High throughput path selection for IEEE 802.11s based Wireless Mesh Networks

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ABSTRACT

The IEEE 802.11s draft is the first attempt to develop a standard fully intended for the rapidly growing Wireless Mesh Networks (WMNs). Performance of a WMN is largely affected by the design of routing protocol and the associated metric. The recent version D2.02 of 802.11s has defined Hybrid Wireless Mesh Protocol (HWMP) and Airtime as the default path selection protocol and metric, respectively. However, Airtime and other well known existing routing metrics do not consider the impact of backoff delay and queueing delay, and hence, ignored some important factors like transmission time of the contending nodes, their loads and densities which might hinder the network performance. In this paper, we first identify the parameters that affect the forwarding time of a packet and then, design a new routing metric referred to as EFD (Expected Forwarding Delay) that estimates the forwarding time of a packet of particular traffic class in a node and selects the best path (high throughput) having minimum cumulative expected forwarding delay. We also made changes to the path selection criteria, metric propagation and route update intervals of HWMP, so that more stable paths can be chosen. Finally, we incorporate our new metric with the modified HWMP and study the performance through extensive simulations. Results indicate that the proposed mechanism outperforms others in terms of average network throughput, end-to-end delay and packet loss rate.

Categories and Subject Descriptors

C.2 [**Computer communication networks**]: Network protocols

General Terms

Design, performance

ICUIMC 2010, Jan 14-15, 2010, Suwon, Korea
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1. INTRODUCTION

Wireless Mesh Networks(WMNs) have emerged as an evolutionary approach to provide low-cost and high bandwidth Internet access to wireless users where static mesh routers form the infrastructure backbone. WMNs have gained tremendous popularity in both academia and industry due to its inherent properties like self-organization, self-configuration, fault tolerance against network failures, easy maintenance and setup, low-cost and large coverage[3]. A typical architecture of IEEE 802.11s based WMN is depicted in Fig.1.

The mesh infrastructure is formed with three types of static wireless nodes termed as Mesh Access Point (MAPs), Mesh Points(MP) and a Mesh Point Portal(MPP). MAPs have the functionalities of both an access point and relay node, whereas, MPs act only as relay nodes and MPP is the gateway node that bridges the WMN to outer world (preferably Internet). Legacy nodes are associated to the MAPs through IEEE 802.11 WiFi mechanism and enjoy the internet connectivity through the multi-hop wireless backbone. The architecture of a WMN exhibits the presence of multiple paths between any source-destination pair. Most of the traffic in a WMN are to/from internet and hence, gateway centric. However, traffic can flow within a mesh if two legacy nodes (STAs) in the same mesh need to communicate. In the first case, proactive mode of HWMP mechanism is used for path selection, whereas, on-demand mode is used in the later case.

In this paper, we focus on designing a path selection mechanism that includes a new routing metric and modification of current HWMP, such that high throughput paths can be

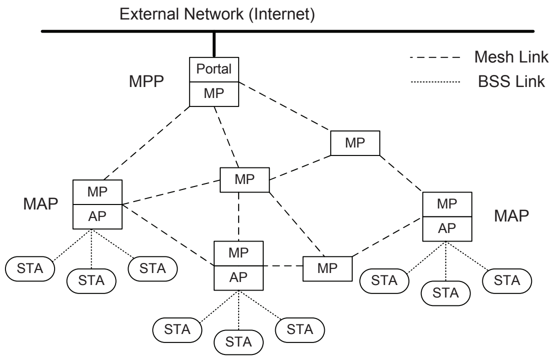

Figure 1: Architecture of an IEEE 802.11s WMN

selected. A routing metric can be defined as a parameter, value or weight associated with a link (termed as link metric) or path (termed as path metric), based on which a routing decision is made, and thus, plays a critical role in the performance of a routing protocol. However, defining a weight for a link in wireless network is considerably harder than in traditional wired network as the condition of a wireless link varies with time. Thus, an unstable value of a link quality metric might forces the proactive routing mechanism (i.e., proactive mode of HWMP) to re-converge again and again [15]. A careful design of the path selection mechanism might deal with metric unstabiliy. Therefore, in addition to design a new metric, we also modify the route selection criteria of HWMP, so that more stable paths can be chosen.

