Interference, Traffic Load and Delay Aware Routing Metric for Wireless Mesh Network

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***Abstract*—The self-organizing property of the wireless mesh network (WMN) has made them suitable for implementing various networking application, such as video surveillance. In WMN, routing protocols and routing metrics play an important part in implementing real-time applications. The routing metric predicts the quality of various paths discovered by the routing protocol. We introduce a routing metric titled Interference, Traffic Load and Delay Aware (ITLDA) to estimate the end-to-end delay of a path, as sum of contention, transmission and queuing delays. Transmission and queuing delays are estimated using the available bandwidth of the link, which is estimated by passive monitoring. The contention delay is estimated using average contention window and channel utilization. Simulation outcomes indicate that the performance of ITLDA is superior to the existing routing metrics.**

***Index Terms*—cross layer design, quality of service, routing, video surveillance, wireless mesh networks.**

I. Introduction

WMNs provide anywhere, anytime wireless Internet access with low up-front investment. To better serve the different delay-sensitive applications like video surveillance, end-to-end delay through multi-hop paths needs to be predicted and assured accurately [1]. Video surveillance is an impressive system for strengthening border and public security. It includes watching a video in real-time and finding specific behaviors that are unacceptable or may suggest the presence or nature of inappropriate behavior. Due to the setup and maintenance of physical cables, it is very expensive to deploy and operate massive-scale diversified video surveillance systems.

WMNs have the following characteristics:

- Multi-hop wireless network: Expands the reach of existing wireless networks over multi-hop paths with smaller link distances.
- Self-organizing, self-configuring nature: When required, we can add and remove nodes from the network, without the involvement of any centralized entity.
- Low up-front deployment cost: Since WMNs use cheap and easily available common-off-the-shelf (COTS) devices for the deployment of mesh backbone, the up-front deployment cost is low.
- Reliability and robustness: With the existence of redundant routes connecting a given source and destination nodes, thereby evading the congested and the bottleneck links, WMNs provide reliable and robust communication among nodes.

We can use multi-radio multi-channel (MRMC) WMN as the backbone for a wireless network of video surveillance. WMN is often the most attractive choice for video surveillance, as it supports the requisite throughput, redundancy and numerous paths to provide efficient, scalable and economical video transmission [2].

As seen in Figure 1, WMNs have 03 different kinds of network devices - mesh routers, mesh clients and gateways. Mesh routers with multi-radio capability develop mesh backbone. In addition to forwarding and routing, each mesh router supports mesh networking. They are also used as wireless network coverage extenders. Mesh clients accesses the Internet through the mesh backbone with a wide variety of devices like cell phones, PDAs, laptops, desktops and so on. Using multi-hop wireless links, mesh routers connect clients to the gateways. Gateways are specialized routers with the bridge capabilities; connect the entire networks to external networks, such as Internet.

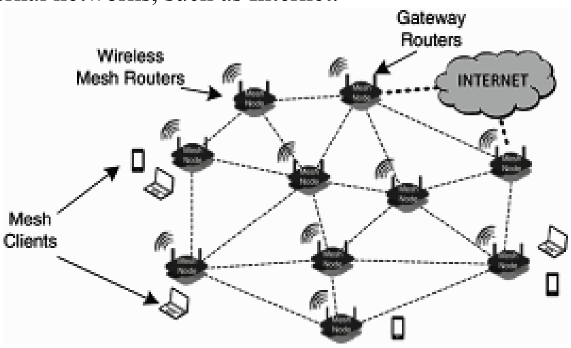

Figure 1. Wireless Mesh Network

In MRMC WMNs, node's radio interfaces are assigned with various orthogonal channels to enhance the network capacity and hence the performance. The routing process has a serious impact on network communication, as it needs to find paths with required quality of service demands [3-4].The routing metric predicts the quality of various paths as discovered by the routing protocol. Hence, devising a routing metric holds a significant influence on network performance. As links share a wireless medium, there is no dedicated bandwidth for a wireless link. Because of this reason, all neighboring node transmissions may have to compete with each other for the link bandwidth. Thus, to choose best paths to fulfill the demands of multimedia applications, routing process need to be conscious about the quality of the link. As interference and load affects the link quality, the routing metric has to measure them effectively. Such measures characterizing the link's quality are acquired from network, MAC and physical layers and then mathematically combined to obtain the quality of the link [5-6]. Therefore, the cross-layer design is used to systematize lower layer measures and utilizes them for making the routing decision [7-8].

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We introduce a cross-layer routing metric titled Interference, Traffic Load and Delay Aware (ITLDA) routing metric. Based on the transmission, channel access and queuing delays, ITLDA estimates a one-hop delay. This estimated one-hop delay is assigned as a weight to individual links. These individual link values are incorporated over a path that is quite analogous to the path's end-to-end delay.

The paper has the following structure with sections titled Background, ITLDA routing metric, Implementation, Performance evaluation and Conclusion.

