ETX Based Routing Metrics

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***Abstract*— Wireless Multi-hop Networks (WMhNs) are supposed to be the forerunner among the currently existing communication technologies. They provide users with flexible structures, feasible cost, convenience, ever growing bandwidths and innovative solutions. The increasing demands of the users provide a challenge to improve the quality of WMhNs. The performance of WMhNs depends upon the efficiency of the routing protocol operating it. The most important component of a routing protocol is routing link metric. Depending on the demands, the routing protocol must choose a realistic routing link metric to select the quality links. This paper surveys routing metrics based on Expected Transmission Count (ETX).**

***Keywords*— ETX, IBETX, mETX, Adv-ILA, Adv-iAWARE, Routing metrics, Wireless Mesh Networks, Wireless Multi-hop Networks.**

I. INTRODUCTION

Routing is a fundamental characteristic of WMhN. The routing protocol is responsible to control the formation, configuration, maintenance of topology of the network, selecting the best path with quality links from source to destination with low end-to-end delay and high throughput. The strength and weakness of routing protocols are reflected directly in WMNs. The strength of the routing protocol is the strength of routing metric used in it to select the best path with quality links.

In our survey we focus on designing a good routing metric for routing protocols in WMhNs and especially in Wireless Mesh Networks WMNs and Wireless Sensor Networks WSNs. A routing protocol must accurately capture the quality of links. In WMN, the characteristics such as static nature of nodes, the shared natures of wireless medium impose challenges for the design of routing metrics. In an effort to understand how these challenges impact routing metric design in mesh networks, our work make the following contributions. First, we analyze the existing routing metrics that have been proposed for routing protocols in wireless multi-hop networks and then compare them based on salient characteristics revealing the advantages and limitations. We propose three routing metrics that address most of the requirements and limitations discovered from the survey and the performance evaluation of routing protocols based on the metrics.

The rest of document is organized as follows. Section II outlines the design requirements and characteristics of a good metric. Section III outlines the survey on existing routing metrics in WMNs. The three routing metrics that we have proposed in this survey are arranged in section IV and finally we outline conclusion and scope towards the future.

II. CHARACTERISTICS AND DESIGN REQUIREMENTS

The performance of wireless networks depends on the efficiency of the routing protocols operating it. The routing link metrics drives the routing protocol to be efficient one. Because, a link metric first considers the quality routes then decides the best end-to-end path. To ensure good performance, routing metric must satisfy four requirements. First, the route stability i.e. no frequent route changes should occur. Second, minimum waited path should be selected. Third, efficient algorithm with polynomial complexity should be used to compare minimum weighted paths. And finally, the routing metrics must not form forwarding loops. The key components that can be utilized to compose a routing metric for mesh networks: number of hops, link capacity, link quality, and channel diversity. We describe some of the desirable characteristics of good metric for WMN.

A. *Interference*

Interference of a network can be of three types.

i. Intra-flow interference:

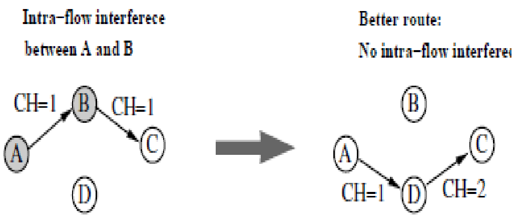

Figure.1.a

Intra-flow interference is a technique in which the radios of two or more links of a single path or flow operate on the same channel. Nodes on the path of the same flow may also compete with each other for channel bandwidths. Such intra-flow interference increases the bandwidth consumption of the flow at each of the nodes along the path resulting throughput of the flow to degrade sharply and delay at each hop to increase dramatically as the hop count of the flow increases. Therefore, the potential of increased congestion levels due to such intra-flow interference must be considered when designing a routing metric for mesh networks. This can be reduced by increasing channel diversity i.e. by selecting non-overlapping channels for adjacent hops of a path. For e.g. as shown in figure.1. a, an interference aware metric should give path A → D → C than the path A → B → C, since the reuse of channel 1 on A → B

→ C creates much more intra-flow interference than that in path A → D → C.

ii. Inter-flow interference:

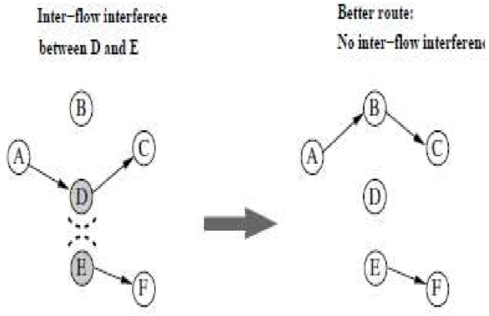

Figure.1.b

Inter-flow interference is the interference caused by other flows that are operating on the same channels and are competing for the medium. The bandwidth of a wireless link is shared between neighboring nodes. A flow through wireless links not only consumes the bandwidth of the nodes along its path, it also contends for bandwidth with the nodes that are in the neighboring area of its path. Inter-flow interference is harder to control than intra-flow interference, due to the involvement of multiple flows and routes. Such inter-flow interference can result in bandwidth starvation for some nodes since these nodes may always experience busy channels. To prevent such starvation, a routing metric must help routing protocols to choose paths that can balance not only the traffic loads along the path of a flow, but also reduce the inter-flow interference imposed in the entire neighboring area. For instance, in figure.1.b, an effective routing should give path A→B→C a lower weight than path A → D → C, since path A→ B → C has much less inter-flow interference than path A → D → C.

iii. *External interference*:

External interference occurs when a link experiences interference outside of the control of any node in the network. Here, we have two kinds of external interference: Controlled Interference, where other nodes external to the network use networking technologies that overlap with those used by the network, and Uncontrolled Interference, which is caused by any other source of radio signals emitted in the same frequency range, but not participating in the same MAC protocol. In summary, to find minimum weight paths with good performance, routing metrics must capture both intra-flow and inter-flow interference.

B. Data Rate

The metric should be able to send the packets at a faster data rates across the network along with the packets loss ratio taken care to account.

