Abstract—The distributed coordination function (DCF) of the IEEE 802.11 standard based medium access control has drawn significant interest from the researchers in the past decade. Many proposals of its performance analysis and modifications to remove its limitations are proposed. In this paper we are considering some recent proposals to make a detailed study of the performance comparison between DCF, CONTI, k-EC, and PREMA, which are various contention resolution schemes proposed in various independent researches. The criteria for performance comparison that we use are collision rate, throughput, and average delay between successful transmissions. Also, we consider queuing delay using an exponential on-off based unsaturated model for these protocols whose implementation and performance is consistent with the saturated mode used in the above contention schemes.

I. INTRODUCTION

Within the last few years the world has encountered a huge revolution in technology, the Wi-Fi revolution, that has made access to the Internet mobile and more convenient. The ubiquitous presence of IEEE 802.11 standard based wireless devices has made it possible and so it draws a lot of attention from the researchers across the world. Wireless access today has become a necessity in our daily lives. Thus, majority of the computers and other mobile devices sold to consumers today come pre-equipped with the Wi-Fi functionality.

Being adopted in the year 1997, IEEE 802.11 was the first wireless LAN standard accepted worldwide [1]. It provides transmission in the 2.4GHz/5GHz band. The IEEE 802.11 series adopted a common MAC protocol that provided medium access schemes. The basic scheme was called distributed coordination function (DCF), which is a carrier sense multiple access protocol with collision avoidance (CSMA/CA) with binary exponential backoff. In the basic access mechanism, a device that wants to transmit a data packet waits until the channel is sensed free for an interval named distributed inter frame spacing (DIFS). However, if two stations detect the channel as free at the same time, a collision occurs. The 802.11 thus defines this collision avoidance basic mechanism that reduces the probability of such collisions. To do so, before transmitting, the device has to keep on sensing the channel for an additional random time after detecting the channel as being idle for a DIFS period. This period is determined by the binary exponential backoff algorithm. It chooses a random number from a uniform distribution in the range \( (0, w - 1) \), where \( w \) is called the contention window size. At the first attempt to transmit a packet, \( w \) is set to the minimum contention window size, \( CW_{\text{min}} \) and with every unsuccessful attempt to transmit a packet, the size of \( w \) doubles until a maximum size is reached for the range, \( CW_{\text{max}} = 2^m CW_{\text{min}} \), where \( m \) is the maximum retry stage. When a packet is successfully transmitted, \( w \) is reset to \( CW_{\text{min}} \). Once the backoff value is chosen, it will be decremented each time the medium is detected to be idle for an interval of one slot time. If any other node captures the channel during this backoff period, it halts its backoff counter and waits for the channel to remain free for another DIFS period. Otherwise, it transmits the data packet when its backoff counter reaches zero. Collision occurs if two devices select the same slot to transmit data and in such cases the corresponding retry counter increments and backoff interval increases. If the data has been successfully transmitted, the receiving station waits for a short inter-frame spacing time (SIFS) and then transmits an acknowledgement (ACK) message to the sender to confirm about the successful transmission.

Over the past decade, enormous research effort is invested to model and evaluate the performance of the IEEE 802.11 protocol [2], [3], [4], [5]. The limitations of the DCF have been identified [6] and many researchers have worked to improve the performance of these standards and proposed many new schemes [7], [8], [9]. We did extensive study of the 802.11 DCF mechanism and other recent proposals. Among them the PREMA [10], k-EC [11], and CONTI [12] are the most promising ones. Their saturation performance analysis is discussed in [12] and other related papers. But a detailed comparison of their unsaturated performance analysis is lacking. This paper undertakes analysis of both the saturation and non-saturation performance of these protocols based on an exponential on-off model. The comparison is based on the collision, packet transmission delay, queuing delay, and throughput for each of these protocols. To make a fair comparison among the schemes we use the physical layer parameters of the 802.11a/g standard.

II. PERFORMANCE METRICS

In this section, we define the parameters based on which we evaluate the performance and efficiency of the various contention resolution schemes in the saturated and unsaturated model. We draw a comparison between these schemes and do this based on the following criteria: collision rate, throughput, queuing delay, and packet transmission delay.
A. Collision Rate

When two nodes/stations try to transmit data packets over the same network at the same time, their packets collide and are lost or destroyed. This is known as collision. Collision rate is defined as the ratio of collisions to total transmissions. An increased rate of collision means higher number of re-transmissions and inefficient use of channel bandwidth. Every mechanism aims to reduce the probability of collision during transmission.