In a typical WMN, multiples paths exist between any source-destination pair. Our goal is to design a routing metric that will enable the routing protocol to select the best path (which will maximize the throughput) from the available paths. Existing routing metrics usually select paths that require minimum aggregate transmission time (which does not reflect the actual end-to-end delay) for a packet in a path, and thus, select the links with high data and success rates. However, a high throughput path is the one which can deliver a packet with the shortest end-to-end forwarding delay and considers the additional factors like loads of the contending nodes, their link quality and type of traffic (in the presence of multiple classes of traffic). We design a new routing metric referred to as Expected Forwarding Delay (EFD) which selects the path that has lowest end-to-end forwarding delay.

The main contributions of our work are: i) Through analyses, we show how the identified factors affect the forwarding delay of a packet, ii) Design the new metric, EFD, that measures expected forwarding delay of a packet of particular traffic class in a path by considering the impact of traffic load, link quality and traffic class of the contending nodes. iii) Make modifications to the HWMP's path selection criteria so that it can select more stable path using EFD iv) Finally, through simulation, we show that our proposed metric outperforms existing routing metric in terms of average network throughput, end-to-end delay and packet loss-rate.

2. RELATED WORKS

Maximizing the throughput for multihop WMNs has been a good area of research in the recent past. A good number of works have devoted in desiging routing metric for WMN. In contrast, very few works have focused on the path selection mechanism for IEEE 802.11s WMNs.

Expected transmission count (ETX) [6] is one of the first routing metrics designed for wireless mesh networks. It is a link metric that estimates the number of transmission attempts (including retransmissions) required for a successful transmission on a particular wireless link. ETX does not consider the impact of varying transmission rates of different wireless links and sizes of data packets. Another limitation of ETX is the use of an active broadcast-based probing scheme to measure the packet loss rates. This does not reflect the link quality accurately, since probing packets are small, and broadcast packets use lower data rates than that of actual data packets [10]. ETX also does not consider the impact of intra-flow and inter-flow interference[1]. Draves et al. [7] proposed the Weighted Cumulative Expected Transmission Time (WCETT) as a path metric for routing in multi-radio multi-channel WMNs. First, they proposed the Expected Transmission Time (ETT) metric to address the issue of varying data rates of different wireless links. ETT measures the actual airtime required to transmit a packet over a wireless link. Note that neither ETT nor ETX considers the presence of multiple channels. Therefore, ETT is extended for multiple channels and termed as WCETT. However, WCETT does not consider the link quality and traffic loads of the contending neighbors and, thus, end up finding paths through more congested areas of the network. Moreover, it fails to handle the inter-flow interference.

Airtime [2] is the default routing metric specified in the IEEE 802.11s draft standard for use with HWMP. This metric defines the amount of channel resource consumed by transmitting a packet over a wireless link and, is analogous to the ETT metric. Like ETT, it also does not consider the contending nodes' load and link quality, and thus, route traffic in links with higher data rates, and results in throughput degradation and congestion in the network. Moreover, Airtime does not consider the impact of multiple traffic classes in a node. Finally, Yang et al. in [16] presented Metric of Interference and Channel Switching (MIC) that incorporates both inter- and intra-flow interference. However, it requires up-to-date information regarding the ETT of each link which add significant overheads and may degrade the overall network performance. Moreover, it assumes that all the nodes located in the collision domain of a particular link contribute to the level of interference, irrespective of whether those nodes are actually generating interfering traffic or not.

Performance of a routing metric largely depends on the type of routing or path selection mechanism that uses the metric. IEEE 802.11s [2] has defined HWMP as the default layer-2 path selection mechanism for WMNs which combines both proactive and reactive modes of routing operation. However, while using link quality metrics with proactive modes, it is

[1] Intra-flow interference occurs when nodes in a single path attempt to transmit packets of the same flow and interfere with each other. Inter-flow interference is the interference suffered among concurrent flows.

difficult to find stable paths. Therefore, we address this issue in our proposed mechanism which is yet unaddressed by existing works. In, [4], the authors have just summarized the operation of HWMP. A tree-based hybrid centralized routing protocol is presented in [12] which uses hop-count as the routing metric. However, incorporating dynamic link quality metrics (such as, ETT, AirTime, MIC) in [12] might force the routing protocol to switch between paths.