C. Locality of Information

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

D. Load Balancing

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

E. Agility

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

F. Isotonicity

The isotonic property is said to be acquired, if a routing metric ensures the order of weights of two paths is preserved, even if they are appended or prefixed by a common third path. More precisely, assume that for any path *a*, its weight is defined by a routing metric, which is a function of *a*, denoted as W(*a*). Denoting the concentration of the two paths *a* and *b* by $a \oplus b$, the definition of isotonicity is *Definition:* A routing metric W(·) is isotonic if $W(a) <= W(b)$ implies both $W(a \oplus b) <= W(b \oplus c)$ and $W(c^1 \oplus a) <= W(c^1 \oplus b)$, for all a, b, c, c^1 (see figure.1.c)

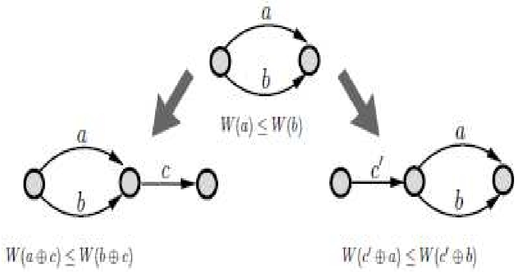

Figure.1.c

Isotonicity is the necessary and sufficient condition for a routing metric for the existence of efficient algorithms to find minimal weight paths, such as Bellman-Ford [1] or Dijkstra's Algorithm.

G. Throughput

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

H. Packet Loss Ratio

In general, an optimal metric should result in minimum packet loss ratios on transfer across the network. It is the number of packet lost over the number of packets sent.

III. ETX BASED ROUTING METRICS

On a wireless link, the number of link layer transmissions of a packet is an appealing cost metric because minimizing the total number of transmissions (and re-transmissions) maximizes the throughput of an individual link then overall network. ETX proposed in [2], [3], measures MAC transmissions and retransmissions to recover from frame losses since the link level re-transmissions depend only on the link level packet errors caused by channel issues. ETX of a wireless link is the estimated average number of transmissions of data frames and ACK frames necessary for the successful transmission of a packet [4]. A node derives ETX by estimating the frame loss ratio at the link 1 to each of its neighbors in the forward direction as Plf, and in the reverse direction as Plr transmitting broadcast probe packets (which are not retransmitted) at the link layer once every second as:

$$ETX_l = \frac{1}{(1 - p_{lf}) \times (1 - p_{lr})} \qquad (4.1)$$

Alternatively, ETX of the link is the inverse of the probability of "Successful packet delivery" or "link reliability":

$$ETX_l = \frac{1}{(p_{lsf}) \times (p_{lsr})} = \frac{1}{reliability(l)} \qquad (4.2)$$

If we increase the frequency of ETX measurements and change the optimum paths accordingly more frequently, it involves significant amount of overhead in the network. It has been shown that the link with a lower ETX metric may in fact lead to a higher observed loss rate at the transport layer. Because good link layer protocols do not retransmit lost packets forever and give up after a threshold number of attempts. The losses occuring in the form of bursts cause to pick the link in the middle of a burst-error situation, which is bad even with a lower ETX.

Consider for example, the figure.3.a which illustrates the packet delivery ratios taken from four distinct links in the Roofnet Wireless Mesh Network [5]. Each of these four links has an ETX around 2 during the testing period. Therefore, if ETX is taken as the metric for quality, these four links are identical. On the other hand, the simple variances of the delivery ratios are quite different for these links, i.e. these wireless links have similar long term average behaviors, even though their short term behaviors are quite different [6]. ETX does improve the throughput of a wireless network (with less mobility) when compared to hop count metric but it does not track the variations on the channel at short time scales due to potential route instability [7].

Table.3.1 lists the performances over ETX, design goal and experimented platforms of the ETX based metrics. The following paragraphs are dedicated for the discussion of up-to-date metrics based on ETX.

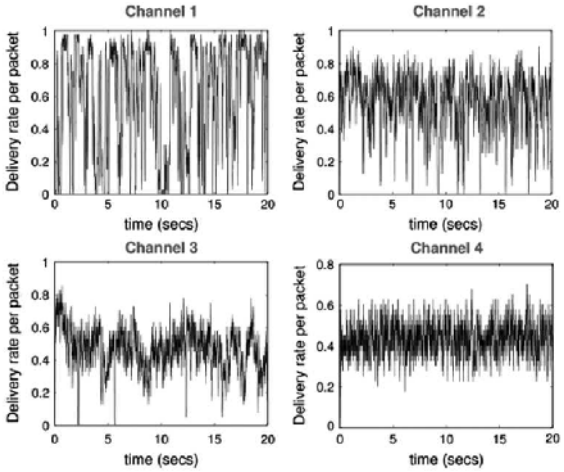

Figure.3.a

A. modified ETX (mETX) and Effective Number of Transmissions (ENT)

In almost all kinds of wireless networks, due to the fast link-quality variation, the metrics based on a time window interval, such as ETX, ETT, WCETT, MIC, MCR, iAWARE etc., may not follow the link quality variations and/or may produce prohibitive control overhead. To cope with the situation, mETX and ENT were proposed in [6], which are aware of the probe size, therefore, the inclusion of the data rate is trivial for them. Along with the link-quality average values, these metrics consider the standard deviation to project physical-layer variations.

- *Modified ETX (mETX)*

Presence of channel variability in ETX became the reason to design mETX. The difference between mETX and ETX is rather than considering probe losses, mETX works at the bit level. The mETX metric computes the bit error probability using the position of the corrupted bit in the probe and the dependence of these bit errors throughout successive transmissions. This is possible because probes are composed by a previously known sequence of bits. The variability of the link is modeled using the statistics of the stochastic process. Then, the mean number of transmissions is analytically calculated and the results show that it can be closely approximated with the statistics of the bit error probability, summed over packet duration. For mETX, the critical time scale for the link variability is the transmission time of a single packet including all its retransmissions. mETX is defined in eq.(4.3) with μ being the estimated average packet loss ratio of a link and σ2 the variance of this value. Like ETX, mETX is additive over concentrated links.

$$mETX = exp(\mu + \frac{\sigma^2}{2}) \qquad (4.3)$$

μ means the impact of slowly varying and static components, like shadowing, slow fading in the channel and σ2 shows the impact of relatively rapid channel variations, as fading, interference, etc. in which the term $\mu\Sigma$ (and hence the ETX) cannot track. μ and $\sigma 2$are estimated by considering the number of erred bits in each probe packet. Complexity of “channel estimation” is the main disadvantage of the mETX, as:

i. Probe packets are to be processed at the bit level raising energy consumption issue in wireless sensor networks (which may not be an issue for wireless mesh networks due to their abundance of processing power)
ii. $\sigma 2$ increases with increased estimation error. A link’s high mETX is due to high channel variability and estimation error which results a better link to be malformed. mETX can be adapted like ETX easily for those wireless links which provide bit rate adaption by normalizing the metric according to the transmission rate.

