RESEARCH ARTICLE OPEN ACCESS

A Review of Analytical Models Evaluating Performance of 802.11 DCF Networks

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ABSTRACT
Network parameters such as throughput, delay, collision probability, loss of packets are the key indicators that determine the performance of 802.11 DCF. Analytical models facilitate in predicting the value of these parameters based on what-if analysis. These models, based on certain assumptions, give accurate solutions. The key design aspect of these models is the analysis of exponential backoff algorithm among the contending nodes. This survey paper starts by giving an overview of 802.11 protocol. We explore various solutions based on Discrete Markov Chains, Fixed Point Analysis, Petri Nets and Mean Value theory for both saturated and non-saturated networks. The paper critically examines the assumptions, methodologies, and deficits of the proposed models. The objective is to provide the thorough summary of the available literature to enable the research community to address the challenges associated with these mathematical tools. In our knowledge, this is the first survey addressing the above objectives.

***Keywords*:** IEEE 802.11, Backoff, Buffer, Collision Probability, Retry

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Date of Submission: 30-08-2017 Date of acceptance: 09-09-2017

I. INTRODUCTION

The advancement in wireless technology has revolutionized the communication era. The technology, which was earlier limited to scientific and military purpose is now being used by common people in their everyday life. Among the plethora of protocols for indoor communications, IEEE 802.11 commonly referred to as wireless LAN (WLAN) has dominated the market and has become a default standard. The initial 802.11 standardswere introduced in 1997. Itwas designed to support two modulations – Frequency Hopping Spread Spectrum and Direct Sequence Spread Spectrum. The standard, however, had serious flaws. The rectifications of these shortcomings lead to the development of IEEE 802.11b [1] and 802.11a [2]. These standards provide detailed Medium Access Control (MAC) and Physical Layer (PHY) specification.The MAC layer provides services through two sub layers, Distributed Coordination Function (DCF) and Point Coordination Function (PCF) as shown in figure 1. The DCF is fundamental protocol utilized by both infrastructure and ad hoc networks to access the channel.while PCF is designed to workon the top of DCF and can be used in infrastructure based networks only.The DCF protocol is based on Carrier Sense Multiple Access with Collision Avoidance Algorithm (CSMA/CA)to share the channel among contending stations. Among the two protocols, DCF is more popular among the research community.Unlike in wired networks, it is not possible to detect collisions in a wireless network. Instead of monitoring the channel continuously collision avoidance mechanism relies on the receipt of acknowledgment,ensuring successful transmission.

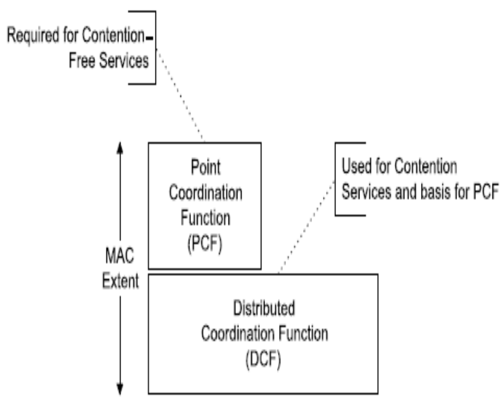

Fig. 1: IEEE 802.11 MACArchitecture (source [1])

The CSMA/CA implements physical carrier sense mechanismand virtual carrier sense mechanism to detect unsuccessful delivery of packets. The physical mechanism is a two-way handshaking process involving exchange of data packets and acknowledgement packets. The RTS- CTS packets are control packets that are exchanged between sender and destination nodes prior to any transmission of data packets. These control packets help the network to achieve two goals: 1. Helps inaddressing the hidden terminal problem and exposed terminal problem. 2. The processensures the reservation ofthe channel in advance to reduce collisions among contending nodes.The above process characterizes the virtual carrier sense mechanism. Binary exponential algorithm is the key component of CSMA/CA. Itschedules transmission attempts among different contending stations to reduce the collision during communication between stations.

In comparison to the wired network, wireless networks have a considerablylower capacity. The realized throughput of a wireless network link is less than theoreticalcapacity claimed in standards.To predict the throughput of the network the key challenge is thatno alternation in the existing flows in the networkshould be permitted otherwise accurate outcomes cannot be attained. Analytical Modeling helps in predicting the variation in results by altering the inputparameters.One of the important input parameter in such models is the rate at which senders emit packets in the network. Broadly, the networks for evaluation purpose are categorized as saturated networks and non-saturated networks. Saturated networks ensure that the packets are always available in the buffer for the next transmission after each successful transmission. In non-saturated networks, the next packet/ frame may or may not be always available after the current transmission of packets is finished, either successfully or unsuccessfully. The key objective for any mathematical model is it captures maximum details of protocol and at the same time it should be simple and fast when evaluating the result-set. Analytical tools based on Markov Chain, fixed point analysis, Petri Nets and mean-value theory have been proposed. The current paper critically examines these models based on their assumptions, methodologies, intimateness to actual standard, validation of results, their pros and cons.The paper is organized as follows: The section II reviewsthe key concepts and working of IEEE 802.11. Section III presents various proposed mathematical models for performance evaluation of saturated networks.The models, evaluating the non-saturated networks are discussed in section IV. Section V provides analytical models dealing with performance evaluation of the DCF access mechanismconsidering the finite buffer size. Section VI concludes this survey.