3. PROBLEM DESCRIPTION AND MOTIVATION

In wireless mesh networks, usually there exist multiple paths between any source-destination pair. End-to-end delay experienced by a packet on different paths ought to be different because of the shared nature of wireless links. Obviously, the path that will take less time to deliver a packet from a source to a destination will be the better choice to route the packet. Our goal is to design a path selection mechanism that can select high throughput paths using a dynamic routing metric. The metric should estimate the end-to-end delay experienced by a packet for the available paths. So that the routing protocol can select the best available path. Eventually, if all the packets can be delivered with lesser delays, overall network throughput will be increased. We first identify the factors that affect the forwarding delay of a packet in a node as:

- *Transmission rate:* A link with a higher transmission rate will take lower transmission time and should outperform links with lower transmission rates. Furthermore, due to the shared nature of wireless medium, the transmission rates of the neighbors (i.e., contending nodes) also affect EFD. The reason is that during the transmission time of the neighbors, a node has to wait for the medium to be free.
- *Success rate:* It represents the number of MAC layer transmission attempts required for a transmission to be successful. A lossy wireless link or a link that experiences more collisions will result in transmitting a packet multiple times on that link. This poses a negative impact on the value of a routing metric.
- *Contending neighbors and their loads:* Number of contending/interfering nodes and their traffic loads in the neighborhood of a forwarding node has a larger impact on the performance of WMN.
- *Load awareness:* It represents the traffic load of the forwarding nodes in a path. If the forwarding nodes are loaded, their queues build up quickly and the queueing delays of the packets increase. On the other hand, selecting a lightly loaded path balances the loads of the network.
- *Traffic priority:* Today's mesh networks are supposed to provide QoS to the flows (for example, EDCA [1] is used in the MAC layer for differentiated services) by supporting different classes of traffic. Therefore, packets of the flows have different priorities depending on the traffic class, and consequently, forwarding time of a packet varies with the traffic class. A low priority packet might be starved in the presence of high priority packet. A longer path or relatively worse path might produce better throughput for low priority packets. On the other hand, distributing the high priority packets in different paths might also balances the load in the network.

Most of the routing metrics proposed in the literature and discussed in Section 2 (for example, ETT, MIC, Air-time etc) determine end-to-end delay by summing up the values of expected transmission time (ETT) on the links in a path, proposed by Draves et. el.[7]. However, ETT does not address all the factors discussed above. More specifically, medium access time not only depends on the number of retransmissions (or transmission) but also on the time required on each transmission attempt. For example, a forwarding node with more contending nodes experiences more interruptions during the backoff process, and this results in higher medium access delay of the node. Further, channel quality of a contending node with low transmission rate might force a node to freeze its backoff counter for a longer period of time. Moreover, a low priority packet might starve forever (by the high priority packets of the contending nodes and the node itself). As a result, a path with minimum expected delay for that traffic class is the best path for the packet, (which might not be the best path in terms of transmission rate and success rate, i.e., ETT). This also ensures load-balancing in the networks.

On the other hand, ETT might direct all the packets of the network towards a single path (i.e., the best path), leading to increased congestion and contention. As a result, queuing delay of a packet increases and the network throughput decreases due to the under utilization of the network resources, if lightly loaded parallel path exists with a little low quality. Moreover, due to increased congestion and contention, a better path will turn into a worse path and ETT will chose a new path. But, due to the nature of ETT, it will forward all the packets to that new better path, the new path will in turn becomes worse.

However, the main challenge in designing a routing metric is to find the parameters that include the aforementioned factors. In the following, we explain and justify the main parameters those explicitly or implicitly incorporate the above factors, and based on which EFD is designed.

3.1 Impact of backoff delay

We define the backoff delay of a packet as the time that a packet spends in the MAC layer prior to the start of the successful transmission. Therefore, the backoff delay includes the unsuccessful transmission attempts (i.e., ETX) for a packet and the transmission time in each unsuccessful attempts (i.e., ETT). Further, it counts the backoff slots in each transmission attempt. However, other factors that a backoff delay includes but ignored by the existing routing metrics are described in the following:

In each transmission attempt, a transmitting node freezes its backoff counter for successful/unsuccessful transmissions by the contending nodes. Number of freezing in an attempt depends on the number of contending nodes of the transmitting node. Thus, less number of contending nodes in a path results in lower medium access time. Further, the load of a contending node determines the probability at which it attempts to access the medium. Therefore, the combination of the number of contenting nodes and their loads, implicitly indicates the level of interference surrounding a node.

