Extension and Comparison of QoS-Enabled Wi-Fi Models in the Presence of Errors

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***Abstract*— In this paper we compare and enhance the three prevailing approaches of IEEE 802.11e Performance analysis. Specifically, the first model utilizes a Markov Chain to describe the state of the Backoff Counter, the second is based on a general probabilistic explanation of the standard and the third forms a queuing network. We have injected, in the proposed models, new ideas to cover the latest update of the QoS-enabled 802.11e standard, and compared all the models showing results regarding the accuracy of each approach. Throughput performance is given for various parameters of the medium while including Gaussian error-prone channel in 802.11e. Results are also provided regarding the effect of the Block-ACK feature. The comparison is performed both in terms of accuracy and structural possibilities and finally the results are validated via simulations with Opnet Modeler. The proposed comparison mathematical analysis can also be extended to other applications and wireless protocols.**

I. Introduction

The rapid evolution of WLANs in conjunction with the proliferation of ubiquitous services have created an increasing need for Quality of Service (QoS) in wireless networks. To address this emerging market need, the 802.11 work-group standardized, in 2005, a new MAC enhancement of the IEEE 802.11 [1], namely the 802.11e [2]. The proposed Enhanced Distributed Channel Access (EDCA) enables Quality of Service (QoS) functionality in WLANs, by differentiating the access mechanism in four Access Categories (AC) in distributed networks.

Several approaches regarding the use of Discrete Time Markov Chains (DTMCs) are provided in the literature by [3], [4], [5] and thus the subject's maturity makes this the best time to compare and propose analyses that could be simpler, diminish the computational complexity, and/or be more accurate with respect to the simulation results. Apart from the DTMC approach, other models have been proposed that lead to precise results, all having advantages and disadvantages. The goal of this paper is to compare the three well known categories of models in the aforementioned context. The models of [4], [6] and [7] are used as the basis, and they are extended according to the needs of a common, error-prone environment, and QoS features of the MAC layer. These extensions carry themselves scientific interest and novelty.

The DTMC model captures the differentiating effect of the Arbitrary Inter-Frame Spacing (AIFS) and the freezing of the backoff counter. The second approach relies on elementary conditional probability arguments, similar to p-persistent modeling. The third model simulates the behavior of the stations that belong to each Access Category. The key assumption in this analysis is that its backoff period is modeled through a $G/G/\infty$ queue and Little's theorem is used to provide its solution.

In these models the effect of *different retransmission limits* among the access categories is studied. *Freezing of backoff counters* is also taken into account. Moreover, a more accurate equation of saturation throughput is provided and a way of incorporating the *inter-collision phenomenon* among the Access Categories. The proposed analyses include also another characteristic, which most of the models after draft 4.0 of 802.11e standard, have omitted. The standard defines that after a successful transmission by an AC, in the next time slot the same AC will choose a value of its backoff counter in the interval [1,CWmin], *which leaves out the value 0*. That corresponds to ruling out the probability after a successful transmission to follow another one, partially mentiond in [8]. In addition, a *Gaussian erroneous channel* for EDCA is used to analyze the Block-ACK effect and *11Mbps channel rate (IEEE 802.11b/e)* is considered, depicting the QoS performance in higher transmission rates. Our simulation results are based on the HCCA model included in the last version of Opnet Modeler^{TM} 12.

The proposed models require advanced knowledge of [2], [3] and [6], since formulas, symbols and other proved explanations are taken as prerequisites. This paper is organized as follows. In Section 2 we provide extended analysis of the three models and in Section 3 a throughput comparison is given for various transmission rates, conditions of the channel and features enabled or disabled. In the last Section a conclusion is made upon the advantages and disadvantages of each approach.

II. Mathematical Analysis of the Models

Before formulating the mathematical analysis, the following assumptions have been made regarding all models. The number of stations N_i is finite, the same for each AC and contend only in a single-hop network. Moreover the channel condition

