Load-aware Traffic Engineering for Mesh Networks

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***Abstract*—The static nature of mesh nodes imposes requirements for designing routing metrics that support high throughput and low packet delay. This paper considers the problem of interference-load aware routing in multi channel wireless mesh networks. We propose a new Interference-Load Aware routing metric, ILA, that finds paths with reduced inter-flow and intra-flow interference. The aim of this metric is to route the traffic through congestion free areas and balance the load amongst the network nodes. We incorporate this new metric in the well known AODV routing protocol and study the performance of ILA through simulations. We show that the proposed metric is able to adapt to changes in interfering traffic better than existing link metrics such as ETT and MIC. We also demonstrate that our metric delivers high throughput in multi channel networks.**

***Index Terms*—Wireless Mesh networks, Intra-flow interference, Inter-flow interference, Traffic interference**

I. INTRODUCTION

Wireless Mesh Networks (WMNs) [1], [2] have emerged recently as a promising technology for next-generation wireless networking to provide better services. A WMN consists of two types of nodes: mesh routers and mesh clients. Mesh routers form the backbone and they have minimal mobility. The mesh client nodes can be stationary or mobile. Like ad hoc networks, each node operates not only as host but also as router, forwarding packets to and from an Internet-connected gateway in a multihop fashion. The gateway and bridging functionalities in mesh routers provide the integration of WMN's with other networks such as Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks. Unlike ad hoc networks, the routing and configuration functionalities of the mesh routers reduces the load on end-user devices. The mesh network is dynamically self-organizing and self configuring, with the nodes in the network automatically establishing and maintaining connectivity among themselves. These features provide many advantages for WMN's like good reliability, market coverage,scalability and low upfront cost. WMN gained significant attention because of the numerous applications it supports, e.g., broadband home networking, community and neighborhood networks, enterprise networking, building automation, etc.

In WMN, the mesh clients can access the network through mesh routers or directly via other mesh clients. To support end to end communication, effective routing algorithms are required to find high throughput paths between source and destination. However, it is more difficult to find paths in wireless networks, as compared to wired networks. This is attributed to many factors. First, the channel errors in wireless links make them unreliable. Second, the communication links break when nodes move out of their transmission range. Third, achievable channel rates may be different in different links because of the dependence of the link quality on path loss and distance between the neighbors. Finally, the interference in the wireless medium from other onging simultaneous wireless transmissions plays a significant role.

To perform efficient routing, good routing metrics are required for path computation. Hop count is a widely used metric in both wired and wireless networks. For wired networks, shortest path is assumed to the path with minimum delay, and therefore hop count is a good cost metric. However for wireless networks, minimum hop count is not an accurate performance metric because it could cause congestion problems and power depletion at some specific nodes. Since WMN's share common characteristics with the ad hoc networks, the routing protocols designed for ad hoc networks can be applied to WMN's. On the other hand, the static nature of mesh routers and the mobile nature of client nodes implies that the routing protocols for ad hoc networks may not be suitable for WMNs. Based on the specific requirements of WMN, we believe that a good routing protocol should find paths with minimum delay, maximum data rate and low levels of interference. Also, an effective routing metric must be able to capture the quality of the links accurately.

In this paper, we propose a new routing metric called as Interference-Load Aware metric, ILA. This metric can be used to find paths between the mesh routers. The mesh clients do not need to participate in a routing algorithm since clients always send data to their respective routers. Only the routers are involved in the path selection and determination. The aim of the proposed metric is to find paths with less congestion, minimum packet loss, low level of interference and high data rate. Towards this end, the mesh routers are required to keep track of the traffic load on themselves, as well as their neighbors. The traffic load of the neighbors is a potential source of interference and paths with high interference should be avoided. The simulation results show that ILA provides better performance than the existing routing metrics for wireless mesh networks.

The rest of the paper is organized as follows. Section II presents an overview of the existing routing metrics for ad hoc and wireless mesh networks. Section III presents the design of the proposed interference aware routing metric, ILA. In section IV, we present an overview of the AODV(Ad hoc On-Demand Distance Vector Routing) protocol and discuss several implementation issues like ETT (Expected Transmission Time) measurement, load estimation of the interfering neighbors, etc. Section V describes the simulation setup and the performance results. Section VI concludes our work and outlines our future directions.

