COMPARATIVE ANALYSIS OF IEEE 802.11 DCF

Er. Saurabh Mittal*

Er. Ankita Mittal**

ABSTRACT

Performance of IEEE 802.11 distributed coordination function (DCF) has been studied by several authors under saturation condition as well as finite load conditions separately .This paper outlines a comparative analysis of performance for IEEE 802.11 DCF using both saturation conditions and finite load conditions in terms of condition collision probability, packet processing rate, probability of successful transmission, channel throughput. In this paper, we present a mathematical model for IEEE 802.11 DCF to capture its behavior under saturation conditions and finite load conditions. Model has been validated by subsequently comparing analytical results with simulation results.

*Senior Assistant Professor, HCTM Kaithal.

**Assistant Professor, HCTM Kaithal

I. INTRODUCTION

In recent years, wireless local area networks (WLANs) have played a key role in the data communications & networking areas, having witnessed a significant development. Much interest has been involved in the design of wireless networks for local area communications. In the 802.11 protocol specification, it specifies two fundamental access mechanisms, ie. Point coordination function (PCF) and distributed coordination function (DCF). DCF is most widely used mechanism and is a random access scheme, based on the career sense multiple access with collision avoidance CSMA/CA protocol. Retransmission of collided packets is managed through binary exponential backoff rules. DCF describes two techniques to employ for packet transmission i.e. basic access mechanism and request-to-send (RTS)/ clear-to-send (CTS) mechanism. The basic access mechanism has been described in Fig. 1. Before initiating a transmission, sending terminal senses whether the medium has been idle for Distributed Interframe Space (DIFS). If there is no transmission ongoing for a short internal (DIFS), the mode may transmit its packet. If the medium is busy, a mode has to wait till the end of current transmission. It will then wait for an additional DIFS time, and then generate a random delay before transmitting its packet. The back off delay is chosen to be a random number of channel slots between 0 and the back off window size (CW). If data packet is not transmitted successfully, the back off window CW is doubled until its maximum value CW_{max}, back off window is reset to CW_{min} whenever a data packet is transmitted successfully after a Short Interframe Space (SIFS). Whenever the backoff value of a node reaches 0, it transmits its packet immediately.

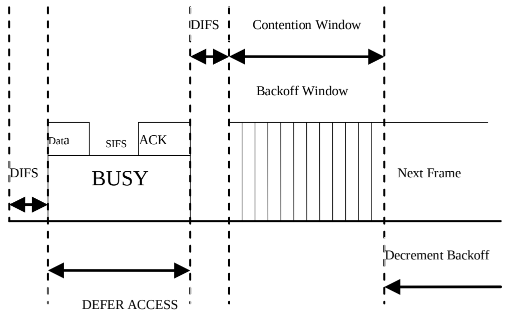

Fig. 1 802.11 Basic Access Method

The RTS/CTS access method is another alternative way of transmission which mainly focuses on the hidden terminal problem and has been illustrated in Fig. 2. Before transmitting a packet, station operating in RTS/CTS mode “reserves” the channel by sending a special Request-to-Send short frame. The destination station acknowledges the receipt of an RTS frame by sending back a Clear-to-Send frame, after which normal packet transmission and

Acknowledge response occurs. If RTS or CTS are not received within the given time frame, the sender retransmits the RTS or CTS frame according to backoff rules as per basic access method.

