An Advanced Semi-Markov Process Model for Performance Analysis of Wireless LANs

#Hao Wang, *Guixia Kang, Kai Huang
Beijing University of Posts and Telecommunications
Key Laboratory of Universal Wireless Communications, Ministry of Education
Beijing, P. R. China
*gxkang@bupt.edu.cn, #wang.hao0716@gmail.com

***Abstract*—During the last decades, there are numerous researches in the field of wireless local area networks (WLANs). A large number of these researches focus on performance analysis of IEEE 802.11 Medium Access Control (MAC) protocols. And the most representative model for MAC mechanism in WLANs is the two-dimensional Markov model, which has been proven to be an accurate model to analyze the performance of WLANs, in the assumption of finite number of terminals and ideal channel conditions. But this two-dimensional Markov model is rather complex, as far as computation and analysis are concerned. Recently, a novel semi-Markov process model for IEEE 802.11 MAC protocols has been put forward to mitigate the complexity of analyzing the performance of WLANs. However, this semi-Markov model has some defects, such as not taking maximum retransmission number into account. In this paper, we propose an advanced semi-Markov process (ASMP) model, which not only withholds the merits of semi-Markov chain model, but also eliminates its shortcomings, thus more accurately calculating the network parameters of WLANs. Simulation results show that our proposed model achieves accurate results with less complexity, and is suitable for evaluating the performance of the MAC protocols.**

Keywords: Medium Access Control (MAC), Binary Exponential Backoff (BEB), Advanced Semi-Markov Process (ASMP), Mean State Holding-Time

I. INTRODUCTION

Over the past few years, the networking world has witnessed an impressive deployment of products based on IEEE 802.11 standard for WLANs. To access the medium in MAC layer, IEEE 802.11 employs a CSMA/CA (carrier sense multiple access with collision avoidance) mechanism with binary exponential backoff (BEB) rules, called Distributed Coordination Function (DCF) in [1]. DCF defines a basic access method, and an optional four-way handshaking technique, known as *request-to-send/clear-to-send* (RTS/CTS) method. We only consider the basic access mechanism in this paper. And our method can be easily applied into the RTS/CTS mechanism.

A station with packets to transmit monitors the channel activities until an idle period equal to a distributed inter-frame space (DIFS) is detected. After sensing an idle DIFS, the station waits for a random backoff period for an additional deferral time before transmission. The backoff period is slotted and is expressed in terms of an integer number of elementary backoff slots. Such a number, called the backoff counter, is decremented by one in terms of slot time as long as the channel is sensed idle, stopped when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. Once the backoff counter reaches zero, the station starts to transmit. At each transmission, the backoff counter is uniformly chosen in the range $[0, CW]$, where CW is the current backoff contention window size. At the very first attempt transmission, CW equals the minimum contention window size $CW_{\min}$. After each unsuccessful transmission, CW is doubled until a maximum contention window size $CW_{\max}$ is reached. Once it reaches $CW_{\max}$, CW shall remain at the value $CW_{\max}$ until it is reset to $CW_{\min}$ after every successful attempt to transmit, or the retransmission counter reaches a predefined retry limit, maximum retransmission number, which is referred to as R hereinafter. When the retry limit is reached, the present packet is dropped. If the destination station successfully receives the packet, it responds with an acknowledgment (ACK) following a short inter-frame space (SIFS) time. If the transmitting station does not receive the ACK within a specified ACK_Timeout, or it detects the transmission of a different packet on the channel, it reschedules the packet transmission. Furthermore, a station shall not transmit within an extended inter-frame space (EIFS) after it detects that the medium is idle, following the reception of an error packet.

There have been considerable researches aiming at analyzing the performance of CSMA/CA mechanism. Although a great number of different models are introduced, most of them are based on the two-dimensional Markov model in [2], which is rather complex as far as simulation and computation are concerned. Hence, we propose an advanced semi-Markov process (ASMP) model in order to accurately simulate the CSMA/CA scheme with much less complexity.

