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Proportional fairness in MAC layer channel access of IEEE 802.11s EDCA based wireless mesh networks

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ABSTRACT

Fairness provisioning in IEEE 802.11s EDCA based Wireless Mesh Networks (WMNs) is a very challenging task due to relayed traffic and traffic load variation among mesh routers. Because of bursty traffic in general purpose community wireless mesh networks, proportional fairness is more suited than max–min fairness, where mesh routers and clients should get channel access proportional to their traffic load. However, proportional fairness is hard to achieve by solving optimization function because of non-linearity and non-concave property of the objective function. In this paper, a probabilistic approach is proposed to provide proportional fairness without solving global non-linear and non-concave optimization. Every mesh node use a load estimation strategy to estimate total traffic load that it needs to forward. The required channel share of a mesh node should be proportional to its traffic load, whereas, the total normalized channel share for all the contending mesh nodes should be kept less than unity to satisfy the clique constraint. The network architecture and contention property in WMN are explored to deduce the required channel share of mesh nodes. A probabilistic approach is used to tune the contention window based on the difference between actual channel share and required channel share, so that the node with more traffic load gets more channel share. A discrete time Markov Chain based modeling is used to deduce the overall network throughput for the proposed scheme. Simulation result shows that the proposed scheme works better than the standard IEEE 802.11s based EDCA MAC in terms of fairness and throughput.

1. Introduction

Wireless Mesh Networks (WMN) [1–3] are next generation wireless broadband networks that draw significant attention these days. This is dynamically self-organized and self-configured network, with the nodes of the network automatically establishing a multi-hop mesh network topology. WMNs are comprised of three types of nodes: mesh routers, mesh gateways and mesh clients. Other than the routing capability for gateway/bridge functions as in a conventional wireless router, a mesh router contains additional routing functions to support mesh networking. In WMN, same coverage can be achieved by a mesh router with much lower transmission power by multi-hop communication. The nodes in a WMN are heterogeneous in nature, with varying data rate in mesh routers and mesh clients. Mesh routers in a WMN can operate with multiple network interfaces and can support multiple channels. However, in this paper a single channel single radio WMN is considered.

There are several candidate network technologies to implement a WMN such as IEEE 802.11 and IEEE 802.16. Among them, IEEE 802.11 is a promising candidate due to its low deployment and communication costs. IEEE 802.11s is an amendment of IEEE 802.11 standard to support multi-hop mesh functionality in IEEE 802.11 Distributed Coordination Function (DCF) based wireless commodity networks. IEEE 802.11s uses an improved

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DCF based channel access mechanism, Enhanced Distributed Channel Access (EDCA), to support QoS based service differentiation in wireless commodity network. The channel access mechanism for EDCA uses contention window (CW) based binary exponential backoff algorithm, similar to DCF channel access, with addition of service differentiation using Arbitrated Inter-frame Space Number (AIFSN). Due to popularity of IEEE 802.11 based commodity wireless standard, IEEE 802.11s is one of the most promising technologies for commodity mesh networking.

This paper reports a fundamental problem in IEEE 802.11s EDCA based multihop networks – fairness problem at MAC layer channel access protocol. Contention Window based channel access with Binary Exponential Backoff in IEEE 802.11 MAC has been used as the defacto for wireless channel access, although it has been initially designed to operate in wireless local area networks. It is known to be unfair in multihop networks [4]. This unfairness is quite evident in busty conditions and cannot be totally resolved even by using multiple radios tuned on multiple channels. IEEE 802.11 provides equal long term transmission opportunities to every contending nodes in the network, and thus it provides channel share proportional to the data rate. WMN is a multi-rate wireless LANs, where mesh routers and mesh clients are with varying data rates. IEEE 802.11 channel access performs poorly in multi-rate network and overall network throughput degrades considerably [5]. The unfairness problem is more trivial in case of IEEE 802.11s EDCA because of high variation in traffic load among mesh clients and mesh routers. The mesh routers have to forward relayed traffic beside the traffic for self-clients (the clients which are directly associated with it). So there is an inevitable contention between the forwarded traffic and traffics from self-clients. The situation becomes worse in high load condition because of huge traffic load variation among different mesh routers. To solve this problem the mesh routers and mesh clients should get channel share proportional to their traffic load. However, binary exponential backoff algorithm of IEEE 802.11s EDCA provides equal air-time channel share to all the contending nodes involved in communication. This provides proportional bandwidth share to all the nodes, where the bandwidth share is proportional to the data rate. As discussed earlier, multi-hop WMN requires bandwidth share proportional to the traffic load, not the data rate. This can be illustrated using an example as follows.

A simple network is shown in Fig. 1. Assuming that flow fairness is implemented at the network with all flows of equal priority, there are $f1$ number of flows originated from (or destined to) the clients of node 1 and $f2$ number of flows originated from (or destined to) the clients of node 2. Node 1 and node 2 receive traffic load from their own clients as $f1 \times c$ and $f2 \times c$ respectively, where c is the maximal bandwidth share that can be allocated to each flow. So node 1 has to forward $f1 \times c$ amount of traffic, whereas node 2 has to forward $(f1 + f2) \times c$ amount of traffic. The gateway has to forward $(f1 + f2) \times c$ amount of traffic. As all the three nodes are in the interference range of each other, if the total available bandwidth is B, node 1, node 2 and GW node should get $\frac{f1}{3\times f1+2\times f2} \times B$, $\frac{f1+f2}{3\times f1+2\times f2} \times B$ and $\frac{f1+f2}{3\times f1+2\times f2} \times B$ amount of bandwidth share respectively. However, IEEE 802.11s EDCA implicitly provides equal access probability for all nodes. Thus when the load between two contending nodes varies significantly, total network throughput can degrade. This problem can be solved if every node can get channel share proportional to their traffic load. Hence per node proportional fairness can be best suited for WMN.

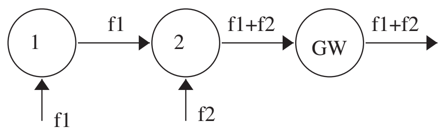


Fig. 1. Multihop network with different traffic load.

Two fairness definitions are widely used in network resource allocation problems – max–min fairness and proportional fairness. Max–min fairness tries to allocate bandwidth equally among users such that the allocated bandwidth of one user cannot be increased without decreasing the allocated bandwidth from another user. On the other hand proportional fairness allocates bandwidth to users in proportion to some specific network parameter, such as traffic load or data rate. It maximizes the sum of logarithms of the allocated bandwidth of each contending users. Consider two wireless mesh routers A and B of same data rate, with average traffic load as six per unit time and 48 per unit time respectively. Router A and router B are in the range of each other. The behavior of standard IEEE 802.11s MAC, Max–min Fair MAC, and Proportional Fair MAC can be illustrated as follows,

- IEEE 802.11s EDCA provides equal time share to both the routers. So channel share is proportional to data rate. However, the data rate of both the routers is equal. Router A achieves equal channel share to router B, which obviously affects fairness because router B has more data to transmit. So network throughput as well as end-to-end throughput are severely affected.
- Max–min fairness binds the traffic demand for router A and router B in a threshold based on their traffic load. The threshold is determined based on the network policy and traffic load. In most of the previous works that provide max–min fairness, this threshold is bounded by the maximal achievable rate of the flows passing through the router, without considering MAC layer traffic demand. In bursty condition, this threshold may degrade the capacity of the network, as max–min fairness creates traffic bottleneck at the collision domains [6]. So overall network throughput degrades at bursty traffic conditions, as it creates a trade-off between capacity and fairness. This makes max–min fairness inefficient in case of WMN.
- Proportional fairness provides eight times more bandwidth to router B. Router A gets bandwidth share of $\frac{6}{6+48} = \frac{1}{9}$ of total bandwidth, whereas router B gets $\frac{48}{6+48} = \frac{8}{9}$ of total bandwidth. Thus all flows passing through these routers get almost equal channel share. This improves network throughput significantly, and also improves end-to-end throughput in a considerable amount.

From the above discussion, it can be concluded, that proportional fairness with respect to traffic load is more suited for heterogeneous wireless mesh networks. However, the objective function of proportional fairness is non-linear and non-concave. Implementing proportional fairness is much more challenging than the max–min fairness [7]. This paper provides a probabilistic approach to provide proportional fairness in IEEE 802.11s EDCA based WMNs.

