2009 IEEE International Advance Computing Conference (IACC 2009)
Patiala, India, 6–7 March 2009

Performance Analysis of the IEEE 802.11 Distributed Coordination Function in High Interference Wireless Local Area Networks considering Capture Effects

P.Kumar, A.Krishnan, K.Poongodi, T.D.Senthil Kumar
K.S.Rangasamy College of Technology

Abstract- In this paper, we propose a new throughput analysis for IEEE 802.11 Distributed Coordination Function (DCF) considering the real channel conditions and capture effects under arbitrary load conditions employing basic access method. The aggregate throughput of a practical Wireless Local Area (WLAN) strongly depends on the channel conditions. In real radio environment, the received signal power at the access point from a station is subjected to deterministic path loss, shadowing and fast multipath fading. We extend the multidimensional Markov chain model initially proposed by Bianchi[1] to characterize the behavior of DCF in order to account both real channel conditions and capture effects, especially in a high interference radio environment.

Index terms – IEEE802.11, DCF, Capture, Rayleigh fading, non-saturation throughput.

I. INTRODUCTION

In the recent years WLANs using the IEEE 802.11 standard have experienced an exponential growth. In the 802.11 protocol, the fundamental access mechanism is the Distributed Co-ordination Function which is based on CSMA/CA protocol. The standard also defines an optional access method, PCF, which is for time bounded traffic. Since the DCF mechanism has been widely adopted in wireless networks, we focus our analysis only on this mechanism.

The performance analysis of WLAN contention based DCF has been studied by several researchers both in saturated and non saturated network conditions. Most of the analytical studies are based on the model proposed by Bianchi[1]. Bianchi developed an analytical model to characterize the behavior of IEEE 802.11 MAC protocol in saturated traffic conditions. His performance evaluation assumes ideal channel conditions, finite number of stations with constant and independent collision probability for each station and hidden terminals and capture effects are not considered.

To improve the performance of IEEE 802.11 DCF protocol, many collision resolution algorithms have been proposed. In [8], the authors proposed a fast collision resolution algorithm. In this algorithm, when a station detects a busy period, it exponentially increases its contention window and generates a new backoff counter. In case that a station detects a number of consecutive idle slots, it exponentially reduces the backoff counter. Cali and Conti[2] proposed a new dynamic tuning mechanism instead of the binary exponential backoff. According to his algorithm each station estimates the current contention level by observing the status of channel independently. Based on this information, a station executes a distributed algorithm to tune its sending probability. In real networks the traffic is mostly unsaturated, so it is important to develop a model taking real network conditions into account. In [5], the authors presented an extension of Bianchi's model to a non saturated environment. They modified the multi-dimensional Markovian state transition model by including state, characterizing the system when there are no packets to be transmitted in the buffer of a station. These states are called post backoff states and denote a kind of virtual backoff counter initiated prior to packet arrival. In [6], the authors proposed a new backoff algorithm to measure the saturation throughput under several conditions and several set of parameters which are adjusted dynamically according to the network conditions.

In [3,4], the authors presented a Markov model to analyze the throughput of IEEE802.11 considering transmission errors and capture effects over Rayleigh fading channels in both saturated and unsaturated network conditions. Their model is very accurate when the contention level of a network is high. As far as, capture is concerned, Hadzi-velkov and Spasenovski[7] have investigated the impact of capture effect on IEEE 802.11 basic service set under the influence of Rayleigh fading and near/far effect.

In this paper, we present an analytical model to characterize the IEEE802.11 DCF considering imperfections of channel and capture effects. We differentiate channel induced errors from packet collision in order to optimize the performance of CSMA/CA under the non saturated network condition.

The paper is organized as follows. In section II, we present the new Markov chain model by extending the model proposed initially by Bianchi. Performance of the proposal scheme is analyzed in section III. In section IV, we discuss numerical results. Finally section V concludes this paper.