II. IEEE 802.11 DCF

IEEE802.11 DCF protocol is designed to work in both infrastructures based networks and ad hoc networks. It works with a single first-in-first-come transmission queue. The key component of this protocol is its exponential backoff algorithm. The backoff process is initiated in following cases i) station tries to access the channel and is found to be busy ii) wheneverthere is unsuccessful transmission and iii) after every successful transmission. When the previous transmission was successful, and the channel is found to be busy, the station defers the transmission until the channel becomes idle again for the period of DIFS. For unsuccessful transmission, the station waits forthe EIFS periodto synchronize its states. After the stipulated time, the station will commence the backoffprocess before transmitting, unless the counter already does not contain a non-zero value. The variable contention window, W, is a random integer that represents the backoff timer. The window is divided into various discrete slots of fixed size. The value of backoff is expressed as

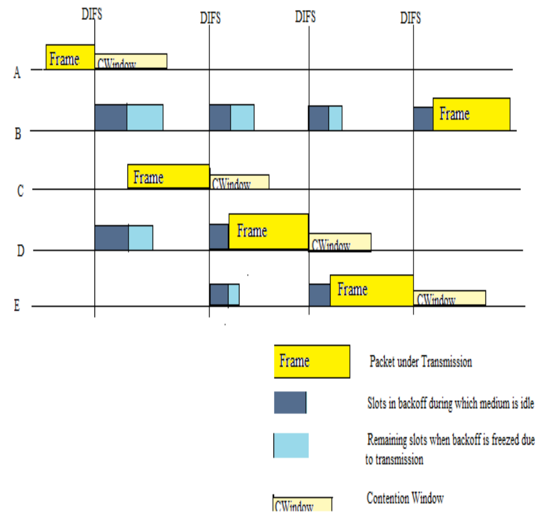

Fig.2: Backoff Procedure (source [1])

$$\text{Backoff} = \text{Random}(\ ) * \text{aslottime} \quad (1)$$

where Random( ) is an integer value drawn from uniform distributed [0, CW] such that $CW_{min} \leq CW \leq CW_{max}$. The value, aslottime, determines the duration of a single slot and is dependent on PHY characteristics.

The backoff counter starts decrementing its slots for the time the medium is found to be idle. If the medium is sensed busy during the countdown, decrement counter of backoff process is paused. Once the channel becomes idle again the decrement process of backoff timer restarts. The transmission process begins only when the backoff count reaches zero. The decrement process of backoff is shown in figure 2. When the frame is transmitted successfully the value ofthe contention window is reset to W_{min} and a new packet, if available, is picked up for the transmission process. In the event of unsuccessful transmission, the value of the contention window is increased exponentially and station retries the transmission process. To limit the number of attempts for transmission 802.11 DCF employs two retry counters, Station Short Retry Count (SSRC) and Station Long Retry Count (SLRC), the value of both is initially zero. Figure 3demonstrates the exponential increase of the contention window for variousbackoff stages. Once the contention window, reaches the maximum value the window size remains same until the retry counter reaches a threshold value.

Once the maximum retry limit associated with the counters is reached, the packet is dropped from the queue. Mathematically, the increment in the value ofthe contention window is represented as

$$W_i = 2^i.W, i \le m' \\ W_i = 2^{m'}.W, i > m' \quad (2)$$

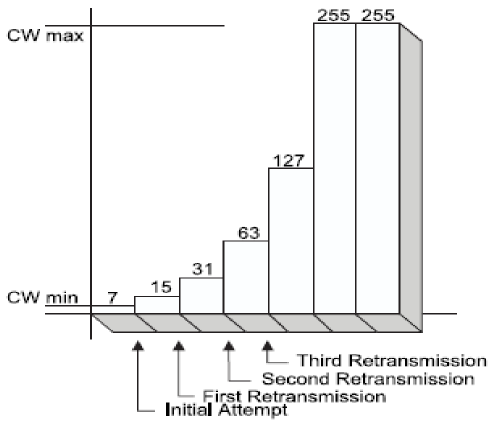

Fig.3: Example of the incremental process of the retry counter and the exponential increase of backoffprocess (source [1])

The variablei represents the backoff stage. The term $W_i$initially takes the minimum value of W_{min}. The contention count is doubled till themaximum value is reached,$W_m= 2^{m'}$ W, where *m'*represents the backoff stage at which contention window attains a maximum value.

