Surpassing Flow Fairness in a Mesh Network: How to Ensure Equity among End Users?

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***Abstract*—Assuring user fairness in IEEE 802.11 wireless mesh network is challenging mainly for two reasons - first, the in-built unfair behavior of IEEE 802.11 contention based channel access in multi-hop forwarding, and second, the capacity degradation of mesh routers near a gateway due to the heavy traffic load. This paper studies the fundamental reason of fairness degradation in a mesh network, using a practical mesh testbed. The experimental results reveal that the flow fairness alone cannot solve this issue, because the near-gateway routers with high traffic load require more bandwidth for traffic forwarding. An improved channel access differentiation technique based on a load estimation strategy is proposed in this paper to reduce the capacity degradation of mesh routers, and to improve the fairness among end users. The proposed protocol is evaluated using results obtained from two different testbed setups. These results show that the proposed protocol improves the end-user fairness, as well as the average throughput in the network.**

***Keywords*-mesh; IEEE 802.11; fairness; capacity; flow control**

I. Introduction

IEEE 802.11 Wireless mesh network [1] has generated interests among researchers because of its capability of replacing the wired infrastructure by wireless backbone. Mesh backbone network is mainly comprised of wireless routers which have two functionalities - to act as the access point (AP) to client nodes, and to relay the traffic from other routers towards or from the gateway. One or more of the mesh routers also act as gateways to connect outside network.

A mesh network over IEEE 802.11 technology experiences severe problem of unfairness among end-users. IEEE 802.11 Enhanced Distributed Channel Access (EDCA) provides equal time share to every contending station when every station has sufficient data to transmit. Therefore, mesh routers with high traffic load (mainly routers near a gateway) suffer from the unavailability of sufficient bandwidth, and the performance degrades drastically for the end users who are multiple hops away. Though several proposals exist in literature to study fairness issues in multi-hop and mesh networks, such as [2]–[4] and their references, they primarily concentrate on end-to-end flow fairness. A second class of works studies fairness issues in channel access protocols, such as [5]–[7] and their references, that mainly focus on prioritizing the channel access of individual users, according to their traffic demand and the quality of service criteria. However, these works do not reveal the fundamental reasons behind the fairness degradation in a mesh network. Assuring end-to-end fairness cannot solve this issue alone, as the capacity of mesh routers near a gateway degrade severely at high traffic load. Therefore traffic control at intermediate routers is necessary to ensure equal transmission opportunity to every end-user.

In our previous paper [8], an improved fairness provisioning protocol has been proposed that estimates traffic load at every intermediate router. The channel access mechanism of every router is either prioritized or deprived based on the traffic load and the contention information in the neighborhood. Therefore, every router gets channel access proportional to its traffic load (called the *proportional fairness* criteria) that ensures traffic equality among all flows. The contention window (CW) of IEEE 802.11 EDCA has been tuned to prioritize or to deprive the channel access of individual routers. However, the load estimation strategy proposed earlier is based on the traffic demand of individual clients that varies with time according to application usage, and thus difficult to compute, account and manage at router level. Further the CW tuning mechanism considers only short-term effect that may result in sudden performance degradation when new flows join in the network, or existing flows terminate.

The objective of this paper is two-fold. The first objective is to study the unfair behavior of end-users in a mesh network even with the support of an end-to-end flow-fairness control protocol, such as fair queuing, and second the second objective is to provide an optimized implementation of the previously proposed protocol [8] with an improved efficiency. A practical testbed of mesh network has been used for this purpose. The major contributions of this paper are summarized as follows.

- The results obtained from a practical testbed are used to study the problem of fairness degradation in a mesh network even with the support of end-to-end flow fairness at transport layer. The study reveals that clients associated with the routers near the gateway reserve the full capacity of the network, as a consequence of which, the flows with large number of hops get starved.
- An improved protocol is proposed over [8] to support channel access based on the traffic load at individual routers. The load estimation strategy only relies on the router level information, such as the size of the interface queue, and therefore free from the time varying information, that may introduce stale results. Further, the CW tuning mechanism is optimized by considering long-term

effects.