II. MARKOV MODEL FOR IEEE 802.11 DCF

Each station is modeled by a two dimensional Markov process ($s(t)$, $b(t)$). Let s(t) be the stochastic process representing the backoff stage of a given station at time t and let b(t) be the stochastic process representing backoff time counter of the station. In the BEB scheme, a node will transmit a packet if its backoff counter is zero. The backoff counter is an integer value uniformly chosen from $[0,CW_i-1]$ where CW_i denotes the contention window at the i^{th} backoff stage. The backoff stage 'i' is incremented by one for

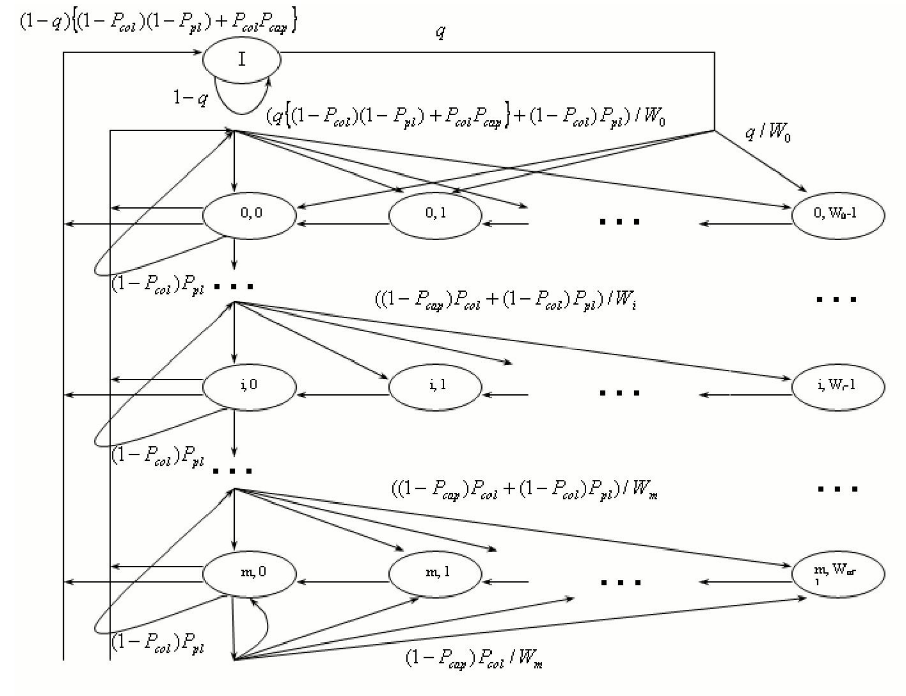

Fig.1. Markov chain model for the backoff procedure of a station

each failed transmission attempt up to the maximum value m, while the contention window is doubled for each backoff stage up to the maximum value $CW_{max} = 2^m CW_{min}$.

Letting $CW_{min} = W_0$, we can summarize the CW as,

$$W_i = \begin{Bmatrix} 2^i W_0, \ 0 \le i \le m \\ 2^m W_0, \ i > m \end{Bmatrix} \tag{1}$$

Our main aim in this section is the effective modification of the MAC protocol in order to characterize the behavior of MAC in the event of channel induced errors. In the basic BEB, the contention window is doubled after every unsuccessful transmission. Unsuccessful transmission happens in two cases:

1) Collision of a packet with other packets
2) Due to error in the channel

Consider a scenario where the contention level of a network is low or moderate. Assume that, there is a transmission failure due to channel induced errors, the basic BEB process will double the contention window size by considering channel errors as a packet collision. This process will unnecessarily increase the backoff overhead. The logic we have behind is that, when a frame corrupted by the channel, we maintain the same contention size instead. In this way, the contending stations will avoid unnecessary backoff increment.

Further more, in real radio environment, the signal power at access point from a given station will be subjected to deterministic path loss, shadowing and fast multi-path fading. Due to this, when more than one station simultaneously transmit to AP, the channel is successfully captured by a station whose signal power level is stronger than the other stations and thus increases the actual throughput. This phenomenon is called capture effect. Based on the above consideration, let us discuss the Markovian model in Fig.1, assuming non-saturation network conditions. We assume that each station has m+1 stages of backoff process. The value of the backoff counter is uniformly chosen in the range $(0,CW_i\text{-}1)$, where $CW_i = 2^i CW_{min}$ and depend on the station's backoff stage *i.* A station in (i,0) state will transit into (i+1,k) state in the event of collision without capture effect. In the event of capture, the Markov model transits into (0,k) state if further packets are available, otherwise it transits into idle state. From state (i,0), the station re-enters the same backoff stage (i,k) in case of unsuccessful transmission due to the packet loss.