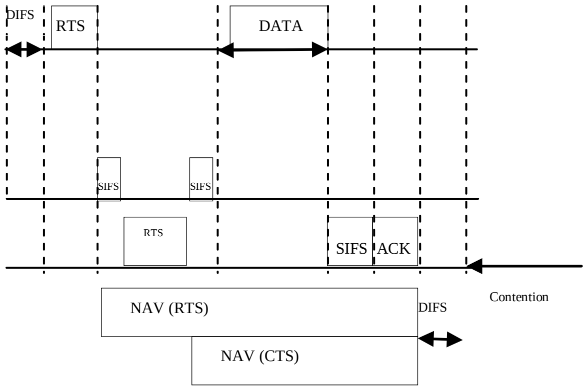

Fig. 2 802.11 Basic Access Method

In this paper, we concentrate on the performance evolution of the DCF scheme, in the assumption of ideal channel conditions and finite load conditions. In the literature, performance evolution of 802.11 has been carried out by means of simulation or by means of analytical models with simplified backoff rule assumptions. (NOT CLEAR)The paper is organized as follows. Section II describes the modeling of DCF. Numerical discussions are presented in section III. In section IV, model has been validated with simulations. Finally we conclude our work in section V.

II. MODELING FOR IEEE 802.11 DCF

In this section, discrete time Markov models have been summarized for DCF as standardized by 802.11 protocols. This model is subsequently used to derive channel throughput, which is defined as the fraction of channel time being used for actual data transmission. In this paper, we concentrate on the "saturation throughput" defined as the limit reached by the system throughput as the offered load increases. The simulated offered load has been generated according to a poisson arrival process of fixed size packets (equal to 8184 bits), where the arrival rate has been varied throughout the simulation to match ideal offered load. The core contribution of this paper is the analytical evaluation of the channel throughput, in the assumption of ideal channel conditions and finite load conditions. During analysis, we assume a fixed number of stations and obtained stationary probability τ that the station transmits a packet in a generic slot time. We express the throughput of both basic and RTS/CTS access methods as function of the computed value τ .

A. Saturation condition

Packet Transmission Probability

In saturation conditions, each station has packet available for transmission, after the completion of each successful transmission. Let s(t) be stochastic process representing back-off stage (0,---,m) of station at time t. Let b(t) be the stochastic process representing the backoff time counter for a given station at time t. It is possible to model the bi-dimensional process{s(t), b(t)} with discrete time Markov chain depicted in Fig. 3**.** Let (i, k) be state representation of discrete time Markov chain where $i \in \{0, ---, m\}$ and k $\{0, \ldots, W_i -1\}$. W_i is given by $W_i = 2^i * W$, where $W=CW_{min}$, and CW_{min} is the minimum contention window length. m is the maximum backoff stage and $CW_{max} = 2^m * W$. The key approximation in our model is that, at each transmission attempt, each packet collides with constant and independent probability p which is referred to as conditional collision probability. For the above Markov Chain, non-null one step transition probabilities for i є (0, m) are given as:-

$$P\{i, k \mid i, k+1\} = 1 \qquad k \in (0, W_i -2)$$

$$P\{0,k \mid i,0\} = \frac{(1-p)}{W_0} \qquad k \in (0,W_0 -1)$$

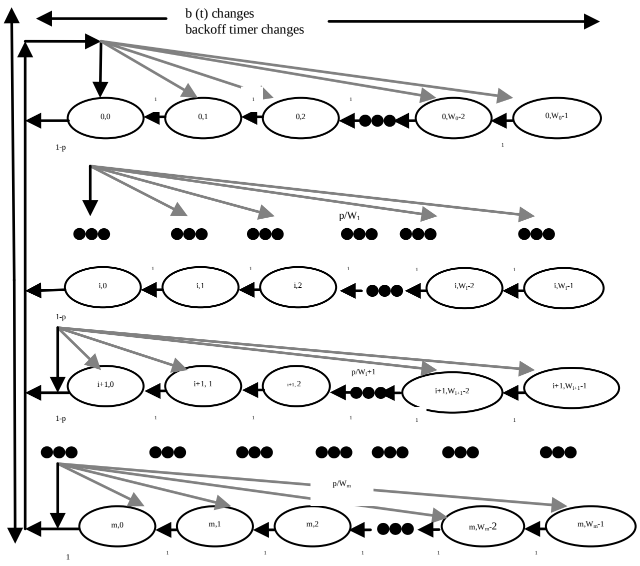

Fig. 3 802.11 Markov Model for Saturation Condition

$$P\{i , k \mid i-1 ,0\} = \frac{(p)}{W_i} \qquad k \in (0,W_i -1)$$

$$P\{m , k \mid m , 0\}= \frac{(p)}{W_m} \qquad k \in (0,W_m -1) \qquad (1)$$

Let n be the number of stations, $(1-\tau)$ is the probability that a station doesn't transmit in a randomly chosen slot, $(1-\tau)^n$ is the joint probability that (n-1) out of n, does not transmit. Thus, p the collision probability of a station which is equal to the probability that, at least 1 out of (n-1) other station transmits. At steady state, each station transmits a packet with probability τ .This yields

