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Load aware traffic engineering for mesh networks

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Abstract

Wireless Mesh Network (WMN) is a multi-hop mesh network that consists of mesh routers and mesh clients, where mesh routers are static and form the backbone of the mesh network. The static nature of mesh nodes imposes requirements for designing routing metrics that support high-throughput and low packet delay. This article 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, WCETT and MIC. We also demonstrate that our metric delivers high-throughput in multi-channel networks.

Keywords: Wireless Mesh Networks; Multi-channel; Intra-flow interference; Inter-flow interference; Load aware routing

1. Introduction

Wireless Mesh Networks (WMNs) [1–3] 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 which guarantees high connectivity, robustness, etc. The mesh client nodes can be stationary or mobile. A simple example of Wireless Mesh Network is presented in Fig. 1.

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 multi-hop fashion. Wireless Mesh Networks are considered as a type of ad hoc networks. But, because the aim of WMN is to diversify the capabilities of the ad hoc network, more sophisticated algorithms and design principles are required for the realization of WMNs. Some of the differences between WMNs and ad hoc networks are outlined below. (a) The mesh routers in WMN form the backbone which provides large coverage, connectivity and robustness. But in ad hoc networks, the connectivity depends on the individual contribution of end-users. (b) 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 and sensor networks. Unlike ad hoc networks, the routing and configuration functionalities of the mesh routers reduces the load on end-user devices. (c) The mesh routers can be equipped with multiple radios to perform routing and access functionalities which improves the capacity of the network. On the other hand, ad hoc networks use same channel for routing, network access, etc., which result in poor performance. (d) Unlike in WMNs, we run into several challenges with routing protocols, network configuration and deployment in ad hoc networks because its topology depends on the movement of users.

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

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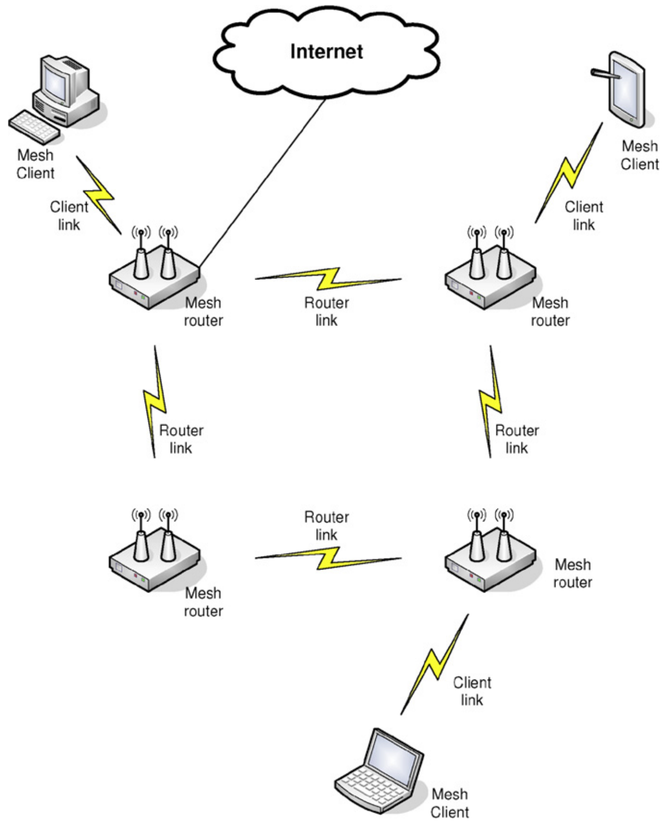

Fig. 1. Wireless Mesh Network with mesh routers and mesh clients. Mesh routers are static and form the backbone of the network whereas mesh clients can be static or mobile. Mesh clients rely on mesh routers to forward the data to destination [1].

