RIFE-MAC: Fair and Efficient Medium Access Control for IEEE 802.11 Based Wireless Mesh Networks

Ashraful Alam Khan, Mahmudun Nabi, Abdullah-Al-Tariq, and Muhammad Mahbub Alam*

Abstract*—Earth-moving improvements in communication technologies in recent years have given rise to exponential surge in high data-rate Wi-Fi applications alongside the IEEE 802.11 based Wireless Mesh Networks (WMNs) that carry the inherent promise of cost-efficient last mile broadband wireless connectivity by extending the range of IEEE 802.11 Wi-Fi beyond the one hop range. Yet IEEE 802.11 based WMN technology is not devoid of some treacherous shortcomings and challenges, mainly in the Medium Access Control (MAC) sub-layer. This is particularly because of MAC sub-layer overheads which abstract the effective exploitation of increased agility ensured by today's physical layer (PHY). Besides, the multi-hop nature of WMNs triggers few more obstacles to medium access mechanism. The overhead of high collision probability and long idle listening during channel contentions, have restricted the expected improvement in data throughput efficiency. Moreover the IEEE 802.11 based WMNs exhibit severe unfairness and starvation of flows for gateway-destined traffics that are being originated from multi- hop stations. Such challenges in recent years have made IEEE 802.11 based WMNs an enticing research topic. In this paper we propose *Receiver-Initiated Fair and Efficient MAC (RIFE-MAC)*, a novel distributed channel access mechanism for IEEE 802.11 based WMNs which not only efficiently maximizes the overall network throughput but also improves the fairness in channel access among flows in WMNs. To attain these desired goals, RIFE-MAC significantly reduces the collision probability, idle time in between consecutive transmissions and unfairness in channel access. We investigate the performance of *RIFE-MAC* through extensive simulation. Simulation results demonstrate the effectiveness and robustness of our approach compared to IEEE 802.11 MAC and few more relevant works.

Index Terms*—IEEE 802.11 based Wireless Mesh Networks, Receiver-Initiated Medium Access Control, Channel Access Fairness, Improved Throughput.

I. Introduction

Wireless Mesh Networks (WMNs) have emerged as a promising high-performance and low-cost solution in achieving last mile broadband access with ubiquitous coverage. Particularly the IEEE 802.11 based WMNs are envisioned to extend the range of IEEE 802.11 Wi-Fi beyond the one hop range. The mesh topology enhances the overall reliability of the network, which is especially essential to ensure last mile broadband access [13]. The general architecture of IEEE 802.11 based WMNs consists of Mesh Access Points (MAPs), Mesh Points (MPs) and Mesh Clients (MCs), where the MAPs and MPs usually have least mobility and constitute the *Wireless Mesh Backbone* of WMN. The network traffic is routed through this Mesh Backbone. One of the prime objectives of IEEE 802.11 based WMNs research is to significantly reduce the bandwidth under-utilization and unfairness in channel access which are specifically undesired for real-time applications in IEEE 802.11 based WMNs. The multi-hop nature of WMNs triggers a number of operational challenges at Wireless Mesh Backbone, specifically for medium access mechanism. The shared nature of the wireless medium, unforeseeable channel quality and presence of hidden terminals are considered to be the some of the major obstacles to improve network performance in Wireless Mesh Backbone [14].

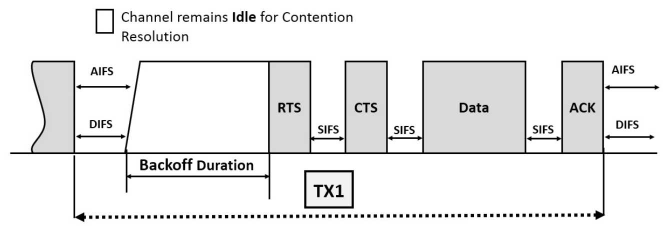

Fig. 1: Collision avoidance handshaking in IEEE 802.11 Distributed Coordination Function (DCF)

Fortunately, the data rates at the physical layer (PHY) of IEEE 802.11 based WMNs are increasing rapidly from hundreds of Mbps to over Gbps, thanks to the growing influence of the communication systems like MIMO, cognitive radios [2], [7], [29]. Despite significant improvement in IEEE 802.11 physical layer technologies, the real throughput is less than the physical throughput owing to the overheads of the IEEE 802.11 MAC sub-layer [9]. Note here that, the IEEE 802.11 default MAC technique called Distributed Coordination Function (DCF) [4] is originally designed for single hop communication, whereas the network layer protocol manages the multi-hop communication. However such hypothesis does not fit well in case of WMNs, since data communication at a node in Wireless Mesh Backbone (e.g., MAP, MP) is hampered by other node that are not only within the distance of a single hop but also two hops away. DCF engages a CSMA/CA with binary exponential backoff

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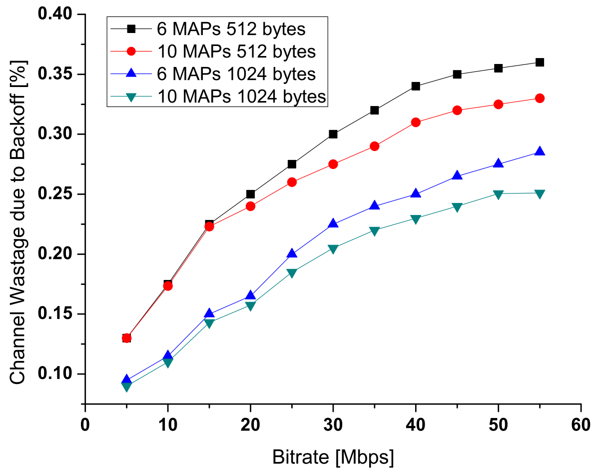


Fig. 2: Channel wastage in 802.11 based WMNs due to overhead of DCF random backoff under varying bitrates

algorithm to arbitrate how multiple nodes (e.g., MAPs, MPs) access a shared channel [4], [35]. One of the major reasons for the decreased MAC efficiency in 802.11 DCF is the idle times in between consecutive transmissions known as *Backoff Time*. When multiple stations simultaneously back off in time domain to win contention, the channel remains idle leading to significant channel under-utilization. The figure1 illustrates the duration of idle listening in channel contention of IEEE 802.11 default MAC. The impact of such channel wastage is huge and the MAC sub-layer efficiency decreases significantly as a consequence. To send a 1500-byte data packet through a 300 Mbps network, only 40 micro seconds time is necessary. But the combined overhead of Distributed Inter-frame Space (DIFS), coupled with backoff time result in another 120 micro seconds. Thus, in this scenario, MAC layer efficiency drops to a mere 25%. Since the medium access in 802.11 based WMNs cannot completely avoid the data collision due to randomness of DCF and hidden terminal problem, the MAC efficiency further decreases once the collision rate becomes higher. Additionally the DCF contention mechanism triggers an exponential increase in backoff range, which evokes the risk of greater channel wastage and causes more than 30% throughput reduction [18].