$$p=1-(1-\tau)^{n-1} \qquad (2)$$

inverting (2), we get

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

This is a continuous and monotone increasing function in the range $p\in(0,1)$ that starts from $\tau(0)=0$ and $\tau(1)=1$.By using global balance equations at each state and using the fact that sum of steady state probability distribution of all states sum upto 1.We can derive following equations:

$$b_{i,k} = b_{i,0} * \left(\frac{W_i - k}{W_i}\right)$$

$$i\in(0,m),\ k\in(0,W_i-1) \qquad (3)$$

All the values $b_{i,k}$ are expressed as functions of the value $b_{0,0}$ and of conditional collision probability p. $b_{0,0}$ is finally determined by imposing the normalization condition, that simplifies as:

$$1= \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^{m} b_{i,0}\sum_{k=0}^{W_i-1}\frac{W_i-k}{W_i}$$

$$=\sum_{i=0}^{m} b_{i,0}\frac{W_i+1}{2}$$

$$= \frac{b_{0,0}}{2}\left[W\left(\sum_{i=0}^{m-1}(2p)^i+\frac{(2p)^m}{(1-p)}\right)+\frac{1}{1-p}\right] \qquad (4)$$

from which,

$$\tau=\frac{b_{0,0}}{(1-p)}$$

$$= \frac{\left(2*(1-2p)\right)}{\left((1-2p)\ (W+1)\ +\ p*W\ \left(1-\ (2p)^{m}\right)\right)} \qquad (5)$$

Transmission probability τ is logically given by (5) as transmission probability of a station is sum of all the distributions in Fig. 3 which accounts for counter hitting value 0.

Throughput

We choose a random slot and observe what is happening in that slot. Let P_{tr} be the probability that there is at least one transmission in the considered slot time. Thus,

$$P_{tr} = 1-(1-\tau)^{n} \qquad (6)$$

The probability P_s that a transmission occurring on the channel is successful is given by the probability that exactly one station transmits on the channel, conditioned on the fact that at least one station transmits.

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^{n}} \qquad (7)$$

Let us consider a system completely managed by the basic access mechanism as well as RTS/CTS case. Let $H=PHY_{hdr} + MAC_{hdr}$ be the packet header, and δ be the propagation delay. We obtain, T_s the average time the channel is sensed busy because of successful transmission and T_C, the average time the channel is sensed busy during collision as

$$T_s^{bas} = H+P+SIFS+\delta+ACK+DIFS+\delta$$

$$T_c^{bas} = H+P+DIFS+\delta$$

$$T_s^{rts} = RTS+SIFS+\delta+CTS+SIFS+\delta+H+$$
$$P+SIFS+\delta+ACK+DIFS+\delta$$

$$T_c^{rts} = RTS+DIFS+\delta$$

Let σ be the duration an empty slot time and P the fixed size of all the packets. We are now able to express S as the ratio

$$S = \left(\frac{E[\text{payload information transmitted in a slot}]}{E[\text{length of slot time}]}\right)$$

$$S = \left(\frac{P_{tr} * P_s * 8184}{\left((1-P_{tr})\ \sigma\ +\ P_{tr} * P_s * T_s\ +\ (1-P_{tr})\ *P_s\ *T_c\right)}\right) \qquad (8)$$