B. Throughput

This parameter indicates the average percentage of total time when the channel is used for transmitting the payload data. We have assumed a data rate of 36 Mbps for data packet transmission and 6 Mbps for control packet as well as MAC and PHY headers transmissions.

C. Packet Transmission Delay

In the unsaturated model, delay is defined as the time spent from when the frame arrives at a node’s transmission queue to the time when it is transmitted successfully. As the number of contending stations increases, it leads to less frequent transmission from the stations and thus the delay increases significantly. In the saturation model, we do not consider queuing delay but only the delay from the head of queue to the time it is successfully transmitted.

D. Queuing Delay

Queuing delay is the average time a packet has to remain in the queue to get the chance of being transmitted. So it is defined as the gap between the arrival time and the time when it reaches its head of queue. It is meaningless to consider queuing delay in saturation mode as the queue is always full.

III. RELATED RESEARCH WORKS

A. CONTI

This MAC scheme attempts to resolve contention in a constant time, and thus it is named CONTI. It is a jamming based scheme that works based on the following parameters: \( n \) - the number of contending stations, \( k \) - the number of backoff slots, \( p \) - probability vector used by the stations to decide whether to transmit a pulse or listen.

Before a contention slot occurs, a station must choose a signal based on a probability chosen from a probability vector of length \( k \). The probability of choosing a signal 1 (i.e., transmit a pulse) is \( p_i \) and that of choosing a signal 0 (i.e., listen) is \( 1 - p_i \). The \( i \)-th element of the probability vector corresponds to \( p_i \). All the nodes use the same probability vector. Each of the \( n \) stations chooses a signal based on this probability and contend over \( k \) slots. During a contention slot, a station with signal 1 transmits a jam, which is only a burst of energy and does not contain any actual data. A station with signal 0 listens to the channel. If it hears a jam, the station is eliminated from the contention. However, if it does not hear the presence of a jam, it stays in the contention and moves on to the next slot. At the last slot, the station(s) that remains transmits its data frame. If there is more than one station at this stage, their frames collide. In order to increase the efficiency of the scheme, the values of the parameters should be optimized.

Fig. 1(a) shows an example of this scheme. There are six contending stations. At the beginning of the contention, stations 2, 4, and 5 have chosen a signal 1 and thus preempt stations 1, 3, and 6 who have chosen a signal 0. In the second slot, these remaining stations choose signal 0 and thus they all listen to the channel, so no one is preempted. The stations move to the third slot where station 5 is preempted by stations 2 and 4. In the last slot, station 2 preempts station 4 and transmits its data frame successfully.

B. PREMA

Another contention resolution scheme goes by the name Prioritized Repeated Eliminations Multiple Access (PREMA), which is once again a jamming based protocol. All the stations contend to access a shared channel and this channel is slotted. In each slot, a station can perform one of two actions. It can either perform carrier sensing or it can send a burst onto the slot. Which action a station will perform depends on a probability parameter. When, for a slot \( i \), the probability is \( P(A_i = tx) = q_i \), the station transmits a short burst onto the channel. If the probability is \( P(A_i = cs) = 1 - q_i = p_i \), the station performs carrier sensing. If the station senses the channel busy, it is eliminated. If it senses the channel to be idle, it increases its idle slots counter by one. PREMA describes a parameter \( h \), and when idle slots = \( h \), the station has successfully eliminated all other stations and thus transmits its data frame. In a saturated model, we ignore the probabilities mentioned above and assume that all nodes want to send a packet. Each node will transmit a burst with length sampled from a geometric distribution with parameter \( q \) followed by a carrier sense slot.

An example is given below to illustrate how this mechanism works (Fig. 1(b)). In this example, \( n = 6, h = 4 \), and \( q = 0.5 \). At the beginning of the contention, all the stations wait for TIFS. After that they either perform carrier sensing or transmit a burst depending on the probability \( q \). In the example S2 and S5 perform carrier sensing and leave the contention as they find the channel to be busy. In the next slots, S3 and S6 are eliminated in the same way. Only S1 and S4 survive the first elimination and move to the second elimination round where S1 is eliminated. S4 performs two more eliminations and when its idle slots = \( h \), it transmits.