A preliminary version of this paper has been presented in [8]. This paper extends previous version of the paper in following aspects:

1. In [8], the scheme deals only with IEEE 802.11 DCF based framework. This paper extends the scheme for IEEE 802.11s EDCA, which is the current standard for WMNs.
2. In the previous version of the paper, traffics are assumed to be from mesh clients to mesh gateway (and vice versa) following a tree structure. This paper generalizes the topology for directed acyclic graph (DAG) based forwarding. The standard routing protocols for WMN follows a loop free strategy which essentially follows a DAG for packet forwarding.
3. A theoretical analysis of the proposed scheme has been provided to show the effect of dynamic CW tuning over network throughput.
4. Extensive simulation results have been provided with larger set of scenarios to justify the effectiveness of proposed scheme.

The proposed scheme uses a dynamic CW tuning based strategy to provide proportional fairness at mesh routers and clients. A load estimation strategy is proposed for MAC layer scheduling. Based on the traffic load, every node tune its CW dynamically to access the channel. The paper provides a theoretical analysis based on Markov-chain model to show the effect of proposed probabilistic approach on overall network throughput. The proposed probabilistic MAC provides more fairness without affecting overall network throughput. This is justified by both theoretical analysis and simulation results.

The rest of the paper is organized as follows: Section 2 describes the works closely related to this paper. In Section 3, the proposed probabilistic MAC is described. A discrete time Markov Chain Model based analysis is reported in Section 4. The simulation results are presented in Section 5. Finally Section 6 concludes the paper.

2. Related works

In Wireless Multi-Hop Network, Bharghavan et al. addressed fairness problem in [9]. In that paper, they showed limitation of Binary Exponential Back-off (BEB) and suggested a different back-off algorithm called Multiplicative Increase and Linear Decrease (MILD). In [10], Nandagopal et al. propose a general analytic framework that comprises of generating flow-contention graph of the network. From this graph a resource constraint graph is extracted. It was shown that achieving fairness in the system is equivalent to solving a utility maximization function, subject to transmission constraints in resource constraint graph.

In [11], the authors proposed a graph theory based algorithm to provide max–min fairness in wireless ad-hoc networks. They proposed a scheme, where interference graph is extracted from network graph and communication graph, and then they propose a max–min optimization on interference graph to schedule nodes. Basically finding maximal cliques in the interference graph is equivalent to finding set of nodes which cannot transmit or receive data simultaneously. They propose a distributed optimization technique to schedule nodes based on maximal clique constraints.

Kanodia et al. proposed a distributed scheduling algorithm, called DWOP [12], targeted to ensure packets accessing the medium in an order defined by an ideal reference scheduler such as FIFO. Zhefei's report [13] analyzes the unfairness of IEEE 802.11 in a systematic way. In his solution for a fair MAC in multi-hop environments, each node collects some contention information and accordingly decides its mode of contention: *aggressive*, *normal* or *restrictive*. In [14], the authors proposed a mechanism to tune congestion window based on the contention mode of the node. In the proposed Adaptive Transmission Control algorithm, each node estimates number of active nodes within contention range in a distributed manner. Based on estimation algorithm, a node tune its CW.

All the above works are based on IEEE 802.11 DCF based wireless multi-hop ad-hoc networks. However wireless mesh networks are inherently different from wireless multi-hop and ad-hoc networks. In [15], the authors shown the capacity of wireless mesh networks. They have discussed impact of relayed traffic on fairness, and finally shown that for WMNs, throughput of each node decreases as $O(1/n)$, where n is the total number of nodes in the network. In another work [16], they introduced a per-flow reservation based mechanism to support fairness in WMN. However per-flow queuing requires high implementation cost, and also may induce the scalability problem in large scale WMN. Besides, per-flow queuing cannot resolve MAC layer contention, and so without a MAC layer support it may waste bandwidth when there are over-injected packets. In [17], the authors describe a distributed min–max fairness among the nodes based on weight estimation of each node in a multi-radio multi channel environment. Their estimation is based on the sending rates of child nodes, which may be highly dynamic in a real environment. Again, they have only considered bandwidth allocation among stationary mesh nodes, and so they have used min–max fairness.

In [18,19], the authors addressed the problems of using IEEE 802.11 DCF in the context of wireless mesh networks and proposed a weighted contention graph based approach to provide end to end flow fairness in wireless mesh networks. They have calculated maximal capacity for each flow and used that capacity to maintain fairness among the flows. In [20], the author proposed a cross layer approach to providing fairness in wireless mesh networks. In his thesis, he proposed implicit ACK based Bidirectional DCF to solve unfairness in single hop networks and then designed two buffer management algorithms which effectively maintain fairness in a multihop WMN.

Yoo and Kim [21] proposed a centralized flow coordination based approach to provide proportional fairness in enterprise wireless mesh networks. In [22], the authors proposed a fair scheduling approach in multiple gateway based wireless mesh networks. The proposed scheduling approach consists of four important steps, namely, requirement tables, requirement propagation, clique generation and schedule generation. The gateways use clique generation technique from contention graph to generate flow schedules. Alicherry et al. [23] provides a joint channel assignment and routing mechanism to optimize throughput in multi-radio wireless mesh networks. They show that throughput optimization also provides fairness among different flows. In [24], the authors proposed a QoS based fair rate allocation mechanism that provides higher priority to real-time flows than elastic flows by reserving necessary bandwidth for the former and fairly allocating left-over bandwidth to the latter.

All the state-of-art works discussed so far related to fairness provisioning in multi-hop wireless networks and wireless mesh networks are of three kinds:

- To provide per-flow max–min fairness [17–20].
- To provide a centralized scheme to estimate node share and provide bandwidth share proportional to the channel share [21,22].
- To provide fairness in some specific network architecture [23,24].

However, per-flow fairness alone cannot solve the problem without MAC layer support in case of heterogeneous WMN, where proportional fairness is more suited than max–min fairness. The scheme proposed in this paper is different from the existing scheme as it deals with per-node proportional fairness.

3. Fairness provisioning in IEEE 802.11s EDCA MAC

A wireless mesh network can be represented as a connected graph $G(V,E)$, where V is the set of nodes, and E is the set of links between them. Here the term 'node' represents both mesh routers and mesh clients. As described earlier, each mesh gateway, mesh router, and mesh client should get channel share proportional to its load. Fig. 2 shows the proposed scheme using a flow diagram. The complete protocol works in five steps as follows:

- Every mesh router and mesh gateway estimates its total traffic load which comprises of traffics from two types of sub-flows – from self-clients, and from other routers as relayed traffic.
- Each node (mesh gateways, mesh routers and mesh clients) estimates its required channel share from its knowledge of contention domain. Every node can get this information by overhearing data and control frames.
- Each node calculates the actual channel share it received, by overhearing data and control frames.
- Based on this estimation, the nodes enter one of the three modes – *aggressive* (if estimated required channel share is more than actual channel share), *normal* (if estimated share equals actual share) or *restrictive* (if estimated required channel share is less than actual channel share).
- The nodes tune its CW, as suggested in [14], to balance the estimated required channel share and its actual channel share.

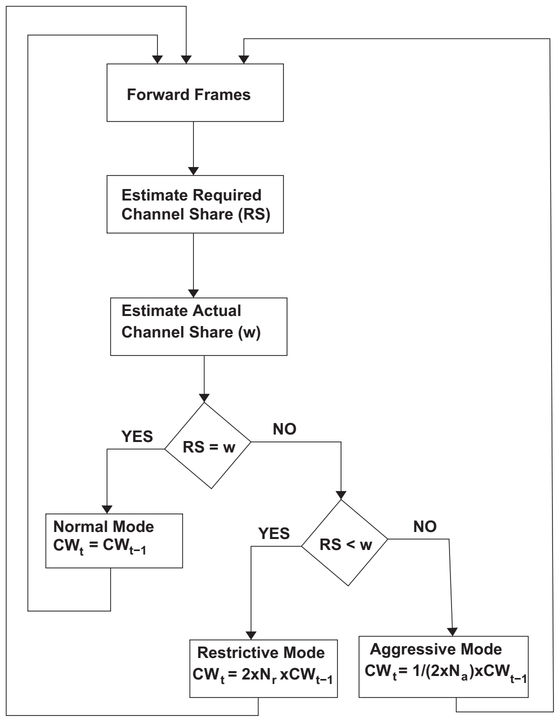


Fig. 2. Proposed probabilistic scheme for tuning CW.

As discussed, every node estimates required channel share from the knowledge of its contention domain. The following subsection defines the notion of contention domain formally. The detailed estimation procedure is discussed in following subsections. The symbols used to describe the proposed scheme have been summarized in Table 1.

3.1. Contention domain

The ***Collision Domain*** of ith link is the set of links formed by the ith link and all other links that have to be inactive for the ith link to have a successful transmission [16]. Similarly ***Contention Domain*** of node N, $CD_N = \{V_N, E_N\}$ is defined as the collision domain E_N associated with the links of node N and the set of corresponding nodes V_N sending data through those links.