B. Finite Load Condition

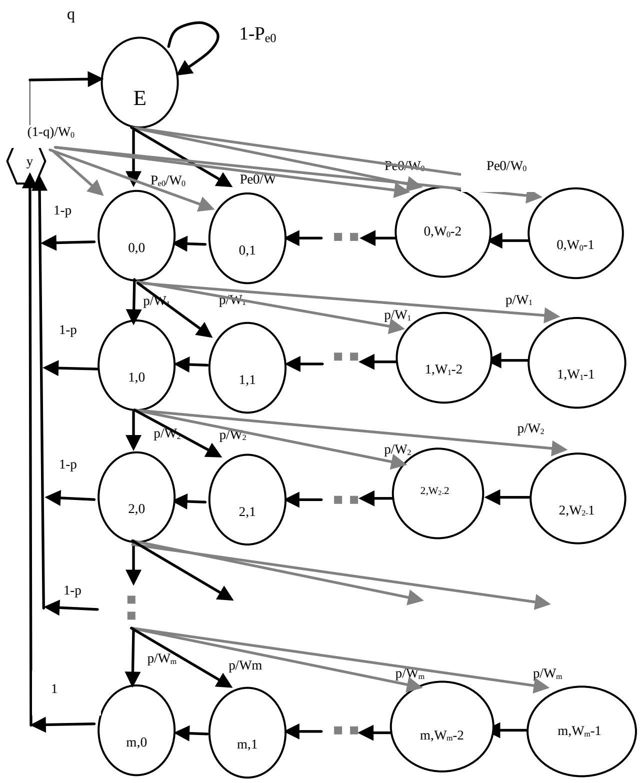

Fig. 4 802.11 Markov Model for Finite Load Condition

We extend the discrete time Markov model given in Fig. 3 by adding another state (i.e.) E to represent node with empty queue, as shown in Fig. 4. A packet gets discarded after m failed retransmissions. Key assumption in this model is that collisions happen with the same probability p regardless of the number of retransmission attempts. In this case, if the sending queue is empty (with probability q), the station enters the empty state b_E, and waits for a packet arrival.

Transmission Probability

To solve for p, we balance the equations from Markov chain model in Fig. 4.

$$P_{0,k} = \frac{W_0 - K}{W_0}.[\, p_{e0}.P_E + (1-q)y]$$

$$P_{0,k} = \frac{W_0 - k}{W_0}.p^i.P_{0,0} = \left[\frac{W_0 - k}{W_0}\right].y \qquad (9)$$

$$P_{i,k} = \frac{W_i - K}{W_i}.p^i.P_{0,0} \qquad for\, 0 < i \le m$$

$$y = \sum_{i=0}^{m}(1-p).P_{i,0} + p.P_{m,0} \qquad (10)$$

$P_E.p_{e0} = q.y$ $\qquad P_{0,0} = \frac{2(1-P_E)}{\beta}$

$$\beta = W_0\left[\frac{1-(2p)^{m+1}}{1-2p}\right] + \left[\frac{1-p^{m+1}}{1-p}\right] \qquad (11)$$

for $0 \le p<1$

The node will only transmit in state $b_{i,0}$ hence the probability τ that a node will transmit in an arbitrary slot time is the probability of being in any of the states $b_{i,0}$.

$$\tau = \sum_{i=0}^{m} P_{i,0} = \varepsilon P_{0,0} \; where \, \varepsilon = \sum_{i=0}^{m} p^i = \frac{1-p^{m+1}}{1-p} \qquad (12)$$

With no hidden terminals, a transmission results in a collision with probability p and can be assumed as

p= 1-(1- τ) ^ (n-1)

Denoting μ as the packet processing rate, λ be the packet arrival rate and Q_l as queue length, using the M/M/1/Q_l queuing model, probability P_E of having no packet for transmission is

$$P_E = \frac{1-\frac{\lambda}{\mu}}{1-(\frac{\lambda}{\mu})^{Q_l+1}} \qquad (13)$$