Moreover the MAC sub-layer efficiency of IEEE 802.11 DCF in WMNs also rapidly decreases with the increase of PHY data rate, since the overheads, such as PHY headers and contention time, typically do not decrease at the same rate [20]. Based on the experiment conducted by [34] figure 2 depicts the proportion of channel under-utilization in 802.11 based WMNs due to overhead of DCF under varying bitrates.

Furthermore due to the randomness of DCF access, the WMNs experience severe fairness problem in terms of channel access among different flows originated from different nodes. Since the distanced nodes contend for channel access at each hop along the delivery path, flows originating from mesh access points (MAPs) get higher throughput than the ones originating from far away while communicating with the gateway. Thus, in turn, results in severe disadvantage, unfairness and starvation of flows for gateway-destined traffics that are being originated from multi-hop stations [26]. Hence MAP-1 shown in Fig. 4 shall always lag behind MAP-3 performance-wise, since MAP-3 is less number of hops away from destination MAP-4 than MAP-1 is.

Another very typical problem in WMNs, the hidden terminal problem which is one of the major causes behind collisions in WMNs, degrades the network throughput even further [6], [37]. Unfortunately, the prominent solution of RTS/CTS handshaking is not an absolute solution and may rather cause throughput to plunge deeper in WMNs.

Numerous researches are available to overcome these overheads of channel under utilization and access unfairness in IEEE 802.11 based WMNs. Some research works including [3], [12], [40] have tried to improve 802.11 DCF efficiency for WMNs by modifying the behavior of DCF backoff mechanism. However significant reduction of idle time in between transmissions and collision probability are not achieved in this approach. Few works including [1], [21], [24], [30], [31], [33], [34] have mentioned substantial improvement in terms of throughput efficiency by introducing back-off operation in frequency domain. However the frequency domain back-off operates only over a certain PHY layer technology called Orthogonal Frequency Domain Multiplexing (OFDM) [8] and requires additional hardware, e.g., radio interface at nodes, which is not cost effective in many cases. Few recent works propose the gradual development of collision free schedule among contending nodes [20], [39], [41]. However such proposals result in slow converges to steady state and are less effective in dynamic and dense networks. To mitigate the unfairness problem in WMNs many research directions are proposed by works in [15], [17], [23], [25], [26]. However many of these solutions do not provide effective solutions to hidden terminal problem. Hence researchers emphasize on the necessity of fair and efficient medium access control mechanism for 802.11 based WMNs which effectively exploits the agility ensured by todays physical layer.

Hence we propose *Receiver-Initiated Fair and Efficient MAC (RIFE-MAC)*, a novel distributed channel access mechanism for IEEE 802.11 based WMNs which not only maximizes the overall network throughput but also ensures fair channel access among contending flows. Through significant reduction of collision probability and idle time in between transmissions, *RIFE-MAC* efficiently minimizes the channel under utilization. Besides the *RIFE-MAC* strictly ensures per-flow fair channel access and also effectively resolves the hidden terminal problem. We investigate the performance of *RIFE-MAC* using simulation in Network Simulator version-2 (NS-2). The results demonstrate that *RIFE-MAC* achieves better throughput and fairness compared to the literature.

The rest of the paper is organized as follows. Section 2 and section 3 describe the network model and related works respectively. We then elaborately discuss the design of *RIFE-MAC* in section 4 and evaluate its performance using simulation in section 5. Finally section 6 provides few brief concluding remarks.