II. BACKGROUND

Many routing metrics were introduced for WMN over time. Some of them are:

Expected Transmission Count (ETX) [9] is built entirely on the number of attempts by the MAC layer to transport a data including retransmissions. It captures packet loss ratios and path length. It doesn't explicitly measure the interference and transmission rate variations between links. Expected Transmission Time (ETT) [10] extends ETX and estimates transmission time using transmission rate. It also doesn't explicitly capture interference and traffic load. ETT may not be able to detect packet losses because of the contention generated by the neighboring node's traffic. Weighted Cumulative ETT (WCETT) [10] extends ETT and computes link quality based on the channel diversity. ETT of each link is added to measure the WCETT. It is non-isotonic metric. Since WCETT does not consider interflow interference and traffic loads, it can lead to paths through congested areas. WCETT with load balancing (WCETT-LB) [11] extends WCETT by considering load to find the optimal path. On each node across a given path, the load-balancing aspect of WCETT-LB calculates traffic concentration and traffic congestion. However, it doesn't estimate inter-flow interference. Contention aware transmission time (CATT) [12] is isotonic, ETT based load aware metric. Based on the location of the link, it assesses contention and rate variation of a link. Active probing is used to obtain interference. CATT metric assume that all neighboring links have the same degree of interference, it may overestimate the link quality. Contention Window Based (CWB) [13] is channel utilization and contention window based routing metric. By calculating the load and interference, CWB attempts to balance traffic over less congested regions. CWB lacks details about how channel utilization is estimated and does not weigh intra-flow interference. CWB is inaccurate whenever the network conditions change rapidly.

Metric for INterference and channel Diversity (MIND) [14] assesses interference and traffic through passive monitoring. By combining physical and logical interference, it uniformly models overall interference. Since this metric uses passive monitoring, it does not create network overhead. MIND may not consider the asymmetry of the links, which could contribute to inconsistencies. MIND is non-isotonic metric and to make it isotonic, real network is decomposed into virtual networks, thereby increasing the design complexity. Channel utilization and Contention Window Based (C2WB) [15] use 802.11 MAC delay model to estimate the link service time. The service time is composed of transmission time, back-off time and defer time and is calculated using ETT, channel utilization, average contention window. Channel contention is used to capture logical interference implicitly and same is used for load balancing. It does not capture physical interference and ETT is computed using static available capacity. Expected link performance (ELP) [16] estimates link performance by considering its loss ratio, capacity, physical and logical interference. It favors forward link-loss ratios over the backward. It does not support channel diversified paths and takes account of different transmission rates of link.

The Expected End-to-End Delay (EED) [17] finds the least delay path. This metric along with inter/intra-flow interference used to design weighted EED (WEED) metric for multi-interface WMN. WEED uses adjustable parameters to compute the routing metric. Interference and Delay Aware (IDA) [18] evaluates the link quality on the basis of transmission and contention delays using logical and physical interference. Since IDA doesn't reflect queuing delay, it may result in a congested path. In Network Adaptive Interference Aware (NAIA) [19] routing metric, load and interference levels are used to discover the paths. Load and interference are balanced dynamically. To find path, NAIA incorporates Inter/intra-channel interferences. This metric uses adjustable parameters to compute the routing metric and is non-isotonic routing metric. Depending on type of the data, a multi criteria routing metric (MRM) [20] finds the link quality. For urgent data, path delay is measured using the transmission time and for non-urgent data, path quality is assessed using hop count and link load. Link load is calculated using fixed transmission rate and it uses adjustable parameters to compute the routing metric. Modified Airtime routing metric Ca[21] is used to find route by considering the quality and load of link and adjusts the metric to the circumstances under which network currently runs at a particular time. This strategy predicts link overload in the future, resulting in the prevention of using the selected link excessively. To predict the link overload, this metric calculates link metric by keeping constant delay, which may not be true as delay varies over time.

As analyzed above, few existing routing metrics use adjustable parameters to balance interference components; however it is hard to tune these parameters as per the current network status. Some routing metrics don't really include load balancing among nodes and may find the path through the congested area. So we need to have a routing metric that captures interference and load uniformly [22] to find lightly congested paths without using any adjustable parameters.

III. ITLDA ROUTING METRIC

This section, we present a cross-layer routing metric titled ITLDA. Restricting end-to-end delay while trying to guarantee better throughput, is advantageous to provide better quality real-time services [23]. In general, a set of variables such as hop-count to the given destination, node density, transmission rate, node's resources, MAC and routing protocols may influence the delay and may produce a long and erratic end-to-end delay. MAC layer affects one-hop delay and the network layer affects the multi-hop end-to-end delay. Logical and physical interference measures are combined to capture interference between the links. By taking parameters average contention window, channel utilization, packet loss ratios from the lower layers, a loosely coupled cross-layer design is used to design ITLDA routing metric.