The remainder of this paper is outlined as follows. In Section II we briefly review the previous related work. Section III presents the advanced semi-Markov process (ASMP) model for CSMA/CA mechanism. Then, the performance evaluation of the proposed model is carried out in Section IV. Concluding remarks are given in Section V.

II. RELATED WORK

This section discusses performance analysis of DCF protocol in the literature.

These researches are on the basis of the two-dimensional Markov model proposed in [2]. The two dimensions of this

This work is supported by the National Science & Technology Specific Program of China (No. 2010ZX03005-001-03), New Century Excellent Talents inUniversity (NCET): NCET-11-0593 and International Science and Technology Cooperation Project (No. 2010DFA11590).

Markov model represent the backoff stages of the BEB mechanism and their backoff counters. Based on two parameters, packet transmission probability (τ) and conditional collision probability (p), Bianchi analyzed the saturation throughput and some other systematic parameters of DCF protocol in [2]. But the original two-dimensional Markov model does not take the maximum retransmission number and the freezing state of backoff counters into consideration, which results in slight deviation of theoretical analysis from performance evaluation obtained from the actual situations. The model proposed in [3] not only takes the maximum retransmission number into account, but also highlights that the hypothesis of uncorrelation between consecutive channel slots and statistical homogeneity is actually not true. By analyzing such a correlation, the model in [3] provides us with more accurate performance analysis for DCF protocol. However, it is obviously complex to analyze the two-dimensional Markov model. The state space $[S]$ of the original two-dimensional Markov model in [2] is given by (1)

$$[S]=\sum_{i=0}^{m}2^{i}\left(CW_{\min}+1\right) \tag{1}$$

where i represents the backoff stage of BEB mechanism, and m represents the highest backoff stage. For Frequency Hop Spread Spectrum (FHSS) physical layer specifications, the state space $[S]$ of the Markov model is as follows,

$$[S]=\sum_{i=0}^{6}2^{i}\left(15+1\right)=16\times\left(2^{7}-1\right)=2032 \tag{2}$$

Obviously, the state space of the original two-dimensional Markov model in [2] is very large with the order of $O(2^{m})$. With more intensive study of IEEE 802.11 DCF protocol, the state space of the subsequent two-dimensional Markov models, which takes other parameters including maximum retransmission number R into consideration, is much larger. Therefore, it is important and imperative to reduce the complexity of the two-dimensional Markov model. A semi-Markov process in [4] was put forward aiming at achieving accurate results for WLANs with less complexity and computation time. Nevertheless, this semi-Markov model is brought forward based upon the two-dimensional Markov model in [2], thereby resulting in same drawbacks as the model in [2]. In this paper, we propose an ASMP model, which reduces the order of state space of the system from $O(2^{m})$ to $O(m)$ and meanwhile provides a simple yet accurate approach for analyzing the essential parameters in wireless networks.

III. ADVANCED SEMI-MARKOV PROCESS

In the ASMP model, a mean state holding-time, the amount of time that a station stays at the present state before making a state transition from the current state, is included to simulate the BEB mechanism, the key of CSMA/CA scheme. The subsequent state of stations in the ASMP model depends on the current state and its state holding-time. Discrete time Markov chains have state holding-times that are equal to a unit time and are independent of the next state transition. The sample paths for the ASMP model are timed sequences of the state transitions. If the process is viewed at times of state transitions, the sample paths are identical to those of a Markov chain. Such a process is known as embedded Markov chain, in which the transition probability P_{ii} is zero according to [5].

In this section, the BEB mechanism is simulated using the ASMP model. In subsection III A, we construct $(R+1)$-state Markov chain to describe the backoff stages of BEB scheme. Given that the backoff interval involved in different backoff stages of BEB mechanism are not equal, this discrete time Markov chain with a unit state holding-time for all the states cannot accurately describe the BEB mechanism, which brings about, in Section III B, the introduction of an embedded Markov chain allowing different state holding-times for different states. However, this embedded Markov chain does not include self-loops (transition from the state i to itself). In subsection III C, we model the backoff intervals of backoff stages of BEB scheme with the ASMP model which allows self-loops and different state holding-times for different states. In addition, the stationary probabilities for the ASMP model are critically deduced. Subsection III D calculates the parameters of interest based on the proposed model.