- The earlier protocol proposed in [8] was evaluated using simulation results only. This paper extensively studies the performance of the proposed protocol using two different testbed setups. The performance of the proposed protocol is compared to the performance of EDCA MAC along with the transport layer fair queuing support.

II. Analysis of Unfairness in Mesh Network

This section analyzes the fundamental reasons of unfairness among end-users in a wireless mesh network, through the results obtained from experiments conducted using an 802.11b testbed in a multi-storied building.

A. Testbed Setup

An 8 node testbed, as shown in Fig. 1, is used where one node is selected for the gateway, and rest other nodes act as mesh routers. It can be noted that the terms AP and routers are used interchangeably, as mesh routers also act as an AP for clients. Each node is a Skiva Easyconnect RT001 N300 WiFi router with RaLink RT-3352 chipset [9]. The Ralink RT-3352 router on chip combines 802.11n draft compliant 2T2R MAC/BBP/PA/RF, a high performance 400MHz MIPS24KEc CPU core, a Gigabit Ethernet MAC, 5-ports integrated 10/100 Ethernet Swtich/PHY, 64MB of SDRAM and 32MB of Flash. The nodes of the testbed are distributed over the corridor of the hostel Brahmaputra at Indian Institute of Technology Guwahati campus. The nodes are located roughly 15-20 meters apart from each other. The dotted lines in Fig. 1 show the approximate connectivity among these mesh routers. The forwarding path is determined based on AODV routing protocol with *expected transmission count* (ETX) as the routing metric [10], so that routing paths are evenly distributed, and do to effect the MAC layer access protocol.

The MAC layer uses IEEE 802.11 EDCA with the support of the transport layer end-to-end flow fairness control protocol as proposed in [11]. The protocol proposed in [11] uses per-flow queuing to maintain and end-to-end bandwidth requirement, and controls the transport layer data rate so that fairness is assured. Though per-flow queuing is not scalable, as well as requires large amount of memory to implement, and several other protocols have been proposed in literature to overcome the shortcoming of per-flow queuing, it is known to perform better than other protocols if queue maintenance is possible [12]. Therefore, it is used for comparison purpose.

During the experiments, on an average 5 clients are associated with every router. The data communications are between clients and the outside network through the mesh gateway. Three batches of experiments are conducted. First, The clients have uploaded a large file of size 1 GB to a server which is connected to the outside network through the mesh gateway. To upload the file, Trivial File Transfer Protocol (TFTP) is used that uses UDP. Next, clients have uploaded the same file using File Transfer Protocol (FTP) that uses TCP. Finally, three different applications are randomly distributed among clients - website browsing including media streaming, TFTP and FTP. For all the experiments, the physical data rate of mesh routers is kept fixed at $6Mbps$. The MAC implementation is capable of sending and receiving raw 802.11 frames using the wireless network interface in monitor mode. The Ralink AP SDK 3.3.0.0 [9] has been used for the development purpose.