Let $\mathbb{N}_i^2$ be the set of nodes in two-hop neighborhood, $\mathbb{N}_i^1$ be the set of nodes in one hop neighborhood; and V_i be the set of nodes in the current contention domain of node i. Then

1. If $k \in V_i$; then $k \in \mathbb{N}_i^2$.
2. If $k \in \mathbb{N}_i^1$; then node i can decide whether $k \in V_i$ by overhearing the RTS and DATA frames. The source address in RTS and DATA frames should be the address of k in this case.

Table 1
Symbols used for node i.

Symbol	Meaning
$\mathbb{N}_i^2$	Set of nodes in the two hop neighborhood
$\mathbb{N}_i^1$	Set of nodes in one hop neighborhood
C_i^u	Rate of uplink traffic
C_i^d	Rate of downlink traffic
uf_i^r	Fraction of uplink traffic forwarded to node r
df_i^r	Fraction of downlink traffic forwarded to node r
RS_i	Required channel share
SL_i	Total traffic load
UAF_i	Uplink activity factor
DAF_i	Downlink activity factor
AF_i	Activity factor
W_e	Timeout interval
n_e'	Previous estimate of number of active nodes
n_e	Current estimate of active number of nodes
S	Scaling factor for CW tuning
$N_{restrictive}$	Number of times the node is in restrictive mode
$N_{aggressive}$	Number of times the node is in aggressive mode
p	Channel access probability
CW	Contention window size
CS_R^i	Required channel share for a client
RS_R^i	Required channel share for a mesh router
w_i	Actual channel share

3. If $k \in \mathbb{N}_i^2$; then node i can decide whether $k \in V_i$ by overhearing the CTS and ACK frames. The destination address in CTS and ACK frames should be the address of k in this case.

The above three conditions are good enough to get information about the active nodes in a contention domain. The first condition says that contention is up to two hop, whereas the second and third conditions say that information about nodes in a contention domain can be populated by overhearing data and control frames. The channel share in a contention domain should satisfy following two constraints-

1. The total normalized channel shares in a contention domain should be less than or equals to unity.
2. Each node in a contention domain should get channel share proportional to their traffic load.

Based on above two constraints, required channel share for node $i(RS_i)$ is formulated as;

$$RS_i = \frac{SL_i}{\sum_{j \in CD_i} SL_j} \tag{1}$$

where SL_i is total traffic load for node i, and CD_i is the contention domain for node i

3.2. Estimation of required channel share

Every mesh nodes estimates its required channel share based on its traffic load and the traffic load of the nodes in its two hop neighborhood. It has been assumed that data is forwarded following a DAG structure, both in up-link and down-link direction, so that no loop is introduced in estimation procedure.

3.2.1. Load estimation at mesh routers

In WMN, there are mainly two types of traffic – uplink traffic and down-link traffic. Based on this, two terms are defined, *Uplink Activity Factor* (UAF) and *Downlink Activity Factor*(DAF). Let, uf_r^i denotes fractional amount of uplink traffic forwarded from router i to router r, and df_r^i denotes fractional amount of download traffic forwarded from router i to router r, as shown in Fig. 3. It can be noted that uf_r^i and df_r^i can be calculated independently at every router from previous traffic forwarding history.

- ***Uplink Activity Factor*** (**UAF**) for router r defined as;

$$UAF_r \leftarrow C_r^u + \sum_{i \in \mathbb{R}_r} UAF_i \times uf_r^i \tag{2}$$

where C_r^u is the rate of up-link traffic received from the clients of router r, and $\mathbb{R}_r$ is the set of mesh routers who have forwarded up-link data to router r in last time interval.

- ***Downlink Activity Factor*** (**DAF**) for router r defined as;

$$DAF_r \leftarrow C_r^d + \sum_{i \in \mathbb{C}_r} DAF_i \times df_r^i \tag{3}$$

where C_r^d is the rate of down-link traffic forwarded to the clients of router r and $\mathbb{C}_r$ is the set of mesh routers who have forwarded down-link data to router r in last time interval.

- ***Activity Factor*** (**AF**) for router r is defined as;

$$AF_r = UAF_r + DAF_r \tag{4}$$

As each individual router requires UAF and DAF values of routers who are currently forwarding relayed data, the value of these two parameters need to be propagated along the network. These values are piggybacked in the DATA and ACK frames. The piggybacked value can be a positive value or '-1'. If the piggybacked value is a positive value that it is valid UAF or DAF value. The next task is to differentiate between UAF and DAF values. Each router also maintains two lists L_{UAF} and L_{DAF} which store the UAF and DAF values of all its neighbors. The proposed distributed scheme using efficient piggybacking is shown in Fig. 4. In the figure, router r executes the procedure. Router i is the previous hop router and router j is the next hop router. p_i is the piggybacked value received with the packet from router i. The following distributed mechanism is used to calculate UAF and DAF values efficiently at every router.

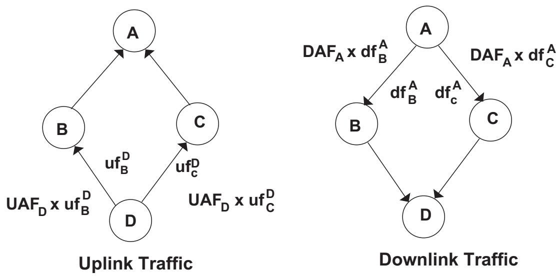


Fig. 3. Uplink and downlink traffic load analysis.

1. Each mesh router i initialize its UAF and DAF values as follows:

$$UAF_r \leftarrow C_r^u \text{ and;}$$
$$DAF_r \leftarrow C_r^d$$

2. The gateway always forwards DATA frame with piggybacked value '-1'.
3. When router r receives a DATA frame from router i, it does following:
   (a) If the piggybacked value is a positive value, then it is the UAF vale of router i, it updates L_{UAF} for router i. In this case, it executes following steps:
   i. Router r calculates its own UAF value using Eq. (2).
   ii. It forwards DATA frame using UAF_r as the piggybacked value to router j.
   iii. In response to that DATA frame, it sends ACK to router i with '-1' as the piggybacked value.

   (b) If the piggybacked value is '-1', then it executes following steps:
   i. It calculates its own DAF value using Eq. (3).
   ii. In response to the DATA frame from router i, it sends ACK frame to router i with DAF_r as the piggybacked value.
   iii. It forwards the DATA frame to the next hop router j with '-1' as the piggybacked value.

4. When router r receives ACK frame from router i it does following:
   (a) If the piggybacked value is a positive value, then it is the DAF value of router i. It updates its L_{DAF} for router i.

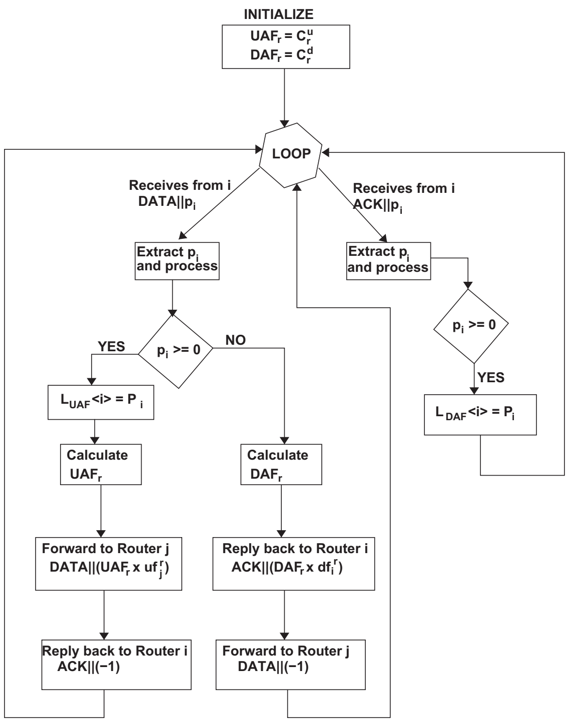


Fig. 4. Distributed algorithm to calculate UAF and DAF.

Clearly the UAF value propagates in $O(1)$ message passing, whereas the DAF value propagates in $O(h)$ message passing; where h is number of hops between mesh gateway and the mesh router for the intended mesh client. After finding out the traffic load of a router in terms of activity factor, the next task is to estimate the number of active mesh routers and mesh clients in a contention domain.

3.2.2. Active mesh nodes in a contention domain

To estimate the number of active routers within the contention range, every mesh router maintains a list. Whenever a mesh router overhears a MAC frame, it inserts the ID of the sender of the flow into the list if the ID does not exist. If the ID already exists, the router simply refreshes the time of the entry containing this ID. In order to prevent stale entries, an entry is deleted after a timeout interval, say W_e, which is set as follows;

$$W_e = \left(1 + \frac{n'_e}{n_e}\right) \times n'_e \tag{5}$$

where n'_e is the previous estimate of active number of nodes and n_e is the current estimate of active number of nodes.