- *Effective Number of Transmissions (ENT)*

The upper layer protocols as Transmission Control Protocol (TCP), Sequenced Packet exchange (SPX), etc. have a limit to tolerate transmissions and re-transmissions. This issue caused ENT to be proposed. ENT therefore, broadcasts probes, limits routes to an acceptable number of transmissions and re-transmissions according to the requirements of upper layer. It measures the number of successive retransmissions per link considering the variance to find a path that achieves high network capacity while ensuring that the end-to-end packet loss rate visible to higher layers (such as TCP) does not exceed a specified value but this may not be sufficient, as it may involve links with high loss rates. ETX and mETX metrics usually select the links which do not obey the transmission threshold required by the algorithms working at higher layers.

Let M be the threshold number of retransmissions (specified by higher layers), Pal (actual probability of a packet loss), using a large deviations approach can be defined as:

$$P_{dl} = exp\left[\frac{-(logM - \mu)}{2\sigma^2}\right] \tag{4.4}$$

G, be the temporal diversity gain for a wireless link:

$$G = \frac{-logP_{dl}}{logM} \tag{4.5}$$

This specifies the desired loss probability Pdl. Now, ENT can be defined as:

$$ENT = exp\,(\mu + 2G\sigma^2) \tag{4.6}$$

If higher layer does not specify any loss probability constraint, i.e. $G = 0$, then for the given Pdl, $2G\sigma 2 <= \log M$, we left with $\mu <= \log M$. If $G > 0$ then there must be efficient resources for the network to put an amount $2G\sigma 2$ (which is directly related to the variability of the channel, $\sigma 2$ and strictness of the loss requirement, G). This interpretation of ENT is analogous to the notion of effective bandwidth, which was developed to model variable traffic sources in queuing networks. Indeed, ENT can be interpreted as the effective bandwidth of the discrete stochastic process, the number of transmissions.

Differences between the two include: (1) an extra degree of freedom due to the factor 2G in ENT. Indeed (mETX is the ENT evaluated at 1/4), (2) ENT is not additive as ETX or mETX. Similarities between the two include: (1) a by-product of ENT reduces the packet loss ratio observed by higher-layer protocols, after any link-layer retransmissions are done, (2) they have same channel estimation procedure. Main feature of ENT is that it can be calibrated. It is useful to have a degree of freedom for the necessary adjustments derivations in [8] are based on certain assumptions, which can be partly violated in different platforms and environments. Both of drawbacks of mETX metric are valid for the ENT as well.

B. *Expected Transmission Time (ETT)*

ETT is the time a data packet needs to be successfully transmitted to each neighbor. To overcome ETX’s shortcomings: (1) it broadcasts at the network basic rate, (2) its probes are smaller than data packets, ETT [4] adjusts ETX to different PHY rates and data-packet sizes. Two approaches to compute the bandwidth of link l, B_l. Eq.4.1 from [9] can be re-written as shown in eq.4.7 followed by eq.4.8 and eq.4.9.

$$ETT_l = ETX_l \times t \tag{4.7}$$

$$ETT_l = ETX_l \times \frac{S_F}{B_l} \tag{4.8}$$

$$ETT_l = ETX_l \times \frac{S_F}{\frac{S_L}{T_S - T_L}} \tag{4.9}$$

Where S_F is the data packet of fixed-size, B is bandwidth of link l, S_L is data packet of largest size, T_S -T_L is an interval between the arrivals of two packets.

This technique uni-casts two packets in sequence, a small one followed by a large one, to estimate the link bandwidth to each neighbor reassuring the inter-arrival time period T_S -T_L between the two packets and reporting it back to the sender. The computed bandwidth is the size of the large packet of the sequence divided by the minimum delay received for that link. Eq.4.2 from [3], i.e. loss probability is estimated by considering that IEEE 802.11 uses data and ACK frames. Lost rate of data is estimated by broadcasting a number of packets of the same size as data frames, one packet for each data rate defined in IEEE 802.11. Loss rate of ACK frames is estimated by broadcasting small packets, of the same size as ACK frames and sent at the basic rate, which is used for ACKs. ETT may choose a path that only uses one channel, even though a patch with more diversified channels has less intra-flow interference and hence higher throughput. Similarly to

ETX, the chosen route is the one with the lowest sum of ETT values

C. Weighted Cumulative ETT (WCETT)

Basically WCETT is based on ETT and is aware of the loss rate (due to ETX) and the bandwidth of the link. [9] Proposed that WCETT can be used for multi-radio, multi-hop WMN. It proposes ETT which improves on ETX by making use of the data rate in each link. The ETT of a link is defined in eq.4.7. ETT explains the expected MAC transmission time of a packet of a size S over certain link l. Given the presence of multiple channels and intra-flow interference, WCETT is defined as:

$$WCETT = (1-\beta) + \sum_{i=1}^{n} ETT_i + \beta \times \max_{1 \le j \le k} X_j \tag{4.10}$$

WCETT is the sum of ETTs of all the links in the path p operating on Xj channel j, in a system with total k orthogonal channels. β is a tunable parameter subject to 0 <= β <=1. WCETT consists of two components: the first component finds the path with the least sum of ETTs; the second accounts for the bottleneck channel dominating the throughput of the total path.

Its advantages include: (1) over performing ETT, it explicitly accounts for the intra-flow interference, providing support for multi-radio or multi-channel wireless networks, (2) its two weighted components of it substitute the simple summation of ETT and attempt to strike a balance between throughput and delay. It does not capture inter-flow interference compared with Interference Aware Routing Metric (iAWARE). It modifies ETT considering intra-flow interference. This metric is a sum of end-to-end delay and channel diversity. Like Minimum Loss (ML) and unlike ETX and ETT WCETT is an end-to-end metric because it must consider all channels used along the route to avoid intra-flow interference.

D. Metric of Interface and Channel switching (MIC)

WCETT does avoid intra-flow interference but it does not (1) guarantee shortest paths (2) avoid inter-flow interference; which may lead WCETT to select congested routes. MIC [10], [11] tackles these issues by providing the features:

Each node estimates the inter-flow interference, by counting the number of interfering nodes in neighborhood.

MIC virtual nodes guarantee minimum-cost routes computation.