We consider a WMN, wherein every node has several radio interfaces [24]. All the nodes are stationary. We assume that a specific channel is pre-assigned to every radio interface of node. There is no interference between radios assigned to different channels; they can be active simultaneously. IEEE-802.11 based MAC is used.

A. Delay Model

We use IEEE 802.11 Distributed Coordination Function (DCF) basic access method for accessing wireless channel. DCF uses CSMA/CA protocol. DCF basic access method uses two-way hand-shaking protocol. Wireless channel access is controlled by short inter-frame space (SIFS), DCF inter-frame space (DIFS) intervals. The exponential back-off algorithm is used to avoid collisions. Before transmitting a frame, each node will have to sense the channel. When channel is idle for the DIFS duration, then the frame is transmitted immediately. Otherwise, node enters a back-off stage, with its back-off timer set randomly between 0 and Contention Window (CW). Consequently, for every time slot, the channel is sensed. If it is idle, then the back-off timer is decremented by one unit else back-off timer is stopped. The source node transmits the frame once the back-off timer hits the zero value. Upon successful acquisition of the frame, receiver waits for the SIFS period and then sends an acknowledgment (ACK) frame. If there is no acknowledgment from the receiver, the sender doubles current value of its CW and randomly resets timer to retransmit the frame.

At node, packet delay is total time from when the packet is at the front of its MAC queue set to be transmitted, till an acknowledgment for this packet is received. According to packet delay model presented in [25], average packet delay at each node can be calculated as the sum of i. time that a node defers before transmitting a packet (T_{def}) ii. time that a node waits due to packet collisions (T_{col}) and iii. time taken for successful transmission of a packet (T_{suc}) and given as

$$D_{avg} = T_{def} + (j+1) * T_{col} + T_{suc} \tag{1}$$

where j is stage number(number of retransmission attempts).

T_{def} is the average time a packet will wait in the back-off phase to get transmitted successfully. It depends on average number of back-off slots and average duration of each back-off slot. Average number of back-off slots can be expressed as average contention window and average duration of each back-off slot can be expressed as channel utilization. T_{col} depends the number of retransmission due to collision and the duration of the collision. T_{suc} is total time required to transmit packet headers, payload and ACKs. For DCF basic access method, durations of T_{col} and T_{suc} are equal, so (1) becomes

$$D_{avg} = T_{def} + \left(j+1\right) + T_{suc} \tag{2}$$

According to the analytical model proposed in [25], with p as collision probability, number of retransmissions j+1 can be obtained using $1/p^{(j+1)}$. The final average packet delay is

$$D_{avg} = T_{def} + \frac{1}{1-p^{j+1}} * T_{suc} \tag{3}$$

The T_{suc} is given as following

$$T_{suc} = DIFS + H + PD + \sigma + SIFS + \sigma + ACK \tag{4}$$

Where, H is time required to transmit packet header, PD is time required to transmit data, ACK is time required to transmit acknowledgement and σ is propagation delay.

The packet payload and ACK are transmitted using the available bandwidth. Passive monitoring is adopted to estimate available bandwidth (ABW). The term p^{j+1} can be approximated as packet error rate (PER). So the final average packet delay is given as

$$D_{avg} = T_{def} + \frac{1}{1-PER} * \frac{S}{ABW} \tag{5}$$

The queuing delay carries a noticeable part of the end-to-end delay. So we need to consider queuing delay as part of one-hop delay. The delay via a node that has several packets in the queue with a shorter transmission time may be greater than that of other node that has few packets in the queue with longer transmission time [17].

B. Available Bandwidth Estimation

While selecting a routing path, we need to estimate the quality of different links in terms of their available bandwidth. Available bandwidth of link can be estimated using either passive monitoring or active probing methods. While designing cross-layer routing metrics, passive monitoring is preferred as it only involves cross-layer information exchange. In ITLDA, we are estimating the available bandwidth of link using passive monitoring.

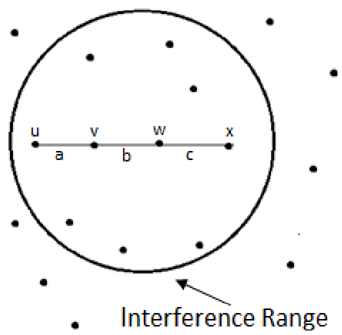

Figure 2. Logical Interference of node

Since nodes in interference range can occupy the shared channel, CSMA/CA protocol might cause logical interference. The Figure 2 shows the logical interference of node w. Logical inter-flow interference is going to be prompted by nodes inside the interference range. Even intra-flow interference might arise once 2-hop nodes share the same channel on a path. The available bandwidth of link L following logical inter-flow interference and physical interference is computed as

$$B_{in,L} = \left(1 - CBT_L\right) * B_{802.11} * \left(1 - IR_L\right) \tag{6}$$

where, CBT_L is Channel Busy Time of link L, $B_{802.11}$ is Nominal bandwidth and IR_L is Interference Ratio of link L.