Mesh routers can estimate up-link and down-link traffic rates for its clients by maintaining a history. Similarly, every mesh client also knows the AF value of its router by reading the piggybacked value in the MAC frames.

3.2.3. Estimation of required channel share from traffic load

The required channel share can be estimated for mesh routers and mesh clients using the estimation as described earlier and Eq. (1), as follows.

3.2.3.1. Estimation of required share by mesh clients. Let CS_R^i be the required share of client i and AF be the activity factor of the router working as the access point for the client i. Then;

$$CS_R^i = \frac{1}{AF} \tag{6}$$

3.2.3.2. Estimation of required share by mesh routers. Let, RS_R^i be the required share for router i, V_i is the contention domain, $\mathbb{R}_i$ is the set of active mesh routers in contention domain V_i and AF_i is the Activity Factor of router i. Then using Eq. (1);

$$RS_R^i = \frac{AF_i}{\sum_{k \in \mathbb{R}_i} AF_k} \tag{7}$$

3.3. Estimation of actual share by mesh routers and clients

The actual share estimation can be done by maintaining a communication history at each node. Whenever a node overhears a DATA or ACK frame transmitted over the medium, it appends sender ID of the frame into its history. If a node overhears both the DATA and ACK frames, belonging to same handshaking, it adds the ID only once. By maintaining such a history a node knows its actual share w_i, by checking how many times (say ϱ) its own ID appears in the latest window with n_w frames. Therefore,

$$w_i = \frac{\varrho}{n_w} \quad (8)$$

3.4. Tuning CW based on the estimation

Based on the estimation of actual share and required share, a node enters one of the three modes – aggressive, restrictive or normal to compensate for the over or under usage in the immediate past. A similar approach like [14] is used to tune the CW probabilistically. When a node generates the back-off timer, rather than using the CW directly, the node uses a scaled value $S \times CW$, where S is the scaling factor determined by the node's mode. A node also records number of times it has been in the aggressive or in the restrictive modes since the latest occurrence of the normal mode, which are represented by $N_{aggressive}$ and $N_{restrictive}$, respectively. Since a node cannot enter aggressive mode from the restrictive mode, and vice-versa, without passing through normal mode, $N_{aggressive}$ and $N_{restrictive}$ are reset to zero whenever the node's mode becomes normal. If a node is in the aggressive mode, the $N_{aggressive}$ is incremented by one when any other nodes transmit a packet. On the other hand, if a node is in the restrictive mode, $N_{restrictive}$ is incremented by one when the node itself transmits a packet. Therefore the scaling factor S should be like this,

$$S = \begin{cases} 1 & \text{normal mode} \\ 2 \times N_{restrictive} & \text{restrictive mode} \\ 1/(2 \times N_{aggressive}) & \text{aggressive mode} \end{cases} \quad (9)$$

To limit the scaling factor, whenever $N_{aggressive}$ or $N_{restrictive}$ reaches a maximum value, it is not allowed to increase any further.

3.5. Analysis of proportional fairness

In the proposed fairness protocol, the required channel share is calculated from Eq. (1). The required share is proportional to the traffic load of a mesh router, keeping the clique constraint for contending nodes to be satisfied. So the objective of every node is to achieve actual channel share equals to required channel share. Now from the Bianchi's Model [25] for saturation condition, let p be the channel access probability, and CW is the contention window size, then,

$$p = \frac{2}{CW - 1}$$

At saturation condition, the channel access probability is inversely proportional to the contention window size. There are several works exist in literature [26–32] that explore this fact in details, and propose some mechanism to find out the value of the contention window directly if the required channel access probability is known. However, the traffic load in a general community wireless mesh network is bursty in nature and the traffic load variation among neighboring routers is very high. So the required channel share fluctuates significantly often. To meet this requirement immediately, the contention window may also fluctuates abruptly. Because of this, the network may go to an unstable state, and the network throughput can degrade drastically. That is why a gradual increase or decrease in CW value is considered in the proposed framework.

The clique constraint for proportional fairness says that the total normalized channel share for all the nodes in a contention domain should be less than or equals to the channel capacity. The clique constraint is taken into consideration so that the proposed probabilistic scheme also behaves well under low load condition. Under low load condition, all the routers works in normal mode, and transmit data at maximal possible rate. In the next section, the effect the proposed probabilistic CW tuning on network throughput is analyzed using a discrete time Markov Chain Model.

4. Analytical model

The proposed probabilistic proportional fairness protocol is modeled using a discrete time Markov Chain. A single contention domain of a multi-hop mesh network is modeled, where all the mesh nodes (including clients, routers and gateways) contend with each other. The objective of this modeling is to show the effect of CW tuning on network throughput over a contention domain. The proposed model can be extended for multiple contention domains using the method mentioned in [33]. The following assumptions are used in the modeling and analysis. The contention domain contains n mesh nodes contending with each other. The maximum back-off stage is considered to be m with finite retry limit. The maximum contention window size is represented as CW_{max}, for simplicity it is taken as w. The time is considered as discrete time slots, where the CW tuning procedure at time t uses estimation up to time $t-1$. In the proposed model both non-saturated and saturated conditions of the network have been considered. The model extends the idea proposed in [34] for analyzing non-saturated throughput in IEEE 802.11s EDCA based channel access.

The complete procedure can be divided in two inter-related process as shown in Fig. 5 – one process to estimate required channel share from the history, and another process to tuning contention window (CW) based on the estimation. There are two inter-related processes with feedback mechanism in time. The input to the estimation process depends on the output of the CW tuning process, and the input to the CW tuning process depends on the output of the estimation process. So the stable state of this complete system can be found out by fixed point iteration on the time series analysis of the combined process.

4.1. Modeling the estimation procedure

In the proposed architecture, the estimation procedure at a node estimates actual channel share from the history of channel access at that node. The estimation procedure can be modeled as a *Poisson Binomial Distribution* with success probabilities $p_1, p_2, \ldots, p_n$; where p_i denotes the success probability at time instance i. Let K be the random variable denoting number of success that can be taken as

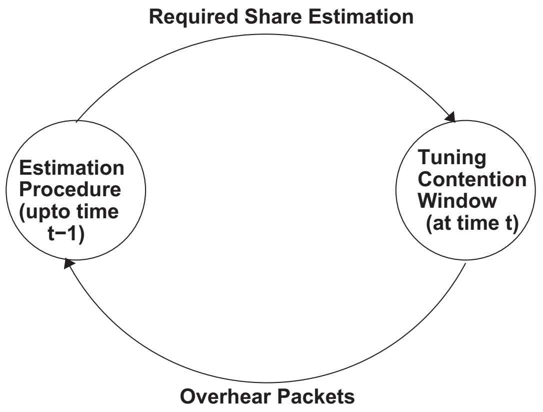


Fig. 5. Estimation and CW tuning.

actual channel share of that node. Then probability for δ successful trials in a series of total n_t trials, denoted as $Pr[K = \delta]$ can be calculated using [35], as follows;

$$Pr[K=\delta] = \begin{cases} \prod_{i=1}^{n_t}(1-p_i) & \delta = 0 \\ \frac{1}{\delta}\sum_{i=1}^{\delta}(-1)^{i-1}Pr[K=\delta-i]T(i) & \delta > 0 \end{cases} \tag{10}$$

where

$$T(i) = \sum_{j=1}^{n_t}\left(\frac{p_j}{1-p_j}\right)^i$$

Let v be the required channel share. So the following probabilities can be obtained.

- **Required channel share is less than the estimated channel share**:

$$Pr[v < K] = Pr[K > v] = \sum_{i=v+1}^{n_t} Pr[K = i] \tag{11}$$

- **Required channel share equals to the estimated channel share**:

$$Pr[v = K] = Pr[K = v] \tag{12}$$

- **Required channel share is greater than the estimated channel share**:

$$Pr[v > K] = Pr[K < v] = \sum_{i=0}^{v-1} Pr[K = i] \tag{13}$$

where

$$Pr[K > v] + Pr[K = v] + Pr[K < v] = 1 \tag{14}$$

Based on this estimation, the CW tuning mechanism can be modeled as a three dimensional Markov chain model as described in next subsection.