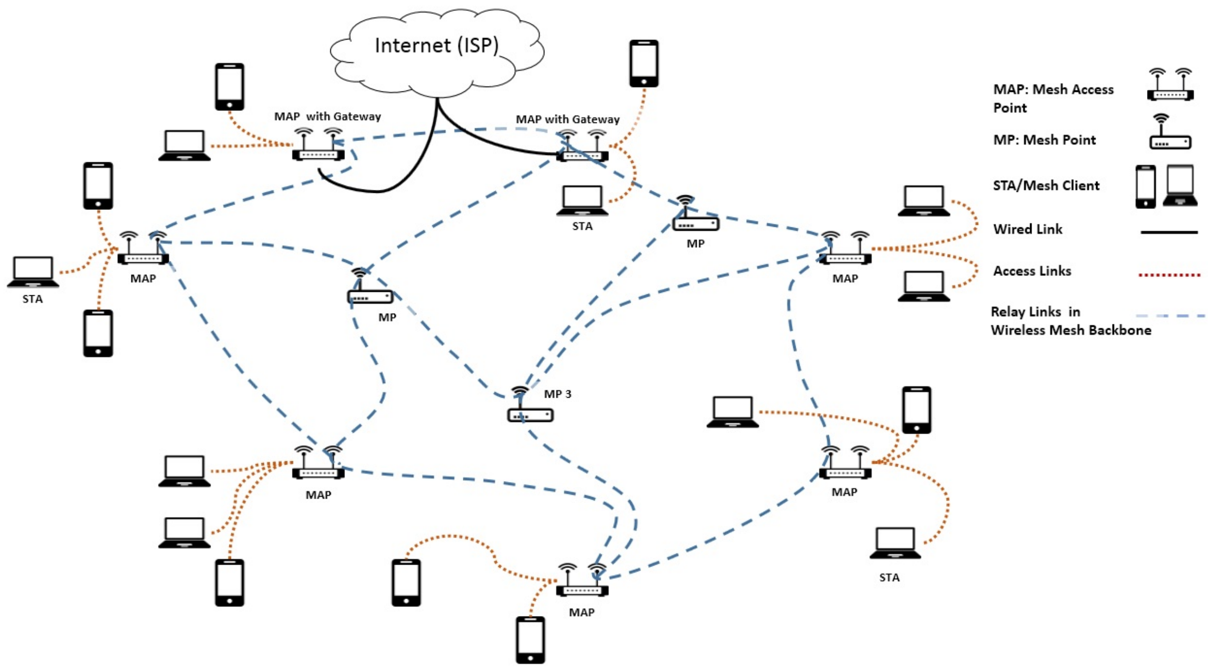


Fig. 3: System model of IEEE 802.11 based WMNs

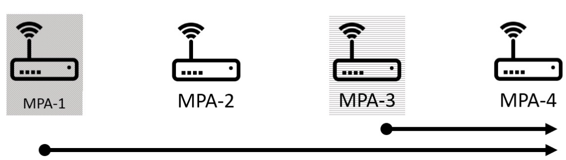


Fig. 4: Channel access unfairness of flows originated from multi-hop stations

II. Network Model and Assumption

In this work, our discussion revolves around the WMN network model shown in Fig. 3. According to the model, an IEEE 802.11 based *Wireless Mesh Network (WMN)* contains Mesh Access Points (MAPs), Mesh Points (MPs) and STAs. In Wireless Mesh Backbone of this WMN, the MAPs and MPs arrange themselves in such order that makes them capable of relaying traffic among STAs in multiple hops. Some MAPs called Gateway MAPs also act as gateways to the Internet and are connected by wired medium. Gateway MAPs serve as connectors between a STAs and the Internet. MAPs of this WMN can include dual interfaces, one of which acts as access interface for communication with subordinate STAs, whereas the other interface acts as the relay for the Mesh Backbone. MPs in this WMN include one interface which is solely tasked with relaying traffic among other MPs and MAPs. The interfaces that are used to relay traffic to other MAPs or MPs are named as relay interfaces, while others, who communicate with client STAs or the Internet, are called access interfaces. As for the STAs, who are equipped with only one interface, can associate themselves with the MAPs and become part of the whole WMN. The networking performance in Wireless Mesh Backbone is our main concern in this work. With a view to distinguish between access interface and relay interface, their implementation is done with with same radio technology operating on different channels. In RIFE-MAC, the access interfaces operate on one single channel environment.

III. Related Work

Since its conception, IEEE 802.11 based WMNs have been marred with difficulties regarding medium access unfairness and channel underutilization as well as throughput degradation. However, in the past few years, a significant amount of research was focused on mitigating the aforementioned hindrances.

Many researches propose the modification of DCF backoff behavior for IEEE 802.11 based WMNs. [3], [12], [40]. In [12] the traditional DCF contention is narrowed down through multiple rounds of smaller ranged contentions. However most of these works do not significantly reduce the channel wastage due to idle listening and collision probability. Moreover such proposals do no effectively consider the unfairness issue among contending flows.

Another group of research gains notable success in boosting network throughput by introducing back-off operation in frequency domain. In *Back2F* [34], *Frequency Pooling* [24] and few more research proposals [21], [30], [31], MAPs and MPs gain knowledge about the backoff values of other contenders in Mash Backbone, by sharing the information with the help of multiple OFDM sub-carriers after DIFS idle period. Though the substantial improvement in terms of throughput efficiency is achieved by frequency domain channel contention, most of these proposals do not ensure strict fair channel access. Moreover the frequency domain channel contention requires huge modification in network infra-structure level e.g., additional dedicated antenna at MPs and can work on OFDM based PHY layer only.

Gradual development of collision free schedule among contending nodes is proposed by few recent research works by [20], [39], [41]. In proposal presented by [41], each MAPs/MPs can iteratively acquire collision-free access through adjusting its next transmission time, if part of its packets suffer from the collision on the current and previous transmission times. In [20], each MAPs/MPs decides its transmission order among all the other contenders within it's neighborhood[1] by controlling respective packet length in such a way that the transmission duration is adapted to implicitly inform required information. However these protocols mostly result in slow convergence to stable and collision free schedule. Besides, these proposals, in general, are less effective in dynamic and dense Wireless Mesh Networks.

Proposed works in [15], [17], [23], [25], [26] have focused on alleviating the unfairness problem among different contending flows. [15] proposes a cross layer scheme which gathers a bulk of information from physical and MAC layer for fair channel utilization per node. The protocol in [17] explicitly allocates minimum airtime limit to each active pair of communicating neighbors in its neighborhood to ensure fair access. However the calculation of airtime limit is sophisticated due to its control overhead. The work by [22] proposes a mechanism called *TXOP* to attenuate the unfairness problem in WMNs by adjusting the transmission opportunity duration at every intermediate MRs, considering the number of flows already served. The *PBA-CDC* in [23] proposes an allocation algorithm to resolve the unfairness. However many of these proposals fail to provide an effective solution to hidden terminal problem with reduced overhead and thus experience reduced throughput. Therefore to utilize the agility available at todays physical layer effectively, it is necessary to find an efficient and fair medium access mechanism for WMNs.

IV. RIFE-MAC: Receiver-Initiated Fair and Efficient MAC

A. Fundamental Idea

In this work, we aspire to increase network throughput and channel access fairness in IEEE 802.11 based WMNs through an effective medium access control mechanism, which in practice, significantly reduces collision probability and idle time in between consecutive transmissions. The fundamental idea behind our proposal is simple but powerful indeed. We propose that if at the very beginning of every transmission opportunity, each contending node in WMN (e.g., MAP, MP) itself distributively discover the most disadvantaged contender as the contention winner without long idle listening, then both the idle time in between two consecutive transmissions and collision probability reduce tremendously. Hence the accurate decision taken by each contender distributively results in greatly improved channel utilization and channel access fairness without requiring any additional infra-structure (e.g., dual antenna or OFDM based PHY) or time domain penalty. Besides, the elimination of hidden terminal problem is also acquired through our proposed protocol. Here we disclose the proposed protocol, called *Receiver-Initiated Fair and Efficient MAC (RIFE-MAC)* with required modification in default MAC for IEEE 802.11 based WMNs.

The *RIFE-MAC* is a sustainable channel access mechanism for IEEE 802.11 based WMNs that significantly improves the network throughput and fairness efficiency. Minimization of idle time in between consecutive transmissions, diminution of collision probability and access dominance by closer nodes and hidden nodes are our key approaches in obtaining aforementioned goals.

RIFE-MAC proposes the reversal of *Collision-Avoidance Handshaking* from *Sender-Initiated* to *Receiver-Initiated* as a method of enabling WMNs to avoid collisions that is caused by hidden nodes. Additionally, to ensure a collision free, efficient and fair channel access, it requires each contending node to maintain a local information table called *Neighborhood State Shelf (NSS)*.