Packet Service Rate

Next we find an expression for μ, the packet service rate (rate at which packets are removed from the queue), in terms of P_E and p. Let t_{access} be the average time spent backing off before a packet is transmitted, and t_{tx} be the packet transmission time. Since at i^th back-off stage the average number of back-off slots is $W_i/2$ and the system enters the next back-off stage with probability p, the average access time t_{access} is given by

$$t_{access} = \frac{\sum_{i=0}^{m} p^i (\frac{W_i}{2} t_{bo})}{\sum_{i=0}^{m} p^i} = \frac{\phi W_0 t_{bo}}{2\varepsilon} \qquad (14)$$

where $\phi = \sum_{i=0}^{m} p^i 2^i = \frac{1-(2p)^{m+1}}{1-2p}$

The transmission time t_{tx} depends on the payload size and the access mechanism and is given as

$$t_{tx} = (1-p)t_{succ} + pt_{coll}$$
$$t_{succ} = H + PL + SIFS + DIFS + ACK + 2\sigma$$
$$t_{coll} = H + PL + DIFS + \sigma$$

where H is the packet header, PL the payload size, τ propagation delay, and t_{succ} and t_{coll} the times taken by successful and unsuccessful transmissions respectively. The average busy period is the transmission period t_{tx}, hence the average time spent in a BO state, t_{bo} can be given as

$$t_{bo} = 1 - P_{n-1} + P_{n-1}t_{tx}$$
$$P_{n-1} = 1-(1-\tau)^{N-1}$$

The average time taken to transmit a packet, t_s, is the total of the transmission time and MAC access time and can be given as

$$t_s = t_{access} + t_{tx}$$

Hence the effective packet service rate (μ_{eff}) is a sum of the rate of successful transmissions (μ_{succ}) and the rate at which packets are discarded (μ_{disc}) can be represented as

$$\mu_{eff} = \mu_{succ} + \mu_{disc} \qquad (15)$$

$$\mu_{succ} = \frac{1-p}{t_s}, \mu_{disc} = \frac{p_{disc}}{t_s}$$

where
$$p_{disc} = \frac{p.P_{m,0}}{\sum_{i=0}^{m} P_{i,0}} = \frac{(1-p)\,p^{m+1}}{1-p^{m+1}}P_{0,0}$$

For small p and m>1, p_{disc} is negligible, hence we may approximate μ_{eff} with μ_{succ}.

$$\mu_{eff} = \mu_{succ}$$

Throughput

For limited load conditions when the packet arrival rate λ is less than the effective packet service rate μ, then the total throughput is the portion of traffic that arrived minus the traffic that is discarded. For calculating throughput under finite load conditions we took into consideration two different conditions which show the throughput as given below. If the packet service rate is less than one (ρ <1) then the throughput under finite load conditions will be given as

$$T_{total} = \left(\frac{N^* \lambda^* \text{ Payload}}{\text{Channel Rate}} \right) \quad (16)$$

In second case the node will be considered to be in saturation condition and the throughput will be calculated as

$$S= \left(\frac{\text{E [payload information transmitted in a slot]}}{\text{E [length of slot time]}} \right) \quad (17)$$

III. RESULTS AND DISCUSSION

In this section, we present numerical results obtained from our model to study the behavior of DCF for saturation conditions and finite load conditions. Table I shows the default parameters used for both saturation condition and finite load condition.

Table I. VALUES FOR SIMULATION & NUMERICAL EVALUATION	
Payload Size(PL)	8184 bits
MAC Header	272 bits
PHY Header	128 bits
ACK	112 bits+ PHY
Channel Bit Rate	1 Mbit/s
Propagation Delay()	1 μ s
SIFS	10 μ s
DIFS	50 μ s
Initial Contention Window(W_0)	16
Maximum No. of Retransmissions(m)	5
Slot Time()	20 μ s
RTS	160 bits + PHY
CTS	112 bits + PHY