4.2. Modeling CW tuning process

Consider process $s(t)$ represents the back-off stage, $b(t)$ represents the back-off counter, and $c(t)$ represents one of the transmission modes – aggressive, normal or restrictive, at time t. A discrete time Markov model is presented in Fig. 6, where a state is represented as $\{(i,j,k)|i \in s(t), j \in b(t), k \in c(t)\}$. The three modes have been denoted by $c(t)$, where $c(t) = 0$ represents aggressive mode, $c(t) = 1$ represents normal mode and $c(t) = 2$ represents restrictive mode. Pr_k is the probability that the node is in mode k that can be calculated using the procedure discussed in previous subsection. *Idle* denotes the idle state of the network when a node is waiting for a incoming packet with probability $1 - q$, where q is the probability the node having a packet to transmit. The value of q can be calculated from data arrival rate using a similar procedure as discussed in [36]. It should be noted that the model represents saturation condition when $q = 1$. Here g is a hidden state and acts as the initial state for a new data packet. The hidden state basically denotes the estimation procedure. The maximum contention window size if $CW_{max} = 2^m W$, and $w_i = 2^i \cdot W$, where W is the minimum contention window. $w_{k,i}$ represents the backoff counter of the node in mode k with ith backoff stage, that is $w_{0,i} = \frac{1}{2}w_i - 1$, $w_{1,i} = w_i - 1$ and $w_{2,i} = 2 \cdot w_i - 1$. The only one-step non-null probabilities are given in Eq. (15). Here $P\{(i_1,j_1,k_1)|(i_2,j_2,k_2)\}$ denotes $P\{s(t) = i_1, b(t) = j_1, c(t) = k_1 | s(t-1) = i_2, b(t-1) = j_2, c(t-1) = k_2\}$.

1. The first equation denotes transition from the hidden state to any of the starting state.
2. The second equation denotes transition for decrements of the back-off counter. This probability is always one.
3. The third equation denotes transition from one back-off stage to the next, if there is a failure in the packet transmission. p Denotes the probability of single packet failure.

$$\begin{cases} (I) & P\{(0,0,k)|g\} = \frac{Pr_k.(q(1-p)+q))}{w_{k,0}} \text{ where } k \in [0,2] \\ (II) & P\{(i,j,k)|(i,j-1,k)\} = 1, \text{ where } i \in [0,m], j \in [0,w_{k,i}], k \in [0,2] \\ (III) & P\{(i,j,k)|(i-1,0,0)\} = \frac{p}{w_{k,i}}, \text{ where } i \in [0,m-1], j \in [0,w_{k,i}], k \in [0,2] \\ (IV) & P\{Idle|(i,0,k)\} = (1-q)(1-p), \text{ where } i \in [0,m-1], k \in [0,2] \\ (V) & P\{Idle|(m,0,k)\} = 1-q, \text{ where } k \in [0,2] \\ (VI) & P\{g|(i,0,k)\} = q(1-p) \text{ where } i \in [0,m-1], k \in [0,2] \\ (VI) & P\{g|(m,0,k)\} = q \text{ where } k \in [0,2] \\ (VII) & P\{g|Idle\} = q \end{cases} \tag{15}$$

4. The fourth and fifth equations denote if there is a successful packet transmission and there is no further packet to transmit. Then the process goes to idle state.
5. The sixth and seventh equations denote if there is a successful packet transmission and there is packets to transmit further. Then the process goes to the hidden state and the renewal process starts.
6. The last equation denotes that if there is a packet to transmit, then the process goes to the hidden state from the Idle state and executes the estimation procedure.

Let $b_{i,j,k}$ be the stationary distribution of the Markov chain presented in Fig. 6, i.e.

$$b_{i,j,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = j, c(t) = k\},$$
$$i \in [0,m], j \in [0, w_{k,i} - 1], k \in [0,2]$$

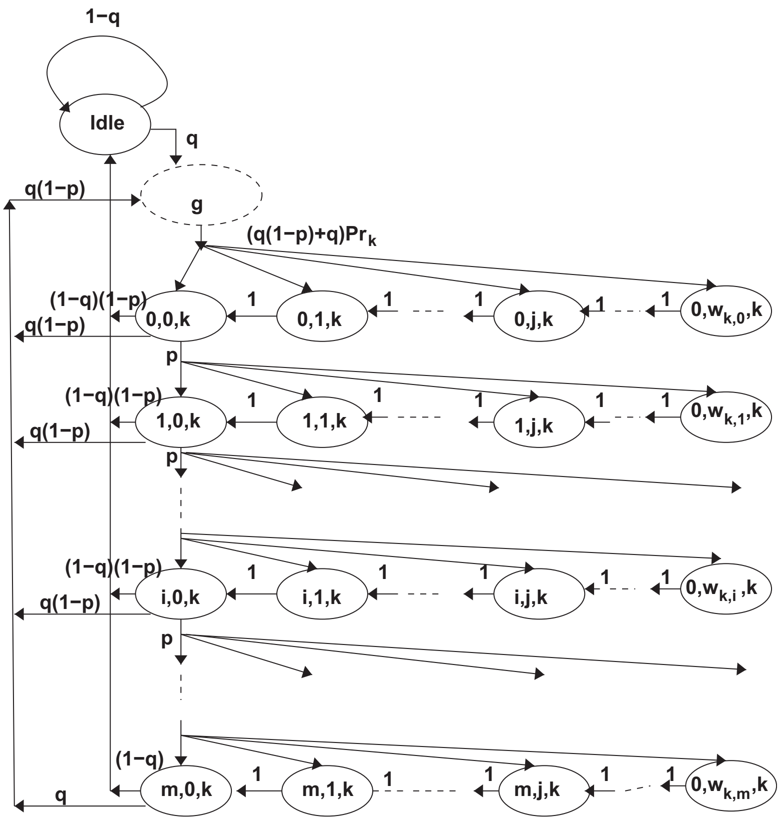


Fig. 6. Markov model for the proposed EDCA with dynamic CW tuning.

Similarly let b_{Idle} is the stationary distribution of the Idle state. Then

$$b_{Idle} = (1-q)(1-p)\sum_{i=0}^{m}\sum_{k=0}^{2} b_{i,0,k} + (1-q)b_{Idle} \tag{16}$$

Solving Eq. (16)

$$b_{idle} = \frac{(1-q)(1-p)}{q}\sum_{i=0}^{m}\sum_{k=0}^{2} b_{i,0,k} \tag{17}$$

In steady state, following equations can be derived through chain regularities

$$b_{i,j,k} = \frac{w_{k,i}-j}{w_{k,i}} q\cdot(1-p) \cdot\left\{Pr_k\sum_{i=0}^{m}\sum_{k=0}^{2} b_{i,0,k} + q\cdot Pr_k\cdot b_{Idle}\right\} \text{ when } i=0 \tag{18}$$

$$b_{i,j,k} = p^{(i-1)}\cdot b_{i-1,0,k} \qquad \text{when } i\in[1,m] \tag{19}$$

and

$$b_{i,0,k} = p^i b_{0,0,k} \tag{20}$$

Let τ denotes that a node successfully transmit a packet in a randomly chosen slot. Then

$$\tau = \sum_{k=0}^{2}\sum_{i=0}^{m} b_{i,0,k} \tag{21}$$

This can be simplified as

$$\tau = \sum_{k=0}^{2} b_{0,0,k}\left(\frac{1-p^{m+1}}{1-p}\right) \tag{22}$$

The normalization equation can be written as follows:

$$1 = \sum_{i=0}^{m}\sum_{k=0}^{2}\sum_{j=0}^{w_{k,i}} b_{i,j,k} + b_{idle} \tag{23}$$

Using this normalized equation and chain regularities as shown in Eqs.)(18)–(20) following equation can be derived;

$$b_{0,0,k} = \frac{2(1-p)(1-2p)q.Pr_k}{q.Pr_k, N+M} \tag{24}$$

where

$$M = 2(1-q)(1-p)(1-2p)$$

$$N = [(W_k+1)(1-2p) + W_k p(1-(2p)^m)]$$

and $W_0 = \frac{CW_{max}}{2^{m+1}}$, $W_1 = \frac{CW_{max}}{2^m}$ and $W_2 = \frac{CW_{max}}{2^{m-1}}$, the average contention window value corresponding to three modes.

The value of τ can be calculated using Eqs. (22) and (24). As CW window tuning procedure at time t uses estimation up to time $t-1$, so it can be written as

$$\tau(t) = \frac{1-p^{m+1}}{1-p} P_s(t-1) \tag{25}$$

where $P_s(t-1) = \sum_{k=0}^{2} b_{0,0,k}(t-1)$ is calculated in the previous iteration using Eq. (24). Now, p and τ are interdependent and can be represented as

$$p = 1 - (1-\tau)^{n-1} \tag{26}$$

Eqs. (22) and (26) can be solved numerically using fixed point iteration. Eq. (25) can be solved using time series iteration on the estimation and CW tuning procedure.