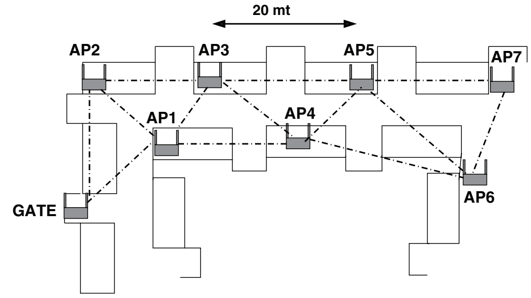

Fig. 1. Location of nodes in the 8-node testbed

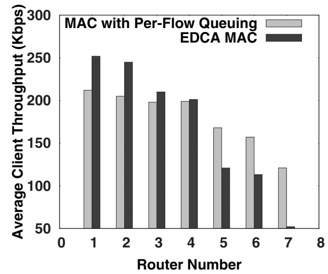

Fig. 2. Clients' avg UDP throughput per router

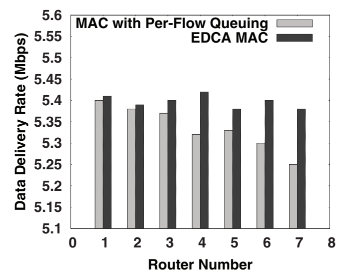

Fig. 3. Per router packet delivery rate

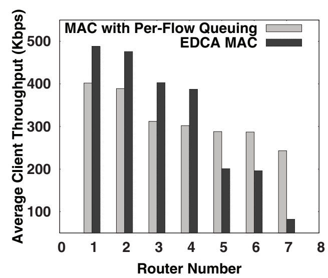

Fig. 4. Clients' avg TCP throughput per router

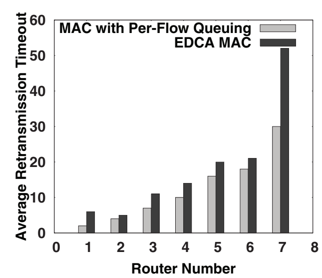

Fig. 5. TCP unfairness analysis

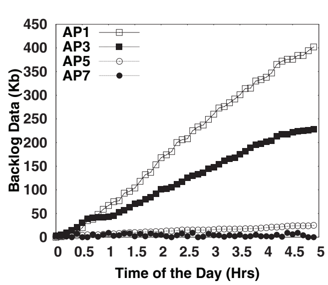

Fig. 6. Router backlog data

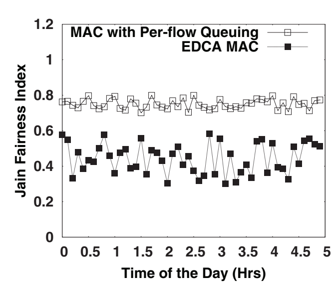

Fig. 7. Jain fairness index

B. Experimental Results and Analysis

Fig. 2 shows the average client throughput for every router in the testbed. The average throughput for clients under mesh routers near the gateway is maximum, and throughput degrades as the number of hops increases. The degradation in UDP throughput is much higher for the standard EDCA MAC compared to the fair-queuing approach. However even in fair queuing, the average UDP throughput for clients under AP7 is almost 50% of the average UDP throughput for clients under AP1. This indicate that unfairness still exist among clients in different hop-distances, and the unfairness becomes more prominent as number of hops increases. Fig. 3 shows the packet delivery rate of individual routers, which indicates that all mesh routers remain in saturation state. Though fair-queuing approach controls the rate of incoming traffic from upper layers, it is independent of the MAC layer traffic forwarding. As an example, clients under AP5 and AP6 are unaware of the forwarding load from AP7. Once AP5 and AP6 get saturated, clients under AP7 starts suffering. As a result, though the data delivery rate for AP7 is very high for EDCA MAC, the average client throughput is very low. Most of the packets transmitted by AP7 are lost at next-hop APs (AP5 and AP7) due to the buffer overflow from the interface queues.

Fig. 4 shows the average client throughput for TCP traffic. TCP has in-built fairness assurance property through the window based flow-control mechanism, that keeps the average bandwidth usage of every TCP flow almost equal. The results obtained from our experiments using TCP traffic revealed that fairness is assured only among clients of the same router. There is severe unfairness among clients from different routers. Fig. 5 explains the reason by explaining TCP behavior using TCP retransmission timeout. TCP retransmission timeout occurs if the TCP client does not receive the acknowledgement packet within a timeout interval (generally kept slightly larger than the round trip time). If a retransmission timeout occurs, TCP decreases the window size to trigger flow control activities. From figure 5, it can be observed that the average retransmission timeout increases exponentially as the number of hops increases. This indicate that the TCP congestion detection and flow control actions are triggered more number of times, as the traffic has to traverse more number of hops. Fig. 6 shows the backlog data of four routers collected over a period of 5 hours. The backlog data at AP1 (which is more closer to the gate) increases rapidly compared to AP3, and the trend follows. A frame generated at the client of AP7 has to wait at the interface queues of AP5, AP3 and AP1, before it gets delivered to the gateway. The waiting time at the queues increases with the number of hops, and after few hops, the waiting time becomes sufficient to affect the retransmission timer.