C. k-EC

The k-round Elimination Contention scheme is, like PREMA, a jamming based scheme. The basic idea of this contention resolution algorithm is to quickly reduce the number of contending nodes through elimination.

This scheme describes a parameter \( k \), which denotes the number of rounds of elimination and another parameter \( m \), which is the maximum number of slots. All the stations that are contending choose a random number uniformly in the range [0 to \( m - 1 \)] and transmit only one jam in that slot number. For
example, if a station chooses 0, it means that it sends a jam in the first slot. The station that is not jamming is listening to the channel by carrier sensing. If this station hears a jam it is out of the contention i.e., eliminated. The other stations move to the next slot.

This scheme is insensitive of the number of stations that are contending to access the channel. Thus it is very effective for use in large networks. Optimized values of $k$ and $m$ are used.

The authors use $k = 7$ and $m = 3$ as empirically obtained best parameters.

Fig. 1(c) illustrates an example of k-EC where $k = 6$. The black bar denotes the time when the medium is jammed.

IV. THE SATURATION MODEL

We present the simulation results for saturation performance of the aforementioned protocols in this section. We compare the performances of DCF, CONTI, PREMA and k-EC based on our simulation results. In order to carry out the simulations for the performance analysis of the schemes, we use the SimJava [13] simulation environment. SimJava is a discrete event simulation library for java.

A. Parameters

The physical layer we consider is the 802.11a/g [14]. In our simulations we are going to use the optimized parameters for each of the contention resolution schemes. For CONTI, we use the number of slots, $k = 7$ and probabilities, $p = \{0.18, 0.31, 0.40, 0.48, 0.48, 0.49, 0.49\}$. For PREMA, number of elimination rounds $h = 4$, geometric distribution parameter, $q = 0.5$, and for k-EC, number of rounds, $k = 7$, maximum length of a round, $m = 3$.

B. Percentage Collision

This part shows the percentage collision of the schemes. The results are shown in Fig. 2(a). We varied the number of stations from 1 to 50 and the results were taken for even number of nodes. We notice that the percentage collision is lowest for PREMA and k-EC. For PREMA, percentage collision varies between 0 to 2.14 percent and for k-EC, this value varies between 0 to 1.82. CONTI has a percentage collision that is slightly higher than these and goes up to 3.55 percent for 50 nodes. Finally, DCF has the highest value for percentage collision that can be as high as 50.42 percent.

C. Throughput

Above all other parameters, we need to understand the effect of increasing number of nodes on the normalized throughput for each of the contention resolution schemes. From Fig. 2(b), we can see that CONTI has the highest throughput although all the schemes have almost identical performances until up to 10 nodes.

From these plots we can draw a few conclusions. The first observation is that CONTI has the best performance in terms of throughput. DCF has similar performance as CONTI for low number of nodes but, its performance starts to fall as the number of nodes increases due to high collision rates. Secondly, PREMA and k-EC are behind DCF and CONTI in terms of throughput. However, k-EC’s throughput is slightly higher than that of PREMA as k-EC requires fewer slots with more number of stations.

D. Average Time Wasted in Contention Resolution

Average time wasted in contention is the amount of time spent or wasted in resolving the contention for each successful packet transmission. The lesser the time wasted in resolving the contention, the better is the contention resolution scheme.

Fig. 2(c) shows our simulation results for the average time wasted in contention for DCF, CONTI, PREMA, and k-EC. From the plots we can see that CONTI wastes the highest amount of time in contention resolution and this value rises steeply with increasing number of nodes. DCF and PREMA have somewhat similar results although at the very beginning with only a few numbers of nodes, all the four contention resolution schemes have similar values for time wasted in contention. k-EC shows the best performance as it wastes the lowest amount of time in contention resolution.