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, delivering video, building automation, in entertainment and sporting venues, etc. Currently, hotspot IEEE 802.11 WLAN deployments are prevalent across coffee shops. A couple of obvious problems with this deployment is the location of access points and the presence of dead zones without service coverage. Though site surveys can be done to eliminate dead zones, it is very expensive. Installation of multiple access points can also be prohibitive cost-wise. The issue with accesspoints can be resolved by replacing accesspoints with mesh routers. In WMN, the mesh routers cooperatively route each others packet to destination. This results in flexible communication. The issue with dead zones can be eliminated inexpensively by adding more mesh routers or by changing the power level or location of mesh routers. The other wireless networks are not capable of multi-hop networking and hence mesh network is most suited for coffee shops, airports, hotels, 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 ongoing simultaneous wireless transmissions plays a significant role.

In general, there are many routes between each pair of nodes in a network. Each route use different set of links with different throughput. The routing protocol should select a path with high-throughput. Routing protocols use route metrics to decide the best route between a pair of nodes [4]. 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 following characteristics of the links accurately.

- *Packet loss ratio.* An effective routing metric should capture the packet loss ratio because lossy links can result in transmitting a packet multiple times on a link which inturn degrades the throughput and maximize the end-to-end delay of the flow in the link.
- *Link capacity.* In wireless network, the maximum transmission rate between a pair of nodes depends on the distance between the pair of nodes unlike in a wired network. Hence when the distance between two nodes increases, the channel quality degrades which inturn results in low link capacity. Therefore a good routing metric should favor a path with higher link capacity.
- *Interference.* Interference among wireless links have a serious impact on the performance of multi-hop wireless networks. Hence a good routing metric should take into account the interference of the wireless links. Two types of interference exists in wireless networks, intra-flow and inter-flow interference. Intra-flow interference is the interference caused when the nodes on the path of same flow contend with each other for the channel bandwidth

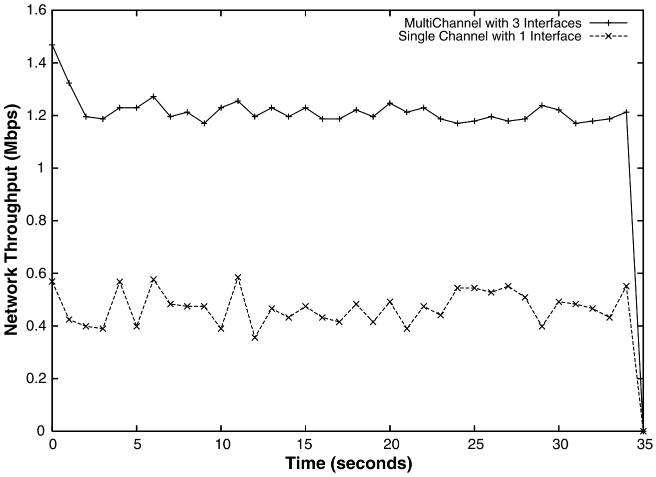

Fig. 2. Throughput of multi-channel versus single channel.

whereas inter-flow interference is the interference caused when the nodes on the adjacent path contend with each other for channel bandwidth. Using multiple channels in multi-radio WMN can greatly improve the throughput of the network [5,6]. Fig. 2 shows the performance of multiple channels in multi-radio WMN as opposed to single channel wireless network.

In this article, 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 the 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 article is organized as follows. Section 2 presents an overview of the existing routing metrics for ad hoc and wireless mesh networks. Section 3 presents the design of the proposed interference aware routing metric, ILA. In Section 4, we present an overview of the Ad Hoc On-Demand Distance Vector Routing (AODV) protocol and discuss several implementation issues like Expected Transmission Time (ETT) measurement, load estimation of the interfering neighbors, etc. Section 5 describes the simulation setup and the performance results. Section 6 concludes our work and outlines our future directions.

2. 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, load aware routing metric for multi-channel Wireless Mesh Networks by presenting an overview of the various routing metrics such as hop count [7], RTT [8], ETX [9], ETT [10], WCETT [11], MIC [12,13], iAWARE [14] proposed for multi-hop wireless mesh networks. This section discusses the details and limitations of the aforementioned routing metrics.

2.1. Hop count

Hop count [4,15] is the most commonly used routing metric in routing protocols such as AODV [16], DSR [17], DSDV [18]. 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.

2.2. Per-Hop Round Trip Time (RTT)

RTT [8] 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 acknowledgment. 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.

2.3. Expected Transmission Count (ETX)

ETX [9] 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 [2,14] 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.

