Analytical Modeling of Enhanced IEEE 802.11 with Multiuser Dynamic OFDMA under Saturation Load

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***Abstract*—Multiuser dynamic OFDMA based IEEE 802.11 distributed coordination function (DCF) has received significant interest from the researchers in recent time. Though several proposals have been made, to the best of our knowledge, none of these have presented an analytical model for this kind of medium access control protocols for IEEE 802.11. This paper provides a simple, nevertheless, very accurate analytical model to estimate the performance characteristics of IEEE 802.11 DCF with OFDMA under the assumptions of ideal channel conditions and saturation load. Our model accounts for important system parameters like throughput, collision rate, transmission delay, average contention window size, average retry count and average time wasted in backoff. Analytical results are verified through extensive simulations.**

I. INTRODUCTION

Wireless local area networks (WLAN) based on the IEEE 802.11 standard is playing a very effective role in providing wireless connectivity at homes, offices, and public places. The fundamental medium access control (MAC) for IEEE 802.11 is distributed coordination function (DCF), which is a carrier sense multiple access protocol with collision avoidance (CSMA/CA). Since its inception in 1997, it has seen several modifications to improve its performance. Technology used in its physical layer (PHY) has been changed significantly. Finally, orthogonal frequency division multiplexing (OFDM) is dominating as the PHY nowadays. In OFDM systems, subcarriers or tones are orthogonal signals of lower-rate input data streams. It results in longer symbol duration compared to the channel delay spread to mitigate multipath effects. For its benefits (frequency diversity, spectral efficiency, low inter symbol interference, etc.), OFDM will remain as the basic prevailing transmission scheme in the future standards that IEEE is now developing.

Significant research efforts have been invested to improve the performance of IEEE 802.11. Multiple input multiple output (MIMO) can incorporate concurrency by enabling nodes to receive n data streams in parallel [1] or eliminate interference from as many as $(n-1)$ neighbors [2]. But it requires the nodes to have at least n antennas and consumes higher energy. Another approach to obtain concurrency is to use OFDMA (Orthogonal Frequency Division Multiple Access). In OFDMA, a group of non-overlapping subcarriers, called sub-channels, are assigned to each user to enable simultaneous multiple data transmissions to a base station or vice versa. Preserving the benefits of OFDM, it can enhance the efficiency of the PHY layer by exploiting frequency diversity, multiuser diversity, adaptive modulation and coding (AMC) and decreasing peak to average power ratio, which is a major drawback in designing OFDM based hardware. WiMAX is using it from the very beginning. IEEE 802.11 can also be benefitted from it. Using OFDMA, we can incorporate multiple concurrent transmissions or receptions in IEEE 802.11 and make more efficient use of the available bandwidth.

There are many works on synchronization [3], spectrum allocation [4] and signaling [5] in OFDMA based systems. But few works discussed about implementing OFDMA in IEEE 802.11. Valentin *et al.* [6] discussed the issues that are needed to be considered to implement OFDMA in IEEE 802.11. Another paper of them [7] described a practical implementation of their proposed system in a real software radio test-bed and showed the effectiveness of their design. They discussed about the MAC and LLC (Logical Link Control) sublayer extensions required for implementing OFDMA, a fair and optimized policy for physical protocol data unit (PPDU) fragmentation, and sub-channel allocation for the nodes. The main drawback of their work is that they considered only downlink traffic, i.e., data is sent from the access point to the wireless stations only. They verified their proposal with simulations but did not show any mathematical analysis. We extended their work to support uplink and thus proposed a complete sub-channelized DCF for IEEE 802.11 based WLANs.