E. Delay

We also evaluated the delay of the four contention resolution schemes. Fig. 2(d) presents a comparison of the average delay. It shows that the delay increases as the number of contending nodes increases, as expected. This is because as the number of contending nodes increases the frequency of packet transmission decreases. With as small as 10 nodes, DCF and CONTI have the smallest delay because they have low collision rates and small number of slots. With increasing number of nodes the average delays of DCF, PREMA and
k-EC starts increasing. CONTI has a small advantage in the delay values over the other schemes.

F. Summary of Observations

From all the above plots and the conclusions that we have drawn, we can summarize that for saturation model, CONTI is the best contention resolution scheme compared to DCF, PREMA, and k-EC. In terms of throughput and Delay, CONTI has shown a very good performance as it had the highest throughput and lowest delay. Although k-EC and PREMA performs better than CONTI in terms of the collision rate and average time spent in contention, the main aim of a contention resolution scheme is to decrease collision but keep the throughput as high as possible, which, CONTI has managed to achieve. While CONTI loses in average time spent in contention, it more than makes up for it in terms of collision rate, throughput, and average delay.

V. THE UNSATURATED MODEL

The results discussed in the previous section was for the saturated model of a network where all the nodes in the network always have a data packet that it wants to transmit. In other words, the queue of a node is assumed never empty. In this part of the paper we consider an unsaturated model that is close to a real networking scenario where a given node does not always have a packet to send. The queue of a node will have a packet as soon as one is generated. In this case, we modify our codes so that a node will first check its queue for a packet that needs to be transmitted before sensing the medium idle for DIFS.

The generation of a packet follows an exponential distribution with parameter called a mean off-time. An off-time using this mean is chosen by the data generator of each node and it waits for this amount of time before pushing a data packet into the node’s queue. The data generator and node entities in the simulation environment work simultaneously and independently to be able to work according to our proposed model.

We study the behavior of the contention resolution schemes in three different scenarios where the mean off-times are 100, 1000 and 10000 µs respectively. In this section, we present the results of our simulation in the unsaturated model for DCF, CONTI, PREMA, and k-EC. We draw a comparison between the percentage collision, throughput, delay, average time wasted in contention, and average queuing delay for three different mean off-times.

A. Mean Off-time = 100 µs

Here the nodes will remain silent with an exponential distribution with mean = 100 µs and then a data packet will be generated. We will find that this data generation rate is actually too high to drive a node into saturation effectively.

1) Collision rate: As expected, the collision rate with mean off-time = 100 µs is similar to the saturated model as the generation time of the packets is very small. Fig. 3(a) shows that DCF has the highest rate of collision.

2) Throughput: With the number of nodes as small as 10, the throughput of DCF and CONTI are similar. As the number of nodes increases the performance of DCF degrades as the collision rate increases (Fig. 3(d)). CONTI has the highest throughput. PREMA and k-EC has a near constant throughput.

3) Delay: Even in the unsaturated model, DCF has the highest amount of delay with the exception that PREMA and k-EC now have a lower delay than CONTI (Fig. 3(g)).

4) Average time wasted in contention: For the unsaturated model, we also calculated the average time wasted in contention and the lower this time, the better the scheme. CONTI wastes the highest amount of time in contention as it sends jam for the entire seven slots (Fig. 3(j)). On the other hand, DCF and PREMA have similar results. k-EC wastes the least amount of time in contention.

5) Average queuing delay: Queuing delay is the time a packet spends in the queue. This time is measured from when the packet is pushed into the queue up until it reaches to the head of queue. The lesser the queuing delay, the better the contention scheme. From Fig. 3(m) we can see that DCF has the worst performance as the packets have to wait for a long time in queue. K-EC and PREMA show similar performance. CONTI has the best performance. As for this case, the nodes reach saturation very quickly, queuing delay becomes constant very quickly.

B. Mean Off-time = 1000 µs

Here, we will find that the network is moderately utilized. For, low number of nodes, much of the overall capacity of the network is wasted and gradually it reaches to saturation with the increase in number of nodes.

1) Collision rate: For mean off-time = 1000 µs, we can see that DCF has the highest rate of collision. CONTI, PREMA and k-EC show almost the same collision rate (Fig. 3(b)).
Fig. 3: Performance measurement of different protocols for IEEE 802.11 DCF.