B. Receiver-Initiated Collision-Avoidance Handshaking

Since it is realized that the receiver of data frame is the point of interest in terms of collision, initiating the request for data frames from the receivers' end ensures that data packets can avoid collision with other packets in the network containing hidden terminals and this can only be done in *Receiver-Initiated Collision-Avoidance Handshaking*. Note here that, Receiver-Initiated Collision-Avoidance Handshaking is originally proposed to ensure energy efficiency in Wireless Sensor Networks (WSNs). However, according to many experiments conducted in [10], [11], [19], [36], *Receiver-Initiated Collision-Avoidance Handshaking* has proven to posses the ability to avoid collisions due to hidden terminal problem in multi hop networks.

In RIFE-MAC, the collision-avoidance handshaking starts with pooling with CTS frame transmitted by the Receiver node of most disadvantaged flow within that neighborhood. Upon successfully receiving CTS frame, the polled Sender replies with Data frame just after SIFS duration. This data transmission procedure terminates with the ACK transmission after SIFS by the Receiver. If the pooled node does not have any more Data frames to be delivered, then it replies with Negative ACK frame. Hence the RIFE-MAC at least in principle, reduces the number of control packets required to avoid collision.

However polling by Receiver itself in RIFE-MAC introduces a big challenging issue in medium access mechanism. That is, deciding whom to poll and how a Receiver should successfully poll its potential Sender of data frame - the node who is carrying the data packet to be sent. Note here that, most of the Receiver-Initiated MAC protocols employ the CSMA based Random Access Mechanism for contention resolution, which does not guarantee collision free and fair access. Thus to ensure a collision free, efficient and fair polling by Receiver

[1]The Receiver along with all the one hop neighbors of the Sender, and one hop neighbors of the Receiver is marked as neighborhood of respective Sender node [32]

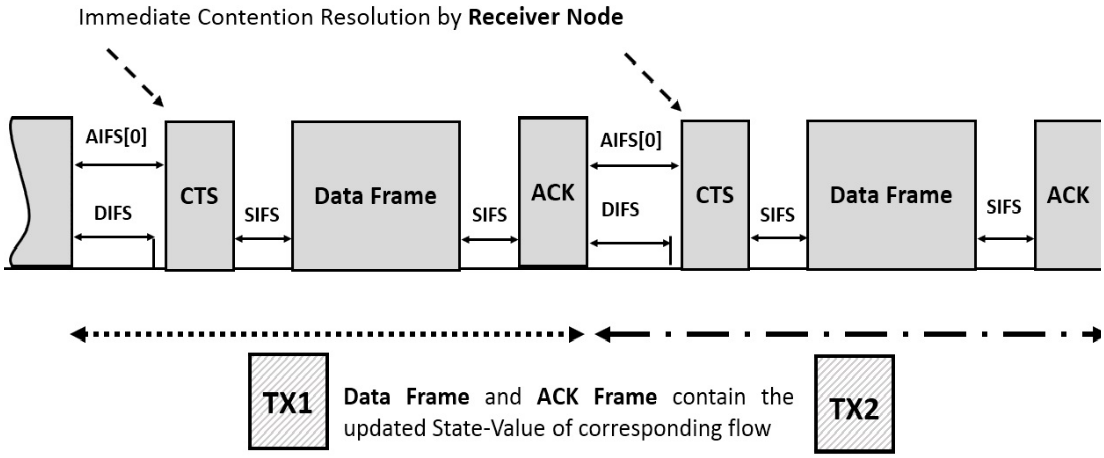


Fig. 5: Collision avoidance channel access with significantly reduced idle listening and collision probability in RIFE-MAC

node, each Receiver node requires to follow an efficient and fair policy.

C. Distributed Contention Resolution

RIFE-MAC distributively resolves the challenges associated with Receiver-Initiated Pooling by utilizing the *Neighborhood State Shelf (NSS)*, maintained at each of the contending nodes in a distributed manner. *NSS* is an information table with three attributes, *(Flow-ID, State-Value , Is-Receiver)*. The *State-Value (SV)* of each contenting single hop flow within the corresponding node's neighborhood, describes the number of kilobytes already transmitted so long by corresponding flow. A single-hop flow has a unique *Flow-Id (F-ID)* represented by, $f^{x,s}$ and $f^{x,s} \in F$ (where F is the set of all flows in WMNs). The $f^{x,s}$ is the flow, originated from node (e.g., MAP/MP) s and currently being forwarded by node x that has a *State Value (SV)*, $SV_t^{x,s}$ at any given time t. Lastly the *Is-Receiver* field of flow $f^{x,s}$ at node i's *NSS* is a boolean field which is set as True if the node x is the Receiver of this flow. It should also be noted that, for the successful operation in RIFE-MAC, the *SV* of each single-hop flow gets periodically updated and remains its consistency in every other neighboring nodes' *NSSs*.

In RIFE-MAC, the flow $f^{x,s}$ with minimum SV within a neighborhood always gets top most priority for channel access. Thus with the help of respective NSS, before each transmission opportunity, every Receiver node distributively and fairly decide whether to poll its potential Sender now or not. Therefore, unlike IEEE 802.11 DCF, only the Receiver of most disadvantaged flow gets the guaranteed opportunity to poll without waiting for long contention window time. Since the contention resolves at the very beginning of each transmission opportunity, every contending nodes know the contention winner distributively without the sacrifice of channel under-utilization.

Thus the RIFE-MAC significantly reduces the collision probability and idle time in between consecutive transmissions by ensuring a guaranteed channel access to the most disadvantaged flow without idle waiting. Moreover, inherent solution for the hidden nodes problem by *Receiver-Initiated Collision-Avoidance Handshaking* contributes further to boost-up the utilization of shared channel as well as network throughput. Besides assuring guaranteed data transmission with improved throughput, the RIFE-MAC also ensures fair channel access by fairly scheduling each single hop flow within a neighborhood. The Fig. 5 depicts the collision avoidance handshaking mechanism of RIFE-MAC. The comparative view of Fig.1 with Fig. 5 discloses the difference between medium access mechanism at RIFE-MAC with IEEE 802.11 DCF and clarify the strength behind boosted network efficiency.

D. Maintaining Neighborhood State Shelf

Assurance of possessing consistent neighborhood knowledge by each of the spatially distributed NSSs within a neighborhood, RIFE-MAC includes a new field at MAC header of Data and ACK frames. RIFE-MAC always piggybacks the updated State-Value, $SV_t^{x,s}$ at time t of flow $f^{x,s}$ inside the associated MAC-headers [5] of Data and ACK frames of corresponding flow. Both the source and forwarding nodes adopt this modification for its associated single hop flows. Through the transmission of Data and ACK frames- all the nodes in neighborhood overhear the corresponding frames and get informed of the updated State-Value of corresponding flow. After overhearing a Data frame transmitted by the Sender, the Receiver and one-hop-neighbor of the Sender become acknowledged about updated State-Value of the transmitted flow. Through ACK frame overhearing, one-hop-neighbors of receiver also get informed of updated State-Value. Thus RIFE-MAC ensures the absolute flooding of updated State-Values amongst every spatially distributed Neighborhood State-Shelves in corresponding neighborhood.