4.3. Saturation throughput analysis

The fraction of time the channel is used to successfully transmit payload bits is called the system throughput [25]. Let S denote the normalized system throughput. Let P_{tr} be the probability that there is at least one data frame transmission in the considered slot time. P_d is the probability of a successful transmission of a data frame. These probabilities can be calculated as

$$P_{tr} = 1 - (1-\tau)^n \tag{27}$$

$$P_d = \frac{n\tau(1-\tau)^{(n-1)}}{P_{tr}} \tag{28}$$

The normalized saturation throughput is given by

$$S = \frac{E[payload\ information\ transmitted\ in\ a\ slot\ time]}{E[length\ of\ a\ slot\ time]}$$

The following notations are used in the computation for S. $E[p]$ is the average packet payload size (in terms of time unit, e.g., μs). P_dP_{tr} is the probability that payload information is transmitted successfully in a slot. The average length of a slot in a data window is computed by considering three mutually exclusive and exhaustive cases. $(1-P_{tr})$ is the probability that a slot is empty, P_dP_{tr} is the probability of successful transmission of data frame and $(1-P_d)P_{tr}$ is the collision probability for a data frame. Therefore

$$S = \frac{P_dP_{tr}E[p]}{(1-P_{tr})\sigma + P_dP_{tr}T_s + (1-P_d)P_{tr}T_c}$$

Let all packets are of same size, so $E[p] = P$, the average payload. T_s and T_c are average time the channel is sensed busy because of a successful transmission or a collision respectively, and σ is the empty slot time. Let $H = PHY_{\mathrm{hdr}} + MAC_{\mathrm{hdr}}$ be the packet header and δ the propagation delay. Then

$$T_s = AIFS + H + E[p] + \delta + SIFS + ACK + \delta$$
$$T_c = AIFS + H + E[p] + SIFS + ACK_{TIMEOUT}$$

To evaluate the proposed method with the simulation results, the proposed scheme is implemented using NS-3 network simulation. The detailed simulation set-up is described in next section for analysis of the proposed fairness model using simulation results. However, for the sake of completeness, the comparison between the theoretical result and the simulation result is shown in Fig. 7a and b. The set of parameters used for theoretical value calculation is shown in Table 2. Similar set of values is considered for simulation. As seen from the graph, the theoretical results are similar to the simulation results.

The proposed scheme improves fairness keeping the average network throughput similar to the standard EDCA mechanism. Furthermore, at high load the aggregate throughput is more in case of the proposed architecture. This can be verified using theoretical comparison as shown in Fig. 8a and b. The throughput for standard EDCA is calculated using Tinnirello's Model [37] with finite retry limit. The proposed fairness scheme improves aggregate throughput at high load.

In next section, the simulation results have been reported to show the improvement in overall network throughput in more details.

5. Simulation results

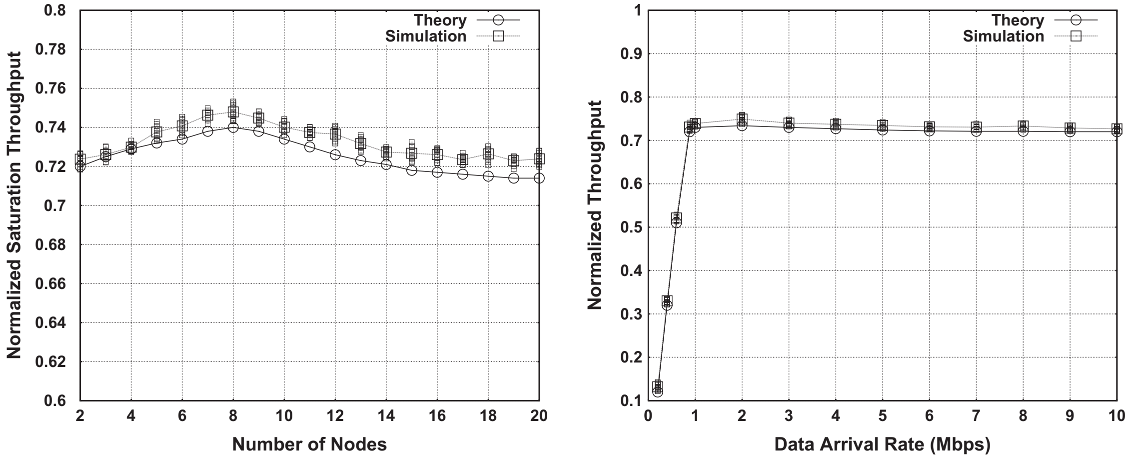
The proposed scheme is simulated using NS-3.9 [38] network simulator. 802.11b has been considered as physical layer standard with 11 Mbps data rate for mesh routers and gateways, and 5.5 Mbps for mesh clients. Random direction 2D mobility model is used to simulate client mobility. Initially clients are distributed uniformly under the routers, and then they start moving using a constant velocity of 3 m/s. The client traffic is generated using Poisson distribution with mean as 512 Kbps. Fifty mesh routers are positioned uniformly in a 10,000 $\times$ 10,000 m arena, with transmission range as 250 m and interference range as 550 m. One of the mesh router works as the mesh gateway. The mesh gateway is positioned at one corner of the arena, to capture the effect of maximum hop distance relaying. For TCP traffic, clients initiates TCP connection to the remote network. The mean connection time for TCP traffic is 10 sec. Every simulation is executed for 500 sec, and the average result of 10 simulations with different seed value is taken to plot the graph. CBR traffic is used for application layer traffic in case of UDP. Similarly, FTP is taken as the application layer traffic for TCP. To reduce the effect of router buffer size on TCP performance, the router buffer size is kept sufficiently large. To simulate the behavior for TCP traffic, a seamless handover scheme is implemented at each mesh router that redirects the data frames to the new access point, when a client switches from one access point to another. The fairness index is calculated as given by Jain's index [39]

$$F(x) = \frac{(\sum x_i)^2}{n(\sum x_i^2)} \tag{29}$$

where x_i is the throughput for flow i, and n is the total number of such flows. In all figures, "Fair WMN MAC" refers to the proposed fairness scheme.

5.1. Fairness and throughput

Fig. 9a shows the UDP throughput for four flows in 802.11s EDCA based MAC, and Fig. 9b shows the corresponding UDP throughput in the proposed fair WMN MAC. Here flows 1 and 2 are down-link flows, and flows 3 and 4 are up-link flows. It can be seen from the figure that the proposed scheme shows substantial improvement in terms of fairness over standard IEEE 802.11s EDCA MAC. Fig. 10a shows the fairness in terms of Jain's Fairness Index as described earlier. It can be seen from the figure that the fair WMN MAC shows more fairness than the IEEE 802.11s EDCA MAC. Similarly Fig. 10b shows the fairness improvement in case of TCP traffic.



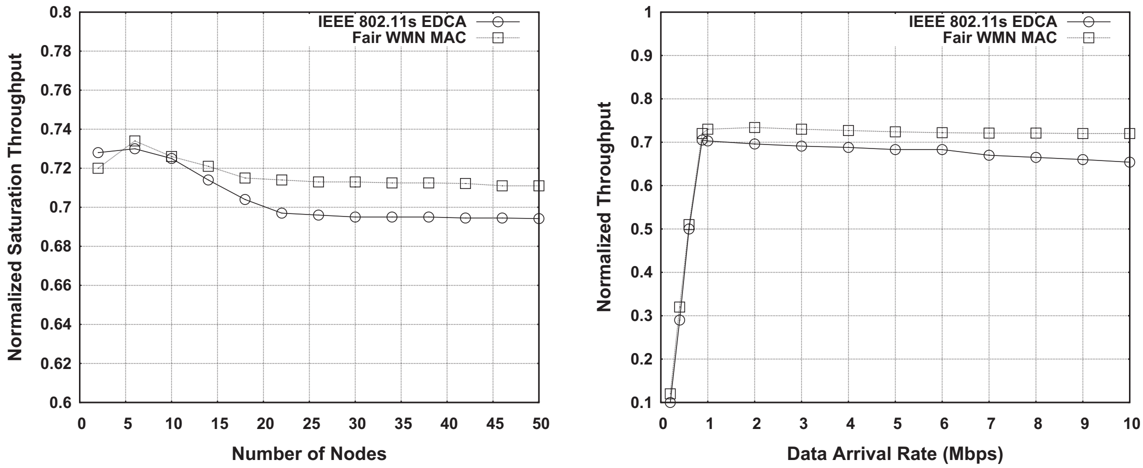
(a) Saturation Throughput (b) Overall Throughput w.r.t Data Rate

Fig. 7. Theory vs. simulation.

Table 2
Set-up parameters.