MIC calculates itself by ETT metric. MIC for a path p is defined as follows:

$$MIC(p) = \frac{1}{N \times min(ETT)} \sum_{i \in p} IRU + \sum_{i \in p} CSC_i \tag{4.11}$$

Where N is the total number of nodes in the network and min(ETT) is the smallest ETT in the network. The two components of MIC, IRU (Interference-aware Resource Usage) is $IRU_l = ETT_l \Diamond N_l$ and CSC (Channel Switching Cost) is defined as:

$$CSC_i = w_1; ifCH(prev(i)) \neq CH(i) \text{ and}$$
$$CSC_i = w_2; ifCH(prev(i)) = CH(i),$$

Where 0 ≤ W1 ≤ W2 and N is the set of neighbors that interfere with the transmissions on link *i*. CH (*i*) represents the channel assigned for node *i*'s transmission and prev(*i*) represents the previous hop of node *i* along the path *p*. MIC takes the inter-flow interference only in two consecutive links. (2) MIC considers interference of a link caused by each interfering node in the neighborhood, counts the amount of interferers on alink only by the position of the interfering nodes no matter whether they are involved in any transmission simultaneously with that link. MIC, therefore, utilizes the measurement of signal power to capture inter-flow and intra-flow interference

E. Interference Aware (iAWARE)

iAWARE considers not only both inter-flow, intra-flow interference and characterized by the physical interference model but also takes link-quality variation into account. This metric uses Signal to Noise Ratio (SNR) and Signal to Interference and Noise Ratio (SINR) to continuously reproduce neighboring interference variations onto routing metrics. The iAWARE metric estimates the average time the medium is busy because of transmission from each interfering neighbor. Higher the interference, higher the iAWARE value. Thus, unlike mETX and ENT, iAWARE considers intra-flow and inter-flow interference, medium instability, and data transmission time. In this model [12], a communication between nodes *u* and *v* on the link (*u* → *v*) is successful, if the SINR at the receiver *v* is above a certain threshold. Let $P_u(v)$ denotes the signal strength of a packet from node *u* to node *v*. iAWARE's first component, finds paths with least path cost and other finds paths with least intra-flow interference (exploiting channel diversity). Moreover, the introduction of SINR is a great breakthrough for inter-flow interference-aware routing compared with other ETX-based metric like MIC.

Definition of the link metric iAWARE of a link j as follows:

$$iAware_j = \frac{ETT_j}{IR_j} \tag{4.12}$$

When IRj for the link j is 1 (no interference), iAWAREj is simply ETTj which captures the link loss ratio and packet transmission rate of the link j. ETTj is weighted with IRj to capture the interference experienced by the link from its neighbors. A link with low ETT and high IRj will have a low iAWARE value. Lower the iAWARE of alink better is the link. We define interference ration IRj (*u*) for node *u* in a link *i* = (*u*,*v*), where IRj(*u*) (0 < IRj(*u*) <=1) can be defined as:

$$IR_i(u) = \frac{SINR_i(u)}{SNRi(u)} \tag{4.13}$$

$$SNR_i(u) = \frac{P_u(v)}{N} \tag{4.14}$$

$$SINR_i(u) = \frac{P_u(v)}{[N + \sum_{w\in\eta(u)-v} \tau(w) P_u(w)]} \qquad (4.15)$$

Here η(*u*) denotes the set of nodes from which node *u* can hear (or sense) a packet and τ (w) is the normalized rate at which node w generates traffic averaged over a period time. τ (w) is 1 when node w sends out packets at the full data rate supported. We use τ (w) to weight the signal strength from an interfering node w as τ (w) gives the fraction of time node w occupies the channel.

F. Distribution Based Expected Transmission Count (DBETX)

Through a complete physical channel view and using cross layer optimizations, Distributed Based Expected Transmission Count (DBETX) is proposed in [13] to improve network performance for varying channels and in the presence of fading.

DBETX's performance over ETX increases with the network density because connectivity increases and more routing options become available. Results show a reduction of up-to 26% in the Average Number of Transmissions (ANT) per link and an increase of up to 32% in the end-to-end availability. Using link measurements, DBETX makes the nodes able to: (i) estimate the probability density function (pdf) of the experimented SNIR, (ii) calculate the expected Bit Error Rate (BER) and, as a consequence, the expected packet error rate (PER), (iii) estimate average number of required transmissions in a given link based on the SNIR, (iv) derive the number of required transmissions taking into account the maximum number of MAC-layer retransmissions, (v) penalize lossy links in order to find routes with lower end-to-end loss rates, (vi) reflect the variations of the wireless channel, (vii) to favor links with a lower loss probability (oppositely from [6]). DBETX metric for a link is defined as:

$$DBETX(l) = E[ANT(i)] \times \frac{1}{1 - P_{out_{MAC}}} \qquad (4.16)$$

$P_{out_{MAC}}$ is the probability when $P_{suc}(x) < P_{limit}$. Where $ANT(l)$ is given by:

$$ANT(i) = \frac{1}{P_{suc}(x)};\ P_{suc} > P_{limit} \qquad (4.17)$$

$$ANT(l) = \frac{1}{P_{limit}(x)};\ P_{suc} \leq P_{limit} \qquad (4.18)$$

MAC layer outage (a condition when current Success Probability (P_{suc}) of a link results in an expected number of retransmissions higher than *MaxRetry*) occurs when the success probability of a link is smaller than the limit Success Probability (P_{limit}) which is P_{limit} = 1÷MaxRetry. In this situation, there is a high probability that the transmitted packet will be discarded due to an excessive number of retransmissions. AND function is the expected number of retransmissions on a link considering the value of MaxRetry, which is the maximum number of retransmissions allowed by the MAC-layer (for IEEE 802.11, it is 7 in the presence of Request to Send/ Clear to Send (RTS/CTS) handshake). DBETX's calculation requires the information of actual behavior of wireless link instead of the average behavior. Due to the difference in the working time scales of the different layers, it is impossible to have a complete view of physical medium based on network level, as the events of interest occur at milli or micro seconds, network level interactions are reduced in order to reduce overhead at a time scale of seconds.