The freezing period of a transmitting node in each interruption depends on the time of the ongoing transmission of its contending nodes. If a contending node experiences bad channel quality (and hence, transmits in a lower rate), the transmitting node might have to wait for a longer period of time in a freezing state. Thus, the duration of an interruption implicitly considers the channel quality of the neighbors, which is un-addressed and ignored by the existing routing metrics. Therefore, a routing metric should account the transmission rate of the neighbors as well.

In 802.11s based WMNs, the MPs use Enhanced Distributed Channel Access (EDCA) mechanism for accessing the wireless media. Unlike DCF, EDCA allows for four different traffic classes and a transmission queue associated at each station. Each traffic class at a station uses its own backoff procedure for channel access [5]. A station retransmits a packet at most M^2 times (where, M is the maximum retransmission limit) before delivering the packet to the next hop or dropping the packet. Thus, the medium access delay of the packets of j-th traffic class, denoted as $d_{acc}(j)$, is

$$d_{acc}(j) = \sum_{i=0}^{M-1} [d_{def}(j) + d_{bo}(i,j)] + \sum_{i=1}^{M-1} d_{col}(j), \qquad (1)$$

where, $d_{def}(j)$ and $d_{col}(j)$ are the defer time and unsuccessful transmission time for j-th traffic class, respectively, and $d_{bo}(i,j)$ is the backoff time of a packet of j-th traffic class at i-th transmission attempt.

For simplicity of analysis, we consider only 3 classes of traffic and the defer times for respective traffic classes are given by

$$E[d_{def}(j)] = \begin{cases} AIFS[1] + E[H] \times E[T] & \text{if } j = 1 \\ AIFS[2/3] & j = 2,3 \end{cases} \qquad (2)$$

where, $AIFS[j]$ ($j = 1,2,3$) is the arbitrary inter frame space according to the 802.11e [1], $E[H]$ is the expected number of interruptions by a neighbor with higher priority packets in a single defer time and $E[T]$ is expected time for an interruption.

Defer time of a node with lower traffic class, $AC[1]$, is affected by the presence of neighboring nodes with packets of higher traffic class, $AC[2]$. Moreover, the backoff delay of a node also includes its defer time. So, an increase in the defer time eventually increases the backoff delay of that node, and a node with lower priority traffic experiences higher backoff delay in the presence of higher priority traffic from its neighboring nodes. Thus, a better path (or, the routing metric) for a flow is not only affected by the conventional parameters (like ETX, ETT), but also is affected by the contending high priority traffic (both the number of nodes having high priority flows and number of high priority flows in each nodes). Therefore, defer time of a packet might be different for different paths and a path with minimum defer time results in lower EFD, if the other parameters are same. This motivates us to consider defer time which contributes to the backoff delay of a particular traffic class.

Note that average backoff delay of a node increases as the number of contending nodes increase.This is because increasing the number of contending nodes results in more interruptions at the tagged station and as a result, the backoff delay increases. Moreover, backoff delay can implicitly determine whether the neighboring nodes are interfering or not, because more number of interfering nodes mean more interruptions in the backoff process of the forwarding node and the backoff delay increases. Note that, use of a lower data rate highly increases the backoff delay for a transmitting node, as the ongoing transmission occupies the channel for a longer period. Conventional routing metrics only consider the link data rate of the forwarding nodes. But, due to the shared nature of wireless medium, data rates of the neighboring nodes are also equally important while selecting a routing path and by incorporating backoff delay in the routing metric we can address this issue.

3.2 Impact of queueing delay

Queueing delay is the amount of time a packet spends waiting in the transmitter's queue before it gets the chance of transmission. So, if a packet is scheduled to transfer through a node that already has enough packets in the transmission queue, then, it will have to wait until other packets in the queue finish their transmission successfully. If we consider only the service time as the routing metric, then most of the packets will be forwarded on a path having less service time. This will increase the queue size and eventually queueing delay of a packet. However, if the same packet is transmitted through a lightly loaded node, it will experience less queueing delay and end-to-end delay will be decreased. So, we need to split the traffic in a manner such that load-balancing can be achieved in the forwarding nodes. This motivates us to incorporate queuing delay of a packet of a particular traffic class in our proposed routing metric.