III. SATURATED ANALYTICAL MODELS

The first analytical model to evaluate MAC DCF using Markov Chain was proposed by Bianchi [3].The proposed model was based on following assumptions 1. Channel conditions are ideal, i.e. packets are lost only due to collision 2. Collision probability, p, was assumed to be independent of the number of retransmissions. 3. Stations were in saturated condition 4. The network is homogeneous with a finite number of stations 5. There are no hidden stations. To make problem tractable a bi-dimensional Markov chain model was proposed. Discrete slots in backoff process is represented using two variables, back off stage, s (t), and backoff counter, b (t) as depicted in figure 4. Depending upon the state of backoff stations contend for the channel once it is free. The random variable τ quantifies probability that a station can transmit in the random chosen slot and expressed as

$$\tau = \frac{2.(1-2p)}{(1-2p)(W+1) + p.W(1-(2p)^m)} \quad (3)$$

To solve an equation (3) the unknown conditional probability,p, needs to be determined. Let the variable n represents the finite stations in the network. At slot t_1 assume any one station commences transmitting packets. During the same slot if one of the remaining n-1 station begins its transmission the collision is bound to happen. The variable p is random variable that represents the probability of collision for the randomly chosen slots when stations can transmit. At steady state, the probability pis expressedas

$$p = 1-(1-\tau)^{n-1} \quad (4)$$

The expression in the equation (4) can be represented as

$$\tau = 1-(1-p)^{\frac{1}{n-1}} \quad (5)$$

The equation number (5) is a monotone increasing function while equation (3) is a monotone decreasing function. The above properties ensure a single solution. Obtained values of τ and pare used to predict various parameter like throughput, delay etc.

The above model does not strictly adhere to the IEEE 802.11 protocol. The protocol suggests that the packet should be dropped once the retry counter breachesits threshold value. On the contrary, in the proposed model even after reaching retry threshold value,the packet is retainedand infinite transmission attempts are allowed till the success is registered at the sender in the form of the ACK packet.The work in [4-5] observed the above deficiency and proposed a new Markov chain model as shown in figure 5.The packet is dropped with absolute probability, once the m^{th}backoff stage is reached.The contention window increments as per equation (2). Approaching the problem in a similar fashion, the value ofτ, the probability of transmission in any given empty random slot is given by

$$\tau = b_{0,0}\frac{1-p^{m+1}}{1-p} \quad (6)$$

where $b_{0,0}$ represents the stationary distribution of chain at (0,0) and represented as

$$b_{0,0} = \begin{cases} \dfrac{2(1-2p)(1-p)}{W(1-(2p)^{m+1})(1-p)+(1-2p)(1-p^{m+1})}, m \le m' \\ \dfrac{2(1-2p)(1-p)}{W(1-(2p)^{m'+1})(1-p)+(1-2p)(1-p^{m+1})+W.2^{m'}.p^{m'+1}.(1-2p)(1-p^{m-m'})}, m > m' \end{cases} \quad (7)$$

The equation (4) represents the collision probability. Equations (5) and equation (6) are solved to determine the value of p and τ. These parameters are then utilized to predict throughput, delay, time to drop

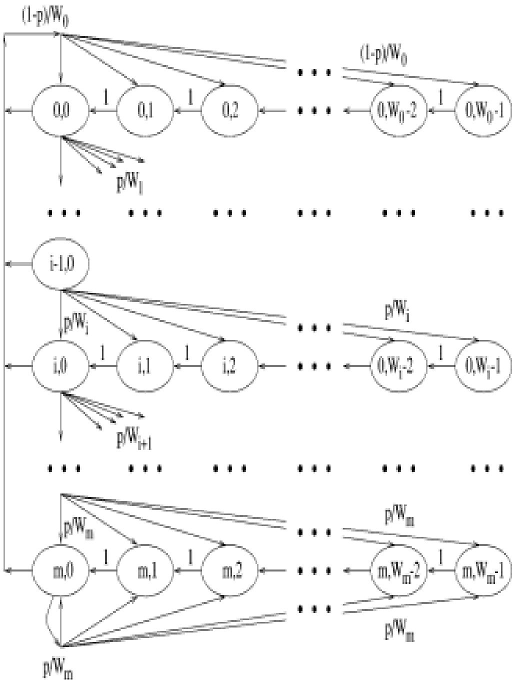

Fig 4. Markov chain proposed by Bianchi (source [3])

packets and packet drop probability. The work in [6] compares two models in detail.

The backoff counter of the node needs to be paused once the medium is busy due to the transmission activity carried out by other stations in the network. The above modelsdisobey the above rule by allowing the backoff counter to be decremented with the absolute probability.Ziouva et al. [7] made two important amendments a) it makes sure that the backoff counter is paused whenever the medium becomes busy b) an addition states is introduced in the Markov chain model. The new state represents the condition if the previous transmission is success and channel is idle for DIFS period, the station proceed with its transmission without invoking the backoff procedure. The introduction of the new state leads to unfair situations in the network because this model will always favor the stations that have registered successful transmission. The assumption of limitless attempt at the last backoff stage is not in agreement with [1].

The model in [7] refines [3] by freezing the backoff counter when the medium is busy. The authors in [8] reported the flaw in the model proposed by [7]. As per [1] backoff period is resumed only when the mediumis idle for DIFS period or EIFS period depending upon the transmission state of the channel.The authors in [8] observed that the above fact introduces error in the result predicted by [7].

