Throughput Formulation and WLAN Optimization in Mixed Data Rates for IEEE 802.11 DCF Mode

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***Abstract*— Analytical throughput formulation introduced for DCF considers stations operate in the same data rates. We introduce a novel method to find the individual throughput of a station when the stations have different signal to noise ratio levels, hence transmit at different rates. The model uses analytical Markov model for DCF and formulation is verified by the simulation.**

I. INTRODUCTION

IEEE 802.11 introduces two different MAC protocols: Distributed Coordination Function and Point Coordination Function. Distributed Coordination Function (DCF) is a contention based MAC protocol and underlying mechanism is CSMA/CA. DCF implements a contention based algorithm in which station senses the channel and transmits if it is idle, otherwise backs off a random interval. After transmitting, station waits for ACK packet to make sure that its transmission is successful. In order to overcome hidden node problem, before data transmission, medium can be reserved by sending RTS packet and data transmission is initiated after getting CTS packet from the RTS addressee. An illustration of the DCF for six stations is in Figure 1. As can be seen from the figure medium is quantized as either an empty slot or transmission. Transmission is either successful or collision. An analytical semi-discrete Markov Model can be constructed by defining events either an empty slot or transmission. Markov Model used here is different than the one in [1], the difference comes from the event definition where in [1] events are either an empty slot or a transmission + empty slot which assumes no consecutive transmission.

Markov Model is seen in Figure 2 where the backoff levels are represented as W_i and $W_i = 2^i CWmin$ for $i < m$ and $W_m = CWmax$. Contention window (CW) limits are determined by the physical layer chosen.

Markov Model assumes that the stations are independent. True model has dependencies between stations since if a station transmits, it is a signal for the other stations to suspend. In order to make the independent assumption reliable, wireless medium has two state Markov chain which are busy and idle and wireless medium traverse from idle to busy with probability p. Therefore channel is not busy with probability $1 - p$. Following the figure, states in the Markov model can be defined as $b_{i,j}$ for $0 \leq i < m$ and $0 \leq j < W_i$. Station transmits when it is in $b_{0,j}$.

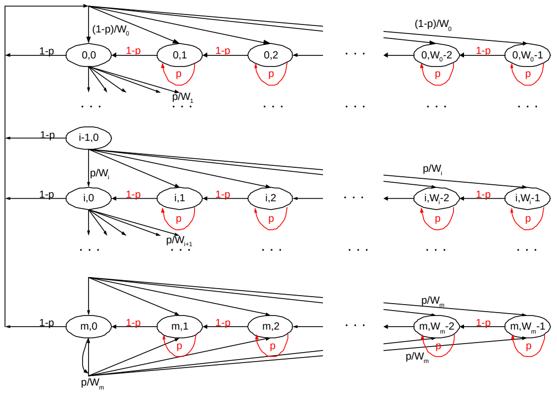

Fig. 2. Markov Model of 802.11 for Multi Level Backoff

Total probability is represented as follows,

$$1 = \sum_{i=0}^{m} \sum_{j=0}^{W_i - 1} b_{i,j} \tag{1}$$

and probability of transmission τ can be found after solving the balance equations as

$$\tau = \frac{1}{\frac{(1-2p)(W+1)+pW(1-(2p)^m)}{2(1-2p)(1-p)}} \tag{2}$$

where τ depends on p. If there are n number of stations, p is coupled with τ as in $p = 1 - (1 - \tau)^{n-1}$ considering the independent assumption.