A. Construction of advanced $(R+1)$-state Markov Chain

The $(R+1)$-state Markov chain in Figure 1 represents the BEB mechanism of IEEE 802.11 DCF protocol. Compared to the semi-Markov model in [4], the ASMP model takes maximum retransmission number and anomalous slots into account. The station with packets to transmit is in state 0. If the transmission is successful, the station loops back to the state 0 and initiates the next packet transmission. For collision, the station in the state i, $i\in[0,R-1]$, proceeds a retransmission and enters into the state $i+1$,. For the station in state R, it will always enter into state 0, no matter whether the transmitting packet is successfully received or not. But it is different that, for successful transmission in state R, the current station initiates a new packet for transmission, while for collision case, it will drop the transmitting packet and then initiate a new packet to transmit. The transition from state i to state $i+1$ indicates an unsuccessful transmission. And the transition from any state i, $i\in[0,R-1]$, to the state 0 indicates a successful transmission. The loopback transition is only possible for the state 0.

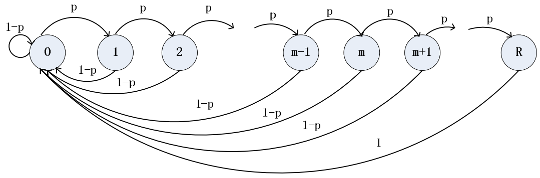

Figure 1. (R+1)-state Markov Chain Model

The state transitions of $(R+1)$-state Markov chain are presented by the state transition probability matrix $[P]$ given by [3], [5]

$$[P]=\begin{pmatrix} (1-p) & p & 0 & 0 & \cdots & 0 & 0 \\ (1-p) & 0 & p & 0 & \cdots & 0 & 0 \\ (1-p) & 0 & 0 & p & \cdots & 0 & 0 \\ (1-p) & 0 & 0 & 0 & \cdots & 0 & 0 \\ . & . & . & . & . & . & . \\ (1-p) & 0 & 0 & 0 & \cdots & p & 0 \\ (1-p) & 0 & 0 & 0 & \cdots & 0 & p \\ 1 & 0 & 0 & 0 & \cdots & 0 & 0 \end{pmatrix} \quad (3)$$

where P_{ij} , $0\le i,j\le R$, is the probability of transition from state i to state j . And $P_{(i-1)i}$, $1\le i\le R$, is equal to conditional collision probability p defined in [3]

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

where τ and N represent packet transmission probability and the number of stations in WLANs. The key approximation validating our model is the assumption of constant and independent conditional collision probability p of a packet transmitted by each station, regardless of the number of retransmissions already suffered, the same as that in [3].

B. Construction of advanced $(R+1)$-state Markov Chain

In this subsection, the semi-Markov chain is transformed into an embedded Markov chain (with $P_{ii}=0,\forall i$), as shown in Figure 2.

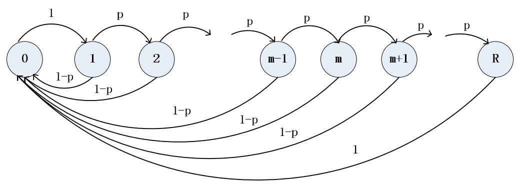

Figure 2. (R+1)-state embedded Markov Chain Model

The element P_{ij}^{e} of state transition probability matrix $[P]^{e}$ of the embedded Markov chain, according to [5], is given by

$$P_{ij}^{e}=\begin{cases} 0 & for \quad i=j \\ \dfrac{P_{ij}}{1-P_{ii}} & for \quad i\neq j \end{cases} \quad (5)$$