G. Exclusive Expected Transmission Time (EETT)

In large scale multi-radio mesh networks (LSMRMNs), most of traffic has much longer paths than in small scale WMNs [14]. When channels are distributed on a long path, EETT selects multi-channel routes with the least interference to minimize the end-to-end throughput. None of the existing routing metrics is capable to evaluate two multi-channel paths accurately when the paths are long. So, EETT well considers channel distribution on long paths which however are very critical in LSMRMNs. In order to meet the above mentioned requirement, EETT is used to give a better evaluation of a multi-channel path. For a N-hop path with K channels, on a link l, its Interference Set (IS) is the set of links that interfere with it (a link's IS also includes the link itself). Then this liks l's EETT is defined as

$$EETT_l = \sum_{l\in IS(l)} ETT_l \qquad (4.19)$$

Physical interpretation of EERR states that EETT of a link l shows the channel used by link l. Link l may have to wait a longer period for transmission on a channel, if there are more neighboring links on that channel with link l resulting in a path with a larger EETT with more severe interference and needs more time to finish the transmission over all links within the path. EETT reflects the optimality of the channel distribution on a path, as this results in less intra-flow interference, if IS(l) includes those links which do not belong to the same path with link l. MIC considers the impact of link l on other links, while EETT considers the impact of other links on l hence EETT is supposed to have better performance since it more accurately reflects the impact of the inter-flow interference

H. Expected Data Rate

To overcome ETX's key limitation of not taking into account the multi-rate links, ETT was proposed to account for multi-rate links. Transmission Contention Degree, (TCD) in [15] was defined to overcome the limitation of ETX and ETT for making conservative estimates for paths longer than 3-4 hops (as all the co-channel links on a path contend with each other) by incorporating time-sharing effects of MAC. TCD is the average fraction of the time for which the outgoing queue of the transmitter link l is non-empty. EDR is defined as

$$EDR_l = \frac{b_l}{ETX_l \times \sum_{i=1}^{n} TCD_l(i)} \qquad (4.20)$$

Where b_l is nominal bit rate of the link l. $\sum_{i=1}^{n} TCD_l(i)$ is used to account for throughput reduction due to equal time-sharing with the contending links provided that all the links have the same nominal bit rate. If the links have different nominal bit rates, they receive the same average throughput, but different time-share of the channel failing to capture the bandwidth-sharing mechanism of 802.11 DCF.

I. Expected Throughput (ETP)

Being proposed in [16], ETP: (1) predicts better routes than ETX and ETT in mesh networks with long paths, they do not make spatial measurements, (2) also measures expected throughput of a link, (3) can easily be implemented in the IBSS mode with minor additions to the beacon message contents, (4) predicts better routes in mesh networks with heterogeneous link rates because ETP captures the bandwidth sharing mechanism of 802.11 DCF more accurately than EDR, ETT, and ETX, as they do not take into account the throughput reduction of fast links due to contention from slow links. (5) ETP is suitable for multi-rate, multi-radio mesh networks.

To state ETP, let link 1 belongs to path P in the contention domain S_l. $S_l \cap P$ is the set of links on path *P* that contend with link 1. r_l be the nominal bit rate of link l. All links have equal number of opportunities for transmission when saturated, as per 802.11 DCF. The expected bandwidth received by each link l is:

$$b_l = \frac{1}{\sum_{j \in S_l \cap P} \frac{1}{r_j}} \qquad (4.21)$$

But the packet losses lower the actual throughput of the link. p_l^f and p_l^r are supposed to be the packet success probabilities of link 1 in the forward and reverse direction respectively, then the ETP of link k is given by:

$$ETP_l = \frac{p_l^{(f)} \times p_l^{(r)}}{b_l} \qquad (4.22)$$

In the form of ETX, we have

$$ETP_l = \frac{1}{ETX_l \times b_l} \qquad (4.23)$$

i.e. it is computing the expected throughput of a link directly. f(p), is the throughput of the bottle-neck link of the path,

$$f(P) = \min_{k \in P} ETP(K) \qquad (4.24)$$

Unlike ETX, ETT and EDR, ETP has a more accurate model for the impact of contention in 802.11 MAC.

J. Multichannel Routing

WCETT lacks switching cost so [17] added it in eq.4.10 and suggested MCR as:

$$MCR = (1-\beta) \times \sum_{l=1}^{n} (ETT_l + Sc(c_l)) + \beta \times \max_{1 \le j \le c} X_j \qquad (4.25)$$

The additional component, Switching Cost, $SC(C_l)$ is defined as follows:

$$SC(c_j) = \sum_{\forall i \neq j}^{n} InterfaceUsage(i) \times Switchingdelay \qquad (4.26)$$

This value does not figure in the time interval that this interface is tuned to channel j, but is idle. Switching Delay is the latency for switching an interface and can be measured offline. When a packet arrives on channel j, $\sum_{\forall i \neq j}^{n}$ InterfaceUsage (i) measures the probability that the switchable interface will be on a different channel (i==j).

Like WCETT, MCR fails to figure the inter-flow interference besides the assumption that all available channels are orthogonal but channel-switching cost makes MCR to be incorporated with the routing protocol like DSR, AODV for multi-channel and channel-switchable wireless network.

K. Medium Time Metric (MTM)

MTM [18] minimizes the time of consumption of physical medium. Due to the shared nature of wireless networks, not only individual links may interfere (intra-flow interference) but transmissions compete for the medium with each other in the same geographical domain. The longer the physical distance of a hop results in the higher energy consumption and the other more hops are affected. The MTM of a packet p on a path P is defined as follows:

$$MTM(P, p) = \sum_{\forall l \in P} \tau(l, P) \qquad (4.27)$$

Where $\tau(l, P)$ is the time required to transfer packet p over link l. $\tau(l, P)$ is defined as:

$$\tau(l, P) = \frac{overhead(l) + \frac{size(p)}{rate(l)}}{reliability(l)} \qquad (4.28)$$

Utilizing eq.4.2 and eq.4.7 and eq.4.28 in the form of ETX is:

$$\tau(l, P) = ETX(overhead(l) + t) \qquad (4.29)$$

Link overhead can be computed from standards and specifications as well as from the type and configuration of the used wireless device. The packet size should be easily available through the routing protocol. Link transfer rate and reliability usually are known to the MAC layer. However, this information often is not accessible to higher network layers because the technique used for auto-rate selection on the MAC layer are considered proprietary. It is possible to estimate the values for transfer rate and link reliability by probing. Though, this information produces un-necessary overhead and less accurate results than inter-layer communication would.

Therefore [18] would favor that radio card manufacturers provide a standard interface in order to enable access to this information by higher network layers. Although we agree with them principally, one should not expect that all problems of measuring transfer rate or link reliability be solved at once thereby. [18] Measured an end-to-end throughput which was equal to minimum hop count and ETX in short distances. When the distances were larger, minimum hop count and ETX found routes with a few hops. MTM selected multi-hop paths with more hops but higher capacity. For this reason, the resulting end-to-end throughput was up to 20 times higher with MTM than with the other metrics.