2.4. Expected Transmission Time (ETT)

ETX does not consider the data rate at which packets are transmitted. ETT [10] 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:

$$\mathrm{ETT}_i = \mathrm{ETX}_i \times \frac{S}{B_i} \tag{1}$$

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.

2.5. Weighted Cumulative Expected Transmission Time (WCETT)

In [11] 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 thus finds the path with less intra-flow interference. WCETT of an n hop path is given as

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

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 and when there are multiple flows in the network, it will route the packet through congested areas resulting in poor throughput.

2.6. Metric of Interference and Channel Switching (MIC)

In [12,13] the authors proposed MIC, which considers inter-flow interference and intra-flow interference. MIC for a path is defined as follows:

$$\mathrm{MIC}(p) = \frac{1}{N \times \min(\mathrm{ETT})} \sum_{i \in p} \mathrm{IRU}_i + \sum_{i \in p} \mathrm{CSC}_i \tag{3}$$

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

$$\mathrm{IRU}_i = \mathrm{ETT}_i \times N_i \tag{4}$$

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

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

where $\mathrm{CH}(i)$ represents the channel assigned for node i's transmission and $\mathrm{prev}(i)$ is the previous hop of node i along the path p. The parameters w_1 and w_2 are chosen such that $0 \leqslant w_1 \leqslant w_2$. 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 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 [14]. 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. Also, MIC fails to capture the link loss ratio, data rate of the link in the absence of interfering neighbors.

In Fig. 3, 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. $\mathrm{ETT}_{\mathrm{AB}} + \mathrm{ETT}_{\mathrm{BD}} > \mathrm{ETT}_{\mathrm{AC}} + \mathrm{ETT}_{\mathrm{CD}}$ 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 drop ratio and transmission rates of the link as the metric IRU will be 0.

2.7. Interference Aware routing metric (iAWARE)

In [14], 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:

$$\mathrm{iAWARE}_p = (1-\alpha) \times \sum_{i=1}^{n} \mathrm{iAWARE}_i + \alpha \times \max_{1 \leqslant j \leqslant k} X_j \tag{6}$$

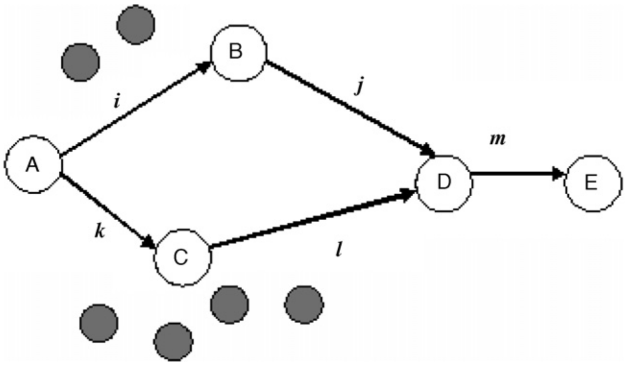

Fig. 3. Interfering nodes.

The component iAWARE_j is given as follows:

$$\mathrm{iAWARE}_j = \frac{\mathrm{ETT}_j}{\mathrm{IR}_j}$$

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 $(\mathrm{IR}_j = 1)$, 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 interference compared to ETT_j, the iAWARE_j metric will have a lower value. This will sometimes 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 weightage to ETT compared to interference of the link.

3. 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 [12,13] captures inter-flow interference by scaling up the ETT of the link by the number of interfering neighbors. The IRU metric of MIC [12] 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.

3.1. 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:

$$\mathrm{MTI}_i(C) = \begin{cases} \mathrm{ETT}_{ij}(C) \times \mathrm{AIL}_{ij}(C), & N_l(C) \neq 0 \\ \mathrm{ETT}_{ij}(C), & N_l(C) = 0 \end{cases} \tag{7}$$

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

$$\mathrm{AIL}_{ij}(C) = \frac{\sum_{N_l} \mathrm{IL}_{ij}(C)}{N_l(C)} \tag{8}$$

where

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

and $\mathrm{IL}_{ij}(C)$, 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.