which results in

$$[P]^{e}=\begin{pmatrix} 0 & 1 & 0 & 0 & \cdots & 0 & 0 \\ (1-p) & 0 & p & 0 & \cdots & 0 & 0 \\ (1-p) & 0 & 0 & p & \cdots & 0 & 0 \\ (1-p) & 0 & 0 & 0 & \cdots & 0 & 0 \\ . & . & . & . & . & . & . \\ (1-p) & 0 & 0 & 0 & \cdots & p & 0 \\ (1-p) & 0 & 0 & 0 & \cdots & 0 & p \\ 1 & 0 & 0 & 0 & \cdots & 0 & 0 \end{pmatrix} \quad (6)$$

The stationary probability $\prod_i^e$ of the state i of the embedded Markov chain is given by [5]

$$\prod_i^e=\sum_{j\neq i}\prod_j^e\prod_{ji}^e \ , \ \forall i\in[0,R] \quad (7)$$

According to the deduction above, we obtain the stationary probabilities of the advanced embedded Markov chain as

$$\prod_0^e=\prod_1^e=\frac{1-p}{2-p-p^R} \quad (8)$$

$$\prod_i^e=\frac{(1-p)\,p^{i-1}}{2-p-p^R},\forall i\in[2,R] \quad (9)$$

which constitute the stationary probability vector $\prod^e$ marked as $[\prod_0^e,\prod_1^e,\prod_2^e,\cdots,\prod_R^e]$.

C. Stationary Probabilities of the ASMP model

On the basis of [5], stationary probabilities vector $\prod^A$ of the ASMP model is represented as $[\prod_0^A,\prod_1^A,\prod_2^A,\cdots,\prod_R^A]$, and

$$\prod_i^A=\frac{\prod_i^e\times E[H_i]}{\sum_{j=0}^{R}\left\{\prod_j^e\times E[H_j]\right\}},0\le i\le R \quad (10)$$

where H_i represents the state holding-time. In this subsection, the backoff interval of the backoff stage i is modeled with the state holding-time, which is a random variable selected uniformly within the range $[0,CW_i]$, for $0\le i\le R$. For convenience of notation, let $W_{\min}$, $W_{\max}$, and W_j denote $CW_{\min}+1$, $CW_{\max}+1$, and CW_j+1 in the j^{th} retransmission for the rest of this paper. We have

$$W_j=\begin{cases} 2^jW=2^jW_{\min}, & j\in[0,m-1],R>m \\ 2^mW=2^mW_{\min}, & j\in[m,R],R>m \\ 2^jW=2^jW_{\min}, & j\in[0,R],R\le m \end{cases} \quad (11)$$

where $m=\log_2(W_{\max}/W_{\min})$, and $W_{\min}=W$.

In addition, according to [3], the backoff counter should be decremented at the end instead of at the beginning, of a slot time, if the channel is sensed idle. In light of this in-depth standpoint, it is conclusive that a slot immediately following a successful transmission cannot be used for transmissions by any other station, except the transmitting station, and that the extra slot after the reception of an EIFS will not be used by any station (including the transmitting station). Therefore, the backoff counter belongs to the range $[0,W-2]$ after successful transmission and to $[0,W-1]$ after a packet drop. Moreover, as the station visits the state 0 successively after successful transmissions, the expected number of consecutive visits to state 0 is equal to $(1-p\cdot\prod_R^e)/p$. Hence, the expected value of the state holding-time of state 0 should take the two cases discussed above into consideration and can be expressed as follows,

$$E[H_0]=\frac{1}{p}\cdot\frac{W-1}{2}\cdot\left(1-p\cdot\prod_R^e\right)+\frac{W}{2}\cdot\left(p\cdot\prod_R^e\right) \quad (12)$$