According to [22], CBT estimates logical interference and load. Using CBT we can measure the channel utilization which can be obtained using passive monitoring. CBT of link L is calculated as

$$CBT_L = \frac{Total\_time - Idle\_time}{Total\_time} \quad (7)$$

where, Total_time is total time of channel assigned to link L and Idle_time is idle time of channel assigned to link L.

The IR_L interference ratio, which can be computed as

$$IR_L = \frac{SINR_L}{SNR_L} \quad (8)$$

where, $SINR_L$ is signal-to-interference-plus-noise-ratio and SNR_L is signal-to-noise-ratio of link L.

The $SINR_L$ of link L is computed as

$$SINR_L = \frac{P_L}{Noise + \sum_{w \in N_l} P_w \tau_w} \quad (9)$$

The SNR_L of link L is computed as

$$SINR_L = \frac{P_L}{Noise} \quad (10)$$

where, P_L is signal strength of link L, N_L is group of nodes interfere with link L and τ_w is amount of time that node w utilizes channel.

$B_{in,L}$ can easily represent logical inter-flow interference, yet it doesn't quantify intra-flow interference. According to [17], links x and y which are near and interfering with each other may be seen as virtual link under the influence of logical intra-flow interference. The available bandwidth of the virtual link following logical interference is computed as

$$B_{xy} = \frac{b_x * b_y}{b_x + b_y} \quad (11)$$

where, b_x is bandwidth of link x and b_y is bandwidth of link y.

The effect of inter-flow interference upon link's available bandwidth can be incorporated with intra-flow interference as following

$$B_{xy} = \frac{B_{in,x} * B_{in,y}}{B_{in,x} + B_{in,y}} \quad (12)$$

To achieve isotonicity, the bandwidth gained from (12) is considered as single-link bandwidth. The available bandwidth of 3 links a, b and c along the routing path (as shown in Figure 2), can be calculated as

- The link 'a'. Since it is the first link, its available bandwidth can be computed using (6).
- As next link 'b' may interfere with link 'a', its available bandwidth can be computed as

$$B_{avail,b} = \begin{cases} B_{in,b} & \text{if ch(b)} \neq ch(a) \\ \dfrac{B_{in,a} * B_{in,b}}{B_{in,a} + B_{in,b}} & \text{if ch(b)} = ch(a) \end{cases} \quad (13)$$

where, ch(a) is channel assigned link a, ch(b) is channel assigned link b.

- The link 'c'. As this link may interfere with link 'b' or link 'a', its available bandwidth can be calculated as

$$B_{avail,c} = \begin{cases} B_{in,c} & \text{ch(c)} \neq \text{ch(b)} \neq \text{ch(a)} \\ \dfrac{B_{in,a} * B_{in,c}}{B_{in,a} + B_{in,c}} & \text{ch(c)} \neq \text{ch(b)=ch(a)} \\ \dfrac{B_{in,b} * B_{in,c}}{B_{in,b} + B_{in,c}} & \text{ch(c)} = \text{ch(b)} \neq \text{ch(a)} \\ \dfrac{B_{ab} * B_{in,c}}{B_{ab} + B_{in,c}} & \text{ch(c)} = \text{ch(b)=ch(a)} \end{cases} \quad (14)$$

where ch(c) is channel assigned link c.

C. ITLDA Routing Metric

At any given node the packet delay is addition of average contention delay, queuing delay, and transmission delay. Average contention delay (ACD) is computed as

$$ACD_L = CW_L * C_n \quad (15)$$

where, CW_L is average contention window and C_n is channel utilization.

CW_L is weighted average of contention window that a packet will experience until correctly delivered and is given as

$$CW_L = \frac{(1 - PER_L)\left(1 - (2PER_L)^R\right)}{\left(1 - PER_L^R\right)(1 - PER_L)} * CW_0 + \frac{1}{2} \quad (16)$$

where, PER_L is packet error rate of wireless link L and CW_0 is contention window at stage 0.

PER_L is the number of packets communicated without getting acknowledgement. It is measured using the link's forward and backward delivery ratios and given as

$$PER_L = d_f * d_r \quad (17)$$

where, d_f is forward and d_r is backward delivery ratios.

For the given channel, channel utilization C_n is computed using the Channel Busy Time (CBT) of link. The packet transmission delay $T_{Tran,L}$ of the link L is calculated as

$$T_{Tran,L} = \frac{1}{PER_L} * \frac{S}{B_{avail,L}} \quad (18)$$

where, S is packet size and $B_{avail,L}$ is available bandwidth of link L.

The queuing delay relies on the transmission delay of link and queue length of the corresponding node. To compute queuing delay, average queue length is used in place of instantaneous queue length. Average queue length is computed as

$$Q_{avg} = (1 - \omega) * Q_{avg} + \omega * Q_{sample} \quad (19)$$

where, Q_{avg} is average queue length, Q_{sample} is current queue length, ω is constant.