Payload of data packet	1024 bytes
Data	1024 bytes + MAC header + PHY header
ACK	14 bytes + PHY header
PHY header	192 μs
MAC header	28 bytes
Basic rate	5.5 Mbps
Data rate	11 Mbps
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
CW_{min}	31
CW_{max}	1023

An important observation is that the proposed scheme improve fairness without any loss in throughput at high load. Table 3 shows the throughput comparison for individual flows in case of TCP traffic, where each flow inject traffic at a rate of 2.5 Mbps. In the table, N denotes number of flows, T_I denotes individual flow throughput, T_A is the aggregate throughput and S_D is the standard deviation. The standard deviation can be used as an informal measure of fairness. The throughput for some of the flows drops significantly in case of 802.11s EDCA MAC due to congestion effect. However the proposed fair MAC scheme distributes overall throughput among different flows, and so all flows get almost equal amount of channel share. Table 4 shows the same for UDP traffic, up-link and down-link respectively. As the mobility effect is different for up-link and down-link flows for connection-less UDP flows, so these two cases are shown separately. In case of UDP traffic the throughput for the proposed scheme is higher than 802.11s EDCA MAC throughput. Furthermore, all flows get almost equal share of the total throughput. For down-link traffic, the aggregate throughput is lower because of mobility effect. As the clients are mobile, some UDP packets gets dropped when the handover occurs between two mesh



(a) Saturation Throughput (b) Overall Throughput w.r.t Data Rate

Fig. 8. Fair WMN vs. IEEE 802.11s EDCA: Theoretical throughput comparison.

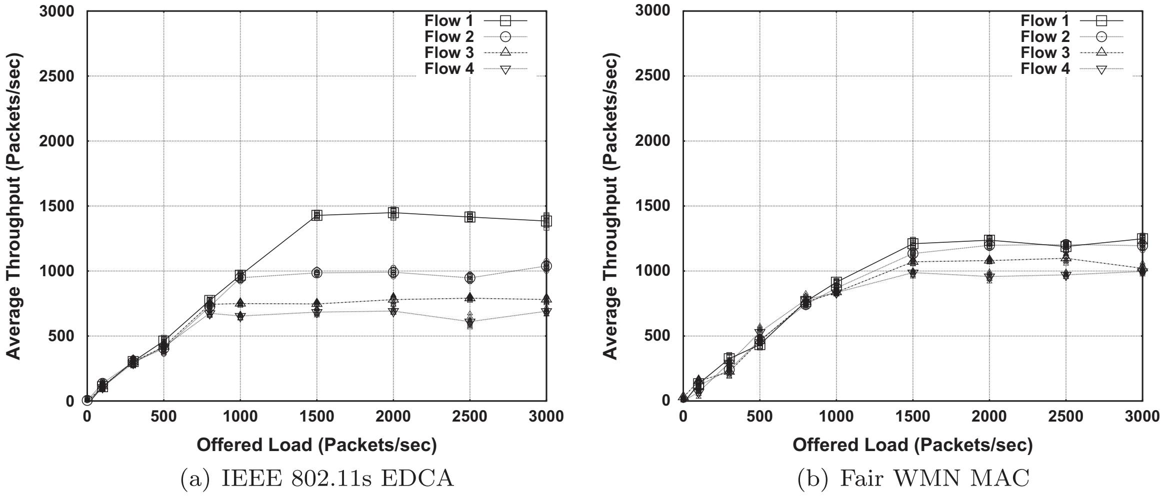


Fig. 9. Throughput for four flows.

routers. UDP does not take care of reliability, and the packets which were already forwarded to the previous router before handover, gets dropped. In all cases, total aggregate throughput is higher in case of proposed fair WMN MAC.

5.2. Load variation and scalability

Fig. 11a and b shows the fairness index for UDP and TCP traffic respectively with respect to number of active routers in a contention domain. As the number of active routers increases, the fairness index drops significantly in case of 802.11s EDCA MAC for both TCP and UDP traffic. However, the proposed probabilistic MAC provides more fairness compared to IEEE 802.11s EDCA MAC. For 20 average mesh routers in a contention domain, there is about 19.72% improvement in fairness for UDP traffic. For TCP traffic there is about 22.22% improvement in Fairness. The problem of unfairness is more with TCP traffic because of following reasons,

- Some of the nodes get very less share of bandwidth in case of IEEE 802.11s EDCA MAC. The TCP flows that passes through those nodes get stalled (as evidenced from Table 3).
- Whenever a TCP flow gets stalled, if it cannot recover within a timeout period, the connection is dropped. From the extensive simulation, it has been observed that there are frequent TCP connection breakdown in case on IEEE 802.11s EDCA MAC. In the proposed scheme, every mesh router gets channel share proportional to its traffic load. As a result every flow gets fair chance for traffic delivery. So every flow receives minimal achievable bandwidth, and no flows get stalled.

Fig. 12a and b give comparison of the proposed scheme and IEEE 802.11s EDCA in terms of load variation among contending mesh routers, for UDP traffic. At low load variance among the contending mesh routers, both the scheme show substantial fairness. However at high load

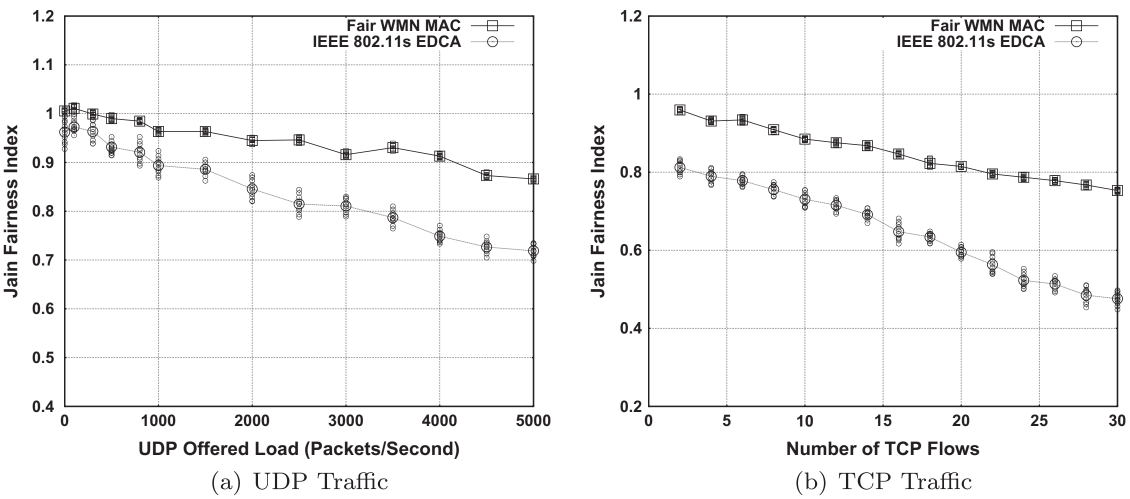


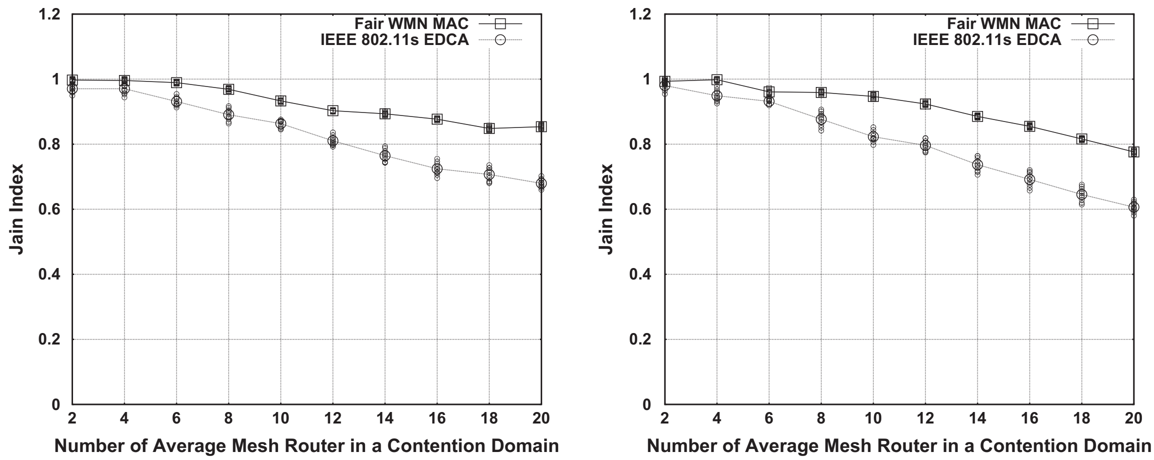
Fig. 10. Fairness index w.r.t. offered load.

Table 3
Throughput for TCP flows.