3.3 Impact of routing metric on path stability

The stability of the metric depends on the nature of the parameters used by the metric and the type of the routing protocols which uses the routing metric. The value of a metric associated with a link can either be static or dynamic (i.e., adaptive). For example, the hop count or the maximum capacity of a link is static. As long as the node is up, the link provides a constant value for the metric. Therefore, this type of metrics provides almost stable value. On the other hand, the value of a dynamic metric depends on the status of the network. As a result, the instantaneous value of a dynamic metric changes very frequently depending on the network status. Most of the existing metrics for the mesh networks are dynamic since this type of metrics can select the best path for a flow/node. A metric becomes unstable when the change of path by the routing protocol changes the value of the metric as well. In this case, new value of the metric forces to change the path again, this in turn, changes the value of the metric. Therefore, the stability of a routing metric also depends on the routing protocol. In fact, routing protocol plays an important role to stabilize a dynamic metric so that the network converges to a certain

[2] The value of M varies according to the traffic class. It is set as 3, 3, 5 and 7, for the traffic classes 0, 1, 2 and 3, respectively

state with optimum network performance. This motivates us to improve the current path selection mechanism so that it can choose a new path only if a certain percentage of change occurs in the metric value.

4. PROPOSED PATH SELECTION MECHANISM

4.1 A new routing metric: EFD

We define the Expected Forwarding Delay (EFD) of a packet in a node as the sojourn time (i.e., the time that a packet stays in a node or the time interval between the arrival of a packet in a node and its successful transmission). We derive EFD for a packet of traffic class j on link l by using Little's formula [11] and is given by:

$$EFD_l^j = \frac{\bar{q}_l^j}{\bar{d}_{acc}(j) + d_{trans}^l}, \qquad (3)$$

where $\bar{q}_l^j$ represents the average queue size of traffic class j on link l, $\bar{d}_{acc}(j)$ represents the average medium access delay (which includes the defer time as well) of a packet of the j-th traffic class on link l and d_{trans}^l is the time required for a successful transmission on link l.

Each forwarding node measures the average queue size ($\bar{q}_l^j$) of a traffic class j by using well-known Exponentially Weighted Moving Average (EWMA) method. The average queue size estimation in a node is updated as

$$\bar{q}_l^j(k) = (1-\alpha) \times \bar{q}_l^j(k) + \alpha \times q_l^j(k), \qquad (4)$$

where $\bar{q}_l^j(k)$ is the estimation of the average queue size at time k , $q_l^j(k)$ is the instantaneous queue size and α is a tuning parameter. Accordingly, $\bar{d}_{acc}(j)$ is also measured using EWMA. The value of d_{trans}^l depends of the specific rate used by link l and we assume that auto rate fallback (ARF) [9] mechanism is running. ARF scheme is well accepted by different WLAN vendors and it requires no probing packets and simple to implement.

Now, if we combine the values of individual EFD of the links for a particular traffic class in a path, we get the value for path metric. So, our path metric, Cumulative Expected Forwarding Delay(CEFD), for a traffic class j and path p is given by

$$CEFD^j = \sum_{l \subset p} EFD_l^j. \qquad (5)$$

Note that CEFD is an additive metric and as the number of links in a path increases, the value of CEFD increases. And among multiple paths between a particular source-destination pair, the path having the lowest CEFD will be the best path.

The proposed metric considers all the factors that have an impact on the EFD. First of all, d_{trans}^l in Eq. 3 estimates the actual air time required for a successful packet transmission that depends on the different data rates (IEEE 802.11a/b/g supports different data rates). Secondly, average backoff delay($\bar{d}_{acc}(j)$) of a link l for a traffic class j, takes into account the success rate, number of contending nodes and their traffic loads, and traffic priority. In other words, it measures the duration of time that includes the time that the medium is detected busy (because of successful or unsuccessful transmissions from contending nodes), the time for unsuccessful transmission or collided transmission and the random backoff slot duration (contention time). Note that, higher priority traffic class has smaller backoff delay than that of lower priority traffic class as Inter Frame Space (IFS) and CW_{min} values are smaller for the former. The EFD of a link uniformly captures both inter-flow and intra-flow interference by taking into account the transmission of other flows and transmission of the same flow on other links in the path within the interference range, respectively.

The average queue size, $\bar{q}_l^j$ of a forwarding node incorporates the issue of load balancing in the proposed metric. The larger the size of the queue in a node, the larger the forwarding time of a packet through that node. Thus the proposed EFD ensures that packets are forwarded through the lightly loaded node and thus EFD achieves load balancing in the forwarding nodes.