3.2. 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:

$$\mathrm{CSC}_i = \begin{cases} w_1 & \mathrm{CH}(\mathrm{prev}(i)) \neq \mathrm{CH}(i) \\ w_2 & \mathrm{CH}(\mathrm{prev}(i)) = \mathrm{CH}(i) \end{cases} \quad 0 \leqslant w_1 \leqslant w_2 \tag{10}$$

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 $\mathrm{prev}(i)$ i.e. previous hop of node i. We denote by $\mathrm{CH}(i)$ the channel that node i uses to transmit to its next hop and $\mathrm{CH}(\mathrm{prev}(i))$ 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 $0 \leqslant w_1 \leqslant w_2$. The w_1 and w_2 parameter in CSC are set to 0.5 and 1, respectively, in [12].

3.3. 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:

$$\mathrm{ILA}(p) = \alpha \times \sum_{\mathrm{link}\, i \in p} \mathrm{MTI}_i + \sum_{\mathrm{node}\, i \in p} \mathrm{CSC}_i \tag{11}$$

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

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

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. The positive factor α when combined with Eq. (11), MTI is made to have the same order of magnitude of CSC.

4. 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 [19].

4.1. Operation of AODV

The AODV routing protocol [16] is a reactive routing protocol and therefore, routes are built only when desired by source nodes. 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.

AODV build routes to destination using a Route Request and Route Reply messages. 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[16]. As the RREP propagates back to the source, 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.

Once the source node receives the RREP message, the data packets are forwarded from source to destination. 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.

4.2. 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 s 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 s 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

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

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).

4.3. Load measurement

An important implementation issue of our metric is the estimation of load of interfering neighbors [20]. 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 [12]. 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.

To implement our proposed metric, ILA, we overload the RREQ and RREP messages of the AODV protocol with the metric ILA and the channel of the link traversed. The channel of the link traversed is used to calculate the Channel Switching Cost. When an intermediate node broadcasts the RREQ message, it will load the link metric and channel information in the RREQ message. RREP message is also appended with the link metric and channel information as it propagates back to the source node.

One of the major issue in overloading RREQ and RREP messages with the metric information is security threat [1,21]. If a malicious node receives RREQ/RREP message, it can forward the message without changing the metric information in RREQ/RREP. The lower the value of the metric, better the path and hence the following nodes will think that this route has better link quality and can result in choosing this route to forward the data packets.

5. Performance evaluation

The performance of the proposed ILA is compared with ETT, WCETT and MIC using ns2. The performance is evaluated in terms of network throughput, average end-to-end delay, packet loss rate, sensitivity of metric to varying interfering traffic and routing overhead. In the case of Wireless Mesh Networks energy constraint is not an issue [1] and hence we have not discussed it in this article.

5.1. Simulation parameters

In our simulations traffic sources are modeled 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 250 m while the carrier-sensing range set as 550 m. The w_1 and w_2 parameter in CSC [12] are set to 0.5 and 1, respectively. In our simulations with AODV, the HELLO messages are sent every 1 s.

5.2. Scenario I

The first topology consists of 12 stationary mesh routers located in 700 m × 700 m 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. Fig. 4 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.

5.3. Scenario II

The topology consists of 30 mesh routers located in 700 m × 700 m network. Each mesh 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, Fig. 5 shows the total network throughput. ILA has a better throughput than MIC, WCETT and ETT. These results are due to the efficient distribution of the traffic in network by ILA.

Fig. 6 shows the average end-to-end delay of metrics. ILA surpassed ETT, WCETT 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 0.4 s and that of MIC was 0.55 s. 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. Fig. 7 shows the packet loss ratio of the network. The results indicate that ILA is better than other metrics. Simulation results are analyzed with the help of