The expected value of state holding-time $E[H_i]$ for state i of the ASMP model is given by

$$E[H_i]=\begin{cases}\frac{W_i}{2}=2^{i-1}W & i\in[1,m-1]\\ \frac{W_i}{2}=2^{m-1}W & i\in[m,R]\end{cases} \tag{13}$$

Using (10) and $\sum_{i=0}^{R}\prod_i^s=1$, the stationary probabilities of the ASMP model are given by

$$\begin{cases}\Pi_0^A=\dfrac{\frac{1}{p}\cdot\frac{W-1}{2}\cdot\left(1-\frac{(1-p)p^R}{2-p-p^R}\right)+\frac{W}{2}\cdot\frac{(1-p)p^R}{2-p-p^R}}{B}\\ \Pi_i^A=\dfrac{(2p)^{i-1}\cdot W}{B} \quad i\in[1,m]\\ \Pi_i^A=\dfrac{p^{i-1}\cdot 2^{m-1}\cdot W}{B} \quad i\in[m+1,R]\end{cases} \tag{14}$$

where

$$B=\frac{1}{p}\cdot\frac{W-1}{2}\cdot\left(1-\frac{(1-p)p^R}{2-p-p^R}\right)+\frac{W}{2}\cdot\frac{(1-p)p^R}{2-p-p^R}$$
$$+\sum_{i=1}^{m}(2p)^{i-1}W+2^{m-1}\cdot W\cdot\sum_{i=m}^{R}p^{i-1}, \tag{15}$$

And stationary probability $\prod_i^A$ represents the fraction of time spent by a station in the backoff stage i.

D. Packet Transmission Probability and Saturation Throughput

In this subsection, the average packet transmission probability and saturation throughput of WLANs are analyzed with the stationary probability distribution of the ASMP model. The packet transmission probability τ is calculated as follows. If the station stays at state i, it will transmit once after an expected time $E[H_i]$, for $1\le i\le R$. For state 0, the station transmits once after an expected time interval of $E[H_0]/((1-p\cdot\prod_R^e)/p)$. Thus, the packet transmission probability, namely the probability τ that a station transmits in a randomly chosen slot, can be expressed as

$$\tau=\frac{\Pi_0^A\left(\frac{1-p\cdot\Pi_R^e}{p}\right)}{E[H_0]}+\frac{\Pi_1^A}{E[H_1]}+\frac{\Pi_2^A}{E[H_2]}+\cdots+\frac{\Pi_R^A}{E[H_R]}$$
$$=\frac{1}{B}\cdot\left(\frac{(2-p)(1-p^R)}{(2-p-p^R)p}+\sum_{i=1}^{R}p^{i-1}\right) \tag{16}$$

Based on reference [3], the saturation throughput of WLANs can be expressed as follows,

$$S=\frac{P_s\overline{E(P)}}{(1-P_b)\delta+P_s\overline{T_s}+(P_b-P_s)\overline{T_c}} \tag{17}$$

where P_b is the probability that the channel is busy and P_s denotes the probability that a successful transmission occurs in a slot time, δ, $\overline{E(P)}$, $\overline{T_s}$, $\overline{T_c}$ denote the duration of an empty slot time, the average payload size accounting for multiple packets transmitted into the same slot, the average time that the channel is sensed busy because of a successful transmission and the average time that the channel experiences a collision, respectively. As in [4], it readily follows that

$$P_b=1-(1-\tau)^N \tag{18}$$

$$P_s=N\tau(1-\tau)^{N-1} \tag{19}$$

We now provide expressions for $\overline{E(P)}$, $\overline{T_s}$, $\overline{T_c}$. Let T_{MPDU}, T_{ACK}, $SIFS$ and $DIFS$ denote the time to transmit the MPDU, the time to transmit an ACK, the SIFS time, and the DIFS time, respectively. According to [3], the first slot anomaly effect described can be accounted by including an extra slot time at the end of a transmission period and noting that, for a successful station, a subsequent collision-free transmission of a frame occurs with probability $1/W_{\min}$. Thus, we have