2) Throughput: Fig. 3(e) shows the throughput comparison of DCF, CONTI, PREMA, and k-EC for mean off-time = 1000 µs. When the number of nodes is small, DCF and CONTI have similar throughput values. As the number of nodes increases, the throughput of DCF decreases as the collision rate increases. PREMA and k-EC have similar throughput values throughout. However, k-EC has an advantage over PREMA as it can eliminate maximum number of nodes in one elimination round. Overall, CONTI has the highest throughput.
3) Delay: DCF has the highest delay. CONTI, PREMA and k-EC have similar values for delay. With increasing number of nodes, the delay for k-EC decreases (Fig. 3(h)).  
4) Average time wasted in contention: For low number of nodes, all the four schemes waste almost the same amount of time in contention. As the number of nodes increase, CONTI has the highest amount of time wasted in contention (Fig. 3(k)).  
5) Average queuing delay: From the plots we can see that DCF has the worst performance as the packets have to spend a very high amount of time in queue before being transmitted. Whereas CONTI, PREMA, and k-EC, the queuing delay is very low. For DCF, the delay goes up to 680.52 $\mu$s whereas for k-EC the delay is 18 $\mu$s which is the lowest (Fig. 3(n)).  

C. Mean Offtime = 10000 $\mu$s  
For such high values of off-time, we will find that the network is underutilized except of high number of nodes.  
1) Collision rate: The lower the collision rate, the better the contention resolution scheme. In the above plots, we can see that DCF has a very high collision rate whereas the collision rates for CONTI, PREMA and k-EC are very low. The collision rate for DCF increases steeply with the increase in number of nodes (Fig. 3(c)).  
2) Throughput: Almost up to 40 nodes, DCF has the highest throughput. However, from 40 nodes onwards the throughput of DCF decreases and we see an increase in the throughput of CONTI, PREMA and k-EC. When the number of nodes is 50 and above, CONTI gives the best throughput result (Fig. 3(f)).  
3) Delay: As the number of nodes increases, the delay for DCF is ever increasing. On the other hand, the delay for CONTI, PREMA and k-EC is relatively very low and thus these three schemes are better in terms of delay (Fig. 3(i)).  
4) Average time wasted in contention: DCF wastes the maximum amount of time in contention. For only a few nodes, CONTI gives a good performance in terms of time wasted in contention. When the number of nodes is larger, k-EC takes lesser time (Fig. 3(l)).  
5) Average queuing delay: The time spent by packets in queue in the DCF scheme is very high compared to the other schemes. CONTI shows the best performance (Fig. 3(o)).  

D. Summery of Non Saturation Performance Analysis  
The first set of results where we used the parameter of 100 $\mu$s off-time was to verify that our proposed unsaturated model behaves similarly to the saturated model with the assumption that a very small off-time will produce near identical results. The remaining two sets of results with parameters 1000 $\mu$s and 10000 $\mu$s off-time were to check if the results of the unsaturated models were consistent with respect to parameter changes. In our findings we observe that we get the expected results with just a few deviations.  
Across all scenarios, we find that CONTI outperforms the remaining contention schemes in terms of throughput and delay. CONTI performs worst when it comes to average time spent in contention and this eventually hampers a potentially greater throughput that can be achieved with this scheme had it not been for the time wasted in contention. Although k-EC outperforms CONTI in terms of contention, average delay and time wasted in contention, its throughput, which is a major contributing factor to the success of a scheme, is very poor. PREMA performs similarly to k-EC except k-EC is better than PREMA. As expected, DCF performs poorly on all accounts except for its throughput and time wasted in contention compared to k-EC and PREMA when the medium is fairly busy. But when the medium is very underutilized, DCF can outperform all three proposals.  

VI. CONCLUSION  
Despite its drawbacks and scopes for improvements, IEEE 802.11 has remained relatively unchanged over the past decade. Many proposals have been made for its performance improvement, but IEEE 802.11 DCF has survived for its simplicity, fairness and ad hoc deployment capabilities. In this paper, we have considered some strong DCF schemes to improve IEEE 802.11 and simulation studies show their comparison for both saturated and unsaturated models. All the proposals in this paper confirm the benefits of fairness and ad-hoc capacity of IEEE 802.11 DCF, thereby suggesting further research in the area of improving future IEEE 802.11 DCF versions.  

REFERENCES  