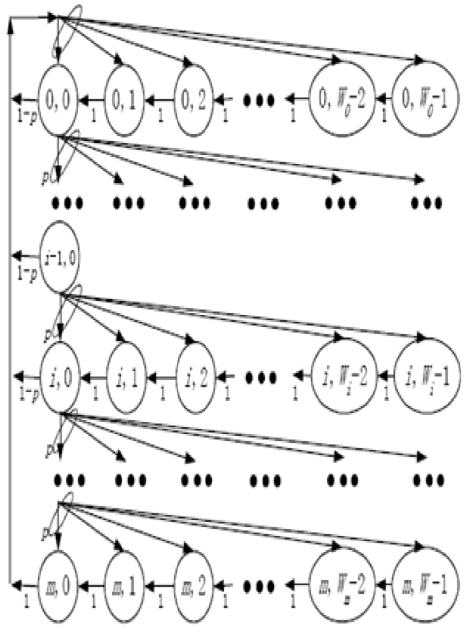

Fig 5. Markov chain proposed by Wu and Chatzimisios models (source [4][5])

The states in the enhanced model is characterizedby three variables instead of two as shown in figure 6. Thefirst variable indicates the status of the channel before the next contention for the channel is made. The value 0 and 1 represents an idle and busy state of the channel. The other two variables represent the backoff stage and backoff counter as in previous models. The variables, p_0 and p_1, represents the probability of the other station transmitting during a slot after an idle or busy slot respectively. The probability that channel slot remains idle once the previous slot is also ideal period is q_0 and probability it becomes idle after a busy period is q_1.Depending upon the previous channel status the author defines two attempt rates τ_i and τ_b that represents the fact that transmission is attempted after an idle or busy period.Xiao [9] improves the model proposed by [3] and [7]. The main characteristics of the model are: a) Consideration of activating and deactivating backoff counter based on the status of channel condition b) Doing away with the assumption that the station can transmit immediately after transmission if channel is idle c) supporting finite retry limit d) improved delay model in comparison to [7].

All the above-discussed models assume the ideal channel condition for transmission. Whenmore than one station attempt for transmission, the channel is captured by one having strongest of the signal power. This phenomenon is known as capture effect. In the real wireless environment, the transmitted signal is subjected to path loss, fading and shadowing.

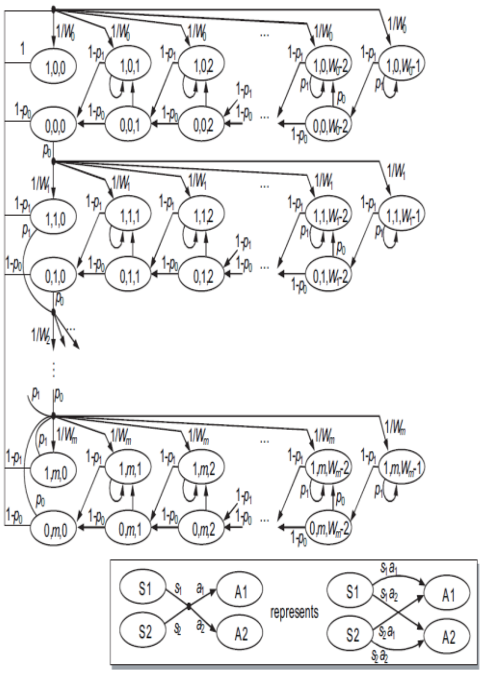

Fig 6. Markov chain Model proposed by Foh et al. (Source [8])

To counter the low performance of IEEE 802.11because of error-prone channel and capture effects, [10] proposed the change in 802.11 protocol and presented a modifiedanalytical model based on [3]. Their idea being that in the event of packet collision, the retry counter is incrementedand new contention window is chosen as in [1]. But if the packet is non-delivered due to capture effect value of retry limit is not incremented and the contention window is randomly selected from retained retry limit. To identify the cause of unsuccessful transmission, the authorsmodified the MAC Header and introduce negative ACK (NACK) packets. The proposed solution suffers from two major disadvantages:i)introduction ofnew fields in the MAC header causes unnecessary overheads and ii)since the channel is error-prone,it is not guaranteed that NACK will always reach the sender.Leaving this arrangement, there is no possible arrangement in wireless networks to determine the reason forundelivered packetslikeerror-prone channel, interference and capture effects. The [11] addresses the performance of 802.11 networks in the error-prone channel where each node incurs a different error-rate.

In [12], the authors presented a Markov model to analyze the throughput of the IEEE802.11 considering transmission errors and capture effects over Rayleigh fading channels in saturated network conditions. Their model claims very accurateresults when the contention level of a network is high.The performance analysis for the fading channel and the bursty error rate was carried out in [13]-[14]. Considering the retry limit, [49] evaluates the throughput and delay for a saturated network in the error-prone channel.

The above models and proposals are based on Markov chain modeling. It is observed that solving the problem through Markovian chain leads to unnecessary complexities. The work in [16-17] evaluatedthe performance of DCF protocol using mean-value theory. It was observed that p-persistent IEEE 802.11 backoff algorithm closely matches the window size of the standard exponential backoff algorithm. This replacement of algorithm helps in maximizing the throughput that nearly matches the theoretical limit. The p-persistent algorithm samples backoff interval using geometrical distribution with parameter p. Their solution involves adjusting the average backoff window to its optimal value by dynamically tuning the backoff process among the stations to achieve the maximum throughput.