Veyseh *et al.* [8] proposed their DCF named CTRMA (Concurrent Transmission or Reception Multiple Access) and compared their work with single-radio single-channel, single-radio multi-channel, and multi-radio multi-channel MAC protocols and found the superiority of their proposal in terms of network throughput. The main drawback of their CTRMA protocol is that, it requires extensive message exchange between the users, in order of $O(d^2C)$ where d is the average number of neighbors and C is the number of sub-channels. Again, message exchange is required every time the network topology changes. They showed very little experimental results and their performance comparison is based on network throughput only. They did not discuss about the average delay or other performance metrics of their system. They assumed a separate control channel for RTS/CTS exchange and information negotiation, which decreases the available data bandwidth. This control channel is narrower than the data channel. So, probability of congestion and collisions in this channel may increase.

In our earlier work [9], we showed some insight about the collision avoidance scheme of IEEE 802.11 DCF and pointed the inherent reasons for its inefficiency. We proposed an OFDMA based MAC for IEEE 802.11 that can support both uplink and downlink. We empirically showed the superiority of our proposed DCF in terms of throughput and delay for saturation load without developing any analytical model. In this paper, we develop a novel Markov chain model for our proposed sub-channelized DCF and analyze the system's performance metrics for saturation load. Based on this model, we will be able to find the collision rate, throughput, average delay, retry count, and other important performance measures. Our analysis focuses light on the important aspects of the system along with close match with the simulation results.

We organize our work into the following sections. Section II discusses about the existing works on performance analysis of IEEE 802.11 DCF. In Section III, we present our approach for incorporating OFDMA in IEEE 802.11 and performance analysis of our sub-channelized MAC. Section IV validates the accuracy of our model by comparing the analytical results with that obtained by means of simulations. Finally, in the concluding section, we consolidate our work and state our future research directions in this area.

II. PRESENT IEEE 802.11 DCF

There have been numerous papers that discussed about the performance of IEEE 802.11 DCF through simulations as well as analytical studies. In his seminal paper [10], Bianchi proposed a very accurate analysis based on realistic assumptions. He modeled IEEE 802.11 DCF using a discrete-time Markov chain. His work is used and verified by Sharma *et al.* [11] and many others. But his analysis is limited for single channel DCF only. Sub-channelized DCF like the one we proposed in [9] requires additional analysis of the system. We will extend Bianchi's model to evaluate the performance of our sub-channelized MAC for IEEE 802.11.

Based on the assumption of constant and independent collision probability p of a packet transmitted by each station, Bianchi found the probability τ that a station transmits in a randomly selected slot and the collision probability p, given a station transmits. One can solve these two equations numerically in the range [0,1] to get the value of τ and p for any number of nodes and use it to obtain the normalized throughput S. His analysis matches almost perfectly with the observed throughput of IEEE 802.11 [12]. It follows from his analysis that as the number of contending nodes increases, IEEE 802.11 DCF can no longer be deemed efficient.

We can understand the reasons behind this inefficiency of IEEE 802.11. Wireless channel is inherently broadcast in nature. Nodes are half-duplex, so they need RTS/CTS mechanism to avoid collisions in large data packets. Again, physical layer convergence protocol (PLCP) header and preamble as well as all the control messages like RTS, CTS and ACK are sent at the lowest data rate (6 Mbps) so that all the nodes can decode it while data can be transmitted at a maximum rate of 54 Mbps (802.11a/g). So, these control messages, though quite small, occupy a significant portion of the transmission time available. According to the analysis shown in [10], RTS collision probability is not negligible, even for moderate number of nodes. Time is also wasted during backoff, DIFS and SIFS intervals. For every successful packet transmission, 195 μs is wasted to exchange these control messages and inter frame spacing times, in addition to the backoff period. Collisions also increase the wasted time in backoff by increasing the contention window size. For every RTS collision, at least another 98 μs is lost. This wastage is not negligible when the number of nodes increases and we need to find a way to reduce this inefficiency of IEEE 802.11 DCF.