The main approximation in our model is that, at each transmission attempt, each packet collides with constant and independent probability P_{col} regardless of previously suffered attempts and transmission errors occur with probability P_{pl} due to the erroneous channel. We also assume that the channel is captured by a station with the probability P_{cap} in the event of collision. Based on the above assumptions we can readily derive the transition probabilities:

$$\begin{aligned}
&P\{i,k/i,k+1\} = 1, \quad k \in [0,W_i-2], i \in [0.m] \\
&P\{0,k/i,0\} = (q(1-P_{col})(1-P_{pl}) + qP_{col}P_{cap})/W_0, \ k \in [0,W_0-1], i \in [0.m] \\
&P\{i,k/i,0\} = (1-P_{col})P_{pl}/W_0, \ k \in [0,W_i-1], i \in [0.m] \\
&P\{i,k/i-1,0\} = P_{col}(1-P_{cap}/Wi), \quad k \in [0,W_i-1], i \in [1.m] \\
&P\{m,k/m,0\} = (P_{col}(1-P_{cap}) + (1-P_{col})P_{pl})/W_m, k \in [0,W_m-1] \\
&P\{I/i,0\} = ((1-q)(1-P_{col})(1-P_{pl}) + (1-q)P_{col}P_{cap})/W_0, \ i \in [0.m] \\
&P\{0,k/I\} = q/W_0, \quad k \in [0,W_0-1] \\
&P\{I/I\} = 1-q
\end{aligned} \tag{2}$$

The first equation represents that, at the beginning of each time slot, the backoff time is decremented. The second equation states that, the initialization of backoff window after successful transmission for a new packet. The third equation accounts that, the maintenance of backoff window in the same stage, if channel error is detected. The fourth and fifth equations represent that, the rescheduling of backoff stage after unsuccessful transmission. The sixth equation states that, after successful transmission the station transit into idle state if station's queue is empty. The seventh equation accounts for the beginning of bakeoff procedure from idle state if a packet arrives at station's queue. Finally, equation eight models the behavior of station during empty queue.

III. PERFORMANCE ANALYSIS AND THROUGHPUT COMPUTATION

Let the stationary distribution of the chain be $b_{i,k} = \lim_{t \to \infty} P\{s(t) = i, b(t) = k\}, i \in (0,m), k \in (0, W_{i-1})$. To obtain the closed form solution we first consider the following relations:

$$b_{i,0} = b_{i-1,0}\{P_{col}(1-P_{cap})\} + b_{i,0}\{(1-P_{col})P_{pl}\} = \left(\frac{P_{col}(1-P_{cap})}{1-(1-P_{col})P_{pl}}\right)^i b_{0,0} \quad (3)$$

$$\sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{\left(1 - \frac{P_{col}(1-P_{cap})}{1-(1-P_{col})P_{pl}}\right)} \quad (4)$$

$$b_{m,0} = \frac{\left(\frac{P_{col}(1-P_{cap})}{1-(1-P_{col})P_{pl}}\right)^m b_{0,0}}{1 - \left(\frac{P_{col}(1-P_{cap})}{1-(1-P_{col})P_{pl}}\right)} \quad (5)$$

The probability to be in the idle state b_{idle} for empty queue is evaluated as follows:

$$b_{\text{idle}} = (1-q)\left[(1-P_{col})(1-P_{pl}) + P_{col}P_{cap}\right]\sum_{i=0}^{m} b_{i,0} + (1-q)b_{\text{idle}} = \frac{(1-q)\left[(1-P_{col})(1-P_{pl}) + P_{col}P_{cap}\right]\sum_{i=0}^{m} b_{i,0}}{q} \quad (6)$$

The above expression states that the empty queue state is reached after a successful transmission of a station from any backoff stage with empty queue or the station waiting in the idle state with probability (1-q).

A closed-form solution to the Markov chain owing to the chain regularities, for each $k \in (1, W_i - 1)$, shown in Eq. 7 at the bottom of the page.