$$\overline{E(P)}=P+\sum_{k=1}^{\infty}(1/W_{\min})^k P=P\frac{W_{\min}}{W_{\min}-1} \tag{20}$$

$$\overline{T_s}=T_s+\sum_{k=1}^{\infty}(1/W_{\min})^k T_s+\delta=T_s\frac{W_{\min}}{W_{\min}-1}+\delta \tag{21}$$

where P denotes the packet payload size and T_s is the successful transmission time of a single-packet transmission for the basic access mechanism,

$$T_s=T_{MPDU}+SIFS+T_{ACK}+DIFS \tag{22}$$

As for the collision case,

$$\overline{T_c}=T_c+\delta \tag{23}$$

where, for the basic model of DCF protocol,

$$T_c=T_{MPDU}+SIFS+T_{ACK}+DIFS \tag{24}$$

IV. PERFORMANCE EVALUATION OF PROPOSED MODEL

Unless otherwise specified, we set T_{slot} to $50\mu s$, $DIFS$ to $128\mu s$, $SIFS$ to $28\mu s$, $ACK_{Timeout}$ to $300\mu s$, W to 32, m to 5, R to 7 and packet payload size P to 8184 bits.

Matlab simulation is carried out to compute the essential network parameters (τ_A, p_A, S_A) of wireless networks and to evaluate the computation time for the ASMP model. The results are validated when compared to those of Tinnirello's model in [3]. τ_T, p_T and S_T denote the values of the packet transmission probability, conditional collision probability and saturation throughput, obtained from Tinnirello's model, respectively. Likewise, τ_A, p_A and S_A represent the values of those parameters obtained from the proposed ASMP model. The outputs of the essential network parameters obtained from the two Markov models are presented in Table I. Moreover, the saturation throughputs S_T and S_A for a constant N of 100 are compared for different variations of $W_{\min}$ (from 8 through 1024), and these results are presented in Table II.

TABLE I. COMPARISON OF ESSENTIAL PARAMETERS OF THE TWO MARKOV MODELS

N	(τ_T, p_T, S_T)	(τ_A, p_A, S_A)
2	(0.0568,0.0568,0.8186)	(0.0574,0.0574,0.8194)
5	(0.0483,0.1791,0.8346)	(0.0492,0.1825,0.8345)
10	(0.0385,0.2990,0.8369)	(0.0390,0.3012,0.8370)
20	(0.0295,0.4298,0.8357)	(0.0293,0.4315,0.8364)
30	(0.0241,0.5082,0.8343)	(0.0242,0.5108,0.8339)
40	(0.0217,0.5652,0.8324)	(0.0216,0.5662,0.8325)
50	(0.0186,0.6113,0.8274)	(0.0187,0.6123,0.8271)
60	(0.0175,0.6466,0.8239)	(0.0175,0.6479,0.8241)
70	(0.0159,0.6781,0.8207)	(0.0159,0.6789,0.8208)
80	(0.0151,0.7006,0.8189)	(0.0152,0.7026,0.8178)
90	(0.0142,0.7258,0.8153)	(0.0144,0.7263,0.8154)
100	(0.0137,0.7467,0.8114)	(0.0137,0.7479,0.8115)
150	(0.0114,0.8235,0.7951)	(0.0115,0.8241,0.7948)

TABLE II. COMPARISON OF ESSENTIAL PARAMETERS FOR VARIATIONS IN $W_{\min}$: FOR CONSTANT N OF 100

$W_{\min}$	(τ_T, p_T, S_T)	(τ_A, p_A, S_A)
8	(0.0330,0.9651,0.6492)	(0.0335,0.9662,0.6439)
16	(0.0208,0.8726,0.7753)	(0.0209,0.8741,0.7741)
32	(0.0139,0.7468,0.8120)	(0.0139,0.7482,0.8117)
64	(0.0094,0.6133,0.8269)	(0.0095,0.6143,0.8268)
128	(0.0067,0.4765,0.8343)	(0.0067,0.4762,0.8341)
256	(0.0046,0.3561,0.8367)	(0.0046,0.3563,0.8366)
512	(0.0024,0.2369,0.8341)	(0.0025,0.2368,0.8341)
1024	(0.0015,0.1458,0.8254)	(0.0015,0.1459,0.8254)