II. RELATED WORK

A good routing metric should find paths with links that have high data rate, low loss ratio and low level of interference. In this section, we describe the need for a new interference aware routing metric for multi channel wireless mesh networks by presenting an overview of the various routing metrics such as hop count [3], RTT [4], ETX [5], ETT [6], WCETT [7], MIC [8], [9] proposed for multi hop wireless mesh networks. This section discusses the details and limitations of the aforementioned routing metrics.

A. Hop Count

Hop count is the most commonly used routing metric in routing protocols such as AODV [10], DSR [11], DSDV [12]. Hop count treats all links in the network to be alike and finds paths with minimum number of hops. It does not consider the difference of transmission rates and packet loss ratios or interference experienced by the links. Hence hop count results in poor performance.

B. Per-hop Round Trip Time (RTT)

RTT [4] is based on measuring the round trip delay of unicast probes between neighboring nodes. To calculate RTT, each node sends a probe packet with the current timestamp to each of its neighbors. Each neighbor responds with a probe acknowledgement. This enables the sending node to calculate the round trip time to each of its neighbors. RTT is designed to capture highly loaded links. But the metric does not take into account the link data rates as well as the interference experienced by the links.

C. Expected Transmission Count (ETX)

ETX [5] is defined as the expected number of MAC layer transmissions needed to successfully deliver a packet from a sender to the receiver. The smaller the ETX metric for a link, better the link. ETX of a route is defined as the summation of the ETX of all the links along the route. ETX captures the effects of both packet loss ratio and path length since both long and lossy paths have large weights under ETX. However, ETX does not consider the data rate at which packets are transmitted over each link. ETX might vary when there is very high load due to 802.11 MAC unfairness [2], [13] or when there is loss of broadcast packets due to collision with packets from hidden terminals. However, when the sender can hear the neighboring transmissions, the sender will not initiate new transmissions. In this case, ETX is not affected as collisions do not happen. The drawbacks of ETX are that it does not capture the intra-flow or inter-flow interference.

D. Expected Transmission Time (ETT)

ETX does not consider the data rate at which packets are transmitted. ETT [6] metric improves upon ETX by capturing the data rate used by each link. The ETT of link i is defined as the expected MAC layer duration for a successful transmission of a packet on link i. ETT_i of the link is expressed as follows:

$$ETT_i = ETX_i \times \frac{S}{B_i} \tag{1}$$

where S is the packet size used and B_i is the bandwidth of the link i. Due to the B_i parameter in the weight of path, ETT metric captures the impact of link capacity on the performance of the path. The drawback of ETT is that it does not fully capture the intra-flow and inter-flow interference in the network. Both ETX and ETT do not consider the presence of multiple channels and therefore find path with less channel diversity.

E. Weighted Cumulative Expected Transmission Time (WCETT)

In [7] the authors propose WCETT for multi-hop 802.11 mesh networks, with multiple radios per node. WCETT has two components. The first component is the sum of transmission times along all hops in the network. The second component accounts for channel diversity of path. WCETT of an n hop path is given as

$$WCETT = (1-\beta) \times \sum_{i=1}^{n} ETT_i + \beta \cdot \max_{1 \le j \le k} X_j \tag{2}$$

WCETT metric takes into account the bandwidth, error rate and channel diversity in the path. But the drawback of this metric is that it does not capture inter-flow interference.

F. Metric of Interference and Channel Switching (MIC)

In [8], [9] the authors proposed MIC, which considers inter-flow interference and intra-flow interference. MIC for a path is defined as follows:

$$MIC(p) = \frac{1}{N \times \min(ETT)} \sum_{i \in p} IRU_i + \sum_{i \in p} CSC_i \tag{3}$$

where N is the total number of nodes in the network. The two components IRU and CSC are expressed as follows:

$$IRU_i = ETT_i \times N_i \tag{4}$$

where N_i is the set of neighbors that interfere with the transmissions on link i.

$$CSC_i = \begin{cases} w_1 & CH(prev(i)) \neq CH(i) \\ w_2 & CH(prev(i)) = CH(i) \end{cases} \tag{5}$$

where CH(i) represents the channel assigned for node i's transmission and prev(i) is the previous hop of node i along the path p. The parameters w_1 and w_2 are chosen such that $0 \le w1 \le w2$. Essentially, the physical meaning of the IRU_i component is the aggregated channel time consumed by the transmissions of neighboring nodes on link i. IRU component