No.	802.11s EDCA MAC (Mbps)			Fair WMN MAC (Mbps)		
	T_I	T_A	S_D	T_I	T_A	S_D
4	2.42, 2.48, 1.77, 2.01	8.69	0.31	2.39, 2.78, 2.22, 2.57	9.97	0.29
5	1.55, 1.62, 1.64, 1.99, 1.99	8.80	0.23	2.04, 2.07, 1.95, 1.83, 2.06	9.94	0.08
6	0.98, 0.97, 1.62, 1.77, 1.32, 1.76	8.42	0.36	1.50, 1.60, 1.63, 1.60, 1.51, 1.54	9.38	0.06
8	0.92, 1.23, 1.26, 1.03, 0.64, 0.70, 0.73, 0.79	7.29	0.34	1.05, 1.09, 1.09, 1.19, 1.08, 1.14,1.05,1.10	8.80	0.09
10	0.58, 1.00, 0.57, 0.79, 0.28, 0.28, 0.50, 0.47, 0.37, 0.21	5.05	0.49	0.78, 0.80, 0.81, 0.84, 0.71, 0.78, 0.81, 0.84, 0.81, 0.90	8.09	0.09

Table 4
Throughput for UDP flows.

No.	802.11s EDCA MAC (Mbps)			Fair WMN MAC (Mbps)		
	T_I	T_A	S_D	T_I	T_A	S_D
Uplink traffic						
4	2.41, 2.22, 2.21, 2.85	9.68	0.43	2.51, 2.66, 2.60, 2.54	10.31	0.08
5	1.80, 2.07, 1.91, 1.34, 1.26	8.39	0.40	2.02, 2.12, 2.01, 2.04, 2.04	10.21	0.07
6	1.53, 1.63, 1.35, 1.50, 1.07, 1.24	8.33	0.24	1.59, 1.62, 1.67, 1.69, 1.73, 1.69	9.98	0.07
7	1.43, 1.27, 0.87, 1.44, 0.89, 1.13, 0.90	7.91	0.31	1.34, 1.29, 1.33, 1.35, 1.39, 1.43, 1.33	9.45	0.08
Downlink traffic						
4	2.34, 2.00, 1.80, 2.01	8.14	0.30	2.28, 2.27, 2.31, 2.36	9.22	0.05
5	1.77, 1.51, 1.47, 1.51, 1.44	7.70	0.23	1.87, 1.83, 1.88, 1.76, 1.84	9.18	0.05
6	1.16, 1.56, 1.02, 1.59, 1.11, 1.02	7.45	0.34	1.49, 1.54, 1.48, 1.42, 1.55, 1.48	8.95	0.06
7	1.35, 0.81, 0.74, 1.11, 1.01, 1.16, 0.82	6.99	0.35	1.21, 1.15, 1.24, 1.22, 1.24, 1.20, 1.19	8.44	0.03



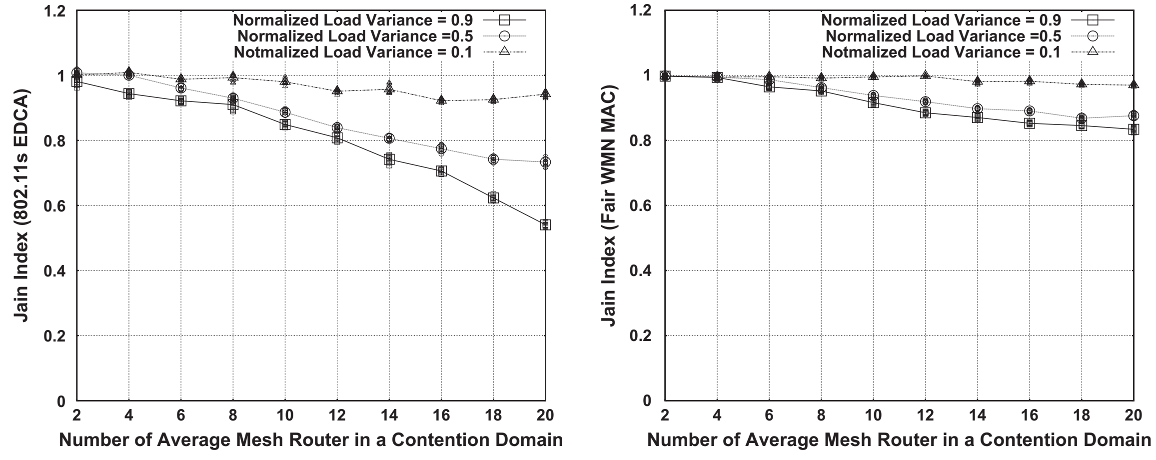
(a) UDP Traffic (b) TCP Traffic

Fig. 11. Fairness index w.r.t. number of mesh routers in a contention domain.

variation, the fairness index for IEEE 802.11s EDCA MAC drops drastically, whereas the proposed scheme shows about 49.09% improvement in fairness index with 20 numbers of contending routers.

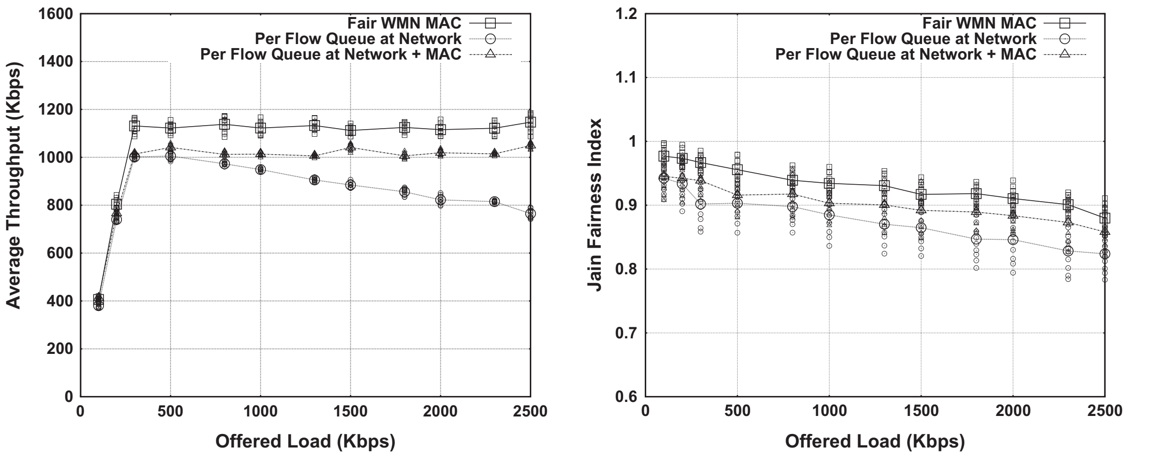
5.3. Comparison with per flow queuing

A comparison with existing per-flow reservation based fair allocation [16] is shown in Fig. 13. This work is chosen for comparison as it considers the effect of MAC layer relayed traffic on fairness. Both the proposed scheme and the scheme reported in [16] provide similar flow fairness, as shown in Fig. 13a. The aggregate throughput comparison is shown in Fig. 13b. While per-flow queuing at Network Layer alone reduces total aggregate throughput significantly at high load, per-flow queuing at MAC layer improves the result. The proposed scheme improves total aggregate throughput further, by reducing high implementation cost for per-flow queuing. It is obvious that per-flow queuing requires to maintain individual queue for every flow at every router. As a result it is not scalable as well as not applicable in wireless scenario, where links are dynamic in nature. This paper deals with per hop basis for a single class traffic in the network. So no explicit queue management is required. Hence this is highly suitable for wireless mesh networks and it is scalable also.



(a) IEEE 802.11s EDCA (b) Fair WMN MAC

Fig. 12. Fairness index and load variation w.r.t. number of mesh routers in a contention domain.



(a) Fairness Index for UDP Traffic (b) Total Aggregate Throughput for UDP Traffic

Fig. 13. Comparison with per-flow queuing.

6. Conclusion

In this paper MAC layer fairness problem in IEEE 802.11s EDCA based wireless mesh networks is described. A proportionally fair MAC protocol is proposed over IEEE 802.11s EDCA MAC. A load estimation strategy is used to estimate load at each mesh router and mesh client. The algorithm estimates current share and required share for each node. Based on the difference between these two, it enters one of the three modes, and accordingly tune CW to probabilistically achieve fairness at MAC layer. This type of fairness is essentially per-node proportional fairness that considers current load at every node. The per-node proportional fairness in turn give fairness among different flows. Simulation results confirm the superiority of the proposed scheme over IEEE 802.11s EDCA MAC. The scheme can also be extended easily to support QoS based fairness by using Arbitration Interframe Spacing (AIFS) based service-differentiation in EDCA mechanism. As CW tuning is mutually independent from AIFS based differentiation, the proposed scheme can solve the fairness problem effectively for multi-class traffic with minimal overhead on channel access mechanism.

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