Another non-Markovian model for evaluation purpose was proposed by Kumar et al. [18]. Assuming ideal conditions, the proposed model simplify and generalize the performance analysis of DCF as compared to the Markov chain based models. The model provides a fixed-point formalization based on renewal theory. It is assumed that all stations use the same backoff parameter. Let, τ, be the average backoff rate for each node. Decoupling approximation is assumed such that the aggregated attemptrate of n-1 station is independent of the backoffprocess of given node. Assumingthe collision probability to be p, the attemptrate can be expressed as

$$\tau = G(p) = \frac{1+p+p^2+\cdots+p^K}{b_0+p.b_1+\cdots+p^k b_k+\cdots+p^K b_K} \quad (8)$$

The term $b_k$represents the mean backoff duration at the k^{th}attempt. The authors have taken care of the fact that the backoff window is exponentially increased to stage k and packet is dropped after K^{th} stage representing retry limits. Under decoupling approximation and with parametersτ and n-1, the attemptrate is binomially distributed and the number of attempts in a successive slot form independent identically distributed sequence. The collision probability is calculated as

$$p = \Gamma\tau = 1-(1-\tau)^{n-1} \quad (9)$$

Equations (8) and (9) represent thefixed-point equation. The fixed-point obtained from these equations are unique and correspond to a value of collision probability. It is further shown that throughput of the network is dependent on the slowest transmission rate.

The authors in [19] use Object Oriented Petri Nets to evaluate the system. The WLAN is divided into two modules: wireless workstation and wireless medium. The wireless workstation is further refined into sub-modules. These submodules representvarious process such as backoff decrement process, transmission process, receivingprocess. The wireless medium is divided into submodules idle and busy. The places, transitions, and the arcs represent classes as in the object-oriented paradigm. The tokens define the attributes that includes source id, destination id and packet length. These attributes help in distinguishing various packets. They are used in labelling places, transition and arcs to represent the flow of packets.The guard functions enable or disable the firing of the transaction. Results obtained from OOPN model agree with NS-2 simulations, validating the proposed solution.

IV. NON- SATURATED ANALYTICAL MODELS

It is reported that even for a network comprising of sender and receiver the throughput is less than capacity of the channel. We will refer the throughput obtained as achievable throughput. When the network operates in saturated mode, throughput of the network is less than achievable throughput. The number of collisions will be high leading to unnecessary delay in delivering the packet. This motivatesthe development ofnon-saturated analytical models.The models based on Markov chain evaluate the performance metrics of non-saturated network modifies the model proposed in [3] by adding the idle statewhich representsthe empty buffer when there are no packets available to transmit.

The work in [20] modifies the Bianchi model [3] by introducing two states, first representing an idle state and second defines the state when the station has the packet, but disabled due toback off.The station exits the idle state on arrival of the new packet in the buffer to enter the second state. The packet is transmitted when the channel is idle for a DIFS time without initiating the backoff process. The condition also, holdsin casethere is an availability of the packet and the previous packet was successfully transmitted.However,the same is not recommended as per IEEE 802.11 standards and leads to unfair situations in the network. The assumption of allowing the packet to retry infinite times does not conform to IEEE 802.11standards. The assumption of infinite buffers to store packets during on-going transmission is not realistic and lead to overestimation of the throughput and high delays.

Liaw et al. [21] model is illustrated in figure 10. Authors have extended model proposed in [3]. The state E and y represent the condition whenthe buffer is empty and the probability that at least one packet is available in the buffer for the next transmission

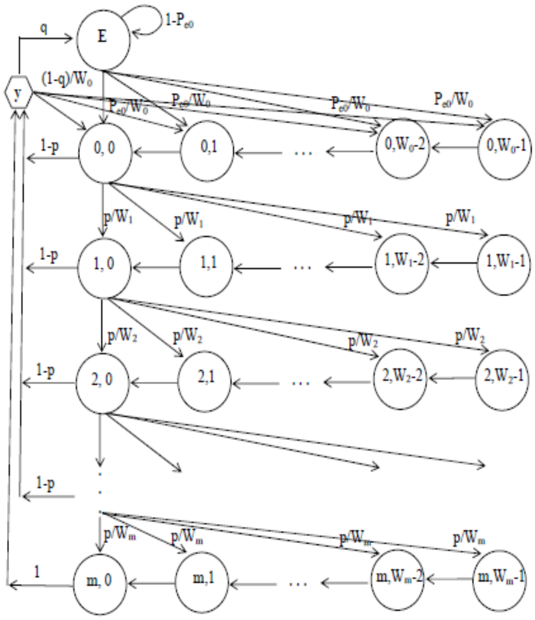

Fig. 7: Markov Model pr0posed by Liaw et al. (Source [21])

process to proceed respectively. Once the retry limit, m, is reached after various unsuccessful attempts the packet is dropped. The analysis was further extended to investigate the effect of hidden terminals on the network. The analysis of the above model by [22] observed that throughput is dependent on the packet arrival rate. It increases linearly with the arrival rate. The increase in packet arrival rate after a critical value pushes the network in the saturated region. The packet arrival rate is dependent on the number of station and packet size. The packet arrival rateis assumed to be homogenous instead the arrival rates in real time scenario are heterogenous.

