks. In *IEEE INFOCOM The 28th Conference on Computer Communications*, pages 46-54. IEEE. 2009

7. Jonathan Guerin, Marius Portmann and Asad Pirzada. Routing Metrics for multi radio Wireless Mesh Networks. *In Telecommunication Networks and Applications Conference,* pages 343 - 348. 2007

8. Bellman Ford Algorithm. *Wikipedia.org.* [Online] 2010. en.wikipedia.org/wiki/Bellman-Ford_algorithm.

9. Douglas S.J. De Couto, Daniel Aguayo,John Bicket and Robert Morris. A High Throughput Path Metric for MultiHop Wireless Routing. *Wireless Networks*, 11(4):419-434. 2005

10. Richard Draves, Jitendra Padhye and Brian Zill. Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks. . In *MobiCom '04: Proceedings of the 10th annual international*

conference on Mobile computing and networking, pages 114-128, New York, NY, USA. ACM.2004

11. G. Holland, N. Vaidya, P. Bahl. A rate adaptive MAC protocol for multi hop Wireless Networks. . *In MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking, pages 236-251, New York, NY, USA. ACM.* 2001

12. B. Sagdehi, V. Kanodia,A. Sabharwal, and E. Knightly. Opportunistic Media Access for Multi rate Ad hoc Networks. *Networks, 11(1-2):39-53.* 2005

13. Keshav, S. A Control- theoretic approach to flow control.*In Proceedings of the conference on Communications architecture & protocols, pages 3-15.* 1993

14. Yaling Yang, Jun Wang and Robin Kravets. Designing Routing Metrics for Mesh Networks. *In IEEE INFOCOM - The 27th Conference on Computer Communications, pages 1615-1623. IEEE. 2008*

15. Yaling Yang, Jun Wang, and Robin Kravets. Interference-aware Load Balancing for Multihop Wireless Networks. *Technical report, University of Illinois at Urbana-Champaign.* 2005

16. S. Agarwal, J. Padhye, V. Padmanabhan, L. Qiu, A. Rao, and B. Zill. *Estimation of Link Interference in Static Multihop Wireless Networks. ACM Internet Measurement Conference (IMC)*, 2005. Pages 51- 62.

17. Herve Aiache, Laure Lebrun, Vania Conan and Stephane Rousseau. LAETT A load dependent metric for balancing Internet traffic in Wireless Mesh Networks. In *Mobile Ad Hoc and Sensor Systems, 2008. MASS 2008.* Pages 629-634.

18. Air interface for fixed broadband wireless access systems. IEEE. Standard 802.16-2004. , 2004, Vol. 16.

19. Weirong Jiangun Zhu, Yun Zhu and Zhiming Zhang. Optimizing Routing Metrics for Large-Scale Multi-Radio Mesh Networks. *In Networking and Mobile Computing, 2007.* Pages 1550-1553.

20. Anjali, Devu Manikantan Shila and Tricha. Load-aware Traffic Engineering for Mesh Networks. In *Computer Communications and Networks, 2007. ICCCN 2007.*Pages 1040-1045.

21. Zhou, Hossam Hassanein and Audrey. Load Balanced Wireless Ad hoc Routing. *Electrical and Computer Engineering,(2:1157-1161) 2001.*

22. Anand Prabhu Subramanian, Milind M Buddhikot and Scott Miller. Interference Aware Routing in Multi-Radio Wireless Mesh Networks. *Wireless Mesh Networks, WiMesh 2006.* Pages 55-63.

23. Kumar, P. Gupta and P. R. The Capacity of Wireless Networks. In *IEEE Transactions on Information Theory*, *2000*.46(2):388-404.

24. K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu. Impact of Interference on Multi-hop Wireless Network Performance. In *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*, *2003*.Pages 66-80

25. Hui Liu, Wei Huang, Xu Zhou and X.H.Wang. A Comprehensive Comparison of Routing Metrics for Wireless Mesh Networks. *Networking, Sensing and Control, 2008. ICNSC 2008.* Pages 955-960.

26. Bhagwat, Charles E. Perkins and Pravin. Highly Dynamic Destination- Sequenced Distance-Vector Routing(DSDV) for Mobile Computers. In *SIGCOMM Comput. Commun 1994. Rev.*, 24(4):234-244.