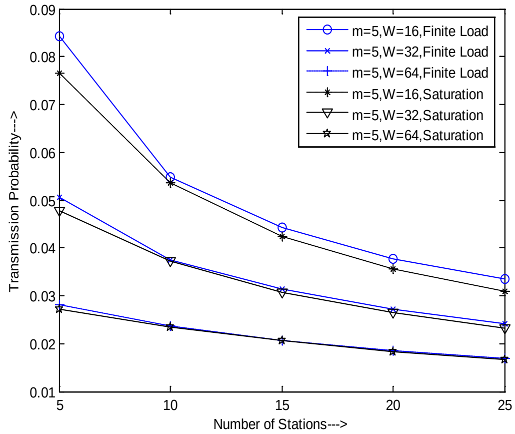

Fig. 5 Transmission Probability (τ) vs. No. of Stations (n)

Fig. 5 shows the decrease in transmission probability with increase in no. of contending stations by varying the number of back off stages for a constant back off window size for saturation condition and finite load condition. It can also be observed that the initial value for minimum no. of stations also gets reduced with increase in minimum size of contention window.

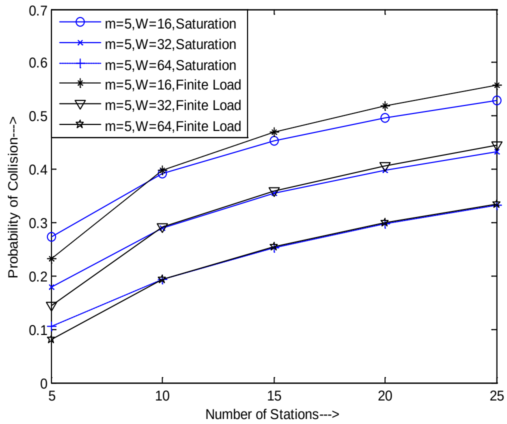

Fig. 6 Collision Probability (τ) vs. No. of Stations (n)

From Fig. 6, it can be seen that the collision probability increases with increase in number of stations. This is obvious because increasing the number of nodes in the network increases the contention for channel access. For finite load condition the collisions increases for a particular back off window size.

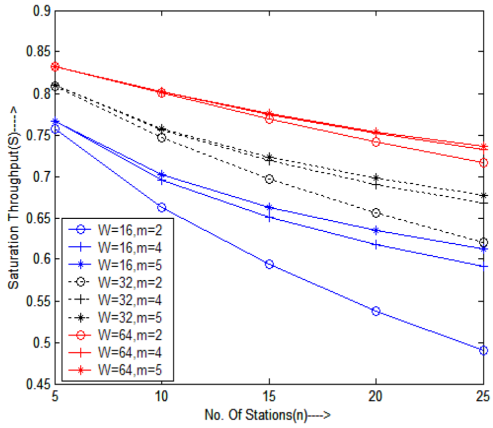

Fig. 7 Saturation Throughput vs. No. of Stations (Saturation Condition)

Although it has been proved above that with decrease in probability of success it can be well understood that the throughput of a channel will decrease when there will be increase in number of stations contending for the channel which can be seen from Fig. 7 for saturation condition. From the Fig 7 when the minimum size of contention window is less then the saturation throughput decreases but with the increase in minimum size of contention window the throughput for RTS/CTS mechanism gets improved.

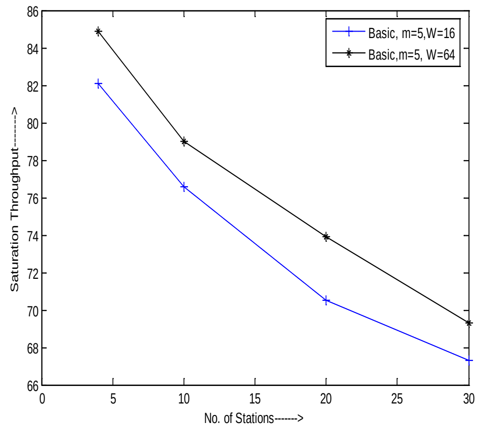

Fig. 8 Saturation Throughput vs. No. of Stations (Finite Load Condition)

Fig 8 shows the effect of increase in no. of stations on the saturation throughput for finite load conditions. Saturation throughput decreases with increase in number of stations although in case of finite load condition the throughput has been reduced a smaller value as compared to ideal channel conditions.