As per standard[1], after every successful transmission the node needs to waits for DIFS and perform backoff operation even if when thereis no packet queued up in its buffer. This process is termed as post backoff. Most analytical model based on the Markov chain does not consider the above feature. The work in [23] modified [3] by adding post backoff states as shown in figure 8. As in [3], backoff states are represented using variables backoff stage and backoff counter. After successfully delivering the packets sender's contention windows will be reset to its initial value. Analytically the model returns to the backoff state s=0. The post-backoff state $(0, k)_e$ represents the fact previous communication was successful and there node's queue is empty.The backoff states where s > 0 represent that the packet has suffered collision and subsequently the backoff stage has been incremented. The offered load q in the model represents the presenceor absence of the packet in the buffer. The value of qis dependent on the traffic

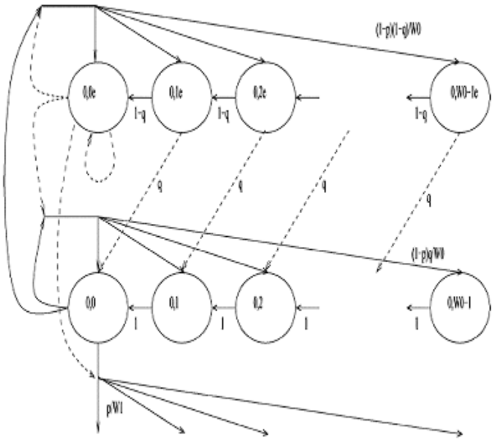

Fig 8. Markov Model proposed by Malone et al. (Source [23])

arrival rate. The equation 10 represents the probability of transmission attempt in any given MAC slot.

$$\tau = b_{(0,0)_e}\left(\frac{q^2W_0}{(1-p)(1-q)-(1-q)^{W_0}} - \frac{q^2(1-p)}{1-q}\right) \quad (10)$$

The variable $b_{(0,0)e}$represents the stationary probability of a node when post backoff is complete but buffer is empty. The expression for the collision probability is same as (4).

Themodel evaluates the performance of the network for both homogeneous and heterogeneous conditions. The model in [24] analyzes the performance of the single hop WLAN for ideal channel conditions with no post backoff procedure. It is shown that MAC throughput increases linearly with the increase in packet rate. Once the saturation level is attained, the graph of throughput falls flat.

Thefixed-point analysis for saturated networks [18] was extended in [25]. Theproposed approach simplifies the mathematical solution to evaluate the non-saturated network.The key contribution of the proposed model is the approximation of the attemptrate in the non-saturated network by scaling the attemptrate of the saturated network with the appropriatefactor. The scaling factor, p_a, is the probability of non-empty buffer. Theattemptrate, τ, per node is defined as

$$\tau = p_a.\ \tau_c \quad (11)$$

The term, τ_c, is same as given in (8). The value of τis zero when the buffer is empty. The collision probability isarticulated in the equation (9). The value of scaling factoris dependent upon the traffic arrival rate λ, and the size of the buffer. The authors propose solutions for two cases of buffer size. Considering Poisson traffic and each node has a small buffer enough to accommodate at least onepackets.The attempt rate for this model is mathematically expressed as

$$\tau = (1-e^{-\rho})*\tau_c \quad (12)$$

The second model assumes a node having an infinite buffer capacity.The steady state probability of non-empty buffer is defined as $\rho=\lambda.Y_c$, where $Y_c$is the service time of the packet, and ρrepresents the traffic intensity of the channel respectively. The scaling factor will be defined as $p_a = \min(1, \rho)$. The expression for non-saturated attempt rate will be

$$\tau = \min(1, \rho) *\tau_c \quad (13)$$

All the above-discussed models assume the ideal channel condition for transmission purpose. Considering the erroneous channel and capture effect, [26] extended the Markovian model by introducing the transition states for packet transmission failures while propagating through the channel.The proposed model does not incorporate the post backoff feature. The model also provides unlimited transmission attempt at the last backoff stage. This provision is not in agreement with [1]. The model proposed in [23] is protracted in [27]. The evaluation considers following observationsa) transmission failure can be due to erroneous channel b)consideration of heterogeneous traffic conditions. Authors devised proportional fairness criteria that address the rate anomaly problem of the Multirate WLAN in 802.11 DCF networks. The problem associated with Multi rate stations is also addressed inErgen et al. [28]. The model introduces an adaptive algorithm which adjusts the packet size of stations that are transmitting at high data rate so that the channel is fairly distributed among stations having different data rates. Literature concerning performance analysis of the network considering the noisy channel, heterogeneous traffic and multi hop paths can further be referenced in [29-34].