The third experiment with mixed TCP and UDP applications has been conducted over a period of 5 hours to get an overview of the fairness statistics. Jain Fairness Index [13] is used as the quantitative measure of the fairness. The fairness index value 1 indicates perfect fairness. Fig. 7 plots the result with respect to the time. EDCA MAC performs very poorly while fair queuing improves fairness among the users. Instead the fairness index is never more than 0.8 even with fair-queuing. This indicates that at least 20% of clients suffer from unfairness in the whole network. Further, sometime the index value even drops near to 0.7. The analysis has confirmed that the index value drops significantly when the traffic load increases suddenly in the network (it has been observed that some file transfer activities have been initiated at that time).

The experiments show that the MAC layer coordination is necessary to ensure fairness in a mesh network, such that the backlog data at mesh routers can be minimized for the perfect operation of the transport layer fairness control. The results reveal that the end-to-end flow control mechanism can not perform well because of the excessive packet losses due to the overflow from the MAC layer interface queue. Therefore, a coordination is required among the MAC layer and the transport layer flow control mechanisms. Though TCP handles buffer overflow by reducing the window size, it helps to control congestion, and to maintain fairness among clients under the same router. However, severe unfairness still exist among clients under different routers at different hop distance away. The unfairness becomes worse with high traffic load, due to the increasing contention among mesh routers, as well as packets overflows from router buffers.

III. MAC Layer Proportional Fairness

The previous protocol proposed in [8] ensures the MAC layer proportional fairness (channel share is proportional to the traffic demand) to provide equal bandwidth share among every client, in spite of their hop-distance from the gateway. This section provides improvements and optimization over the proportional fairness protocol to support it in real testbed.

A. Background of the Fairness Protocol

The proportional fairness protocol proposed in [8] works as follows,

(i) Every mesh router estimates the total traffic load using the traffic demand for the up-link and the down-link clients. The total load of a router is termed as the *'Activity Factor'* (AF).

(ii) Every router estimates the required channel share as the ratio of its own AF value to the summation of AF values of all its neighbors (more specifically, two hop neighborhood that can contend for channel access).

(iii) The routers further estimate the *actual channel share* from the previous history. This is calculated as the ratio of number of packets transmitted by this routers to the number of overheard packets (packets from neighbors).

(iv) By comparing the required channel share with the actual channel share, every router enters one of the states - *restrictive* (actual channel share is more), *aggressive* (actual channel share is less) and *normal*.

(v) Based on the current state, mesh routers tune their CW values to prioritize or to deprive their channel share. In aggressive mode, CW value is decreased to prioritize channel share, and in restrictive mode, CW is increased to deprive channel share.

The protocol has two fundamental shortcomings. First, the total load is estimated using traffic demand of individual clients, that is a time varying metric, and second, the CW

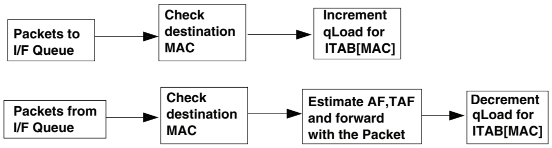

Fig. 8. Estimation of AF value

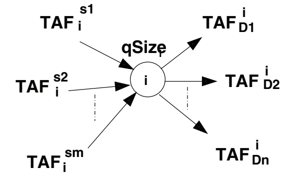

Fig. 9. Load Propagation

tuning mechanism may result in instability when new flows join, and existing flows are terminated. To assure equity among the end users by providing proportional fairness at the MAC layer, following two conditions must be satisfied,

C.1. The backlog data at the interface queue of all mesh routers should be independent of hop-distance from the gateway. Ideally, the backlog data should be zero at all mesh routers to assure equal waiting time for all flows. This assures that the transport layer flow control mechanism would be able to deliver data based on the end-to-end path statistics, and all the flows would be treated in the similar way, in spite of their hop distance from the gateway. Reducing the backlog data at the interface queue assures that the local flows (flows originated from clients under a router) do not reserve the full capacity of the router.

C.2. The transport layer flow control protocol should consider the effective delivery rate of the router for the flow assignment such that the backlog data at the interface queue is minimized.