Each node updates the state value, $SV_t^{x,s}$ of each contending flow upon overhearing any Data and/or ACK transmissions form corresponding flow according to the equation (1). Where, $SV_{t-1}^{x,s}$ is the previous state value of flow $f^{x,s}$ at time $t-1$ and V represents the number of Kilobytes (Kb) already transmitted by $f^{x,s}$ so long. Note here that, the frame size in IEEE 802.11 wireless networks usually ranges from 0-2.31 Kilobytes [28]. The $P^{f^{x,s}}$ is an entity representing the Priority Code Point (PCP) [38] of flow $f^{x,s}$ available at IEEE 802.11e based

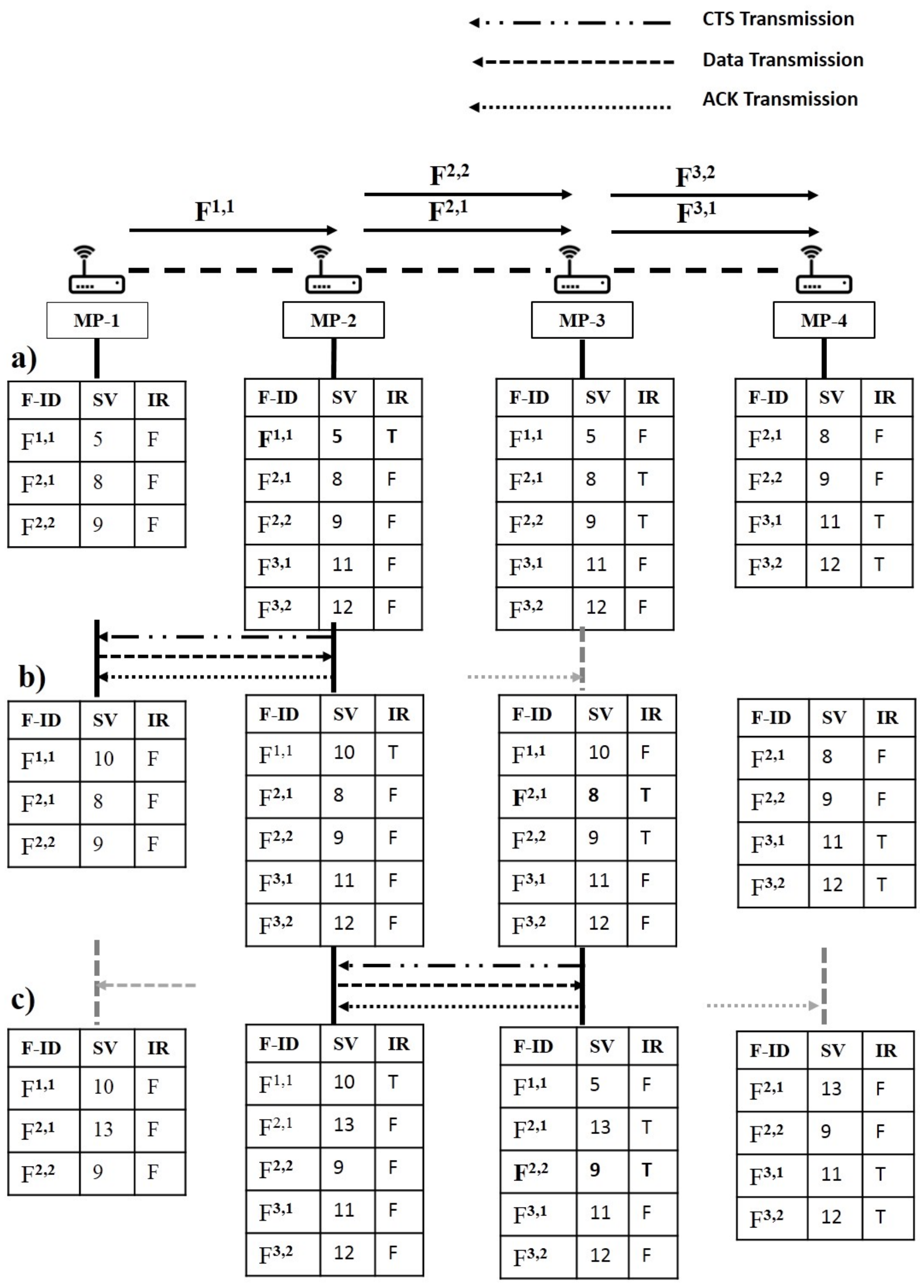


Fig. 6: Illustration of collision avoidance handshaking in RIFE-MAC with two Data transmission rounds.

WMNs for Quality of Service (QoS) assurance. Thus the State-Value of a flow with highest priority (e.g., eight (8) designation of 'Voice') increases slowly than the flow with lowest priority (e.g., one (1) designation of 'Background'). Since the flow with smallest State-Value gets the channel access earlier than remaining flows because of having higher State-Values in RIFE-MAC scheduling policy, all flows eventually get fair access from shared channel. For non-QoS services the default value of Priority Code Point is one (1). The Max_{Value} is a global constant in the network used to decide the upper-limit of SV. It is usually a large integer known by each contending nodes in a WMN.

$$SV_t^{x,s} = (SV_{t-1}^{x,s} + V/P^{f^{x,s}})\%Max_{Value} \tag{1}$$

E. Data Transmission Paradigm

Since, in RIFE-MAC, every data transmission procedure is initiated by Receiver, only the Receiver i of the flow with minimum State-Value, initiates data transmission within a neighborhood. By analyzing the minimum State-Value and *Is-Receiver* values, the appropriate Receiver gets the notification on its turn to poll the potential Sender. To act on the notification, the Receiver waits for AIFS[0] duration [27], the duration of DIFS with one more slot, to check if the channel remains idle. Once it finds the channel to be idle for AIFS[0] duration, a CTS frame is transmitted without waiting for variable length contention window time. The remaining handshaking follows the transmission of Data and ACK frames each after SIFS duration respectively by Sender and Receiver nodes. Thus

RIFE-MAC eliminates the channel under-utilization due to traditional backing off and RTS transmission.