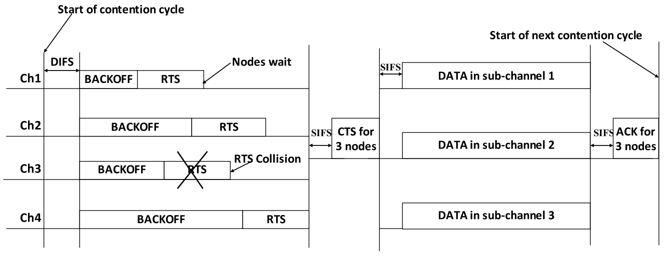

Fig. 1: The proposed DCF.

III. ANALYSIS OF THE PROPOSED DCF

A. The Proposal

In [9], we proposed a sub-channelized DCF based on the fact that the probability of collision decreases significantly when the number of sub-channels increases. With the help of *Birthday Problem*, we showed that the probability of k or more collisions for our sub-channelized DCF is always less than that of a single channel DCF. Of course, introducing sub-channelization adds some overhead. First of all, as RTS transmissions of different groups need to be synchronized, some bandwidth is unused in the contention cycle. Again, as bandwidth is shared among multiple nodes in the data cycle, average delay for each packet transmission may increase. In [9], our simulations showed that, for saturation load, gain of sub-channelization overcomes the overhead of it. Average transmission delay and collision in RTS messages effectively decrease while throughout increases to a significant extent. Before we propose a complete analysis of our proposed DCF, let us restate it briefly in the following steps. For a complete description, please see [9].

1) Access point (AP) determines the set of associated nodes and divides them into multiple groups. Nodes in the same group share the same frequency sub-channel and contend among themselves to capture the channel as in IEEE 802.11 DCF.
2) After transmitting RTS, the sender(s) waits for CTS. Other nodes in its group halt their backoff until the next contention cycle starts so that there can be no more than one successful RTS sent from one group in one contention cycle. The contention cycle ends as soon as each group has transmitted an RTS (successful/unduccessful).

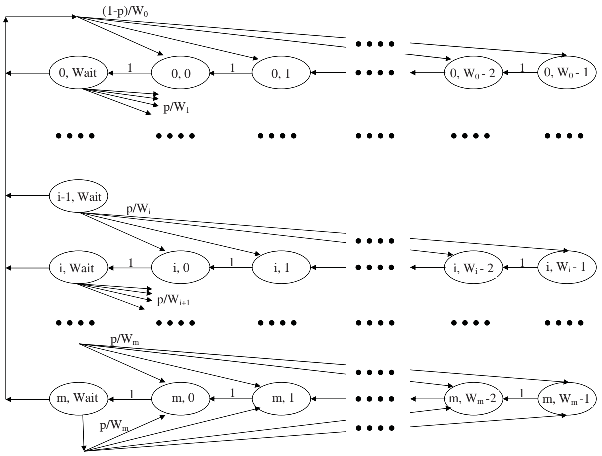

Fig. 2: Markov model of the proposed DCF.

3) AP calculates the subcarrier assignment using some allocation algorithm described in [4]. Then it informs the nodes that have successfully completed RTS transmission about the assigned subcarriers using one consolidated CTS.
4) After waiting SIFS time, nodes transmit data simultaneously using their assigned subcarriers.
5) Finally, after waiting SIFS time, AP transmits ACK in a single message.

We can summarize our proposed DCF in Fig. 1.

B. Markov Model of the Proposed DCF

Let $b(t)$ be the stochastic process representing the backoff counter value for a given station. Backoff counter of the nodes decreases at the beginning of each slot time. As the value of the backoff counter depends on its backoff stage, $b(t)$ is non-Markovian. Now, let us denote $W = CW_{min}$, m as the maximum backoff stage such that $CW_{max} = 2^m W$, and backoff window size at i-th stage is $W_i = 2^i W$, $i \in (0, m)$. Let $s(t)$ be the stochastic process representing the backoff stage $(0, \dots, m)$ of a station at time t. If we assume that each packet collides with constant and independent probability p regardless of its backoff stage, it is possible to model the bidimensional process $\{s(t), b(t)\}$ with the discrete-time Markov chain depicted in Fig. 2. The one step transition probabilities for this Markov chain are