The queuing delay $T_{Que,L}$ of link L is calculated as

$$T_{Que,L} = \frac{1}{PER_L} * \frac{S * Q_{avg}}{B_{avail,L}} \quad (20)$$

The overall delay of link L is sum of average contention delay, transmission delay and queuing delay and can be stated as

$$ITLDA_L = ACD_L + T_{Tran,L} + T_{Que,L} \quad (21)$$

The overall delay of path p is can be computed as

$$ITLDA_p = \sum_{L \in p}^{n} ITLDA_L \quad (22)$$

IV. IMPLEMENTATION

The ITLDA is implemented by modifying the Ad-hoc on demand distance vector (AODV) routing protocol [26]. To send data to destination, source creates and broadcast Route Request (RREQ) packet to its neighbors. We extend original RREQ by including a new field labeled E2EDelay to represent end-to-end delay between source and destination.

Every intermediate node that receives RREQ packet computes PER, channel utilization and available bandwidth and then passes all computed information to the network layer. At network layer, node computes the one-hop delay and adds it to the E2EDelay. When RREQ packet moves towards destination, every intermediate node updates the hop count and E2EDelay values and establishes the reverse path to source. Whenever an intermediate node gets the already forwarded RREQ packet, node will rebroadcast RREQ packet, if value of E2EDelay received from RREQ packet has a smaller E2EDelay value than the value from routing table or if E2EDelay values are equal, but the hop-count of received RREQ packet is smaller.

Whenever a RREQ packet reaches the destination, it makes a routing table entry to the source with a route having the least E2EDelay value. It then creates a route reply (RREP) packet to send it towards the source using newly established route. As RREP packet progresses towards the source, every intermediate node updates the values of hop-count and E2EDelay. It then creates/updates its routing table entry to destination and routes the updated RREP packet in the direction of the source. An intermediate node may send an RREP packet; given it has a newer path to the source than the one previously known.

When the source gets the first RREP, it begins transmitting data towards destination. However, if an additional RREP with better E2EDelay is received later, the routing table of the source code would be updated with better route. Then the updated new route will be used for further data transmission.

The parameters used in the computation of ITLDA are implemented as following.

i) PER value of link: As per (17) PER of link are calculated using d_f and d_r. Each node periodically broadcasts fixed-size HELLO packet for every second. Every node learns the HELLO packets received from its neighbors over last 10 seconds and sends this data (say FHCount) in its HELLO packet. Based on FHCount received from neighbours, each node calculates the d_f value. Based on the number of HELLO packets received during latest 10 seconds each node calculates the d_r.

ii) Channel Busy Time (CBT): To calculate CBT, we monitor the wireless channel status regularly to check its state. The counter is used to keep track of idle time (Idle_Time) of the channel. For every 2 seconds (i.e. Total_time in (7), CBT is calculated.

V. Performance Evaluation

The effectiveness of ITLDA is compared against the IDA [18] and ELP [16] routing metrics. Following are the design issues related to the IDA and ELP.

In several circumstances, queuing delay carries a noticeable part of the total link delay. But in IDA, the link delay is estimated using average contention delay and transmission delay. Without considering traffic load, ELP selects the end-to-end path. In ITLDA, queuing delay is considered in the link delay estimation.

In IDA, the available bandwidth is estimated using packet pair probing. Excessive probe packets transmission will produce a significant load that disturb the network operation and will have serious impact on the application traffic and estimation accuracy [27]. In packet pair probing, it is assumed that there is no traffic on the link (cross traffic), which is far from reality [28]. Cross-traffic may underestimate or overestimate link capacity. The transmission of cross-traffic packets between pair of probing packets may result in an underestimation of link capacity. At any given link, whenever cross-traffic holds the first probe packet more than the second packet, it may result in the overestimation of link capacity.ELP has no provision to estimate the bandwidth of the contending links. In ITLDA, we have estimated the available bandwidth using the passive mechanism that combines logical and physical interference measures.

IDA does not apprehend intra-flow interference. For better network performance, routing metric needs to capture both inter-flow and intra-flow interference. ELP captures intra-flow interference using different sized probe packets and hence increases the routing overhead. In ITLDA, logical intra-flow interference is measured and is used to estimate the available bandwidth.

The ITLDA routing metric is simulated using network simulator 3 with version ns3.28. The simulation details are tabulated in Table I.

TABLE I. SIMULATION PARAMETER

Parameter	Value
Simulation Time	100s
Network Area	1200*1200
Data Rate	11Mbps
Number of nodes(routers)	48(Grid), 100(Random)
Number of gateways and its position	1 and positioned at centre
Transmission/ Interference Range	250M/550M
Maximum hop-count	5
Queue Type and Size	Drop Tail and 25 packets
Traffic Type	CBR/UDP and FTP/TCP
Packet Size	1024 Bytes

A. *Simulation Results on Grid Topology (UDP/CBR traffic)*

To measure the performance of metrics, we have carried out simulations with 5 different CBR flows using UDP.