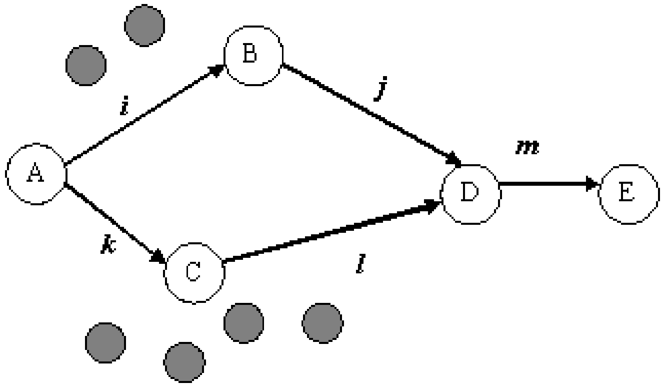

Fig. 1. Interfering Nodes

captures the inter-flow interference and CSC component captures the intra-flow interference along path p.

MIC captures inter-flow interference by scaling up the ETT of the link by the number of interfering neighbors. However, the degree of interference caused by the each interfering node is not the same and it depends on the amount of traffic generated by the interfering node [13]. An interferer that is not involved in any transmission simultaneously but close to the sender or receiver will not cause any interference. MIC fails to capture the aforementioned characteristics of interference.

In figure 1, we show a sample network to illustrate the limitations of MIC metric. The colored nodes represent the interfering neighbors. In this topology, node A wants to communicate with node E. Node A can send traffic to node E either over path ijm or klm. Let's assume that path ij has higher ETT than path kl i.e. $ETT_{AB} + ETT_{BD} > ETT_{AC} + ETT_{CD}$ and the interfering neighbors close to path i cause more interference compared to interfering neighbors close to path kl. Since MIC takes into account the number of interfering neighbors and not the load of the interfering neighbors, it favors path ijm over klm resulting in choosing the path with poorer performance. Also, in the absence of interfering neighbors, MIC fails to capture the link loss ratio and transmission rates of the link as the metric IRU will be 0.

G. Interference Aware Routing Metric (iAWARE)

In [13], authors propose iAWARE for Multi-Radio Mesh Networks. iAWARE captures the effects of variation in link loss-ratio, differences in transmission rate as well as inter-flow and intra-flow interference. The cumulative path metric $iAWARE_p$ of a path p is defined as follows:

$$iAWARE_p = (1-\alpha) \times \sum_{i=1}^{n} iAWARE_i + \alpha \times \max_{1 \le j \le k} X_j \tag{6}$$

The component $iAWARE_j$ is given as follows.

$$iAWARE_j = \frac{ETT_j}{IR_j}$$

where IR_j is the Interference Ratio of link j and ETT_j is the Expected Transmission Time of link j. When there is no interference (IR_j = 1), $iAWARE_j$ is equal to ETT_j and the metric will capture the link loss ratio and packet transmission rate of the link j. But, when a link has higher IR_j than ETT_j, the $iAWARE_j$ metric will have a lower value. This will result in the $iAWARE_j$ metric chooosing a path with lower ETT but higher interference. The drawback of this metric is that it gives more weightage to ETT compared to interference of the link.

III. DESIGN OF INTERFERENCE-LOAD AWARE ROUTING METRIC (ILA)

In this section, we present the proposed Interference-Load Aware routing metric, ILA. This metric addresses the aforementioned limitations of existing metrics such as hop count, ETX, ETT, WCETT, MIC, iAWARE for wireless mesh networks. This routing metric finds paths with less congestion, low level of interference, low packet drop ratio and high data rate. MIC [8], [9] captures inter-flow interference by scaling up the ETT of the link by the number of interfering neighbors. The IRU metric of MIC [8] over estimates the link metric. As mentioned before, the degree of interference depends on the amount of traffic generated by the interfering node. An interferer that is not involved in any transmission simultaneously but close to the sender or receiver will not cause any interference. MIC fails to capture the aforementioned characteristics of interference.

The Interference-Load Aware, ILA, metric is composed of two components: Metric of Traffic Interference (MTI) and Channel Switching Cost (CSC). The two metrics of ILA capture the effects of intra-flow and inter-flow interference, difference in transmission rates, packet loss ratio and congested areas.