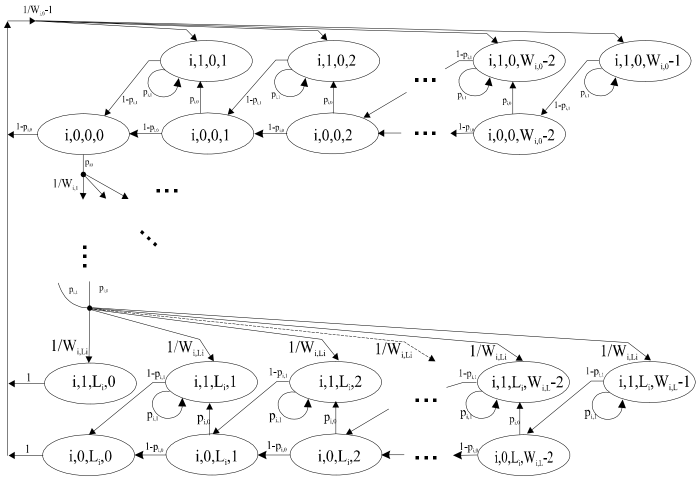

Fig. 1. Analytical Markov Chain/DTMC for each Access Category AC[i].

is erroneous and the network is saturated, which means that there is always a packet ready for transmission.

A. DTMC Model

The model presents the effect of contending terminals on the channel access probability of each Access Class (AC). The current slot is divided according to the state of the previous one. If it was idle, all Access Categories of all stations may access the channel if their backoff counter is decremented to zero. On the other hand, if the previous slot was busy, another division must take place. A busy slot can occur if there is a collision or a transmission of another station. In the first case the stations that did not participate in the collision freeze their backoff counter and will not be able to transmit. Whereas the stations that collided can transmit in the next slot if they choose a new backoff value equal to 0.

In the second case, when there is a successful transmission none of the stations can transmit in the next time slot. This happens specifically for the standard IEEE 802.11e [2] and not for the legacy IEEE 802.11. The latter defines that after a successful transmission the contention window starts from 1 and not 0.

All these are considered in the provided analysis and are shown in the DTMC of Fig. 1, which refers to each Access Category separately. Note that the state $\{i, 1, 0, 0\}$ is missing. The contention window $W_{i,j}$ is given for several values of class i, backoff stage j and persistent factor pf_i: L_i is the maximum retry

$$W_{i,j} = \begin{cases} \lfloor (pf_i)^j W_{i,0} \rceil & j = 0, 1, ..., m_i - 1 \\ \lfloor (pf_i)^{m_i} W_{i,0} \rceil & j = m_i, ..., L_i \end{cases} \tag{1}$$

where $\lfloor \cdot \rceil$ is the closest integer function.

The DTMC can be described by the stationary probabilities $b_{i,w,j,k}$, where $i = \{0, 1, 2, 3\}$ describes the Access Category. Variable w represents the condition of the previous slot, where 1 is for the busy channel and 0 for the idle channel and $k \in [0, 1, ..., W_{i,j} - 1]$ accounts for the backoff delay. The probability $p_{i,0}$ (or $p_{i,1}$) that another terminal's Access Category is transmitting after an idle period (or after a busy period). The probability that the channel remains idle after an idle period is represented $q_{i,0}$ (or after a busy period $q_{i,1}$). The basic relations between the states are the same with equations (2) in [4]. The difference in our analysis can be found in the definition of $\psi_{i,j}$:

$$\psi_{i,j} = \begin{cases} \dfrac{1}{W_{i,0} - 1} & j = 0 \\ \dfrac{p_{i,0}}{W_{i,1}} & j = 1 \\ \dfrac{p_{i,0}}{W_{i,1}} \Pi_{i,j} & j = 2, 3, ..., m_i \\ \dfrac{p_{i,0}}{W_{i,1}} \Pi_{i,m_i} P_{i,j} & j = m_i + 1, ..., L_i \end{cases} \tag{2}$$

$\Pi_{i,j}$ and $P_{i,j}$ are defined as:

$$\Pi_{i,j} = \prod_{x=2}^{j} \left[\frac{p_{i,1}}{W_{i,x}} + \frac{p_{i,0}}{W_{i,x}} (W_{i,x-1} - 1) \right]$$

$$P_{i,j} = \prod_{x=m_i+1}^{j} \left[\frac{p_{i,1}}{W_{i,m_i}} + \frac{p_{i,0}}{W_{i,m_i}} (W_{i,m_i} - 1) \right]$$

Applying the normalization condition for each Access Category's DTMC, $b_{i,1,0,0}$ is calculated as:

$$b_{i,0,0,0} = \frac{2(1 - p_{i,1})}{K_i + \Lambda_i} \tag{3}$$

$$K_i = W_{i,0}(1 - p_{i,1}) + p_{i,0}(W_{i,1} - 1)(2 - p_{i,1}) + \\ + 2p_{i,0}(W_{i,0} - 2) + 4$$

$$\Lambda_i = \sum_{j=2}^{L_i} \psi_{i,j} W_{i,j} \left[(W_{i,j} - 1)(1 - p_{i,1} + p_{i,0}) + 2 \right]$$