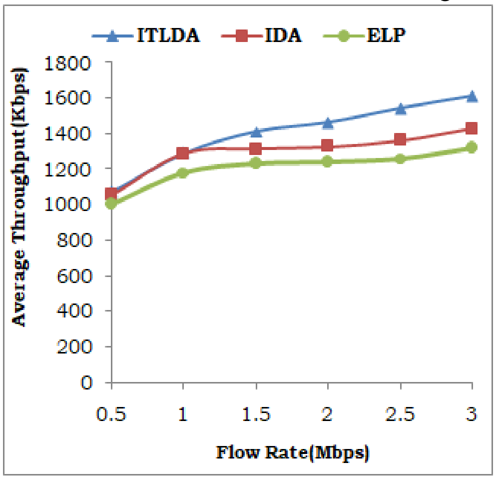

Figure 3. Grid Topology: Average Throughput (UDP/CBR)

We can see from Figure 3, initially, because of minimal interference due to the limited load, the average throughput of all routing metrics is approximately the same. When the load increases, a clear gap is starting to emerge between the routing metrics. As IDA and ELP select paths based on interference and the channel access delay without considering the queuing delay, they may select path that consists of links through the congested nodes that have more packets in the queue. Due to the limited size, as network load increase queue starts dropping packets resulting in reduced average throughput. As IDA and ITLDA able consider the bandwidth of contending links, both perform better than the ELP. As ITLDA select paths based on interference and the channel access delay along with consideration of queuing delay, it is able to redirect the traffic to lightly loaded paths and less congested regions. Because of this, more packets are routed to the destinations resulting in better average throughput. ITLDA has 7.4% and 10.1% more average throughput as compared to the IDA and ELP routing metrics respectively.

Figure 4 shows average packet loss ratio of all routing metrics. ITLDA spreads interfering traffic across nodes and decreases the probability of packet loss owing to data collision in exceedingly congested areas. Because of these reasons, ITLDA routing metric has 11% and 15% less average packet loss ratio as compared to the IDA and ELP routing metrics respectively.

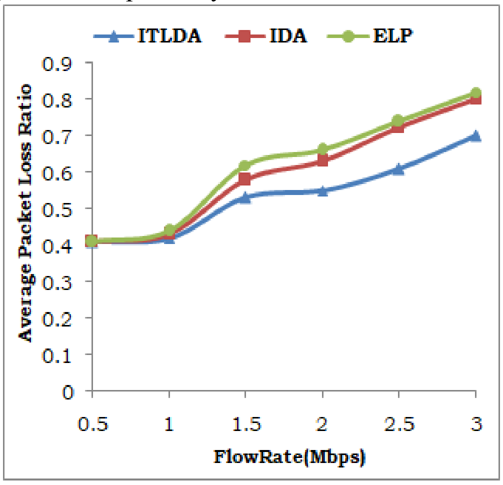

Figure 4. Grid Topology: Average Packet Loss Ratio (UDP/CBR)

Since every delay component of end-to-end delay is considered explicitly, ITLDA avoids the formation of congested regions by finding the path with minimum delay. As network load increases, end-to-end delay of the all routing metrics tends to increase. When the network has more traffic (with flow rate more than 1.5 Mbps), more packets will get enqueued, resulting in queuing delay becoming a dominant part of end-to-end delay. Due to the capability to detect and avoid heavy loaded regions, ITLDA has less end-to-end delay as compared to IDA and ELP. Figure 5 indicate that the average end-to-end delay of ITLDA is 29.4% and 34.8% less than IDA and ELP routing metrics respectively.

Normalized Routing Load (NRL) represents the number of routing packets sent per data packet received at the destination. It measures the overhead caused by the routing protocol. Lower overhead lets more network resources to be accessible for the data packet delivery. Figure 6 displays the NRL of all routing metrics. ITLDA and ELP are implemented using AODV and they use i) Route Request and Route Reply control packets ii) HELLO packets for calculation of PER. Apart from these packets, ELP uses probe packets to estimate the logical interference, ELP has slightly more overhead as compared to ITLDA. IDA implemented using OLSR and it uses s i) Topology Information and Multiple Interface Declaration control packets. ii) HELLO packets for calculation of PER and to discover neighboring nodes iii) probe packets for estimation of the available bandwidth. Along with using control packets to maintain an up-to-date routing table, for estimation of the available bandwidth IDA also uses probe packets over predefined number of samples, so it has more number of routing control packets as compared to ITLDA and ELP.