From the two tables, it is readily apparent that the outputs of the ASMP model are close to those of Tinnirello's model with a maximum difference of 0.1 percent for the saturation throughput. And the increase in N leads to an increase in p as well as a decrease in τ , while the saturation throughput does not have large variations, which is consistent to the theoretical analysis in [2]. Table II presents the variations of τ , p and S with respect to N for both Tinnirello's model and the ASMP model, as well as with respect to $W_{\min}$ for a constant N of 100. And it is easy to conclude that the results of the three parameters obtained from the ASMP model is rather close to those obtained from Tinnirello's model, thus verifying the accuracy of the proposed ASMP model.

For the computation time, various cases, characterized by different number N of contending stations in wireless LANs, are considered and the results are presented in Table III, where C_T , C_A respectively represent the time required to compute the essential parameters and the saturation for Tinnirello's model and the proposed ASMP model. Based on the results in Table III, the proposed ASMP model apparently requires less than one-tenth of the time required for computing these parameters of Tinnirello's model. Therefore, from the computation time point of view, the proposed ASMP model is more effective than Tinnirello's model in [3].

TABLE III. COMPARISON OF COMPUTATION TIME OF THE TWO MODELS

N	C_T (in ms)	C_A (in ms)
2	1.400021	0.101950
5	0.793254	0.082756
10	0.839486	0.079642
20	0.812346	0.098759
30	0.798647	0.080756
40	0.796481	0.082759
50	0.795823	0.095783
60	0.808426	0.082195
70	0.799431	0.081149
80	0.776594	0.081628
90	0.812567	0.083451
100	0.798769	0.082184
150	0.822163	0.083152

V. CONCLUSIONS

In this paper, the Binary Exponential Backoff (BEB) mechanism of IEEE 802.11 DCF protocols is modeled with the Advanced Semi-Markov Process (ASMP) model. By introducing the state holding-time, the ASMP model is proposed to lower the number of state spaces and reduce the complexity of calculating the essential parameters influencing the overall performance of WLANs. Additionally, the ASMP model has considered the maximum retransmission number and anomalous slots, thus guaranteeing the accuracy of the simulation results. The ASMP model presents a simpler but accurate approach to compute the essential parameters, such as conditional packet probability, packet transmission probability and saturation throughput without compromising the accuracy. Then, matlab evaluation has proved that the ASMP model required only one-tenth of the time needed to compute these essential parameters for Tinnirello's model. Hence, the ASMP model achieves accurate results with less complexity and computation time, thus making it more suitable to analyze sophisticated protocols such as IEEE 802.11e.

REFERENCES

[1] Stuart J. Kerry, Al Petrick, Harry R. Worstell…IEEE 802.11n, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Higher Throughput," Feb. 2007.

[2] G. Bianchi, "*Performance analysis of the IEEE 802.11 Distributed Function*", IEEE Journal on Selected Areas in Communications, vol. 18, no. 3, March 2000, pp. 535-547, March 2000.

[3] I. Tinnirello, G. Bianchi and Y. Xiao, "Refinements on IEEE 802.11Distributed Coordination Function Modeling Approaches," IEEE Trans.Vehicular Tech., vol. 59, no. 3, pp. 1055-1067, Mar. 2010

[4] Kadiyala. M.K, Shikha D., Pendse R., Jaggi N., "Semi-Markov process based model for performance analysis of wireless LANs", IEEE PERCOM Workshops, pp. 613-618, Mar. 2011.

[5] R. Nelson, Probability, Stochastic Processes and Queuing Theory: Mathematics of Computer Performance and Analysis, ser. Springer-Verlag, New York, 1995.