Failure to incorporate capture effect and freezing of backoff counter when the channel is seized motivatesthe work in [35]. The authors use a class of Petri Nets namely stochastic reward nets to address the above problems. The mean delay analysis is carried out assuming each node to beM/G/1 queue.The models consider that the packets are dropped once the threshold limit is achieved. The model can be extended for evaluating multi-hop systems and network system with multiple data rates.The model proposed in [36] evaluates the performance of multi-hop ad hoc networks. The nodes in the network are mobile and follow the random mobility model. Their solution is based on Stochastic Reward Nets. The main assumptions of the model are a) Homogenous Network where nodes move randomly. b) All nodes are independent and behave identically. The model takes into consideration the hidden terminalswhich interfere during the transmission between source and destination. The framework evaluates the network as a function of transmission range, carrier sense range, interference range, node density and packet arrival rate. Based on the idea of decomposition and fixed-point iteration, the model is divided into five modules: the path length model, the path analysis model, data link model, network layer model and transport layer model. The path length model is based on fixed point iteration while latter four are represented as SRN. The above five models are further categorized into two groups a) Mobility Model b) Layer Model. The Path Length model and Path Analysis model constitutes the Mobility model. This model analyzes the path between source and destination. The main features are a) calculation of the number of hops between source-destination when nodes are mobile b) availability of the path for transmission and calculating the average rate of failure and repair between communicating nodes. Layer model determines the key performance metrics across the protocol stack giving the holistic approach to the model.

The colored Petri net model for 802.11 DCF insides proposed in [37].The solution methodology takes into consideration almost all aspect of protocol,including physicaland carrier sense range, backoff process, traffic generation, hidden terminal and exposed terminal problem. Appropriate color sets are used to differentiate between places, tokens (packets), transition, data flow and control flow to make mathematical solution tractable. The firing of transition for different tokens among places is guarded through Timed Colored Petri Nets. The methodology involves modeling all aspect of protocol for a single node and then duplicate it to represent the number of nodes in the network. This simple method of duplication suffers from scalability problem. As the size of the network grows the state space of solution grows tremendously making analysis intractable. Colored Petri Nets can produce compact model by exploiting the symmetries among the nodes with the help of folding technique.The color sets are used to represent various tokens which present different packets including RTS, CTS, Data, and ACK. These tokens can be folded into one place. Similarly, depending upon the type of token transition actions can be distinguished through a different color set. The different facets of the station can be folded to reduce redundancy. The transition firing between places for exchange tokens is guarded through Boolean expression which is represented through the timed color Petri nets. The models are divided into several connected sub modules. These sub modules represent different aspects of protocol. The scalability problem is addressed through special module 'init'. When transition is fired, this module initializes the marking of places. At present the model can support up to 100 nodes.

V. TH PRESENCE OF THE FINITE BUFFER IN NONSATURATED MODELS

The analytical models presented in section IV assumed the presence of either small buffer memory or infinite buffers. No detailed analysis of their effect on performance evaluation of the network was presented. In amore realistic network,it is important to consider the effect of buffers on MAC behavior. In this section presents literature that investigates the impact of buffers on various network parameters.

Assuming each node to have finite buffer space, the work in [38] observed that models assuming queuing decoupling equations yield erroneous results when the offered load is not homogenous.The work in [39] extends [23] by accommodating buffer space. The queue in buffer to store the packets is modeled as a Markov chain. At given time buffer is either empty or it can accommodate one or more packet depending upon its capacity to store packets. Figure 9 illustrates the above observation.The variable Π_1 denotes the state of the buffer when there is only one packet in the buffer and $\Pi_q$signify the presence of more than one packet in the buffer. Taking into consideration the traffic arrival rate and solving the buffer model the probability of the packet in the buffer, q, is expressed as

$$q = (1-e^{-\lambda T})(1 + q_{tmp}) / (1 + (1-e^{-\lambda T})q_{tmp})$$
$$q_{tmp}= (p + p(1-p)) / (1-p)^2 \quad (21)$$

It was shown that performance of the network in term of throughput increases in case of buffered nodes.

The absence of the retry limit in analytical models tends to overestimate the throughput. Similarly, the lack of buffer space leads to underutilization of the channel. The work in [40] presents a new analytical model addressing both problems. Assuming the single hop network, itwas reported that RTS-CTS do not necessarily increase the performance of the network. By discarding collision decoupling approximation Garetto et al. [41] stressed that it is necessary to take into consideration the count of stations that have non-empty buffers. The authors concluded that exclusion of this observation shows that the model overestimates the throughput. The number of contending nodes during a period is dependent on the traffic arrival rate. It can be concluded that number of station is not constant variable. The backoff state is now tagged with three variables viz backoff stage, backoff counter and

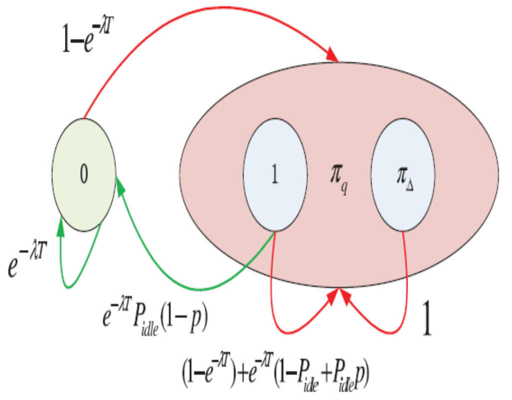

Fig 9. Markov chain Model representing the buffer memory state (source [40])

number of stations with at least one packet in their buffer. The results obtained from the proposed model is validated with simulation work. The work does not specify the size of buffer taken to predict the result set.