The probabilities of accessing the channel in a time slot $\tau_{i,w}$ ($w = idle$ or $w = busy$) and the probability that the channel is idle in a period P_{idle} are defined as in eq. (3) and (1) of [4]. The probabilities that the channel remains idle after an idle (or a busy) time slot are again calculated by eq. (4) in [4]. The probability of another AC transmitting is relatively complex. An inter-collision handler and a virtual collision handler must also be taken into account. In the proposed analysis these handlers are introduced by means of a correlation measure r between the difference in AIFS of the two colliding services (i_1 and i_2) and the mean consecutive number of idle slots $E[\Psi]$. The phenomenon of inter-collision happens when two ACs wait for the same period of time (sum of backoff and AIFS). The correlation measure makes sure that only possible pairs of inter-colliding services are taken into account:

$$r(i_1, i_2) = \max[1 - \frac{AIFS[i_1] - AIFS[i_2]}{E[\Psi]}, 0], i_1 \geq i_2 \tag{4}$$

where $E[\Psi] = \min(\frac{P_{idle}}{1 - P_{idle}}, 1)$.

This specific correlation measure simplifies the analysis, because it does not increase the complexity of the mathematical analysis when trying to solve the DTMC. Thus, the probabilities of a collision after an idle or busy slot are:

$$p_{i,0} = 1 - \prod_{z<i} (1-\tau_{z,idle})^{\lfloor N_z \cdot r(z,i) \rceil} \times \times (1-\tau_{i,idle})^{N_i - 1} \prod_{z>i}^{3} (1-\tau_{z,idle})^{N_z} \tag{5}$$

$$p_{i,1} = 1 - (1-\tau_{i,busy})^{N_i-1} \prod_{z>i}^{3} (1-\tau_{z,busy})^{N_z}$$

The successful transmission probability in a time slot of an AC is

$$\begin{aligned} P_{s,i} = P_{idle} \cdot N_i \cdot \tau_{i,idle} \cdot \prod_{z<i} (1-\tau_{z,idle})^{\lfloor N_z \cdot r(z,i) \rceil} \times \\ \times (1-\tau_{i,idle})^{N_i-1} \cdot \prod_{z>i} (1-\tau_{z,idle}) N_z + \\ + (1-P_{idle}) \cdot N_i \cdot \tau_{i,busy} \cdot (1-\tau_{i,busy})^{N_i-1} \times \\ \times \prod_{z>i} (1-\tau_{z,busy})^{N_z} \end{aligned} \tag{6}$$

B. Probabilistic Model

This approach is based on conditional probabilities of each Access Category independently as shown in [6]. The model is extended so as to include the four ACs of the IEEE 802.11e, its additional features and an alternative, more accurate, calculation of the mean backoff duration.

Two events are defined here. The first is called TX_i and means that a station's AC is transmitting a frame into a time slot and the second is $s = j$ is that the station's AC is in backoff stage j where $j \epsilon [0, L_i]$, and L_i is dependant upon the access method. From Bayes' Theorem we have

$$P(TX_i) \frac{P(s=j|TX_i)}{P(TX_i|s=j)} = P(s_i = j) \tag{7}$$

The sum of all the events, since each Access Category is supposed as an independent BEB, equals to one:

$$\sum_{j=0}^{L_i} P(s_i = j) = 1 \tag{8}$$

Combining the above equations τ_i is as follows

$$\tau_i = P(TX_i) = \frac{1}{\sum_{j=0}^{L_i} \frac{P(s=j|TX_i)}{P(TX_i|s=j)}} \tag{9}$$

From the above we must find $P(s = j|TX_i)$ and $P(TX_i|s = j)$. The first conditional probability represents the probability an AC transmitting while being in stage j. It is readily seen that the Exponential Backoff Algorithm can be solved based on a complex truncated geometric distribution (truncated due to the upper limit). However, some cases need special care, especially since the standard [2] does not allow an instant access of the channel after a successful transmission by the same Access Category.

$$P(s=j|TX_i) = \begin{cases} \frac{(1-p_i)p_i^j}{1-p_i^{L_i+1}} & j = 0, 1..., L_i \end{cases} \tag{10}$$