Considering normalization conditions, and making use of the above equations we obtain the following:

$$\sum_{i=0}^{m}\sum_{k=0}^{Wi-1} b_{i,k} + b_{\text{idle}} = 1$$
$$= \frac{b_{0,0}}{2}\left[W_0\left(\sum_{i=0}^{m-1}(2P)^i + \frac{(2P)^m}{1-p}\right) + \frac{1}{1-p}\right] + \frac{(1-q)\left[(1-P_{col})(1-P_{pl}) + P_{col}P_{cap}\right]\sum_{i=0}^{m} b_{i,0}}{q}$$

from which, we obtain Eq. 8.

Where we assume, $P = \frac{P_{col}(1-P_{cap})}{1-(1-P_{col})P_{pl}}$

Now we can express the probability τ that a station transmits in a randomly chosen slot time when the backoff time is zero as,

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-P} \quad (9)$$

By substituting Eq.8 in Eq.9, we obtain the Eq.10 shown at the bottom of the page.

Note that, when m=0, that is no exponential backoff is considered, and assuming P_{cap}=P_{pl}=0, the probability τ results to be independent of collision probability.

$$\tau = \frac{2}{W_0 + 1} \quad (11)$$

which is the result found in[1] for constant backoff window.

$$b_{i,k} = \frac{W_{i-k}}{W_i}\left\{\begin{array}{l} (q(1-P_{col})(1-P_{pl}) + qP_{col}P_{cap})\sum_{i=0}^{m} b_{i,0} + qb_i + b_{i,0}(1-P_{col})P_{pl}, i = 0 \\ P_{col}(1-P_{cap})b_{i-1,0} + (1-P_{col})P_{pl}b_{i,0}, 1 \le i \le m \\ (P_{col}(1-P_{cap}))(b_{m-1.0} + b_{m,0}) + (1-P_{col})P_{pl}b_{m,0}, i = m \end{array}\right\} \quad (7)$$

$$b_{0,0} = \frac{2(1-P)(1-2P)q}{qW_0(1-P)(1-(2P)^m) + qW_0(2P)^m(1-2P) + q(1-2P) + 2(1-P)(1-2P)(1-q)(1-(1-P_{col})P_{pl})} \quad (8)$$

$$\tau = \frac{2(1-2P)q}{qW_0(1-P)(1-(2P)^m) + qW_0(2P)^m(1-2P) + q(1-2P) + 2(1-P)(1-2P)(1-q)(1-(1-P_{col})P_{pl})} \quad (10)$$

However, in general, the probability τ depends on the conditional collision probability P_{col}, capture probability P_{cap} and probability of packet loss P_{ppl}. The conditional collision probability depends on the capture probability because capture effect is the sub event of collision, i.e. without collision there is no capture effect. Therefore the probability P_{col} can be expressed as,

$$P_{col} = 1-(1-\tau)^{n-1} - P_{cap} \quad (12)$$

A. Capture probability

To compute the capture probability, we use the model proposed by Hadzi-velkov and Spasenovski[9]. In Rayleigh fading channel, the transmitted instantaneous power is exponentially distributed according to

$$f(p) = \frac{1}{p_0}\exp(-\frac{p}{p_0}),\ p > 0 \quad (13)$$

Where p_0 represent the local mean power of the transmitted frame at the receiver and is determined by

$$p_0 = A.r_i^{-x}.P_{TR}$$

Where r_i is the mutual distance from transmitter to receiver, x is the path loss exponent, Ar_i^{-x} is the deterministic path loss and P_{TR} is the transmitted signal power. During simultaneous transmission of multiple stations, a receiver captures a frame if the power of detected frame P_{df} sufficiently exceeds the joint power of 'n' interfering contenders

$$P_{\text{int}} = \sum_{k=1}^{n} P_k$$

by a certain threshold factor for the duration of a certain time period. Thus capture probability is the probability of signal to interference ratio

$$\gamma = \frac{P_{df}}{P_{\text{int}}} \quad (14)$$

exceeding the product $z_0 g(S_f)$ where z_0 is known as the capture ratio and $g(S_f)$ is processing gain of the correlation receiver. The conditional capture probability P_{cap} can be expressed over i interfering frames as,

$$\begin{aligned} P_{cap}(z_0 g(S_f)\mid i) &= prob(\gamma > z_0 g(S_f)/i) \\ &= [1+z_0 g(S_f)]^{-i} \end{aligned} \quad (15)$$