4.2 Incorporating with HWMP

Hybrid Wireless Mesh Protocol is the default path selection protocol defined in the draft 2.02 of 802.11s. As specified in [2] [4] , only a single active routing protocol and a corresponding path selection metric should be used in a single WMN. HWMP uses AirTime cost metric as the default routing metric. Instead, we incorporate EFD as the routing metric used in HWMP. In the current draft, the metric identifier value of Airtime cost metric is set to 0, whereas values $1-254$ are reserved for future use. So, we use the value 1 for EFD in the Active path selection metric identifier field. This information is embedded in the "Mesh configuration" element which is used to advertise mesh services. Whenever an MP establishes a link with another MP, it uses peer link open and peer link confirm frames. The "Mesh configuration" element is contained on those frames and also in Beacon frames transmitted by the MPs. Thus, all the MPs can be notified about the default routing protocol(HWMP) and the metric(EFD) they are going to use.

4.3 Basic Path selection

In the On-demand mode, a source MP broadcasts path request (PREQ) message requesting a route to the destination with EFD field initialized to zero. Note that an MP may receive multiple copies of same PREQ from a source through different paths. After receiving a PREQ, an intermediate MP creates a path to the source or updates its current path if the PREQ contains a greater sequence number, or the sequence number is the same as current path and the PREQ offers a better EFD value than the current path. If a new path is created or an update occurs, the PREQ is then rebroadcasted with an updated metric field that reflects the CEFD of the path to the source. The destination MP unicasts a path reply(PREP) message after creating or updating a path to the source. Note that in case of on-demand mode, the changed metric value only affects the selection of new paths and existing paths remain unchanged. Therefore, we assume that incorporating EFD with on-demand HWMP provides stable network operations.

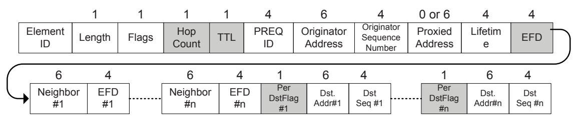

Figure 2: Modified format of a PREQ message

The *proactive tree building mode* can be executed in two ways to let the MPs in the WMN to create a path with the root or portal MP (MPP). First, in the *proactive PREQ* mechanism, the root MP periodically broadcasts a proactive PREQ message with increasing sequence number, destination address set to all 1's and the EFD value initialized to zero. After receiving a proactive PREQ, each MP creates or updates its forwarding information to the root MP, updates the EFD value and hop-count of PREQ and retransmits the updated PREQ. A proactive PREP from an MP, establishes the path from the root MP to that MP.

Whereas in the case of *proactive RANN mechanism*, the root MP starts to periodically broadcast a root announcement (RANN) message which propagates the metric information across the network. Upon reception of a RANN message, an MP that wants to create or refresh a path to the root MP, sends a unicast PREQ to the root MP. The root MP then unicasts a PREP in response to each PREQ. The unicast PREQ creates the reverse path from the root MP to the originating MP, while the PREP creates the forward path from the MP to the root MP.

4.4 Improvements to HWMP

We have made the following modifications to the basic HWMP to provide more stable routes having less signaling overhead and high throughput.

4.4.1 New Path selection criteria

By modifying the condition that triggers a route update, HWMP can add stability to the dynamic metric such as EFD and able to select paths that are more stable. In our proposed path selection mechanism, a route update is enforced by a mesh node only if a new path provides 20% improvement on the metric value. We have found in the simulation that this minimum threshold provides route stability for most of the simulation runs and our improved result justify that. Moreover, we have used EWMA to estimate the parameters of the metric. Thus, abrupt changes will not occur in the metric value. Thus, a combination of both the averaging by EWMA and the enforcement of the thresholding are expected to provide route stability.

4.4.2 Increased update interval

We have proposed to increase the interval of route update message announcement of HWMP. In HWMP, an MPP announces a RANN or proactive PREQ messages after a fixed interval (i.e.dot11MeshHWMPrannInterval) [2]. The specified value of such an interval is defined as $1000TUs$, where $1TU = 1024\mu s$. However, mesh routers are static in nature and the topology of a WMN do not changes frequently. Therefore, we assume that the link quality among static mesh routers do not changes abruptly. We therefore increase the update interval and set it to 1500 TUs which minimizes the signaling overhead caused by the changes in the metric.