Fig. 6 illustrates an example of contention resolution followed by Data transmission in a sample mesh network according to RIFE-MAC. In stage-a), the MP-2 finds the flow, $f^{1,1}$, with minimum SV in its NSS and IS_Receiver having True value. Since all the NSSs within the neighborhood of $f^{1,1}$ (i.e., NSS in MP-2 and NSS in MP-3) also possess the same knowledge, the Receiver node MP-2 successfully polls the MP-1 with a CTS frame after AIFS[0] idle time. The successful transmission of Data and ACK frames updates the SV of $f^{1,1}$ in all NSSs within its neighborhood. The updated SV of $f^{1,1}$ is 10 here considering the Data frame of 5 Kilobytes size. Stage-b) of fig. 6 depicts the updated NSSs which allows the $f^{2,1}$ to be the contention winner for the next transmission opportunity. Hence the MP-3 polls the MP-2 with CTS frame without any listening on channel idly for long time.

F. Handling Newly Joined and Backlogged Flows

The collision avoidance handshaking in RIFE-MAC is initiated by CTS transmission from Receiver node. However, in case of a newly joined flow or backlogged flow - a Sender - still needs to depend on the RTS frame transmission from Sender to initiate the handshaking. Since the intended Receiver of the newly joined flow or backlogged flow does not have any prior knowledge of its potential Sender and flow itself, the Sender itself has to initiate the collision-avoidance handshaking in this circumstance. However to avoid the collision with most disadvantaged flow, the RIFE-MAC reserves the first *Slot Time* after DISF period for channel access by newly joined or backlogged flows.

Based on the outcome of certain probability, the Sender of a newly joined flow initiates it's collision-avoidance handshaking with RTS transmission while the channel remains idle for more than DIFS duration but less than AIFS[0] time. In case of multiple newly joined or/and backlogged flows, these flows avoid RTS collision among themselves by distributively deciding RTS transmission based on certain probabilistic outcome. Once the RTS frame is successfully transmitted, the scheduled Receiver loses this particular transmission opportunity and gets the transmission opportunity next time according to RIFE-MAC scheduling policy. The successful transmissions of RTS, CTS, Data and ACK frames by a newly joined or backlogged flow result in all the stations within the neighborhood getting informed of corresponding flow and updating their respective NSSs accordingly.

However, if a newly joined flow sets its State-Value to lowest possible value, then, in general, it becomes much lower than remaining SVs in the neighborhood resulting in the flow dominating channel access for significantly long amount of time. To avoid such unexpected channel access, the newly joined flow picks a local minimum State-Value within its neighborhood as it's Initial State-Value, $SV_0^{x,s}$ according to equation (2).

$$SV_0^{x,s} = \min_{\forall x,s \in neighborhood(f^{x,s})} SV_t^{x,s} \tag{2}$$

TABLE I: Simulation parameters

Particular	Value
Channel data rate	36[Mbps]/-
Antenna type	Omni direction/-
Ratio Propagation	Two-ray ground/-
Transmission range	200[m]
Carrier sensing range	300[m]
Contention Window	CW_{min}=32, CW_{max}=1024
Contention type	TCP/FTP (TCP Tahoe)
Network topology type	String, Random
Network Density	5 to 30 nodes within 1400m X 1400m are.
Packet size	1[KB]

G. Breaking the Tie in Neighborhood State Shelf

It is not very unusual that, more than one Receiver nodes hold equal State-Values for their own receiving flows which are also minimum in respective NSSs. In such circumstance, failing to identify and resolve this access tie results in collision and throughput degradation in WMNs.

The RIFE-MAC resolves this tie among corresponding most disadvantaged flows distributively with the assistance of a *Tiebreaker-Function* run by each of the Receivers engaged in current tie. The *Tiebreaker-Function* checks the MAC addresses of *Forwarding Nodes*, let x_1 and x_2 associated with corresponding most disadvantaged flows f^{x_1,s_1} and f^{x_2,s_2}. The *Hexadecimal Summation* of last three octets in 48-bit MAC address space [2] is used as a decision variable to break such access tie. The entity holding the lowest summation is decided as winner in RIFE-MAC. For example, if MP x_1 and MP x_2 are two forwarding nodes of flows with a tie. The MAC addresses of MP x_1 and MP x_2 expressed in hexadecimal are 06-1B-00-06-00-0A and 06-1B-00-06-01-08 respectively. The hexadecimal summation of last three octets are $(06+00+0A) = 10$ and $(06+01+08) = 0F$ respectively for MP x_1 and MP x_2. Thus the flow forwarded by MP x_2 gains the channel access.

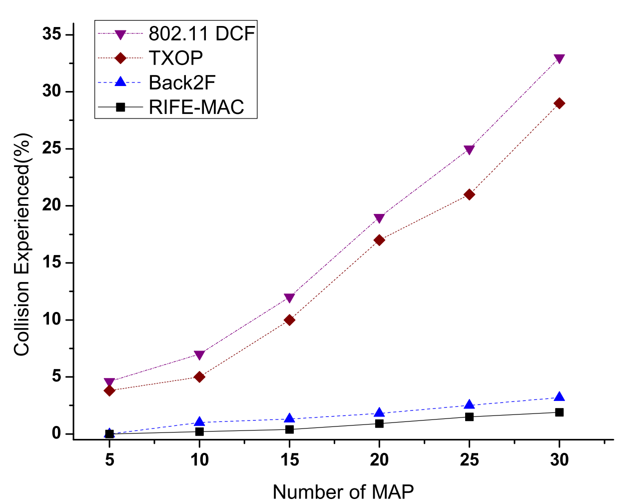
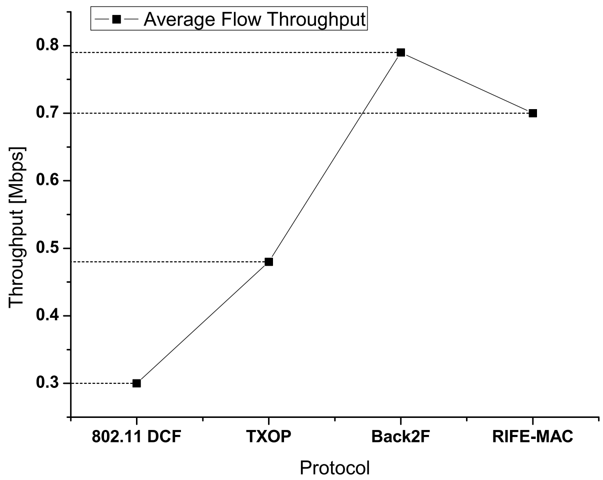
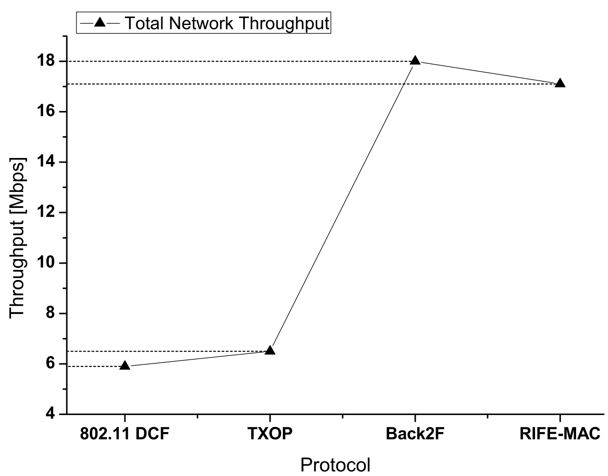