For DSSS using 11 chip spreading factor (s_f=11),

$$g(S_f) = \frac{2}{3S_f}$$

Now the frame capture probanility can be expressed as,

$$P_{cap}(z_0, n) = \sum_{i=1}^{n-1} R_i P_{cap}(z_0 g(S_f)\mid i) \quad (16)$$

Where R_i is the probability of 'i' interfering frames being generated in the generic time slot, according to

$$R_i = \binom{n}{i+1}\tau^{i+1}(1-\tau)^{n-i-1}$$

B. Probability of packet loss

Let we assume that an L-byte long frame has to be transmitted with a physical mode m, where m=1, 2, 3 & 4 for the data rates 1, 2, 5.5 & 11 Mbps respectively. The probability of a successful transmission can be expressed as

$$P_{sucess}^{m}(L) = (1-P_{data}^{m}(L)).(1-P_{ack}^{m}) \quad (17)$$

Where, $P_{data}^{m}(L)$ - Probability of error for data frame

P_{ack}^{m} - Probability of error for acknowledgement frame.

An acknowledgement frame is transmitted at the rate equal to or lower than the data frame rate, and is 14 bytes long, which is usually much shorter than the data frame. Therefore, the error probability of the ACK frame is very low compared to the error probability of the data frame and hence we can approximate the probability of successful transmission as:

$$P_{sucess}^{m}(L) \approx 1 - P_{data}^{m}(L)$$

The probability of packet loss can be expressed as

$$P_{pl} = 1 - P_{sucess}^{m}(L) \quad (18)$$

Now we can drive the probability of error for data frame as

$$P_{data}^{m}(L) = 1-(1-P_e^{1}(PLCP).(1-P_e^{m}(MAC+L)) \quad (19)$$

Where, $P_e^{1}(PLCP)$ - error probabilities of the PLCP in physical mode 1

$P_e^{m}(MAC+L)$ - error probability of the data plus MAC header in physical mode m

Now, $$P_e^{m}(L) = 1-(1-P_b^{m})^{8L} \quad (20)$$

Where P_b^{m} is probability of bit error rate for the physical mode used. The probability of bit error calculation is well approximated by [9].

For physical mode 1, i.e. DBPSK P_b^{1} is calculated by

$$P_b^{1} = \frac{1}{2}e^{-\gamma_b} \quad (21)$$

For physical mode 2, i.e. DQPSK P_b^{2} is calculated by

$$P_b^{2} = Q_1(a,b) - \frac{1}{2}I_0(ab)e^{-\frac{1}{2}[a^2+b^2]} \quad (22)$$

where $a = \sqrt{2\gamma_b(1-\sqrt{\frac{1}{2}})}$; $b = \sqrt{2\gamma_b(1+\sqrt{\frac{1}{2}})}$

Here γ_b is referred as the signal to noise ratio per bit and it can be expressed as

$$\gamma_b[dB] = 10\log\left(\frac{V}{M}\right) + SNR[dB] \quad (23)$$

Where V is number of chips per symbol and M is the number of bits per symbol. $I_0(ab)$ is the modified Bessel function of order zero and defined as

$$I_i(x) = \sum_{k=0}^{\infty} \frac{(x/2)^{(i+2k)}}{k!.\Gamma(i+k+1)} \tag{24}$$

Where r(x) is the gamma function, $Q_1(a,b)$ is the Marcum Q function defined as

$$Q_1(a,b) = e^{-(a^2+b^2)/2} \sum_{k=0}^{\infty} \left(\frac{a}{b}\right)^k I_k(ab) \tag{25}$$

C. Throughput computation

Next step is the computation of the non saturation system throughput, defined as the fraction of time the channel is used successfully to transmit the bits. Let P_{tr} be the probability that there is at least one transmission in the considered time slot, with n stations contending for the channel, and each transmits with probability τ,

$$P_{tr} = 1-(1-\tau)^n \tag{26}$$

The probability P_s that a transmission on the channel is successful is given by the probability that exactly one station transmit on the channel or probability that two or more stations transmit simultaneously where one station captures the channel due to capture effects,

$$P_s = \frac{n\tau(1-\tau)^{n-1} + P_{cap}}{1-(1-\tau)^n} \tag{27}$$

Now we can express throughput as,

$$S = \frac{E[payload\ \inf ormation\ transmitted\ in\ a\ time\ slot]}{E[length\ of\ a\ time\ slot]}$$

$$= \frac{P_{tr}P_s(1-P_{pl})E[PL]}{(1-P_{tr})\sigma + P_{tr}(1-P_s)T_c + P_{tr}P_sP_{pl}T_e + P_{tr}P_s(1-P_{pl})T_s} \tag{28}$$