$$\begin{array}{lll}
P\{i,k \mid i,k+1\} = 1 & k \in (0, W_i - 2) & i \in (0,m) \\
P\{i, Wait \mid i, 0\} = 1 & i \in (0,m) & \\
P\{0,k \mid i, Wait\} = \frac{(1-p)}{W_0} & k \in (0, W_i - 1) & i \in (0,m) \\
P\{i,k \mid i-1, Wait\} = \frac{p}{W_i} & k \in (0, W_i - 1) & i \in (1,m) \\
P\{m,k \mid m, Wait\} = \frac{p}{W_m} & k \in (0, W_m - 1). &
\end{array} \tag{1}$$

We adopt the short notation $P\{i_1, k_1 \mid i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1 \mid s(t) = i_0, b(t) = k_0\}$. The first equation in (1) says that at the beginning of each slot time, the backoff counter is decremented. The second equation says that when the backoff counter of a node reaches 0, it transmits RTS and enters into a *waiting stage* as discussed in the previous chapter. From the waiting stage, it can go to backoff stage 0 if no collision has occurred during its RTS transmission (3rd equation). Otherwise, it moves into the next backoff stage (4th equation). Finally, the last equation in (1) says that once the backoff stage reaches m, nodes stay there until it can complete a successful transmission.

Let $b_{i,k} = \lim_{t \to \infty} P\{s(t) = i, b(t) = k\}$, $i \in (0, m)$, $k \in (0, W_i - 1)$ be the stationary distribution of the Markov chain and $b_{i,Wait}$ be the steady state probability of being in the wait states. To calculate the closed form solution for this Markov chain, first note that

$$\begin{array}{ll}
b_{i,Wait} = b_{i,0} & 0 \le i \le m \\
b_{i-1,0} \cdot p = b_{i,0} \rightarrow b_{i,0} = p^i \cdot b_{0,0} & 0 < i < m \\
b_{m-1,0} \cdot p = (1-p) b_{m,0} \rightarrow b_{m,0} = \frac{p^m}{1-p} b_{0,0}. &
\end{array} \tag{2}$$

So, because of the chain regularities, for each $k \in (0, W_i - 1)$,

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} (1-p) \sum_{j=0}^{m} b_{j,0}, & i = 0; \\ p \cdot b_{i-1,0}, & 0 < i < m; \\ p \cdot (b_{m-1,0} + b_{m,0}), & i = m. \end{cases} \tag{3}$$

By using (2) and the fact that $\sum_{i=0}^{m} b_{i,0} = b_{0,0}/(1-p)$, (3) can be rewritten as

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \qquad i \in (0, m) \qquad k \in (0, W_i - 1). \tag{4}$$

So, all the values of $b_{i,k}$ can be represented using $b_{0,0}$ and p. Now if we impose the normalizing condition,

$$1 = \sum_{i=0}^{m} \Big(\sum_{k=0}^{W_i - 1} b_{i,k} + b_{i,Wait} \Big) \tag{5}$$

we can find,

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+3) + pW(1-(2p)^m)}. \tag{6}$$

Introducing the *wait state* after each $(i, 0)$ state has increased the denominator of $b_{0,0}$ by introducing $(W + 3)$ instead of $(W + 1)$ in [10]. As expected, the value of all the $b_{i,k}$ decreases a little bit. RTS transmission occurs when the backoff counter reaches zero. So, we can find the probability τ that a node transmits in a randomly chosen slot,

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{2(1-2p)}{(1-2p)(W+3) + pW(1-(2p)^m)}. \tag{7}$$

As the nodes are divided into multiple groups, the number of contending nodes in a sub-channel is decreased; consequently the value of τ decreases slightly than in [10]. It does not vary much as we are considering saturation load. Now, in case of our sub-channelized MAC, a node contends with other nodes in its group only. If there are n nodes and c sub-channels, then the i-th sub-channel has $n_i = \lceil n/c \rceil$ nodes, for $i \le n$ mod c, or $\lfloor n/c \rfloor$ nodes, otherwise. So, the collision probability becomes [1]

$$p = 1 - (1-\tau)^{n/c - 1}. \tag{8}$$

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[1] We use the general notation of n/c to mean $\lceil n/c \rceil$ or $\lfloor n/c \rfloor$, whichever appropriate.