The other conditional probability is $P(TX_i|s = j)$, which is the probability that an AC transmits while being in backoff stage j. Let us envision the transmission process as independent transmission cycles, which consist of the transmission time and a delay caused by the Backoff Duration. This procedure is repeated until the successful transmission the above probability is defined as the number of slots spent for a transmission divided by the delay of the whole cycle $E[BD]_i$. Thus, we have that

$$P(TX_i|s=j) = \frac{1}{1+E[BD]_{i,j}} \tag{11}$$

1) Mean Backoff Duration: In order to find the Mean Backoff Duration, the duration of each exponential backoff must be found, which should include the finite limit of $CWi - H[j-1]$ and the freezing of backoff counter each time the slot is detected busy. For example if there were k freezings, then the delay would be, $E[SD]_{i,j} = \sum_{k=0}^{CW_i - H[j-1]} \left(kp^k\right) \cdot (1-p_i)$, which gives finally

$$E[SD]_{i,j} = \frac{CW_i - H[j-1]}{2 \cdot (1-p_i)} \tag{12}$$

Taking into account all the possible series of the exponential backoff, the Mean Backoff Duration is given from

$$E[BD]_{i,j} = \begin{cases} \sum_{k=0}^{CW_{i,j}-1} \frac{BD_{i,j}^k}{CW_{i,j}} & 0 \le j \le m_i \\ E[BD]_{i,m_i} & m_i \le j \le L_i \end{cases} \tag{13}$$

C. Queuing network model

This analysis is based on the Choi et al letter [7]. In this model the mathematical approach towards the network is different from the previous ones, because it models the behavior of each AC, which contains N_i stations, instead of a single station. Apart from that, each Backoff Stage is modeled by a $G/G/\infty$ queuing system. The infinite number of parallel servers are used so that each queue can serve all stations simultaneously without a queueing delay. In addition, the same assumptions that were made in the previous models exist also here. However, similarly to the previous models, the first queue has a shorter length than the other ones. This solution is based on the assumption that the transmission probability can be expressed as the total attempt rate λ_i, divided by the number of stations of each AC independently.

$$\tau_i = \frac{\lambda_i}{N_i} \tag{14}$$

Let us define $\lambda_{i,j}$ as the arrival rate and $\mu_{i,j}$ as the average service rate, at each queue of each AC, where $\mu_{i,k}$ is found from the Backoff Duration of each queue and its analytical solution is derived from equation (13). From Little's Law the number of stations in each queue and in each AC can be found by

$$N_{i,j} = \frac{\lambda_{i,j}}{\mu_{i,j}} \tag{15}$$

The transition probability from each queue occupancy value to the next one is related to the arrival rates. However, it should be noted that the first backoff window is not chosen.

$$\lambda_{i,j+1} = p_i \lambda_{i,j} \qquad j = 0, ..., L_i \tag{16}$$

where the total attempt rate λ_i is given by

$$\lambda_i = \sum_{j=0}^{L_i} \lambda_{i,j} = \lambda_{i,0} \sum_{j=0}^{L_i} p_i^j \tag{17}$$

and the average service rate of each queue is found from

$$\mu_{i,j} = \frac{1}{1 + E[BD]_{i,j}} \tag{18}$$

The reason for adding 1 to $E[BD]_{i,j}$ is the extra slot for transmission. Having calculated $\lambda_{i,j}$ and $\mu_{i,j}$ we can use again Little's theorem

$$N_i = \sum_{j=0}^{L_i} N_{i,j} = \lambda_{i,0} \sum_{j=1}^{L_i} p_i^j \left(1 + E[BD]_{i,j}\right) \tag{19}$$

In equation (19) the sum is too complicated to be solved and it needs computer numerical tools. Finally τ_i is computed from equation (14).

From the above mathematical results we can see that equations (14) and (9) are the same, leading to the conclusion that both approaches give similar results.

III. Performance Analysis

A. Throughput with Block-ACK disabled

The saturation throughput for every AC and for packets with mean length $E[L]$ is given by

$$S_i = \frac{p_{e,i} P_{s,i} E[L]}{T_{slot,i}} \tag{20}$$

where

$$T_{slot,i} = P_{idle}\sigma + \sum_{i=0}^{3} \left[(1 - p_{e,i}) P_{s,i} T_{s,i}\right] + (Pc + p_{e,i} P_{s,i})\, T_{c,i} \tag{21}$$

The probability of error affects the successful transmission probability only. Thus whenever both the events of successful transmission probability and error happen, they are regarded as collisions. An approach much different to [9] and [10] which incorrectly implement the BER probability in the probabilities section, although the Backoff Level does not see errors.