Where, T_c is the average time that the channel sensed busy due to collision, T_s is the average time that the channel sensed busy due to successful transmission, T_e is the average time that the channel is occupied with error affected data frame and σ is the empty time slot. For the basic access method we can express the above terms as,

T_c= H + E[PL] + $ACK_{timeout}$
T_s= H + E[PL] + SIFS + ACK + DIFS + $2\tau_{pd}$
T_e= H + E[PL] + $ACK_{timeout}$
Here, H - Physical header + MAC header
E[PL] - Average payload length
τ_{pd} - propagation delay

D. Estimation of probability q

The probability q is directly related to the packet arrival rate of each station's queue. The most common

MAC header	24 bytes
PHY header	16 bytes
Payload size	1024 bytes
ACK	14 bytes
RTS	20 bytes
CTS	14 bytes
τ_{pd}	1 μs
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
ACK timeout	300 μs
CTS timeout	300 μs

Table I
Network parameters

queuing process is the poisson distribution. In our analysis we use the model proposed by [5] to measure the probability q through the following relation:

$$q = 1 - e^{-\lambda E[T]} \tag{29}$$

where, λ is the packet arrival rate[pkt/s], and E[T] is the expected slot time, and it is given by the following relation:

$$E[T] = (1-P_{tr})\sigma + P_{tr}(1-P_s)T_c + P_{tr}P_sP_{pl}T_e + P_{tr}P_s(1-P_{pl})T \tag{30}$$

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we present numerical results that illustrate the impact of both non ideal transmission channel and capture effects on the system throughput. The network parameters used in these results are shown in Table.I, and we assume W_0 = 32 and m = 5. In Fig.2, the result shows that the channel with high SNR value leads to improved network performance. Note that the performance of the network is better than the good quality channel for small number of stations. Fig.3 shows the behavior of system throughput for different SNR values, for three different packet arrival rates.

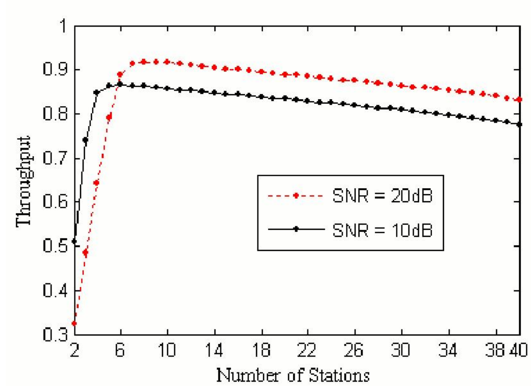

Fig.2. Throughput as a function of contending stations for two different SNR values with z_0= 6dB and λ=20pkt/s.

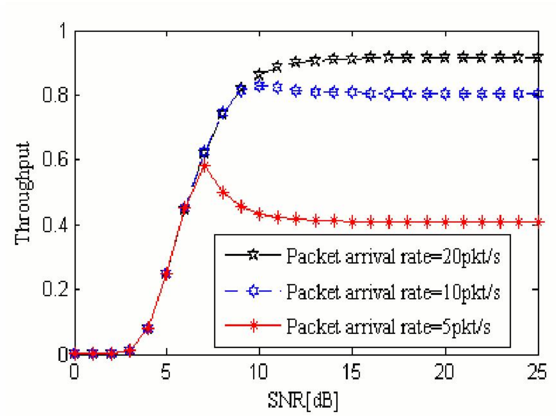

Fig.3. Throughput as a function of SNR for different packet arrival rates with z_0= 6dB and n=10.

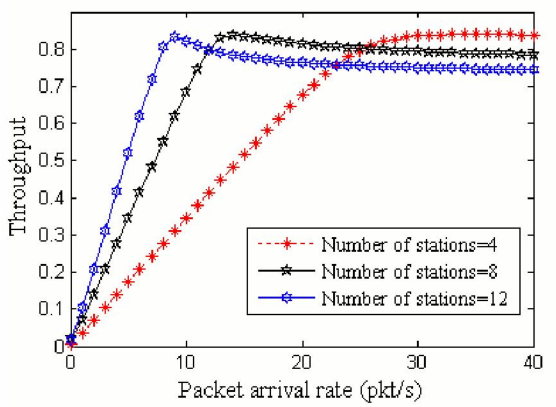

Fig.4. Throughput as a function of packet arrival rate for three different number of stations with z_0=24dB and SNR=10dB.