Equation (7) and (8) represent a non linear system of two unknowns - τ and p, which can be solved using numerical techniques. It is easy to prove that this system has a unique solution. Inverting 8, we obtain $\tau^*(p) = 1-(1-p)^{1/(n/c-1)}$. This equation is a continuous and monotonically increasing function of p in the range $(0,1)$ with $\tau^*(0) = 0$ and $\tau^*(1) = 1$. Equation (7) is also continuous in the range $p \in (0,1)$ as the alternate form of this equation is valid for the critical value of $p = 0.5$

$$\tau(0.5) = \frac{2}{2+W+mW/2}. \tag{9}$$

From (7), $\tau(p)$ is a monotonically decreasing function of p starting from $\tau(0) = 2/(3+W)$ to $\tau(1) = 2/(3+2^m W)$. So, equation (7) and (8) can be solved numerically to obtain the unique values of τ and p for any values of n and c.

Now, let us analyze what can happen in a randomly chosen slot. Let P_{tr} be the probability that there is at least one transmission in that slot. As n/c nodes are now contending in a group and each of them transmits with probability τ,

$$P_{tr} = 1-(1-\tau)^{n/c}. \tag{10}$$

So, the probability P_s that a slot contains a successful transmission is given by the probability that exactly one station transmits in a sub-channel, conditioned on the fact that at least one station transmits, i.e.,

$$P_s = \frac{(n/c)\tau(1-\tau)^{n/c-1}}{P_{tr}} = \frac{(n/c)\tau(1-\tau)^{n/c-1}}{1-(1-\tau)^{n/c}}. \tag{11}$$

We will now use this analysis to calculate important performance measures of our proposed DCF.

C. Saturation Performance Analysis

Based on our Markov chain model, we can find the expected number of RTS messages per channel in each contention cycle.

$$E[RTS] = \sum_{j=1}^{n_i} j \cdot \frac{{}^{n_i}C_j \tau^j (1-\tau)^{n_i-j}}{P_{tr}}. \tag{12}$$

We can also estimate the expected number of CTS message from one contention period in our sub-channelized DCF, $\overline{r} = c \cdot P_s$.We will use this value to estimate the amount of data transmitted in one cycle. But to analyze the throughput, we also need to find the expected duration of the contention period. As our DCF requires at least one RTS transmission (successful or unsuccessful) from each sub-channel, we need to find the expected slot time at which the last RTS is sent. This analysis is also applicable for standard IEEE 802.11 if we calculate the value of τ from [10] instead of (7).

First, as the collision probability is p, the probability of a successful transmission is geometrically distributed and it requires each node to try $1/(1-p)$ times on average to transmit a packet successfully. So the average number of retransmissions is $p/(1-p)$. Then the expected contention window size is:

$$\overline{W} = E[\text{Contention Window Size}] = 2^{p/(1-p)} \cdot W. \tag{13}$$

TABLE I: IEEE 802.11 a/g OFDM PHY Parameter Set

Parameter	Value	Parameter	Value
Maximum Retry Stage (m)	5	CW_{min}	32
Propagation Delay (δ)	1 μs	CW_{max}	1024
Symbol Duration (γ)	4 μs	SIFS	10 μs
Basic Bit Rate (BBR)	6 Mbps	DIFS	28 μs
Maximum Bit Rate (BR)	54 Mbps	EIFS	37 μs
tPCLPPreamble	16 μs	Slot Time (σ)	9 μs
MACHeader	272 bits	tPCLPHeader	4 μs