4.4.3 Active propagation of metric values

One of the problems with most of the routing protocols like HWMP [2], AODV[13], LQSR [14], is to propagate the value of the metric used for selecting the route. In basic HWMP, a source node broadcasts a PREQ message with EFD field initialized to zero and the next node in the path needs to rebroadcast the PREQ adding the EFD value of the link from where it receives the PREQ. But, the value of EFD for a link can be calculated on the source end of the link. So, nodes need to exchange this value periodically which is not specified in the draft of 802.11s. This periodic exchange of control message incurs extra overhead and also routes are selected based on the older EFD values. So, we propose a method to actively propagate the values of EFD with the PREQ messages.

In this method, a source node first calculates the EFD values of its neighbor as listed in the neighbor table and locally broadcasts the PREQ message along with the values of EFD per link. So, the next hop node in a path can instantaneously get the values of previous hop link and adds the EFD value for the next hop link in its PREQ. The route establishment procedure will be same as HWMP, but now metric values are actively propagating with PREQ messages. The benefits are twofold. Firstly, route selection will be more accurate as MPs use more recent EFD values. Secondly, overhead will be less in the proposed method, as extra message exchange is not required. However, size of the PREQ message will be increased in case of active propagation. Note that in a typical WMN, the number of neighboring MPs or MAPs is expected to be low. So, it is feasible to add per neighbor EFD values in the PREQ message as shown in modified PREQ format in Fig. 2.

5. PERFORMANCE EVALUATION

We have done extensive simulations to evaluate the performance of our proposed path selection mechanism with EFD and compare it with the well known existing routing metrics, for example, ETX, ETT, AirTime and MIC by implementing them with the modified HWMP for 802.11s WMN in ns-2 [8]. We have used a mesh network with 50 stationary mesh routers randomly deployed in an area of $1500m \times 1500m$. We have used both intra-mesh flows and flows that are destined for the Internet through the gateway. We consider a packet size of 1024 Bytes. The transmission range is 250m whereas the interference range (carrier sense range) is set to 550m. We consider UDP as the transport layer and all flows are sent at a constant bit rate. The sources of the flows are randomly chosen for both intra and inter-mesh traffic whereas the destination is the gateway node for inter-mesh traffic. On-demand mode of HWMP is used for intra-mesh traffic and proactive mode is used for inter-mesh traffic. Each simulation run was executed for 15 times and the average results are plotted in the graphs. We have considered the following performance metrics: i) Average network throughput, ii) Average end-to-end delay and iii) Packet loss rate. Simulation results are shown for different network scenarios to show the impact of traffic load and different traffic classes on the performance metrics.

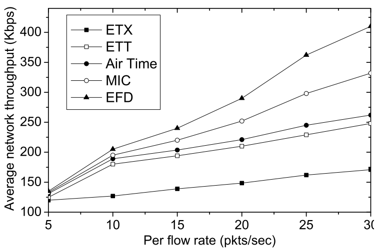

Figure 3: Average network throughput for different traffic loads of the flows.

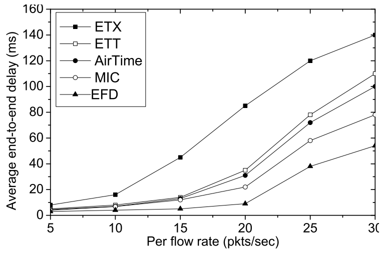

Figure 4: Average end-to-end delay with increasing loads of the active flows.

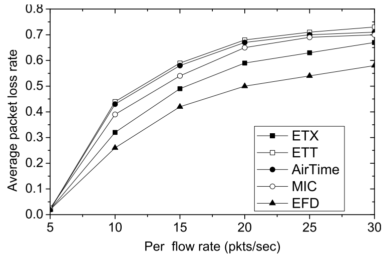

Figure 5: Average packet loss rate with increasing loads of the active flows.

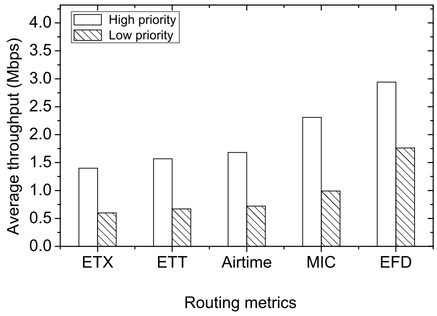

Figure 6: Average throughput of flows with different traffic priorities.