Throughput increases as a function of SNR and packet arrival rate. The result also shows that the system performance is improved for small SNR values, for low packet arrival rates.

Figs.4 and 5. reveals that peak performance tends to reduce for increasing packet arrival rate as number of stations increases due to the presence of capture effects. Note that reducing rate is more as the number of stations increases. When the packet arrival rate increases, the network traffic condition enters into saturation condition i.e. $q \rightarrow 1$ as $\lambda \rightarrow \infty$. The throughput of the system attains its saturation state faster for low capture ratio as the number stations increases.

V. CONCLUSION

In this paper we have proposed an analytical model to estimate the non saturation throughput of IEEE802.11 Distributed Coordination Function taking into account of both real transmission channel and capture effects. Using the proposed model we have evaluated the throughput performance of IEEE802.11 DCF for basic access method. Based on this model we derive a novel and generalized expression for the

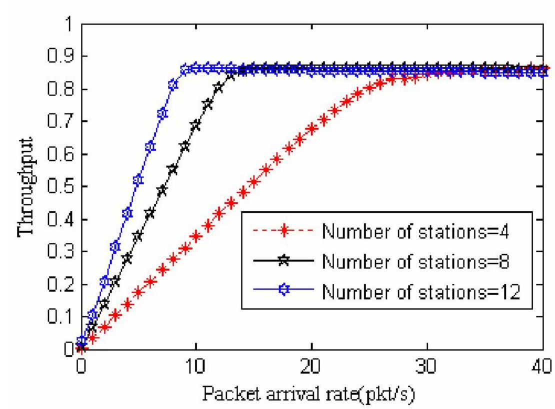

Fig.5. Throughput as a function of packet arrival rate for three different number of stations with z_0=6dB and SNR=10dB.

station's transmission probability, which is more realistic, such as arbitrary load conditions and and non ideal channel conditions. Our study shows that an optimally chosen number of contending stations can significantly improves the network throughput.

REFERENCES

[1] G.Bianchi, " Performance Analysis of the IEEE 802.11 Distributed Coordination Function", IEEE Journal on Selected Area in Communications, vol.18, no.3, pp. 535-547, March 2000.

[2] F. Cali, M. Conti, E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit", IEEE/ACM Trans. Netw. Vol.8, no.6, pp.785-799, December 2000.

[3] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Unsaturated Throughput Analysis of IEEE 802.11 in Presence of Ideal Transmission Channel and Capture Effects", IEEE Trans. Wireless commun., vol. 7, no. 4, pp. 1276-1286, April 2008.

[4] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Saturation Throughput Analysis of IEEE 802.11 in Presence of Ideal Transmission Channel and Capture Effects", IEEE Trans. Commun., vol. 56, no. 7, pp. 1178-1188, July 2008.

[5] David Malone, Ken Duffy, and Doug Leith, "Modeling the 802.11 Distributed Coordination Function in Nonsaturated Heterogeneous Conditions", IEEE/ACM Trans. Networking, vol.15, no.1, pp 159-172, February 2007.

[6] Hadi Minooei, Hassan Nojumi "Performance evaluation of a new backoff method for IEEE 802.11", Elsevier journal on Computer Communication, vol. 30, issue. 18 pp. 3698-3704, December 2007.

[7] Z. Hadzi-Velkov and B. Spasenovski, "Capture effect in IEEE 802.11 basic service area under influence of Rayleigh fading and near/far effect", In Proc. of 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Vol.1, pp.172 - 176, Sept. 2002.

[8] Y.Kwon, Y.Fang, and H.Latchman, "Design of MAC protocols with fast collision for wireless local area networks," IEEE Trans. Wireless commun., vol. 3, no. 3, pp. 793-807, May 2004.

[9] J. G. Proakis, Digital Communications, New York: Mc-Graw Hill, 2001 (4^{th} ed).

[10] IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, P802.11, November 1997.