Each node randomly selects its backoff counter from these $\overline{W}$ slots with uniform distribution. So we can estimate the expected value of the last slot selected among all the groups

$$E[\text{Last Slot}] = \sum_{i=0}^{\overline{W}-1} i \cdot (P(x \le i) - P(x \le (i-1))) \tag{14}$$

where

$$P(x \le i) = (1-(1-i/\overline{W})^{n/c})^c. \tag{15}$$

So, the expected contention time is,

$$T_{cont} = DIFS + \sigma \cdot E[\text{Last Slot}] + T_{RTS} + \delta + SIFS + \delta. \tag{16}$$

Here T_{RTS} is the time required to send an RTS message. We can also find the time used for transmitting data

$$T_{data} = T_{CTS} + SIFS + \delta + T_{MPDU} + SIFS + \delta + T_{ACK}. \tag{17}$$

Time for transmitting control messages and data packets in our system can be calculated using the following equations. We have assumed payload size of 1024 bytes and data rate of 36 Mbps for MAC layer frames. PLCP preamble and header (except the service and the tail bits) must be transmitted using the lowest data rate (6 Mbps). All the parameters should be calculated using the same time unit (μs for our case).

$$\begin{aligned} T_{RTS} &= 20c + 22.75\gamma c/3 \\ T_{CTS} &= 20 + (16.75 + 8\overline{r})\gamma/3 \\ T_{Payload} &= 1024\overline{r}\gamma/18 \\ T_{MPDU} &= 20\overline{r} + ((36.75 + 1024)\overline{r})\gamma/18 \\ T_{ACK} &= 20 + (16.75 + 6\overline{r})\gamma/3. \end{aligned} \tag{18}$$

Physical layer parameters used to get analytical results are described in Table I [13]. We can calculate the saturation throughput S using all these values that we have derived.

$$S = \frac{T_{Payload}}{T_{cont} + T_{data}}. \tag{19}$$

As there are $\overline{r}$ successful transmissions in one cycle, we can also calculate the average time required for each packet to be transmitted successfully.

$$T_{Packet} = \frac{T_{cont} + T_{data}}{\overline{r}}. \tag{20}$$

From this, we can calculate the number of packets that the system can serve in a given time. The number of CTS and data packets transmitted in one time unit,

$$N_{CTS} = \frac{\overline{r}}{T_{cont} + T_{data}}. \tag{21}$$

We will now use this analysis to estimate the transmission delay for a packet from when it is in the head of queue (HoQ) of its corresponding node. Note that there are n contending nodes and we are considering saturation load. So, if we assume that all the nodes will share the medium fairly, then the average time after which a node will be able transmit a packet can be calculated as

$$T_{Delay} = n \cdot T_{Packet}. \tag{22}$$

We will see the validity of our analysis through extensive simulations in the next section.

IV. SIMULATION RESULTS

To analyze the performance of our proposed DCF, we developed a discrete event driven simulation using SimJava2 [14] and examined every aspect of our system. We assumed perfect channel conditions so that we can consider only the impact of our modifications. We tried to remain close to the IEEE 802.11 a/g protocol. We varied the number of nodes from 1 to 50 and experimented with 2, 4, 8, and 16 sub-channels to examine the performance of our proposed DCF.

Fig. 3(a) shows the number of RTS message in a unit time vs. the number of nodes present in the system. In all cases, the number of RTS message increases as the number of nodes increases. But, for the same number of nodes, total number of RTS message decreases as we increase the number of sub-channels. This is due to the fact that as c increases, less time is wasted in contention cycle and less RTS messages are wasted in collisions. We will see in the next figure that the total number of successful RTS message increases when we increase c.

Fig. 3(b) shows that the number of CTS message in a unit time increases significantly as we increase the number of sub-channels, i.e., the system can handle more amount of data in a unit time. When there are too few nodes, number of CTS message is low. Then it increases to its maximum and stays there as we are considering saturation load. When the number of nodes contending in a sub-channel is very large (say greater than 15), number of CTS message starts to decrease slightly. Data throughput is directly related with the number of CTS message and we can see a similar trend in Fig. 3(c). Surprisingly, we found that traditional 802.11 uses the channel to transmit payload data for only 44% of the total time on an average, whereas we can easily reach up to 65%.