L. Estimated Transmission Time (EstdTT)

Neglecting the overhead, [20] assumed 1500 bytes as a constant size of the packet and suggested Estimated Transmission metric as

$$EstdTT = \frac{1}{reliability(l) \times rate(l)} \qquad (4.30)$$

This can be alternatively written using eq.4.2 as

$$EstdTT = \frac{ETX(l)}{rate(l)} \qquad (4.31)$$

M. *ETX Distance*

ETX metric is combined with greedy forwarding to optimize routing path without relying the frequently broadcast route probing messages (as in original ETX) in [21]. ETX virtual distance between pair-wise nodes x_i and x_j as the minimal ETX among all the routing paths connecting x_i and x_j, i.e.

$$\delta(x_i, x_j) = \min_{l_i \in L}(l_i) \qquad (4.32)$$

Where, L is the set of hops or paths connecting x_i and x_j. It has been suggested that ETX distances between pair-wise nodes in a WSN can be inferred from their virtual coordinates. Making the comparison of the ETX distances between neighboring nodes, the greedy forwarding can determine the next hop. ETX distance comparison based greedy forwarding guides a packet towards the correct direction and deliver the packet through consecutive hop by hop forwarding, as ETX distance directly reflects the length of a communication path between pair-wise nodes in a WSN.

N. *Multicast ETX*

This energy-efficient routing metric [22], aims to minimize the total transmission energy, in the presence of an unreliable link layer, for the path:

$$C(s,d) = \frac{C(s,u) + W(u,d)}{1 - P_{el}} \qquad (4.33)$$

C(*s*,*d*) is the expected energy-cost of transmission from a source *s* and destination *d*, l is the link between *u* and *d* in the path, P_{el} is the error rate of that link, and W(*u*,*d*) is the transmission energy required between nodes *u* and *d* . [19] Modified the metric given by eq.4.33 to a new metric, METX setting W(*u*,*d*) to 1 as WMNs are not energy sensitive. Eq.4.34 gives us the total expected number of transmissions needed by all the nodes along a path from asource to a destination in order to guarantee successful reception of atleast one packet at the receiver:

$$METX = \sum_{i=1}^{n} \frac{1}{\prod_{j=1}^{n}(1 - P_{ej})} \qquad (4.34)$$

In terms of ETX, using eq.4.1

$$METX = \sum_{i=1}^{n} \frac{1}{\prod_{j=1}^{n} \frac{1}{ETX_j}} \qquad (4.35)$$

i denotes i^{th} link from a source to destination comprising *n* links.

Metric	Performance over ETX	Target Platform(s)	Design Requirement(s)
ETX		Multi-Hop Networks	Maximizing throughput
Modified ETX	1.Accurate loss estimation. 2. 50% less packet loss	Time-Varying WMN's	Selecting good paths among time-varying binary symmetric channel
ENT	1.Accuracy of loss estimation 2.50% less packet loss 3.Least link layer trans.	Time-Varying WMNs	Selecting good paths among time-varying binary symmetric channel
ETT	Ignores intra-flow interference	Multi-Radio, Multi-Hop WMNs	Measuring loss rate bandwidth
WCETT	Multiple Channels	Multi-Radio, Multi-Hop WMNs	Choosing high throughput paths
MIC	It Captures both inter-flow and intra- flow interference	Multi-hop Wireless Networks	Efficient calculation for min. weight path – loop-free rtng
iAWARE	Considers intra-flow + inter-flow interference, medium instability, and data-transmission time	Multi-Radio WMNs	Finding better paths with less interflow and intra-flow interference
DBETX	1.Improves performance for varying channels 2.Outperforms ETX for fading.	Facing Wireless Channels	Maximizes throughput for fading Channels
EETT	Select multi-channel routes with least interference to maximize end-to-end throughput.	Large-Scale Multi-Radio Mesh Networks	Maximizing end-to-end throughput
EDR	1.Finds degree of contention 2.Quantifies impact of link loss 3.Considers concurrent trans if links do not interfere	Multi-Hop Wireless Networks	Finding high-throughput paths
ETP	More Accurate Throughput Estimations.	Multi-rate Multi-channel Mesh Networks	Maximizing throughput
MCR	Uses multiple channels using multiple interfaces	Multi-Channel Multi-Interface Ad-hoc Networks	Increase network capacity by multiple channels
MTM	1.MAC-related overhead 2.Gives higher throughput. 3. Selects more reliable links	Multi-rate Ad-hoc Wireless Networks	avoiding long range links selected by shortest path
EstdTT (SrcRR Algorithm)	1.Predicts best 802.11 trans. rate 2.Reduces loss rate avoiding TCPs timeouts and idle time 3. improves the choice of link transmission bit-rate.	802.11 Mesh Networks	Improving varying link loss rates, transient bursts of losses, poor transmit bit-rate selection, failure to identify high throughput routes,
ETX Distance	1.Greedy forwarding based on ETX Distance,2.Outperforms previous geographic routing approaches	Geographical WSN's	Greedy forwarding
Multicast ETX	Improves throughput at cost of min. energy consumption.	Multi-hop Wireless Networks	Energy-efficient reliable comm. for unreliable or lossy link

Table.3.1

IV. PROPOSED ROUTING METRICS

A. *Adv-iAWARE*

Adv-iAWARE is a metric which is based on the existing routing metrics such as iAWARE, LAETT and EETT. The path metric of Adv-iAWARE is defined as follows:

$$Adv-iAWARE(P) = \sum_{link(i,j)=1}^{n} Adv-iAWARE_{ij} \qquad (4.36)$$

The link metric is defined as follows

$$Adv-iAWARE_{ij} = \frac{EETT_{ij}}{IR_{ij}}$$

$EETT_{ij}$ =Exclusive expected transmission time of a link ij

IR_{ij} =Interference Ratio

$$EETT_{ij} = \sum_{link(i,j)\in s(i,j)} LAETT_{ij} \qquad (4.37)$$

$LAETT_{ij}$ = Load aware expected transmission time;

IS(i,j) = Interference set of link(i,j) (mentioned in EETT section)

Explanation

In Adv-iAWARE metric, we first calculate the LAETT values of all the links in the path. This LAETT value considers the link quality, remaining capacity and packet size into consideration. Now, EETT value of each link is calculated. For any link in the path, the EETT value of the link is summation of all the LAETT values of links which are in the interference set (IS) of this link. A links interference set also includes the link itself. EETT of a link *l* represents the busy degree of the channel used by link *l*. It is a worst case estimation of transmission time for passing link l. If there are more neighboring links on the sane channel with link *l*, link *l* may have to wait for a longer period to do the transmission on that channel. As a result, a path with larger EETT indicates that it has more severe interference and needs more time to finish the transmission over all links within the path. In essence, a better channel distribution over a path results in less intra- flow interference. Hence EETT can accurately reflect the optimality of channel distribution on a path. The interference ratio (IR_j) calculates the inter-flow and external interference.