If the above two conditions are satisfied, the waiting times of the packets for every flow at the interface queue become negligible, and the transport layer flow control protocol works perfectly. To assure condition C.1, estimation of AF value at every mesh router should consider the backlog data at the interface queue, rather than the traffic demand of individual clients. This way AF value can be computed locally at every router without the possibility of the stale information.

B. Estimation of AF Value

The AF estimation procedure is shown in Fig. 8. Every router stores a table at MAC layer, termed as $ITAB$ that contains the MAC addresses of all its one-hop neighbors and a corresponding entry, called $qLoad$. Whenever a packet is enqueued to the interface queue, the $qLoad$ entry in the $ITAB$ for corresponding destination MAC is incremented by one. Similarly, whenever a packet is dequeued from the interface queue, the corresponding $qLoad$ entry in the $ITAB$ for destination MAC is decremented. Before forwarding the packet, every router estimates the AF value and a portion of the AF value, called the *transferred AF* (TAF), is piggybacked with the packet. The AF and TAF values are estimated as follows.

Let AF_i denotes the AF value for router i. AF_i is calculated as,

$$AF_i = \sum_{k \in \mathbb{N}_i} TAF_i^k + qSize_i \quad (1)$$

where TAF_i^k denotes TAF from router k to router i, $qSize_i$ is the size of the interface queue of router i and $\mathbb{N}_i$ is the set of one-hop neighbors. If a router $k \in \mathbb{N}_i$ does not transfer data to router i, then $TAF_i^k = 0$. Let $qLoad_k$ denotes the entry in $ITAB$ for the MAC address of the destination router k. Then TAF_i^k can be represented as,

$$TAF_i^k = AF_k \times \frac{qLoad_i}{qSize_k} \quad (2)$$

Let us consider Fig. 9. TAF represents the amount of traffic to be relayed from the neighbors and $qSize_i$ represents amount of backlog traffic (both the relayed and from the client). Therefore, router i should get sufficient channel access to forward the complete traffic to clear its interface queue. Further, the status of the interface queue gives an estimation of the percentage of data to be forwarded to a specific neighbor for multiple forwarders. It can be noted that when the backlog data is very small, the system is already in fair state. The problem occurs when the traffic load is high, resulting in large amount of backlog data at the interface queues. It can be shown theoretically through queuing analysis that equation (1) and equation (2) provide a good estimation when traffic load is high. However, the analysis is not given here due to space constraint. Based on the estimation of AF value, the *required channel share* of every router can be calculated using the similar procedure proposed in [8].

C. Cross Layer Interaction

As discussed earlier, condition C.2 is required to control the incoming traffic from the transport layer using efficient flow control mechanism. It has been observed that almost all the existing flow control algorithms consider the actual data rate of a mesh router for the flow assignment. There exist very few approaches, such as back-pressure routing [14] and its variants, where mesh routers near the gateway falsely create a congestion effect to reduce the data rates for the flows originated from away routers. However, back-pressure effect introduces extra delay in the network [15]. In the current approach, a cross layer interaction mechanism is used. Let *required channel share* and actual physical data rate for router i be RS_i and λ. Then the effective delivery rate for router i, denoted as Z_i, can be expressed as,

$$Z_i = RS_i \times \lambda \quad (3)$$

This information is periodically forwarded to the transport layer flow control protocol. The flow control mechanism assigns flows based on the effective delivery rate, and condition C.2 can be assured.

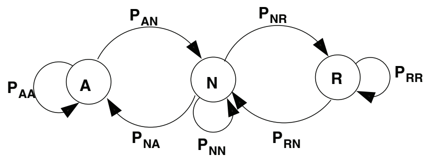

Fig. 10. Three state Markov model depicting state transition

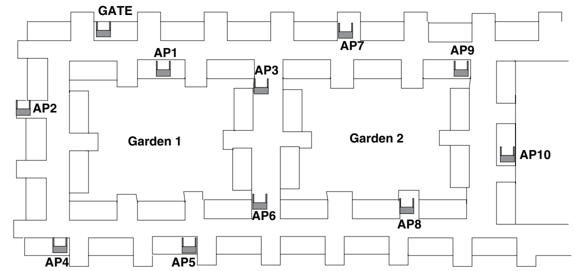

Fig. 11. Location of nodes in the 11 node testbed

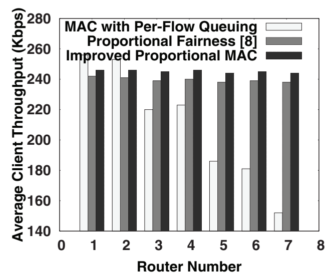

Fig. 12. Throughput/Client (N8)