Following [1], "the throughput is the fraction of time the channel is used to successfully transmit payload bits." Define the probability P_{tr} that there is at least one transmission in the considered slot time and the probability P_s that a transmission occurring on the channel is successful as

$$\begin{aligned} P_{tr} &= 1 - (1 - \tau)^n \\ P_s &= n\tau(1 - \tau)^{n-1}. \end{aligned} \tag{3}$$

Let's express the total throughput S as the ratio

$$S = \frac{P_s E[P]}{(1 - P_{tr})\sigma + P_s T_s^i + (P_{tr} - P_s)T_c^i}. \tag{5}$$

where $E[P]$ is the average packet payload size, P_s is the probability for successful transmission. The average length of empty

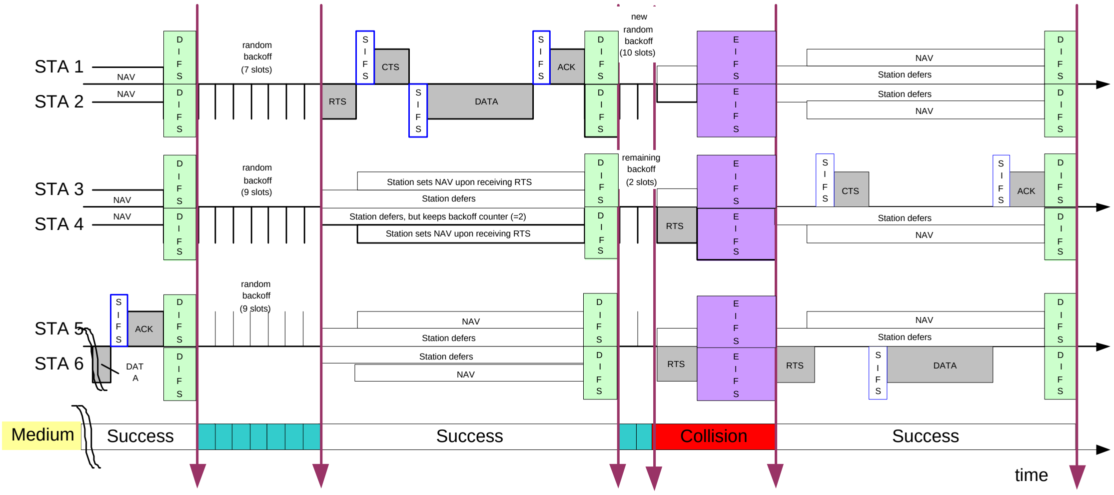

Fig. 1. An illustration of DCF Mechanism

$$
\begin{aligned}
&BasicAccessMechanism\\
T_s^i &= T_{DATA}^i + SIFS + \delta + T_{ACK}^i + \delta + DIFS\\
T_c^i &= T_{DATA}^{i*} + \delta + EIFS\\
&RTS/CTSAccessMechanism\\
T_s^i &= T_{RTS}^i + SIFS + \delta + T_{CTS}^i + SIFS + \delta + T_{DATA}^i + SIFS + \delta + T_{ACK}^i + \delta + DIFS\\
T_c^i &= T_{RTS}^i + \delta + EIFS.
\end{aligned}
\tag{4}
$$

slot time is with probability $1 - P_{tr}$ and with probability $(P_{tr} - P_s)$ there is a collision. If the stations have data rate R^i, T_s^i is the average time the channel is sensed busy due to a successful transmission, and T_c^i is the average time the channel is sensed busy by each station during a collision, represented in (4). σ is the duration of an empty slot time [1].

T_{DATA}^i is the time that takes to send a packet with size $E[P]$ and T_{RTS}^i,T_{CTS}^i,T_{ACK}^i are the times that take to send the corresponding frames. T_{DATA}^{i*} stands for average time that takes to send $E[P^*]$ which is the average length of the longest packet payload involved in a collision. When all packets have the same size, $E[P] = E[P^*]$ [1]. δ is the propagation delay. Unlike the "basic" access mechanism, T_c^i only contains T_{RTS}^i since only possibility to experience a collision occurs during the RTS frame transmission.

In this formulation every station is considered to have the same data rate R^i. Throughput is fairly distributed and individual throughput is $S_{indv} = \frac{1}{n}S$.

II. FORMULATION

We evaluate the throughput when different stations have different SNR ratios, hence different data rates. The protocol gives each station the same chance to transmit, and different data rates only affect the slot duration. Suppose there are n stations, D different data rates, $R^1 < \cdots < R^D$, and n^i stations have rate R^i with corresponding slot durations T_s^i and T_c^i.