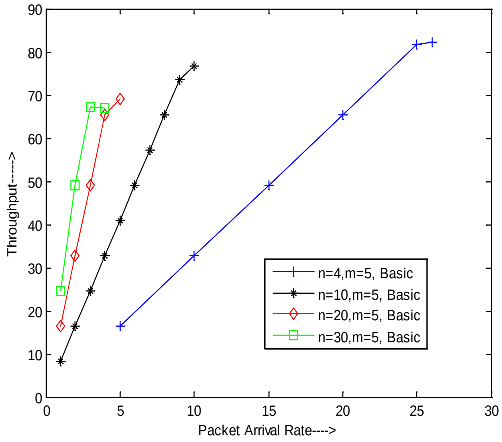

Fig. 9 Throughput vs. Packet Arrival Rate (Finite Load Condition)

Fig 9 shows the effect of varying packet arrival rate on the throughput under finite load condition. In Fig initially up to some particular value of packet arrival rate for a particular number of stations the throughput goes linearly but after some range the throughput goes into saturation and remain constant while increasing packet arrival rate further.

IV. MODEL VALIDATION

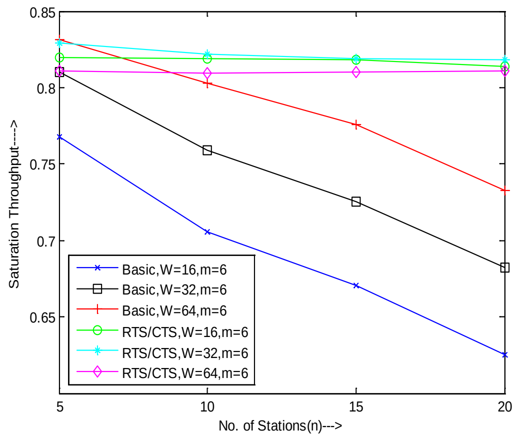

Fig. 10 Saturation Throughput: Simulation Results

To verify the analytical model, simulations were performed using C++ program to observe the throughput. For the saturation condition the simulation results have been shown in Fig. 10. The simulation results for finite load condition have been shown in Fig. 11. The total system throughput was measured over a period of 90 seconds for a range of varying packet arrival rates. The maximum throughput closely matches that from the analytical model. The results obtained through simulations also shows the throughput saturates after reaching maximum throughput value.

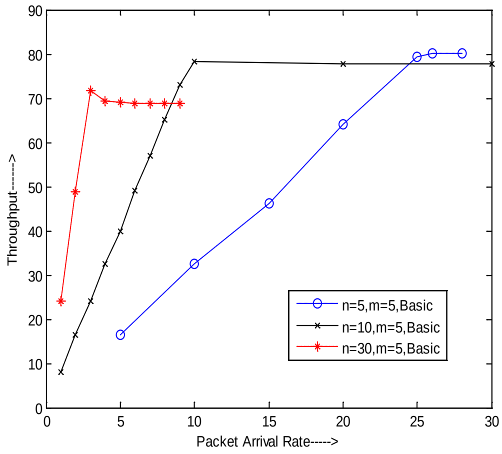

Fig. 11 Throughput performance for finite load condition: Simulation Results

V. CONCLUSIONS

In summary, we have presented an analytical model to study the performance of IEEE 802.11 DCF under the saturation condition and finite load conditions. In the analysis, we derive some common network performance metrics such as packet transmission probability, collision probability and the channel throughput. It is very interesting to note that the maximum achievable throughput is the same in finite load condition as for saturation condition after which it goes into saturation. Also with increase in packet arrival rate from the contending nodes the throughput remains same. The validation of model is carried out by comparing the theoretical results with simulation results using C++ programming.

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