Fig. 7: Collision experience in 802.11 DCF, TXOP, Back2F, and RIFE-MAC.

[2]A MAC address is a unique identifier assigned to network interfaces card (NIC) for communications at the data link layer



(a) Average flow throughput in RIFE-MAC.



(b) Total network throughput in RIFE-MAC.

Fig. 8: Comparative throughput efficiency of RIFE-MAC

H. *Impact of Inconsistent Neighborhood State Shelf*

Failing to successfully overhear transmitted Data or ACK frames of certain flow (destined for others) for a long period of time by any neighboring node brings some inconsistency in its NSS. During that time, corresponding NSS carries backdated State-Value for missed flow which is lower than the actual value. Though such situation is not so usual, yet in such cases the RIFE-MAC still can avoid collisions, since Receiver of each flow always have the accurate State-Value. However a Receiver may experience the affect of False Negative information because of having backdated lower Sate-Value in its NSS. In such scenario, the corresponding Receiver considers the flow with backdated value as contention winner instead of flow associate with the Receiver itself. Thus none of the contender attempts for transmission after AIFS[0] time. The RIFE-MAC adopts a policy as a solution to such channel underutilization. If the channel remains idle for AIFS[0] and two additional *Slot Time* duration, then the Receiver with second minimum State-Value becomes the contention winner.

V. Performance Evaluation

In this section, we concentrate on extensively simulating RIFE-MAC, IEEE 802.11 DCF and other relevant literatures (e.g., Back2F [34], TXOP [22], etc), with a view to evaluating RIFE-MAC's performance along with presenting a comparative study among the aforementioned works. Our simulation considers a single channel environment within a WMN consisting of 5 to 30 Mesh Access Points and Mesh Points. The parameters, which are the best values used throughout all simulations, are briefed in table I. Each of our experiments run for 300 seconds and the results are averaged over 5 different runs.

A. *Collision Avoidance Efficiency*

Here we analyze the effect of collision over RIFE-MAC. To evaluate the worst case vulnerability of collisions in WMNs, we consider a high density topology with increasing number of randomly placed contenders according to parameters given in table I. Figure 7 shows the experimental outcome, expressed as percentage of collision experienced by 20 different concurrent TCP flows cumulatively in considered protocols. As shown in Fig. 7, the collision experienced by RIFE-MAC is very negligible, since it can handle channel contention mechanism more efficiently than other protocols. Moreover, the network density significantly causes huge collisions in IEEE 802.11 DCF and TXOP mechanism. Since the channel contention in IEEE 802.11 DCF and TXOP solely depend on random backoff, the probability of picking same random backoff in those protocol increases in high density network. On the other hand, both Back2F and RIFE-MAC can explicitly discover the contention winner and thus experience negligible collision. However the limitation of successfully discriminating adjacent OFDM sub-carriers in certain frequency domain contentions, the Back2F protocol also experiences collisions in few attempts. According to our experiments, increasing the number of contenders beyond 20 still results in less than 2% collision for RIFE-MAC which is also slightly less than collision experienced by Back2F protocol.

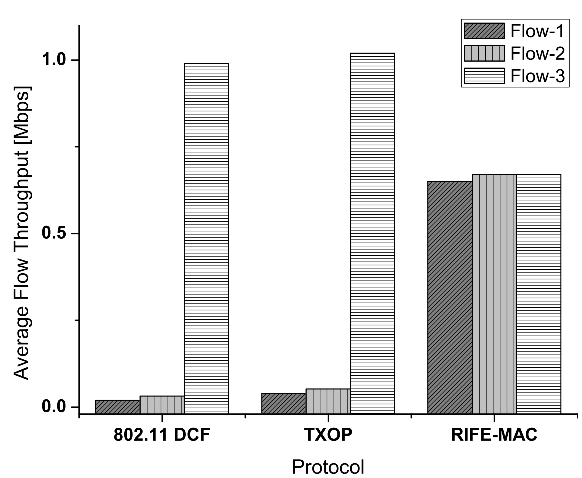
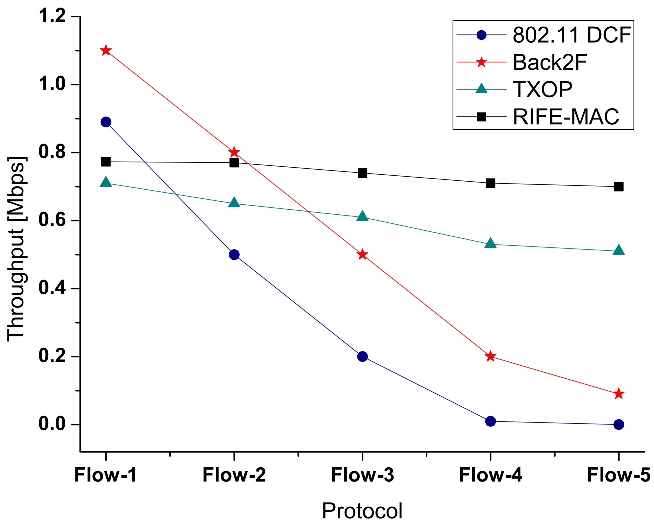
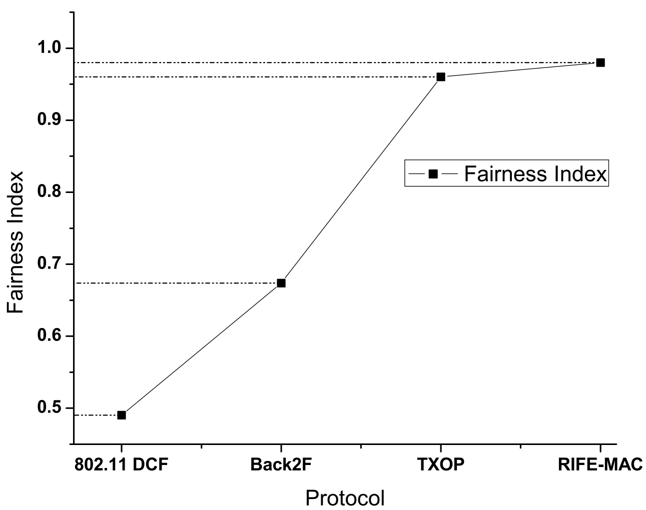


Fig. 9: Comparative network performance in RIFE-MAC at the presence of hidden terminals.