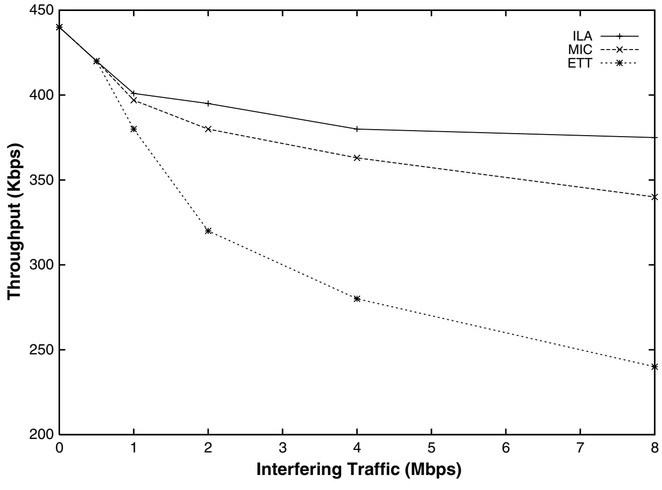

Fig. 4. Scenario I: the behavior of metrics with varying interfering traffic.

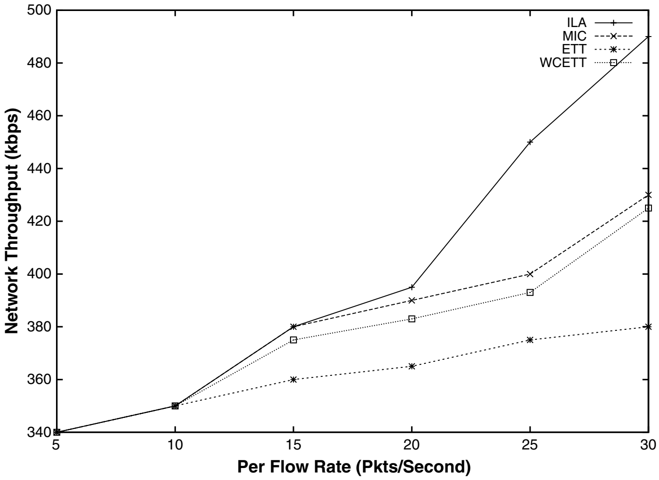

Fig. 5. Scenario II: total network throughput.

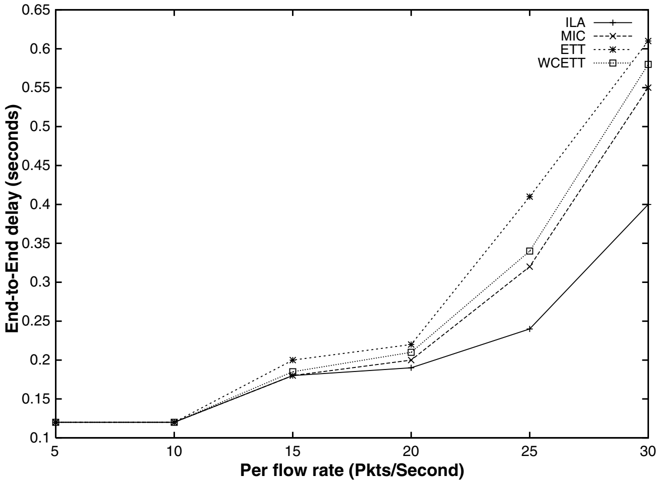

Fig. 6. Scenario II: average end-to-end packet delay.

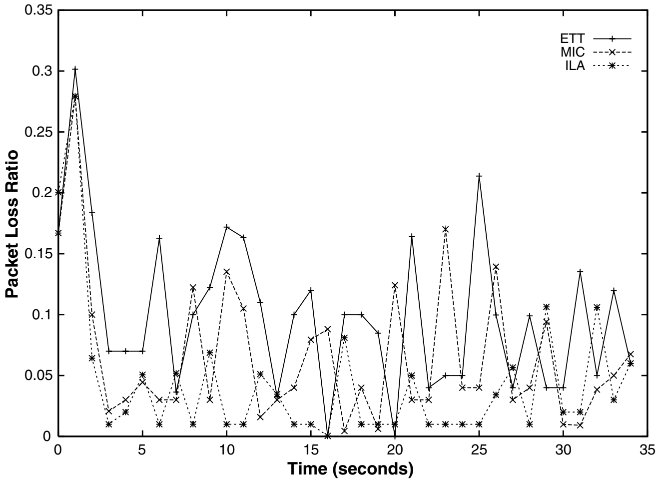

Fig. 7. Scenario II: packet loss ratio.