Advantages

- Unlike the iAWARE metric, Adv-iAWARE does not have an individual summation component that captures intra-flow interference. As explained above, EETT considers intra-flow interference in Adv -iAWARE and hence is isotonic.
- In the absence of interference (IR_j=1), $iAWARE_{ij}$ is equal to ETT_{ij} and the metric will capture the link loss ratio and packet transmission rate of $link_{ij}$. But when a link has higher IR_{ij} than ETT_{ij}, the $iAWARE_{ij}$ metric will have a lower value. This will result in $iAWARE_{ij}$ 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. Adv-iAWARE overcomes this drawback. Adv-$iAWARE_{ij}$ is the ratio of $EETT_{ij}$ and IR_{ij}. EETT considers intra-flow as well as inter-flow interference. So, if a link has high interference then not only IR value but also EETT value will be high. Thus Adv-iAWARE selects path with less interference.
- It even considers load balancing as it uses LAETT metric which takes care of load balancing.
- It has all advantages of iAWARE, EETT and LAETT routing metrics.

Drawbacks

- There may be considerable amount of traffic overhead to calculate the link metric; it needs knowledge of interference set.
- Inter-flow interference is calculated twice, both in $EETT_{ij}$ and IR_{ij}. This might be redundant.
- This metric does not consider the cost of channel switching delay. We do not consider this routing characteristic because if a path has less intra-flow interference, it should have different channels on all the links in the path. So, this path has high channel switching cost. Now, consider a path which has low channel switching delay. This path may have links on same channels which may increase intra-flow interference. For this reason, we consider channel switching delay not to be an effective routing metric.

B. Adv-ILA

This metric is a modified version of ILA with inputs from metrics such as LAETT and EETT. This metric addresses the limitations of existing metrics such as hop count, ETT, ETX, WCETT, MIC etc for WMN. This metric finds paths with less congestion, low level of interference, low packet drop ratio and high data rate. The path metric of Adv -ILA is as follows

$$= \sum_{link_{i,j} \in p} (MTI_{ij}) \tag{4.38}$$

where MTI_{ij} =Metric of interference on link ij. MTI metric is defined as follows

$MTI_i(C) = EETT_{ij}(C) * AIL_{ij}(C),\ N_l(C) \neq 0$

$MTI_i(C) = EETT_{ij}(C),\ N_l(C) = 0$

$AIL_{ij}(C)$ is same as in ILA

$EETT_{ij}$ and $LAETT_{ij}$ are same as in Adv-iAWARE.

Explanation

In Adv-ILA metric, first the LAETT values of all the links in the path are calculated. This LAETT value takes the link quality, remaining capacity and packet size into consideration. Next EETT value of each link is calculated similar to the one mentioned in Adv -iAWARE metric. EETT does better channel distribution over a path which results in less intra-flow interference. MTI value which is the product of $EETT_{ij}$ (C) and AIL_{ij} (C) considers inter-flow interference on the link. The calculation of AIL_{ij} of a link is mentioned in ILA section of the paper. It is aimed at decreasing the packet delay due to the load of neighboring nodes. In this way, the Adv-ILA metric effectively considers intra-flow, inter-flow and external interference along with packet loss ratio, high data rate, congestion.

Advantages

- Unlike the ILA metric, Adv -ILA does not have an individual summation component that captures intra-flow interference. As explained above, EETT considers intra-flow interference in Adv-ILA and hence is isotonic.
- In ILA metric, the second component CSC captures intra-flow interference only in two consecutive links. But Adv- ILA overcomes this drawback. Instead of the second term, it uses EETT which effectively considers

interference on all the links in the path that interfere with each other.

- Adv-ILA considers load balancing as it uses LAETT metric which addresses load balancing.
- It has all the advantages of ILA, ETT and LAETT routing metrics.

Drawbacks

- There may be considerable amount of traffic overhead. To calculate the link metric, it needs the knowledge of interference set (IS) etc.
- This metric also considers inter-flow interference twice i.e. in $EETT_{ij}$ as well as in AIL_{ij}. So, this may lead to redundant computation of inter-flow interference.
- The method of computing interference load (IL_{ij}) is not effectively mentioned in the ILA metric.
- This metric also does not consider channel switching delay.

C. *Interference and Bandwidth aware ETX (IBETX)*

[24] understood that finding the delivery ratios is the primary quantity of interest for selecting quality links. Then comes the issue of contention due to neighbors in a wireless medium. Third most important task is to find high throughput paths that are ignored by ETX. Keeping these concerns in view, IBETX is designed as threefold metric. Firstly, it directly calculates the Expected Link Delivery (ELD), d_{exp}; that avoids the computational burden, as generated by ETX and bypasses the congested regions in the network like ETX. Secondly, it provides the nodes with the information of nominal bit rates and makes them able to compute Expected Link Bandwidth (ELB), b_{exp} , of all the wireless links in the same contention domain by cross layer approach. Thirdly, long-path penalization by ETX is encountered by calculating the interference, I_{exp}, named as Expected Link Interference (ELI) also by **cross-layered approach**.

Then we define IBETX as follows

$$IBETX = \frac{d_{exp}}{b_{exp}} \times I_{exp} \tag{4.39}$$

Following sub sections give the details that how above given three mechanisms help IBETX to achieve the performance gains.

ELD:

This part of the metric finds the paths with the least expected number of (re)transmissions that may be used onwards for data packet delivery. In other words, the metric estimates the number of required retransmissions calculating the delivery ratios in forward direction by d_f and in reverse direction by d_r of a wireless link mn, as given below

$$d_{exp}(mn) = d_f \times d_r \tag{4.40}$$

Besides the presence of losses, the main objective of this part is to find the paths with high throughput. To compute d_f and d_r, each node broadcasts a probe packet (134byte) every second. Each probe keeps the number of probes previously received from each neighbor in the last 10s. Thus each node remembers the loss rates of probes on the links to all neighbors in both directions. The quantity d_{exp} in addition to considering lossy links also helps to decrease the energy consumed per packet, avoiding retransmissions. It detects and suitably handles asymmetry by incorporating loss ratios in both directions. It does not route around congested links by avoiding the oscillations that cause more end-to-end delay and by selecting the routes which are either idle or they have less traffic to pass with better delivery ratios by increasing the throughput and better utilizing the network.