A. Metric of Traffic Interference (MTI)

The Metric of Traffic Interference considers the traffic load of interfering neighbors as opposed to number of interfering neighbors in MIC. The shared nature of wireless medium results in both inter-flow and intra-flow interference. The inter-flow interference happens when neighboring nodes compete with each other for channel bandwidth when they transmit on the same channel. The degree of interference depends on the amount of load generated by the interfering node and not on the number of interfering nodes. This metric (ILA) considers the traffic of interfering nodes to capture the inter-flow interference. The MTI metric is defined as follows:

$$MTI_i(C) = \begin{cases} ETT_{ij}(C) \times AIL_{ij}(C) & , N_l(C) \neq 0 \\ ETT_{ij}(C) & , N_l(C) = 0 \end{cases} \tag{7}$$

where AIL_{ij} is the average load of the neighbors that may interfere with the transmission between nodes i and j over channel C. $AIL_{ij}(C)$, Average Interfering Load, is given as

$$AIL_{ij}(C) = \frac{\sum_{N_l} IL_{ij}(C)}{N_l(C)} \tag{8}$$

where

$$N_l(C) = N_i(C) \cup N_j(C) \tag{9}$$

and $IL_{ij}(C)$, Interfering Load, is the load of the interfering neighbor. $N_l(C)$ is the set of interfering neighbors of nodes i and node j. ETT_{ij} captures the difference in transmission rate and loss ratio of links. The AIL_{ij} defines the neighboring activity of the nodes. When there is no interfering neighbor, MTI metric selects the path with high transmission rate and low loss ratio. In the presence of interfering neighbors, MTI metric selects the path with minimum traffic load and minimum interference.

B. Channel Switching Cost (CSC)

Intra-flow and Inter-flow interference exist in mesh networks. The MTI metric captures the inter-flow interference. To capture the intra-flow interference, CSC, similar to MIC is included in ILA. Between two paths that have same MTI weight, the nodes that use different channels to transmit data have less intra-flow interference than the path that always uses the same channel. The CSC metric is defined as follows:

$$CSC_i = \begin{cases} w_1 & CH(prev(i)) \neq CH(i) \\ w_2 & CH(prev(i)) = CH(i) \end{cases} \tag{10}$$

$$0 \leq w1 \leq w2$$

Consider a node i, which is equipped with multiple radios and configured to different channels. To eliminate intra-flow interference, the node i should transmit to the next hop using a channel different from the channel it used to receive the data from prev(i) i.e. previous hop of node i. We denote by CH(i) the channel that node i uses to transmit to its next hop and CH(prev(i)) the channel used by the previous hop of node i. If the node i uses same channel to receive the data from previous hop and transmit to next hop, a higher weight is assigned i.e. w_2. Instead, if node i uses two different channels for reception and transmission a lower weight of w_1 is assigned such that $0 \leq w_1 \leq w_2$.

C. Interference-Load Aware routing metric (ILA)

To capture all the characteristics of a mesh network, our metric combines MTI and CSC to form a new path weight function as follows

$$ILA(p) = \alpha \times \sum_{linki \in p} MTI_i + \sum_{nodei \in p} CSC_i \tag{11}$$

where p stands for the path in the network. The MTI component in the above weight function captures the inter-flow interference and hence the congested areas. It is also aimed at decreasing the packet delay due to the load of neighboring nodes. The CSC component captures the performance of flows routed through path p. It is aimed at increasing throughput of individual flows. To balance the impact of the difference in magnitude of the two components, scaling factor α is applied to MTI metric. α is given as

$$1/\alpha = \begin{cases} min(ETT) \times min(AIL) & ,N_l(C) \neq 0 \\ min(ETT) & ,N_l(C) = 0 \end{cases} \tag{12}$$

where $\min(ETT)$ and $\min(AIL)$ is the smallest ETT and average load in the network. Using the scaling factor normalizes the MTI metric such that the two metrics have the same order of magnitude.

IV. IMPLEMENTATION DETAILS

In this section, we describe the details about operation of AODV protocol and several implementation issues for the ILA like ETT measurement, load estimation of interfering neighbors etc. The proposed metric was incorporated in the AODV implementation in ns2 [14].

A. Operation of AODV

The AODV routing protocol [10] is a reactive routing protocol and therefore, routes are determined only when needed. HELLO messages may be used to detect and monitor links to neighbors. If HELLO messages are employed, each active node periodically broadcasts a HELLO message, which will be received by its neighbors. Because nodes periodically send HELLO messages, if a node fails to receive several HELLO messages from a neighbor, a link break is detected.

When a source has data to transmit to an unknown destination, it broadcasts a Route Request (RREQ) for that destination. At each intermediate node, when a RREQ is received a route to the source is created. If the receiving node has not received this RREQ before, is not the destination and does not have a current route to the destination, it rebroadcasts the RREQ. If the receiving node is the destination or has a current route to the destination, it generates a Route Reply (RREP). The RREP is unicast in a hop-by-hop fashion to the source. As the RREP propagates, each intermediate node creates a route to the destination. When the source receives the RREP, it records the route to the destination and can begin sending data. If multiple RREPs are received by the source, the route with the shortest metric is chosen.