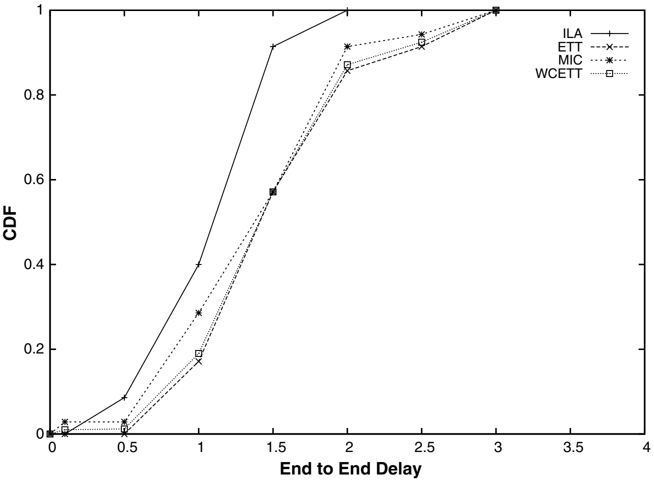

Fig. 8. Scenario II: CDF versus end-to-end delay.

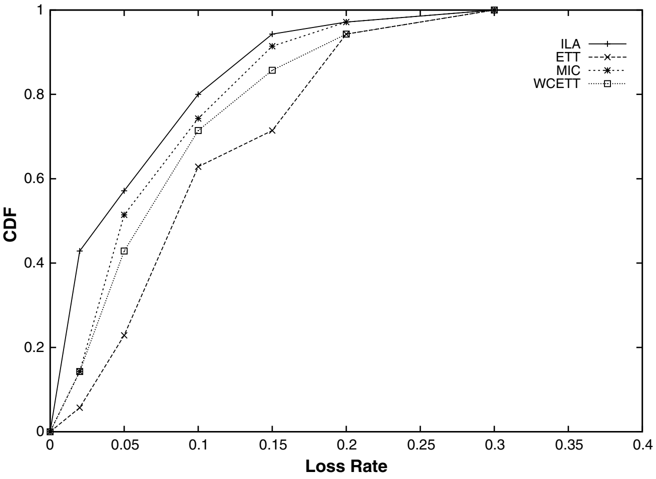

Fig. 9. Scenario II: CDF versus packet loss rate.

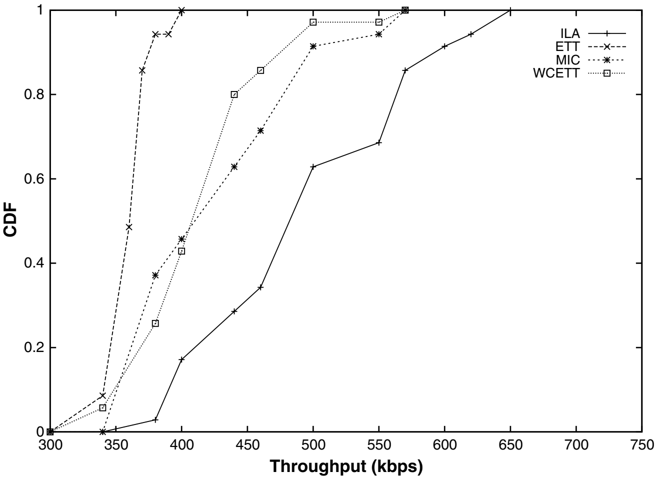

Fig. 10. Scenario II: CDF versus throughput.

Cumulative Distribution Function (CDF) plots. Figs. 8–10 show the CDF plots for end-to-end delay, packet loss rate and throughput. The CDF plots are analyzed according to following formula.