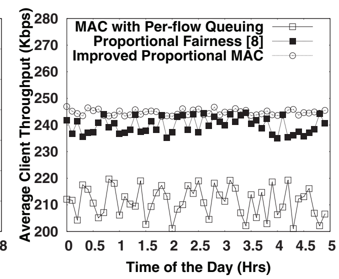

Fig. 13. Average Throughput (N8)

D. CW Tuning based on Statistical Analysis

The CW tuning mechanism proposed in [8] considers only the short term effect, and thus may trap into local performance degradation, when new flows are introduced or existing flows terminate. This is because, sudden changes in the traffic load are not considered in the CW tuning mechanism. For example, let a new file transfer application be introduced in router i. Then the traffic for router i increases suddenly. However, the overall condition of the network cannot be stimulated until the new flow is completely distributed in the network, and the network becomes steady. Therefore, without predicting the future network stability condition, router i may suddenly increase its channel demand, that may affect its neighbors.

As discussed earlier, every router maintains three states - *aggressive*, *normal* and *restrictive*. Based on the current state, mesh routers either decrease or increase their CW values to either prioritize or to deprive channel access. In the proposed protocol, mesh routers do not change the state immediately, if they find differences in the required channel share and the actual channel share. Rather, they do a statistical analysis based on a three-state discrete time Markov model to check whether state change is required or not. Fig. 10 shows the three state Markov model for the state transition, where state 'A' represents the *aggressive* mode, state 'N' represents the *normal* mode and state 'R' represents the *restrictive* mode. The transition probabilities P_{uv} depicts the probability of transition from state u to state v, where $u, v \in \{A, N, R\}$. Every router maintains the time duration it is in the current state, and it was in the immediate past state. Let t_A, t_N and t_R denotes the time duration the router is in state 'A', state 'N' and state 'R'. Based on the completeness of Markovian process, the transition probabilities are represented as follows;

$$P_{AN} = \frac{t_A}{t_A + t_N}; \qquad P_{AA} = 1 - P_{AN}; \quad (4)$$

$$P_{RN} = \frac{t_R}{t_N + t_R}; \qquad P_{RR} = 1 - P_{RN}; \quad (5)$$

$$P_{NA} = \frac{t_N}{t_A + t_N + t_R}; \quad (6)$$

$$P_{NR} = \frac{t_N}{t_A + t_N + t_R}; \qquad P_{NN} = 1 - P_{NA} - P_{NR}; \quad (7)$$

Assume router i wants to transit from state u to state v. Let AF_{iu} denote the average AF value till now, when the router is in state u, and AF_{ic} is the current AF value for which the router wants to change its state based on the comparison between the actual channel share and the required channel share. The transition decision is respected if and only if $P_{uv} \times AF_{ic} > P_{uu} \times AF_{iu}$, otherwise the router does not changes its state.

In the proposed protocol, the decision of changing state is based on the statistics of AF values and the corresponding state transition probability. It depicts whether the changes in the AF values are sufficient enough to change the current state. Thus small changes in the AF values do not trigger state changes, if the current state is stable enough. This statistical decision reduces unnecessary state transitions, and avoids trapping in the local performance degradation.

IV. Experimental Results

The proposed protocol has been implemented using Ralink SDK as an extension to the existing 802.11 EDCA MAC. Two different topologies have been used for the experiments. The first topology is the earlier one, as shown in Fig. 1. Another sparse topology has been used, with 11 APs, as shown in Fig. 11. Though the second topology can sustain only at $2Mbps$ data rate using IEEE 802.11b, the worse case analysis is possible with maximum network load with different types of application traffic. All the three batches of experiments, as stated in Section 2, have been conducted. However, the results for only the third experiment (with simultaneous different types of application) have been reported and analyzed here for space constraints. In the figures, 'N8' denotes the 8 node testbed, and 'N11' denotes the 11 node testbed.