(a) Comparative per-flow throughput fairness of RIFE-MAC



(b) Comparative Fairness Index.

Fig. 10: Comparative Fairness efficiency of RIFE-MAC

B. *Throughput Efficiency*

To compare the throughput of RIFE-MAC with others, we run the experiment on random-placement topology with 25 different competing TCP flows originating form 20 MAPs, where each MAP operates under saturated traffic load. The figure 8 illustrates that average flow throughput and total network throughput of RIFE-MAC and others. As we can see, both average and cumulative throughput efficiencies in RIFE-MAC are higher than that of 802.11 DCF or TXOP. Successful contention resolution without long idle waiting and collision avoidance unlike DCF and TXOP makes RIFE-MAC stand out in such scenarios. However in this experiment, the Back2F outperforms RIFE-MAC by small margin. It is to be noted here that the Back2F does not require to transmit RTS and CTS frames during collision avoidance handshaking, since in Back2F every sender itself explicitly gets informed of the contention winner (e.g., minimum backoff value holder) at the cost of additional listening antenna and OFDM based specific PHY layer.Thus RIFE-MAC ensures significantly boosted throughput performance than 802.11 DCF and TXOP without assistance of additional infrastructure.

C. *Network Efficiency at the Presence of Hidden Terminals*

We conducted this experiment to measure the network performance of different protocols including RIFE-MAC on a topology containing hidden nodes. We placed 5 MAPs in which two sender MAPs transmit packets to a third MAP. The distances between these Senders to the common Receiver are the same and these two Senders are hidden to each other (i.e., the CCA check at each Sender almost always indicates a clear channel, even when the other Sender is transmitting packets). The flow-1 and flow-2, associated with these MAPs, are identified as having hidden node problems. On the other hand, there exits another flow called flow-3 between two remaining MAPs where no hidden terminal exists.

The simulation result for this experiment is shown in Figure 9. When we compare the flow throughput acquired by these three flows, we can see that when compared to non affected flow-3, both flow-1 and flow-2, upon encountering hidden terminal, achieve very low throughput except for RIFE-MAC. Because of the presence of hidden nodes and RTS/CTS collision, both TXOP and 802.11 DCF experience many data losses and long node queue with undelivered data. Whereas, in RIFE-MAC, no nodes solely rely on Carrier Sensing for contention resolution but on NSS which distributively resolves the contention. Thus in RIFE-MAC, hidden nodes can also avoid collisions since they have appropriate and updated neighborhood knowledge.

D. *Fairness Efficiency*

We conducted this experiment considering a string topology with five MAPs and one Gateway MAP shown in figure 11, where each of the MAP has a saturated traffic flow destined for Gateway MAP. Each flows uses the same parameters shown in table I. Figure 10a shows the uneven throughput distribution experienced by different flows in 802.11 DCF and Back2F protocol. In 802.11 DCF and Back2F, the flows originated from far e.g., flow-3, flow-4, flow-5 retains only a meagre average flow throughput than the closer flows e.g., flow-2 and flow-1. On the other hand, for TXOP and RIFE-MAC, the slopes of the curves are not as steep as the previous ones. Due to the effective use of NSS, RIFE-MAC outperforms TXOP

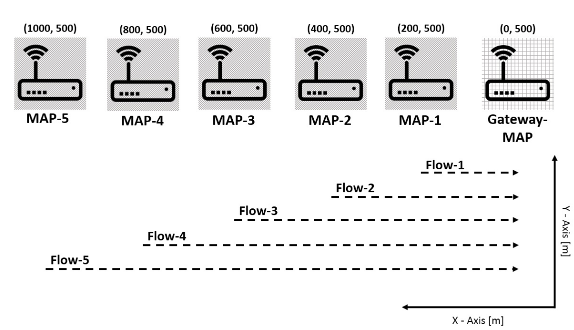


Fig. 11: Considered string topology in simulation

by ensuring almost equal throughput distribution among all flows in this experiment. Thus, the throughput distribution is partially fair in case of TXOP protocol and completely fair in our case. The figure 10b illustrates the calculated fairness index achieved by these protocols in this experiment. The fairness index, *FI* is calculated according to the equation (3) [16]. The X_i and n are the throughput achieved by a flow, $F_i = F^{x,s} \in F$ and the total number of flows in the network respectively.

$$FI = \frac{|\sum_{i=1}^{n} X_i|^2}{n * \sum_{i=1}^{n} {X_i}^2} \tag{3}$$

Evidently from figure 10, RIFE-MAC achieves nearly 99% per-flow throughput fairness. However, neither Back2F nor 802.11 could gain that level of fairness as their contention resolutions which depend on randomization to pick values. On the contrary, RIFE-MAC ensures strict fairness in terms of throughput by utilizing service experience history within neighborhood. Unlike TXOP, RIFE-MAC allocates the top most priority to the most disadvantaged flow during contention resolution and thus appears at the top of the Fairness Index.

VI. CONCLUSION

The main purpose of this work is to ensure improved channel access fairness and significantly boosted the overall network throughput. *Receiver-Initiated Fair and Efficient MAC (RIFE-MAC)* for IEEE 802.11 based WMNs, lets multiple flows to get fair chance to access channel as well as minimizes channel wastage and collision probability with simple but effective mechanism. Finally, we investigated the performance of *RIFE-MAC* using simulation in Network Simulator version-2 which corroborates our aforementioned claims more than other literatures.

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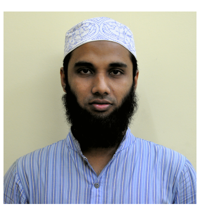

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