This is true that $ETX = \frac{1}{d_f \times d_r}$ produces more overhead than minimum hop count metric but this overhead is negligible, when compared to raise in the throughput. Keeping this in the view, ELD not only achieves higher throughput value but also over performs ETX. Because, ELD avoids the computational overhead generated by ETX that first takes inverse of all d_{exp}'s and then adds them up, whereas, ELD only takes their sum. Our network consists of 50 nodes, where this overhead is small but in general, this overhead is directly proportional to the number of nodes or links

ELB:

In the wireless environment, slow links lower the bandwidth of the faster ones in their neighborhood. Consequently, all contending links get the same probabilities for transmission due to underlying 802.11 Distribution Coordination Function (DCF) mechanisms [16]. This means that nominal bit rate information of the contending links is an important link quality factor. Suppose, we are interested to find the best path between two nodes m and n among a set of contending links either on a source-destination path P or on a non source-destination path N P but in the same contention domain. Then the expected bandwidth of the link mn can be written in the following way.

$$b_{exp}(mn) = \frac{1}{\sum_{i \in P \cap NP} \frac{1}{r_i}} \tag{4.41}$$

Here r_i is the transmission rate of the i^{th} link in the domain P ∩N P . Thus capturing the bandwidth sharing mechanism of 802.11 DCF, b_{exp}(mn) considers the accurate throughput reduction of the faster links due the slower ones and predicts the better routes. Moreover, b_{exp}(mn) also encounters the longer paths that are ignored by ETX and ETX-based metrics.

ELI:

The delivery ratio d_{exp}(mn) and bandwidth b_{exp}(mn) calculated in the previous subsections help to directly achieve the primary objective, i.e., quality routes but they do not explicitly reveal interference of the links. Interference helps to consider the longer paths ignored by ETX and all those

ETX-based metrics that do not calculate the interference among the neighbor links. To exactly measure the congestion in the medium and collisions due to hidden nodes, interference also finds the optimal paths in the wireless network. Moreover, since the probes used to calculate dexp(mn) are very small in size, so, they are successfully received even in a congested network, by depicting the wrong image of link qualities. For example, if a link has only capacity to carry probe packets, it pretends the congested link to be quality link because of its high delivery ratios. Infect, it is not able to carry data packets [23]. We, therefore, incorporate a mechanism to calculate the interference in our metric and define ELI that is an expected value calculated by all the nodes on the same source-destination path.

The 802.11's basic Medium Access Control (MAC) is DCF that besides enabling the nodes to sense the link before sending data, also avoids collisions by employing the virtual carrier sensing. DCF achieves this using Request To Send (RTS) and Clear To Send (CTS) control packets that consequently set the Network Allocation Vector (NAV), i.e., N AV = τRT S + τC T S . The NAV is a counter kept that is and maintained by all nodes in the domain with an amount of time that must elapse until the wireless medium becomes idle. Any node cannot transmit until NAV becomes zero. It stores the channel reservation information to avoid the hidden terminal problem. Using the cross-layer approach, DCF periodically probes the MAC to find the time period for which the link is busy; τbusy . The interference, a node m has to suffer, is expressed as

$$i_m = \frac{\tau_{busy}}{\tau_t}$$

Where τbusy is the is the duration for which the medium remains busy; in the case of receiving packets it is Rx state (or communication is going-on with other nodes) and the NAV pending. In the interference expression for node m, τt is the total window time (10s). If a node n is at the transmitting end, its τbusy is given as: τRx + τTx + τRT S + τC T S. Thus the interferences for sending node n and receiving node m are given as

$$i_m = \frac{\tau_{R_x} + \tau_{RTS} + \tau_{CTS}}{\tau_t} \tag{4.42}$$

$$i_n = \frac{\tau_{R_x} + \tau_{T_x} + \tau_{RTS} + \tau_{CTS}}{\tau_t} \tag{4.43}$$

$$i_{mn} = Max(i_m, i_n) \tag{4.44}$$

The link *mn* formed by nodes m and n are suffering from an interference, i_{mn} , that is the maximum of the interferences calculated in eq.(4.42) and eq.(4.43), is calculated by eq.(4.44). The receiving node m saves the information of interference computed by eq.(4.42) and sending node *n* by eq.(4.43).Then we calculate the expected interference of the link *mn* as

$$I_{exp}(mn) = \frac{i_{mn}}{1 + i_{mn}} \tag{4.45}$$

Being shared in nature, wireless medium has a problem of interference due to contention. This causes packet loss due to collisions that consequently reduces the bandwidth of links. We, therefore, added I_{exp} factor, that handles the inter-flow interference among the contending nodes. As discussed in section III, the longer paths with higher throughputs are ignored by ETX and ETX-based metrics, ELI would not let any path (independent of number of hop-counts) to be ignored while selecting high throughput paths.

IBETX value for the end-to-end path *P* is calculated by eq.(4.46), where *mn*'s are the links on *P*

$$IBETX(P) = \sum_{mn=1}^{n} IBETX(mn) \tag{4.46}$$

$$f(P_{best}) = \min(IBETX(P_1), IBETX(P_2), , , , , IBETX(n)) \tag{4.47}$$

Hence, on directly calculating the loss probability, expected bandwidth and expected interference based on the degree of contention present on the links, IBETX successfully finds the quality links.

CONCLUSIONS AND FUTURE WORK

In this survey, we have performed a comprehensive analysis of the various routing metrics that have been proposed for routing protocols in Wireless Multi-hop Networks especially Wireless Mesh Networks.

After minimum hop count which usually selects lossy links, ETX is the most widely used routing link metric (in the presence of least mobility of nodes and availability of links). We therefore, analyzed and compared the performance of those wireless routing which are ETX based and are used by the recent routing protocols. Overheads occurred and throughputs achieved due to the factors added to ETX have been listed and discussed.

We surveyed a newly proposed a new quality link metric for wireless multi-hop networks. IBETX have overcome the performance leaks in ETX due to its unawareness from the MAC layer. Using cross-layer approach, IBETX metric has provided with the MAC layer information. ELD found the high throughput paths more efficiently than ETX and ELP by avoiding the overhead due to computational complexities in both. ELB found the quality links from all active links in the same contention domain. ELI part along with ELB removed the deficiency in ETX and ETX based metrics to ignore the longer paths while selecting quality links, though the longer paths usually give higher throughputs.

Future work goals are to simulate these metrics with the most widely used protocols, as DSR, AODV, OLSR, etc and to analyze their performance over recently proposed ETX metrics, and design an enhance IBETX which supports multi-channel networks

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