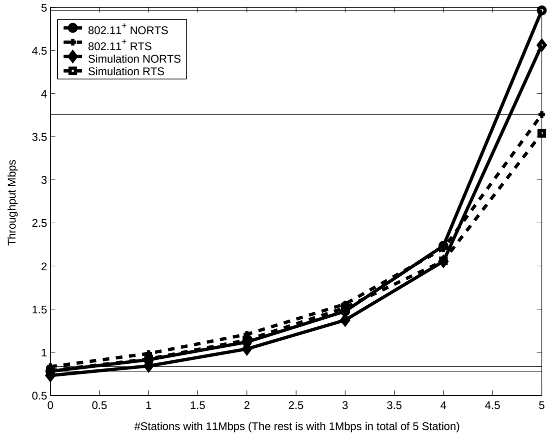

Fig. 3. Throughput

Successful duration value can be evaluated by averaging the successful duration values of each station since only one station involves in a successful duration. Since we now that each station has P_s/n as the probability of having a successful transmission. Then, the new successful duration value $\bar{T}_s$ is given by (6).

When calculating the collision duration, we have to consider the stations that involve in the collision and how many times they involve. During a collision, duration value for that collision is determined by the station that has the lowest data rate.

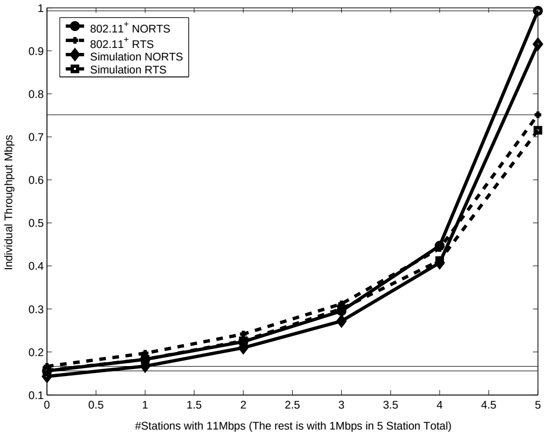

Fig. 4. Individual Throughput

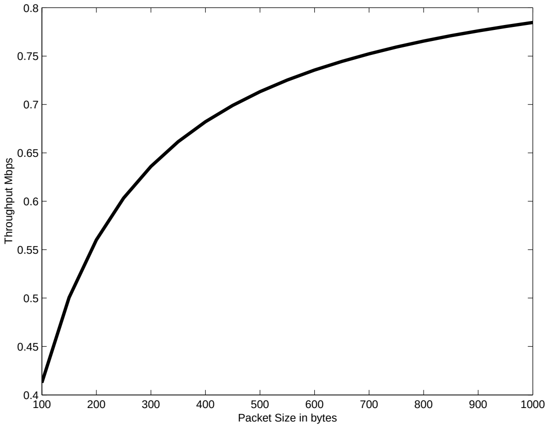

Fig. 5. Throughput after Optimization (No RTS/CTS)

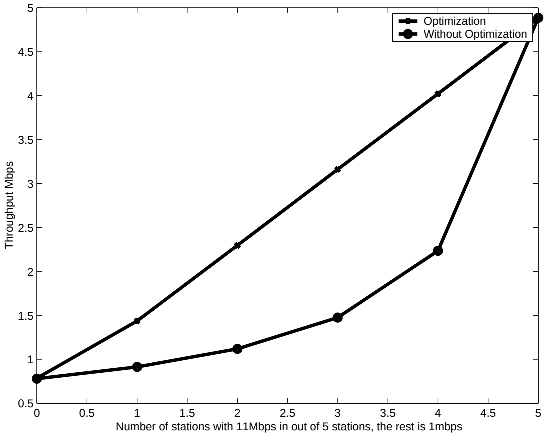

Fig. 6. Throughput after Optimization (No RTS/CTS)