As data flows from the source to the destination, each node along the route updates the timers associated with the routes to the source and destination, maintaining the routes in the routing table. If a route is not used for some period of time, a node cannot be sure whether the route is still valid; consequently, the node removes the route from its routing table. If data is flowing and a link break is detected, a Route Error (RERR) is sent to the source of the data. As the RERR propagates towards the source, each intermediate node invalidates routes to any unreachable destinations. When the source of the data receives the RERR, it invalidates the route and reinitiates route discovery if necessary.

B. ETT Measurement

The HELLO messages employed by AODV are used to compute the expected transmission count (ETX). Each node broadcasts periodic HELLO message i.e. every 1 second with a TTL of 1 to its neighboring nodes. Each node remembers the message it receives during the last w seconds. We used a time interval of 10 seconds in our implementation. The delivery ratios d_f(forward delivery) and d_r(reverse delivery) are measured using the periodic HELLO message. The expected transmission count of a link is computed as

$$ETX = \frac{1}{d_f \times d_r} \tag{13}$$

The ETX of a route is the summation of the ETX's of all links along the path. The ETT of link is then computed using the ETX, link bandwidth and the size of the packet (1024 bytes in our implementation).

C. Load Measurement

An important implementation issue of our metric is the estimation of load of interfering neighbors [15]. The static nature of mesh networks makes it possible to measure whether two nodes are in each other's interference range at the time when the network is established. If two nodes are in each others interfering range, their carrier-sensing mechanisms prevent them from transmitting simultaneously [8]. Therefore if more than one node starts 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 transmitting. Hence, whether two nodes are in each other's interference range can be determined by measuring the broadcasting rates of two nodes.

The HELLO messages employed by AODV are modified to allow the nodes to exchange their load information. When a node sends a HELLO message, it includes its current load in the message. Every node will maintain a list of its neighboring nodes and their loads. When a node receives a HELLO message from a neighbor, it checks its list of neighbors. If the neighbor is already in the list, it updates the load of the neighbor with the new load in the message. Else, it adds the neighbor to the list. If a node fails to receive three consecutive HELLO messages from a neighbor already on the list, the result will be the removal of the neighbor from the list. The load information in the neighbor list can be used to compute the load of the interfering neighbors. We measured the traffic load in bytes which gives an accurate measurement of traffic load as opposed to measuring the traffic in number of packets because the size of the packets may vary.

V. SIMULATION RESULTS

The performance of the proposed ILA is compared with ETT and MIC using ns-2. The performance is evaluated in terms of network throughput, average end to end delay and sensitivity of metric to varying interfering traffic.

A. Simulation Parameters

In our simulations traffic sources are modelled as bulk TCP transfers. Packets have a size of 1024 bytes and are sent at a deterministic rate. The sending rate is varied as an input parameter to gradually increase the offered load to the network. The sources of the flow are randomly located in the mesh network. The transmission range is set as 250m while the carrier sensing range set as 550m. The w_1 and w_2 parameter in CSC are set to 0.5 and 1 respectively. In our simulations with AODV, the HELLO messages are sent every 1 second.

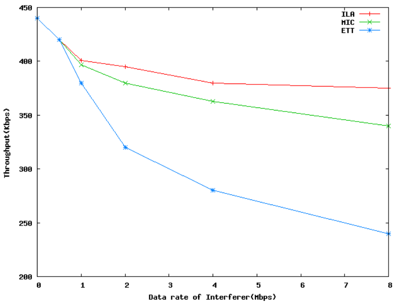

Fig. 2. Scenario 1: Sensitivity of metrics to interfering traffic

B. Scenario I

The first topology consists of 12 stationary mesh routers located in 700m x 700m area. Each node in this scenario has only one radio and all of them are configured to same channel. In this scenario, we study the behavior of different routing metrics in the presence of interfering traffic by observing the throughput of a single link. Figure 2 shows the throughput of the link in the presence of interfering traffic and behavior of metrics. The throughput decreases in the presence of interfering traffic. We can see that when there is no interference in the network, ETT has the same behavior as MIC and ILA. But when the interfering traffic increases, ETT becomes insensitive to interfering traffic among neighbor nodes. The MIC metric overestimates the interference and scales up the ETT with the number of interfering nodes. The results show that ILA performs well in the presence of interfering traffic by distributing the traffic among the network nodes and in a way to avoid the creation of highly congested areas.