Then we can consider the rate of collisions in RTS messages. We can see from Fig. 3(d) that as the number of nodes increases, collision increases rapidly and it can be as high as 53% with single channel DCF. Introducing sub-channelization can effectively decrease collisions and save available transmission time and power. Collisions have further impact on contention window size, which is doubled each time a collision occurs, until it reaches its maximum. In traditional IEEE 802.11, we can see that the average contention window size is much higher than our proposed protocol (Fig. 3(e)). The impact of collisions is also reflected in the average number of transmissions that a node needs to make in order to transmit a packet successfully. Fig. 3(f) shows that in our proposed DCF, we need much less retransmissions and thus save transmission power and time.

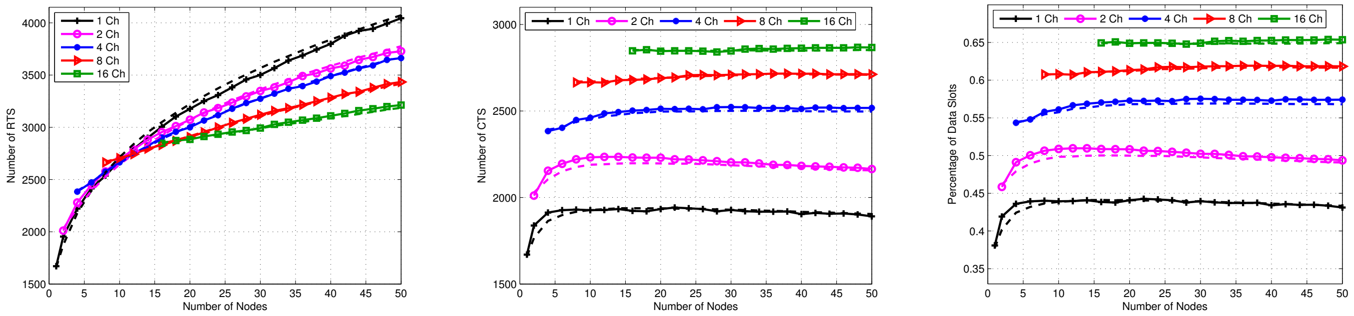
Now let us consider the time wasted in backoff. Our protocol requires at least one RTS transmission from each sub-channel in each contention cycle, so there is some overhead. From (Fig. 3(g)), we can see that the time that the nodes require to stay in the contention cycle increases as we increase the number of sub-channels, c. But at the same time, we have saved $(c-1)$ inter frame spacing times and have transmitted $\overline{r}$ data packets. So, the average backoff time wasted to successfully transmit one data packet does not vary much. In fact it decreases for higher values of n and c (Fig. 3(h)). The experimental values here are a little bit deviated from the theoretical analysis. This is because when multiple nodes with different contention window size select their backoff slots, the node with the lower contention window size has higher probability of winning the bid. But in our theoretical analysis, we assumed that all the nodes have the same contention window size. As the number of nodes in a sub-channel increases, this discrepancy is reduced. We will work to find a better approximation of the backoff period in future, but for now, this deviation is very insignificant compared to the packet transmission delay and has almost no impact on other parameters that we have formulated.

As our final performance metric, we consider the time between when a packet reaches its head of queue to the time it is successfully transmitted in Fig. 3(i). We can see that the benefits of our proposed DCF overcome the overhead in backoff and the transmission delay effectively decreases.