Regarding these, average collision duration $\bar{T_c}$ is given by (6). The throughput of a station is now given by (8). Note that the throughput S_{indv} is the *same* for all stations and total throughput S is nS_{indv}.

$$\bar{T_s} = \frac{P_s}{n}\sum_{i=1}^{D} n^i T_s^i \qquad (6)$$

$$\bar{T_c} = \sum_{i=1}^{n-1}\sum_{j=1}^{D}\sum_{k=1}^{n^j}\binom{n-k-\sum_{l=1}^{j-1} n^l}{i} \times T_c^j \tau^{i+1}(1-\tau)^{n-1-i} \qquad (7)$$

$$S_{indv} = \frac{1}{n}\frac{P_s E[P]}{(1-P_{tr})\sigma + \bar{T_s} + \bar{T_c}} \qquad (8)$$

III. VERIFICATION

In the performance analysis, we have 5 nodes and $D = [\ 1 \quad 2 \quad 5.5 \quad 11\ ]Mbps$. $E[P]$ is 1000 bytes and stations operate in saturation throughput. Note that RTS and CTS packets are sent with 1Mbps all the time.

We started each station with 1Mbps and shifted one of them in each step to 11Mbps. At the fifth iteration we have 5 stations each with 11Mbps. We simulated this in OPNET and the Figures 3 and 4 show that the analytical formula closely approximates the actual performance. The individual throughput of the stations has also found equal and the throughput distribution among stations is verified to be equal thereby one of the individual realization is plotted in Figure 4.

As can be inferred from the graph, when there are 4 stations with 11Mbps and one station with 1Mbps, the throughput performance is almost half of when all is with 11Mbps. A lower data rate causes a considerable degradation for all the stations.

IV. WLAN OPTIMIZATION

A typical optimization is reducing varying packet size with respect to data rate. As the data rate lowers, the stations can tend to send the packets in lower sizes not to make the high data rate station suffer.

Figure 5 shows that throughput increases monotonically with the increase in packet size if all stations operate with the same data rate. Optimal packet size for a given station can be found by taking the derivative of $Sindv$ with respect to P^i where duration values are $T_s^i(P^i)$, and $T_c^i(P^i)$ and $E[P]$ is P^i for station i. Intuitively, the optimal packet size for lower data rate station is the packet size that equates the duration values to the duration values of the highest data rate station. If highest data rate station is m then packet size of station with k data rate is given as follows;

$$EP^k = floor(\frac{k * EP^m}{m} - 30 * \frac{(k-m)}{m}) \qquad (9)$$

Figure 6 shows the improvement in throughput, Stations with 1 Mbps data rate decrease down their packet size from 1000 bytes to 118 if there is a 11 Mbps station in the moment.

The advantage is in total throughput on the other hand in individual throughput, high data rate stations are better off but the low data rate stations are worse off as seen in Figure 7

V. CONCLUSION

A novel throughput formulation is introduced if the stations in the network operate with mixed data rates. Formulation changes the Markov model and duration values introduced in [1] considerably, performance analysis verifies and as well as shows that lower data rate station degrades the performance of

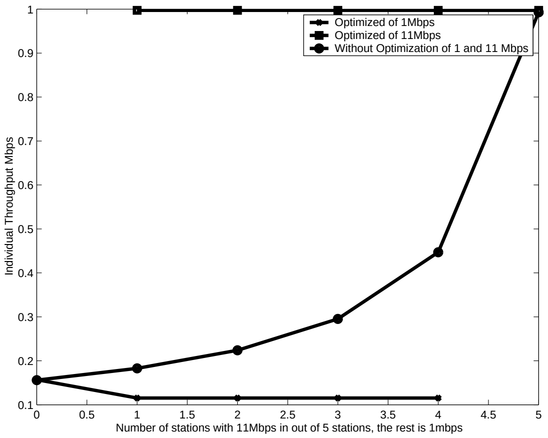

Fig. 7. Individual Throughput after Optimization (No RTS/CTS)

the system but have the same individual throughput with higher data rate station.

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