C. Scenario II

The topology consists of 30 nodes located in 700m x 700m network. Each node has two radios and each radio can be configured to one of the three channels. To show the performance of proposed metric ILA in multi channel network, Figure 3, 4 show the total network throughput and the average end-to-end packet delay of the network. ILA has a better throughput than MIC and ETT. These results are due to the efficient distribution of the traffic in network by ILA.

ILA also surpassed ETT and MIC in the average end-to-end delay metric. The end-to-end delay for ILA at a per flow rate of 30 was 0.4s and that of MIC was 0.55s. Because MIC does not balance traffic load over the network nodes, it created highly congested regions in which the data packets suffered a long buffering time. On the other hand, ILA avoided the creation of such congested regions by selecting the route based on load metric of interfering neighbors, less interference and high transmission rates. Figure 5, 6 show the total network throughput versus time. From figure 5, we can see that metrics have the same behavior in the absence of interfering traffic whereas from figure 6, we can see that the metrics have different behavior in the presence of interfering traffic.

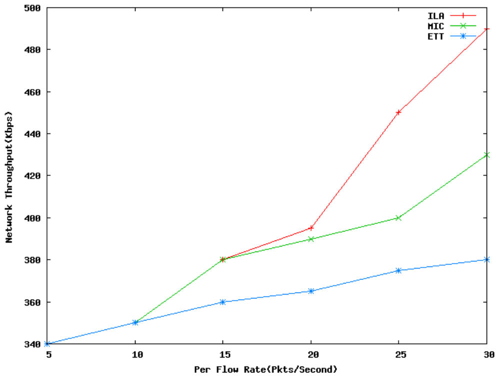

Fig. 3. Scenario 2: Total Network Throughput

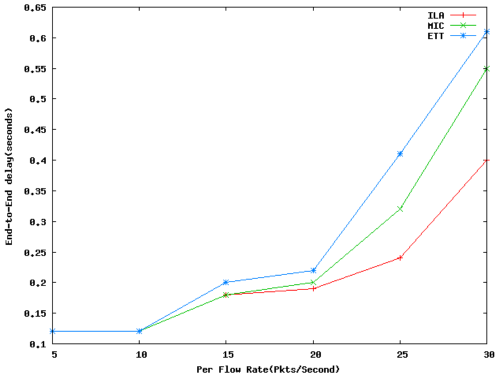

Fig. 4. Scenario 2: Average End to End Packet Delay

VI. CONCLUSIONS

In this paper, we proposed a new routing metric for multihop wireless mesh networks. This metric is based on the load on interfering neighbors and link transmission rates. We integrated this metric in the well known AODV routing protocol and compared to existing routing metrics for wireless mesh networks. We presented a simulation study that showed how this metric outperformed the existing routing metrics. Our future work is to investigate the performance of these existing routing metrics in scenarios where we have partial information about interfering nodes or where some neighbors are non-cooperative in wireless mesh networks.

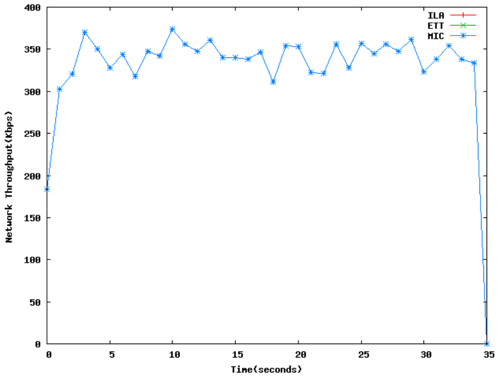

Fig. 5. Scenario 2: Network Throughput in the absence of interfering traffic

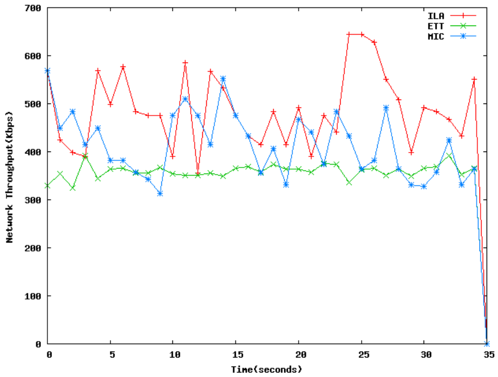

Fig. 6. Scenario 2: Network Throughput in the presence of interfering traffic

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