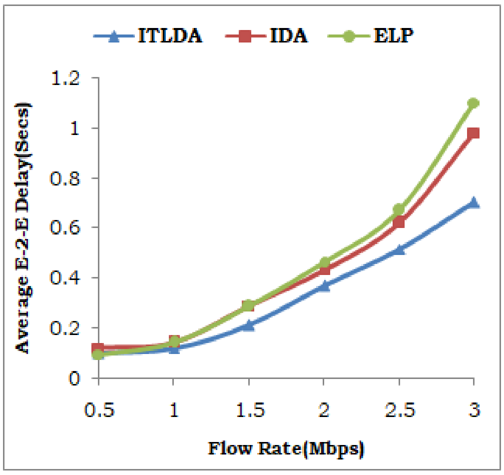

Figure 5. Grid Topology: Average End-to-End Delay (UDP/CBR)

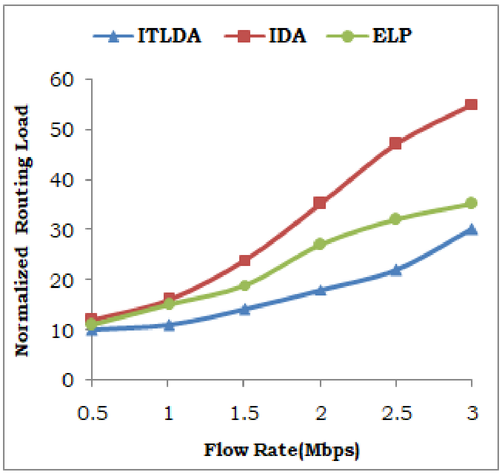

Figure 6. Grid Topology: Normalized Routing Load (UDP/CBR)

B. Simulation Results with Varying Number of Flows (UDP/CBR traffic)

To measure the ITLDA's performance with different number of flows, we have carried out simulations with 100 nodes placed randomly over given area. The number of flows is varied from 5 to 25 with constant flow rate of 2Mbps. Pairs of source-destination are chosen randomly.

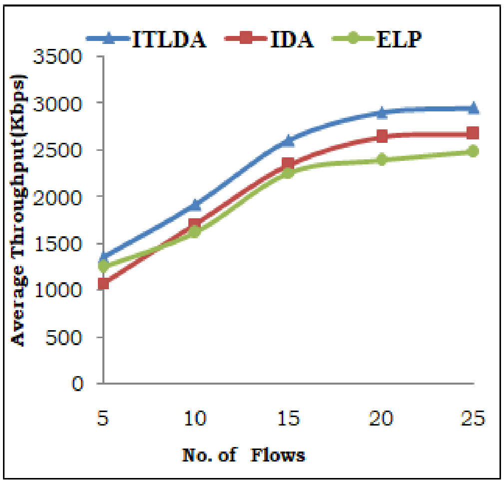

Figure 7. Random Topology: Average Throughput (UDP/CBR)

For the different numbers of flow, the ITLDA routing metric has higher average throughput than IDA and ELP. The Figure 7 indicates, average throughput of ITLDA is 10.9% and 14.6% more than IDA and ELP routing metrics respectively.

The end-to-end delay of all routing metrics continues to increase as network load increases. The Figure 8 shows average packet loss ratio of ITLDA routing metric is 9.5% and 13.2% lesser than IDA and ELP routing metrics respectively.

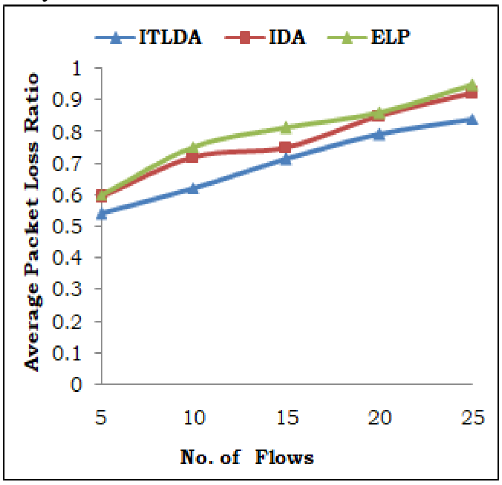

Figure 8. Random Topology: Average Packet Loss Ratio (UDP/CBR)

As seen from the Figure 9, ITLDA's average end-to-end delay is 28.1% and 34.8% less than IDA and ELP routing metrics respectively.