Fig. 12 shows the average clients' throughput per router from the 8 node testbed. It can be noted that every router operates at $6Mbps$. The proportional fairness protocol proposed in [8] improves fairness among clients by distributing the channel bandwidth proportionally among mesh routers, and evenly among clients. The improved load estimation mechanism proposed in this paper (mentioned as the 'improved proportional MAC' in the graphs) further improves the average

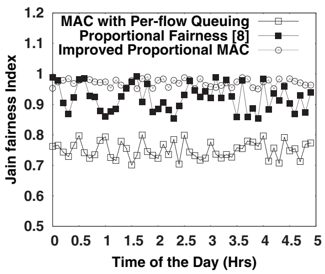

Fig. 14. Jain Fairness Index (N8)

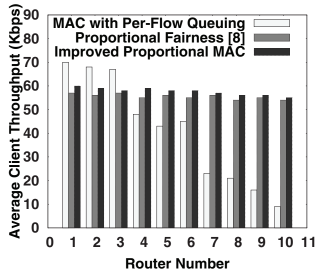

Fig. 15. Throughput/Client (N11)

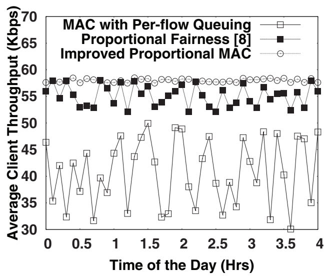

Fig. 16. Average Throughput (N11)

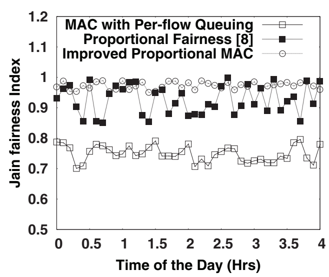

Fig. 17. Jain Fairness Index (N11)

throughput, as well as the fairness, by avoiding the local traps during the state change of a mesh router. This is visible clearly from Fig. 13 that shows the average throughput of all clients with respect to the time. Though the average clients' throughput for the protocol proposed in [8] is more than the EDCA MAC with fair-queuing, the throughput value drops several times due to the local trapping as discussed earlier. The proposed protocol in this paper maintains constant throughput with respect to the time. The average throughput is improved around 14% for the protocol proposed in [8], and around 16.7% for the proposed protocol in this paper, compared to the EDCA with fair-queuing. The comparison in Jain fairness index is shown in Fig. 14. For the proposed protocol, a high value of the fairness index is maintained constantly with respect to the time.

Similar trend is followed for the 11 node testbed, as shown in Fig. 15 to Fig. 17. However, average throughput is less compared to the 8 node testbed, as mesh routers can sustain maximum at $2Mbps$ rate compared to $6Mbps$ in the 8 node testbed. For such an overloaded network, the percentage improvement in average throughput is considerably high, as shown in Fig. 16. In the 11 node testbed, the average throughput is improved around 35.37% for the protocol proposed in [8], and around 40.49% for the proposed protocol in this paper, compared to the EDCA with fair-queuing. Fig. 17 shows the fairness index with respect to the time. The index value drops several times in case of the earlier protocol [8], because of the false CW tuning as a result of the stale information from clients. In the protocol presented in this paper, the average fairness index maintains a steady value at 0.95 in average. This shows that even for a network with heavy traffic load, the proposed protocol is efficient to provide equity among end-users, and improves average network throughput considerably.

V. Conclusion

This paper studies the fundamental reason of unfairness in IEEE 802.11 wireless mesh networks using results obtained from a practical testbed. Clients associated with the routers near the gateway reserve the full capacity, as a consequence of which, the flows with large number of hops get starved. The analysis shows that MAC layer proportional fairness is required for correct performance of transport layer end-to-end fair scheduling algorithms. This paper proposes an improved load estimation and CW tuning strategy over the previously proposed proportional fairness protocol. The effectiveness of the proposed protocol is justified through experimental results obtained from two different testbed setups.

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