From the CDF plots for end-to-end delays

$$\text{End-to-End Delay} = Pr\{\text{Delay} \leqslant X\}$$

From the CDF plots for packet loss rate

$$\text{Packet Loss Rate} = Pr\{\text{Loss Rate} \leqslant Y\}$$

From the CDF plots for Throughput

$$\text{Throughput} = Pr\{\text{Throughput} \leqslant Z\}$$

In Fig. 8, it can be seen that for ILA, 60 percent of time the end-to-end delay is less than 1 s, for ETT, WCETT and MIC the delay is greater than 1.5 s. In Fig. 9, the results indicate that for ILA, 80 percent of time the packet loss rate is less than 0.1 whereas for ETT, packet loss rate is greater than 0.15. Because MIC gives importance for the number of interfering nodes and not their traffic, it created congested regions in which the data packets suffered a long buffering time and loss. On the other hand, ILA avoided the creation of such congested regions by selecting the route based on traffic of interfering neighbors. From the CDF plot for throughput in Fig. 10 our results show that for ILA, 80 percent of time the throughput is above 500 kbp, whereas for MIC the throughput is less than 450 kbp and for ETT the throughput is less than 350 kbp. These results are due to the efficient balancing of the traffic in network by ILA.

Figs. 11 and 12 show the total network throughput versus time. From Fig. 11, we can see that metrics have the same behavior in the absence of interfering traffic whereas from Fig. 12, we can see that the metrics have different behavior in the presence of interfering traffic. The variations in the network throughput plot of Fig. 12 is due to the varying interfering and data traffic. During pause times 24, 25 and 27 s, the Interfering Load is reduced compared to other pause times and hence more packets are sent during this period.

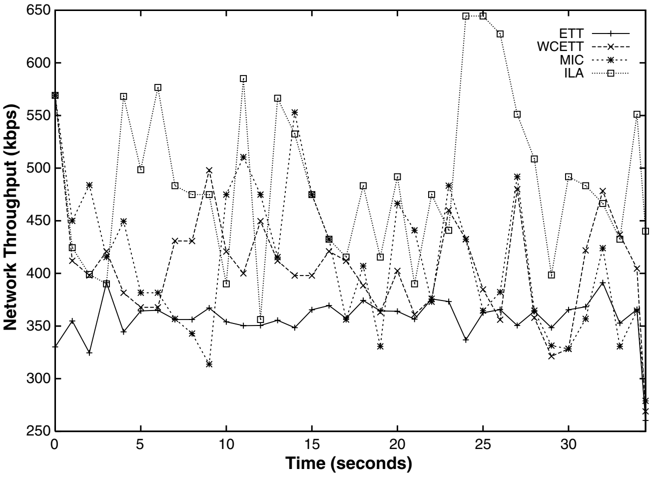

Fig. 12. Scenario II: network throughput in the presence of interfering traffic.

Table 1
Comparison of metrics performance

Metrics	Overhead (percent)	Throughput (kbp)	Delay (s)
ILA	22.7	379.5	0.39
MIC	21.5	341	0.47
ETT	19	241.3	0.58

The other important performance metric is Routing overhead which is calculated on the basis of MAC packets sent for routing and data traffic. Table 1 summarizes the performance metrics for ILA, MIC and ETT. From Table 1, we can see that though ILA has slight overhead compared to MIC and ETT, it has better performance in terms of throughput and end-to-end delay as opposed to MIC and ETT because ILA forwarded the data traffic through less congested paths.

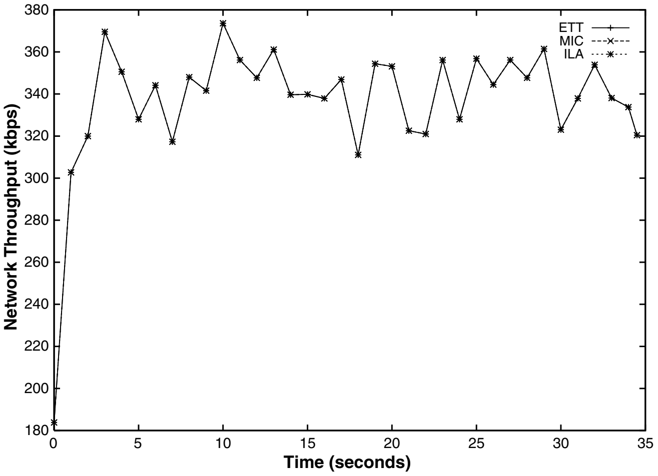

Fig. 11. Scenario II: network throughput in the absence of interfering traffic.

6. Conclusions

In this article, we present a new routing metric for multi-hop 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.

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