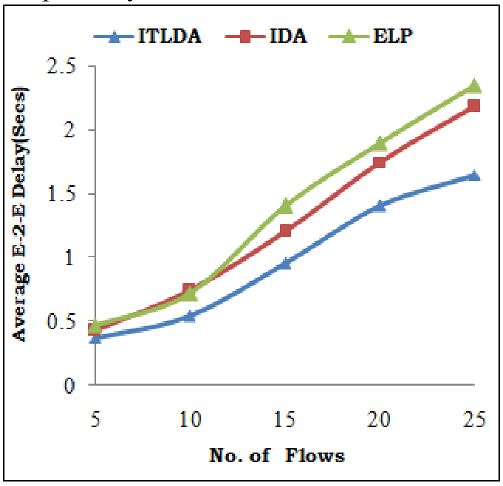

Figure 9. Random Topology: Average End-to-End Delay (UDP/CBR)

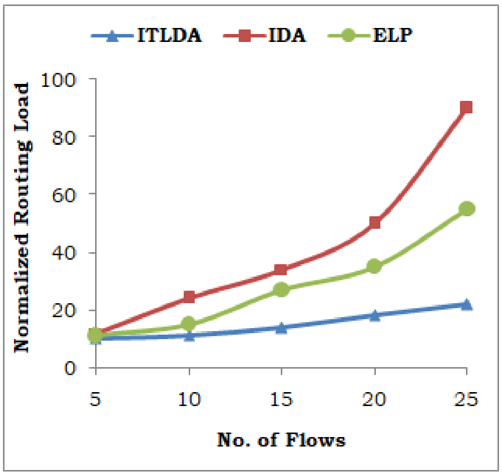

Figure 10. Random Topology: Normalized Routing Load (UDP/CBR)

Figure 10 shows the NRL of ITLDA, ELP and IDA routing metrics. As network size increases, along with sending probe packets the available bandwidth, IDA also has to send more control packets to keep up-to-date routing tables. Because ofthis, NRL of IDA is more as compared to ITLDA. As the network size in-creases, more Route Request and Route Reply messages need to be transmitted to search for route, there is a slight increase in the NRL of ITLDA and ELP.

C. *Simulation Results on Grid Topology (FTP/TCP traffic)*

We examine the performance of all three metrics using 5 different FTP flows using TCP.

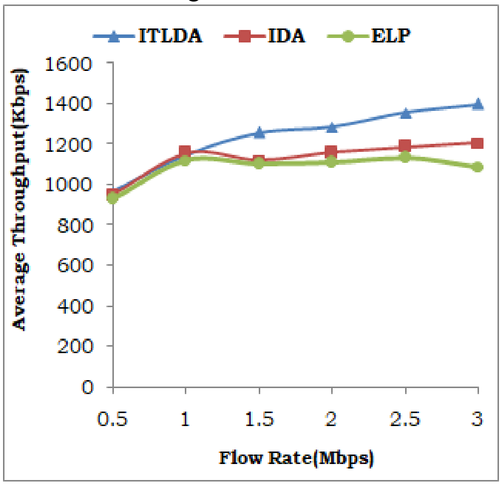

Figure 11. Grid Topology: Average Throughput (TCP/FTP)

TCP traffic results in lower average throughput as compared to the UDP traffic. The reason is, whenever TCP sender notices a packet loss, additive increase /multiplicative decrease (AIMD) mechanism of TCP reduces the data transmission rate to evade the network congestion. For TCP traffic, Figure 11 shows the average throughput of ITLDA is 8.6% and 12.4% more than the IDA and ELP respectively.

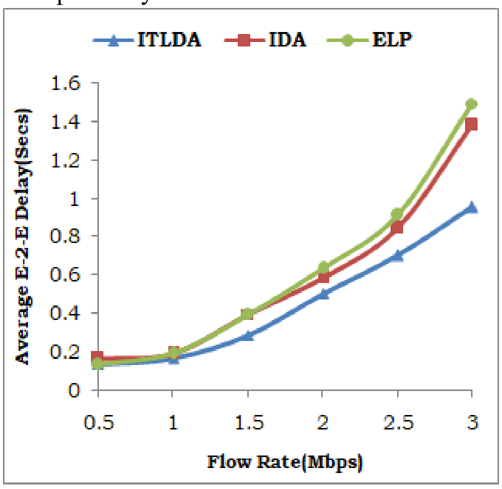

Figure 12. Grid Topology: Average End-to-End Delay (TCP/FTP)

In contrast to UDP traffic, TCP traffic leads to higher average end-to-end delays. The TCP retransmission policy and the congestion control mechanism add more transmission delay to increase the average end-to-end delay. As seen from the Figure 12, the average end-to-end delay of ITLDA routing metric is 29.7% and 37.4% less than IDA and ELP routing metrics respectively.

For different kind of traffic, the performance of ITLDA routing metric is better than both IDA and ELP routing metrics.

VI. Conclusion

The proposed ITLDA routing metric finds best path on the basis of channel utilization, node's current load, physical interference and available bandwidth of link. IDA uses active probing to find the available bandwidth. ELP has no provision to estimate the bandwidth of the contending links. ITLDA uses logical and physical interference models to approximate the available bandwidth. IDA and ELP routing metrics does not consider queuing delay as part of delay estimation. ITLDA routing metric finds the optimum paths by considering all major components of end-to-end delay including queuing delay. Even without using any adjustable parameter, ITLDA can perform better under different network conditions. Simulation results indicate that performance of ITLDA routing metric is better than the IDA and ELP routing metrics.

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