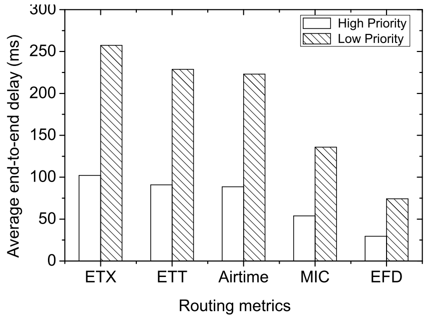

Figure 7: Average end-to-end delay of flows with different traffic priorities.

In the first scenario, we have assumed that the network size is fixed and there are a fixed number of flows in the network. There are 50 nodes in the network, and 20 flows are generating data with randomly selected sources and destinations. We gradually increase the data generation rates of the flows from 5 $pkts/sec$ to 30 $pkts/sec$ to measure the impact of traffic load on the routing metrics.

Most existing routing metrics only consider link quality, and thus, the network throughput does not increase at the expected rate with increasing loads. As shown in Fig. 3, for ETX, ETT and Airtime metrics, the network throughput increases very slowly with increasing loads, because all these metrics forward the packets toward the best path. In contrast, MIC selects the path based on the number of neighbors of the forwarding node, and hence, achieves a slightly better network throughput than others. However, MIC cannot differentiate a neighbor and a contending node, and therefore, cannot estimate the ultimate load of the neighbors. On the contrary, EFD selects paths considering the number of contending nodes and their loads (i.e., the expected number of interruptions in each transmission attempt), and therefore, outperforms all the existing metrics in terms of achieved throughput.

Figure 4 shows the average end-to-end delays for different metrics. EFD performs better in terms of average end-to-end delay than ETX, ETT, Airtime and MIC. Because ETT and Airtime only consider the data rates of links and prefer links that have higher data rates, both these metrics tend to forward all packets to the same path, which results in network congestion. Also, MIC does not balance the traffic load over the network nodes, and thus creates congested regions. In contrast, the average end-to-end delay for a packet that uses EFD is less, as this metric chooses paths with less medium access, transmission and queuing delays.

Figure 5 shows the average packet loss rate of the network with increasing traffic loads. In general, as the traffic load increases, the packet loss rate of all the metrics tends to increase. Due to their inability to address load balancing, most of the packets tend to choose paths with high data rate when ETT, Airtime, or MIC metrics are used. This results in buffer drops in the intermediate nodes. Moreover, as ETT and Airtime do not address the effects of interference, packets are also lost due to interference or collision from contending nodes. In contrast, EFD prefers paths in less congested regions of the network, and packets experience only low to medium contention. Therefore, the packet loss rate when using EFD is lower than that when using the other metrics.

In the second scenario, we investigate the impact of traffic priority on path selection. We make use of a network comprising 50 nodes and 20 flows. Among the flows, 10 flows are high priority flows while the remaining 10 flows are low priority flows. Figure 6 and 7 show the average throughput and end-to-end delay achieved by the different traffic classes using different metrics, respectively. As shown in the figures, both high priority low priority traffic achieves better performance using EFD in terms of throughput and delay. Because the existing metrics forward traffic without considering their priorities, paths are not selected for particular classes. Therefore, low priority traffic starves in the MAC layer for getting access to the medium. Furthermore, the low priority traffic contends with the high priority traffic and reduces the throughput and increases the delay of the high priority traffic. In contrast, EFD forwards the traffic by considering the best path for a particular traffic class. Thus, for most cases, the low priority packets avoid the paths used by the high priority packets, resulting in shorter delays and high throughput. This also reduces the loads and contentions of the high priority traffic and they achieve a better performance.

6. CONCLUSIONS

In this paper, we have presented a path selection mechanism that includes a new routing metric, EFD, which selects the path having minimum forwarding delay. We also make an extension to the current HWMP path selection mechanism (such as introducing new path selection criteria, increases route update interval and active propagation of metric values). By incorporating backoff delay and queuing delay along with the transmission delay, EFD addresses all factors (transmission rate, success rate, contenting neighbors and their loads, load-awareness, and traffic priority) that affect the forwarding delay of a packet in a node. Moreover,the modified HWMP can select more stable paths using EFD metric. Simulation results demonstrate that it performs significantly better with EFD than the existing routing metrics.

7. ACKNOWLEDGMENTS

This work was supported by the IT R&D program of MKE / KEIT. [2009-S-014-01, On the development of Sensing based Emotive Service Mobile Handheld Devices].
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