The authors in [42] proposed two models based on M/G/1/K queueing system. The first model is based on the ideology that collision probability is not an independent variable rather it depends upon is dependent on backoff stage. The second model evaluate the metrics assuming constant and independent collision probability. It is reported that the first model performs better than the second model. Another contribution of the authors is the model based on M/MMGI/1/K queuing system. The resultant model can be deployed for sensitivity analysis and can be extended to model different network configurations.

Itwas observed in [43] thatthe service time is an important factor to correctly evaluate the 802.11 DCF protocol.The service time is defined as the time interval from the time packet becomes the head of the queue and starts contending for transmission to the time instant that either packet is transmitted successfully or is dropped after reaching the retry limit. The backoff process is modeled as the Markov chain. The transition variables denotetheprobability generating function of probability of successful delivery, probability of collisions and probability when medium is idle.Using Mason Gain formula, the generalized transition diagram determines the service time of the packet.Assuming, the Poisson traffic arrival rate and buffer at each node is represented as M/G/1/K queue, the authors use classical queuing theorems to determine various parameterslike average queue length,MAC service time, average waiting time, throughput, and delay.

The evaluation of DCF network for non-saturation conditions, considering an arbitrary buffer is proposedin [44].Assuming i) The traffic arrival rate is assumed to follow Poisson distribution with parameter λ. ii) The buffer in nodes is treated using M/G/1/K queuing model where K represents the maximumamount of buffer space to accommodate the packets awaiting their transmission. The authors proposed two methods to calculate the probabilities $p_0$and service time of the packet. The first method uses recursive equations given in [45] for M/G/1/K queue. The second method is based on the observation that the queue length distribution of finite queue can be derived from that of the infinite queue. Authors use the lattice-Poisson algorithm to compute the desired parameter. It was observed that as the length of the buffer increases the time required to solve the expressions increases. To accelerate the computations, Lattice- Poisson algorithm [46]is employed. It was concluded that increasing the buffer size can increase the throughput slightly, but this increasesthe packet delay with no reduction in packet loss rate. The model can be used to predict the results for heterogenous arrival rates, packet size and buffer size. The model computes the different metrics quickly making it suitable for its use in real time applications.

Many more analytical models based on queuing theory can be referenced in [47-50]. Itwas reported in [51] increasing buffer size may increase the packet delay and expedites the packet loss experienced by the station and with no substantial gain in throughput due to contention based nature of medium access protocol. The number of active stations and channel condition can vary with the passage of time. This affects the service time which affects throughput and delay. Authors in [52] observed that there is no fixed buffer size that ensures high throughput and low delay. Two dynamic algorithms have been proposed that tune the buffer size of the node such that wireless link is utilized efficiently while avoiding long queuing delays.

The work in [53] evaluated the performance of DCF using stochastic Petri nets. The model assumes ideal channel conditions. The proposed literature incorporated most aspects of the protocols. The authors present a detailed model followed by two compact mathematical tractable models. The detailed model uses indistinguishable tokens, timed and immediate transitions. The firing time distribution can be exponential, deterministic or general. Transitions are preemptive in nature and guarded. The transitions can fire depending upon the number of tokens in place. It is reported that analytical analysis is not possible due to large state space and firing events of multiple non-exponential transitions. Two compact models are proposed to make the problem analytically tractable. In the first model, the number of states are reduced in comparison to detailed model. The evaluation in this model is carried out for the buffer that can store at a single packet. The detailed collision process in previous model is folded into the single state. The states representing an idle buffer or consecutivepackets are merged into other states. The second model incorporates arbitrary buffer size. The state representing the collision, successful transmission and deferment process of backoff are replaced with the probabilities of these events to occur. The analysis of the three models are carried out using SPNica and simulated on SPNL component of TimeNET. The analytical results and simulation agrees with other, validating the models.

VI. CONCLUSION

Analytical Models are cost effective alternative for evaluating network metrics. They provide the advantage to predict the performance parameters without disturbing the flow of real network.Different mathematical techniques like Markov Chain, renewal theory, mean-value theory, Petri Nets have been successfully applied to predict the network metrics. Most the modelsavailable in literature are based ona discrete Markov chain. These models are mathematical tractable, but involve complex calculations. There is the lack of literature that analyzes the performance of multi-hop networks using Markov chain. Different Petri Nets like stochastic Petri nets, stochastic reward nets, colored Petri nets and object oriented Petri nets have been successfully employed to model and capture essential features of DCF protocol. Complex problem involving multi hop networks are successfully solved using Petri Nets. Fixed-point analysis reduces the complexities involved in Markov based models. This increases the computation speed of models to evaluate and predict the network metrics. It can be concludedthat evaluation of network assuming buffer storage in the node can be dealt easily using this approach.

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Neeraj Gupta. "A Review of Analytical Models Evaluating Performance of 802.11 DCF Networks ." International Journal of Engineering Research and Applications (IJERA) , vol. 7, no. 9, 2017, pp. 30–41.