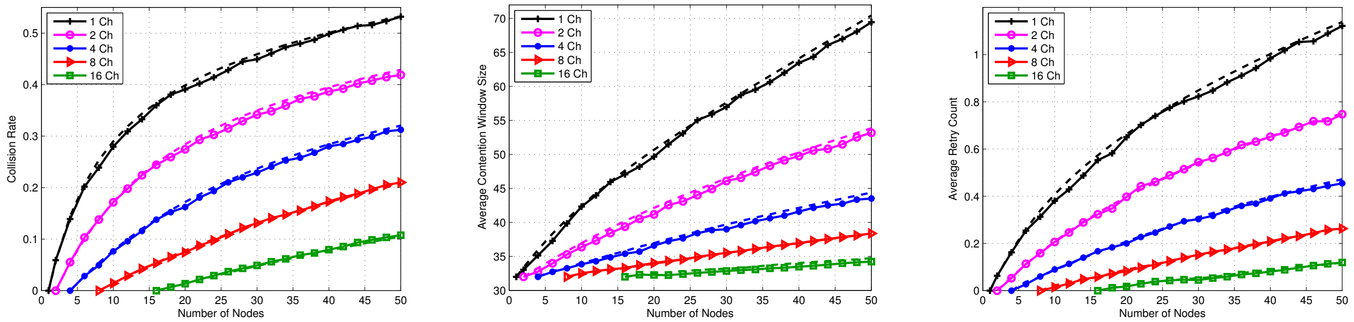
All these experiments shows that by reducing collisions and saving the wasted time in inter-frame spaces, we can reduce the transmission delay by up to 30% and increase the throughput by up to 50%. Our theoretical analysis matches very closely to the simulation results in most of the cases and the graphs are almost identical. We can hope that incorporation of adaptive modulation ad coding will increase the throughput of our new DCF further.

V. CONCLUSION

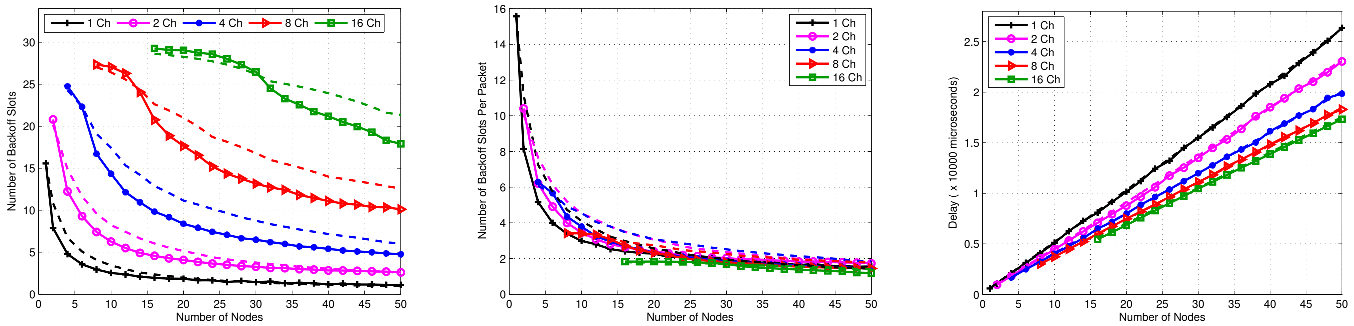
In this paper, we have presented a simple analytical model to evaluate the saturation performance of a sub-channelized DCF for IEEE 802.11. Comparison with simulation results shows that the model is extremely accurate in predicting the system's performance metrics. We have demonstrated that dividing the nodes into discrete groups and allowing multiple concurrent transmissions can significantly reduce collisions in IEEE 802.11 DCF and improve the performance of the wireless LAN. We are now working to model the system for imperfect channel conditions and non-saturation load. In that context, determining the optimal number of sub-channels and efficiently allocating nodes to them remain as a major research challenge.



(a) Number of RTS message per second (b) Number of CTS message per second (c) Percentage of data slots



(d) RTS collision rate (e) Average contention window size (f) Average no. of retransmissions per packet



(g) Duration of backoff period per cycle (h) Duration of backoff period per packet (i) Packet transmission delay

Fig. 3: Performance measures of the proposed DCF. Analytical results are shown using dotted lines of the same color.

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