Since the errors are uniformly distributed, the error events are independent and identical distributed (i.i.d.), thus the frame error probability is given by

$$p_{e,i} = \left(1 - p_{e,i}^{data}\right)\left(1 - p_{e,i}^{ACK}\right)\left(1 - p_e^{RTS}\right)\left(1 - p_e^{CTS}\right)$$

$p_{e,i}^{data}$ and $p_{e,i}^{ACK}$ show the uniformly distributed errors in the data packet and in the acknowledgement, and the same for the the probabilities $p_{e,i}^{RTS}$ and $p_{e,i}^{CTS}$ which are used only in RTS and CTS access method. If Basic access method is used then $p_{e,i}^{RTS} = p_{e,i}^{CTS} = 0$.

The collision probability thus is

$$Pc = 1 - P_{idle} - \sum_{i=0}^{3} P_{s,i} \tag{22}$$

We must also mention that whenever the retry limit is reached the packet is dropped. However such a probability is included in Pc and the retransmissions required after a collision or a drop are based on the upper layer and do not affect the performance of the studied MAC layer.

B. Throughput with Block-ACK enabled

Another characteristic of the IEEE 802.11e standard is the Block-ACK feature, which not is obligatory. However Block-ACK can mitigate the overhead problem, especially in higher data rates which are supported by the forthcoming 802.11n. Data Rates of nearly 432Mbps tend to have 10% of MAC efficiency [10].

The Block-ACK feature allows a number of data units to be transmitted and afterwards the sender sends a Block ACK request (BAR) and receives a Block ACK (BA) frame. Throughput is increased since less ACK frames are used for a transmission. Analysis of the Block ACK scheme (BTA) is not within the scope of the paper and more information can be found in the standard [2]. The problem with errors in the BTA scheme is similar to the RTS/CTS and requires to change all the above equations which include errors in RTS and CTS frames with errors in BAR and BA frames and to make all the respective errors of ACK equal to zero. However since the errors are uniformly distributed, the probability of error in one of these packets is equal. Finally

$$S_i' = \frac{(1 - p_{e,i}) \cdot P_{s,i}' \cdot F \cdot E[L]}{P_{idle}\sigma + \sum_{i=0}^{3}(1 - p_{e,i}) P_{s,i}' T_{s,i} + (Pc + p_{e,i} P_{s,i})} \tag{23}$$

The time for successful transmission $T_{s,i}$ thus is much bigger since it includes F frames and SIFS time, plus the exchange of the BAR and BA. Moreover H is the Physical Layer Header and δ the transmission delay.

$$\begin{aligned} T_{s,i}^{basic} &= T_{E,i} = F \cdot (H + E[L] + SIFS + \delta) + \\ &\quad + AIFS[i] + H + T_{BAR} + SIFS + \delta \\ &\quad + H + T_{BA} + \delta \end{aligned} \tag{24}$$

$$\begin{aligned} T_{c,i} &= F \cdot (H + E[L] + SIFS + \delta) + \\ &\quad + EIFS[i] + H + T_{BAR} + \delta \end{aligned} \tag{25}$$

where $EIFS[i] = SIFS + H + T_{BA} + AIFS[i]$.

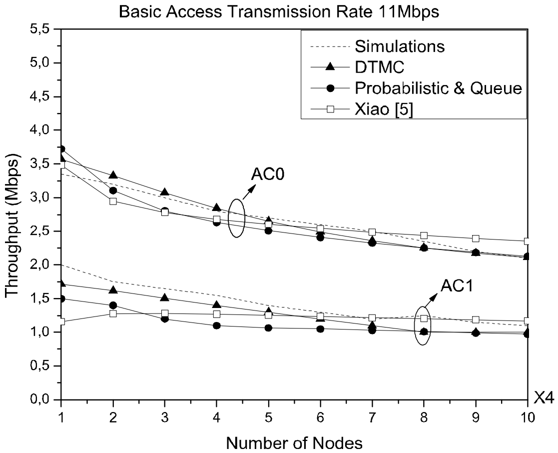

Fig. 2. Model comparison for saturation throughput using basic access method in IEEE 802.11b/e and without errors.

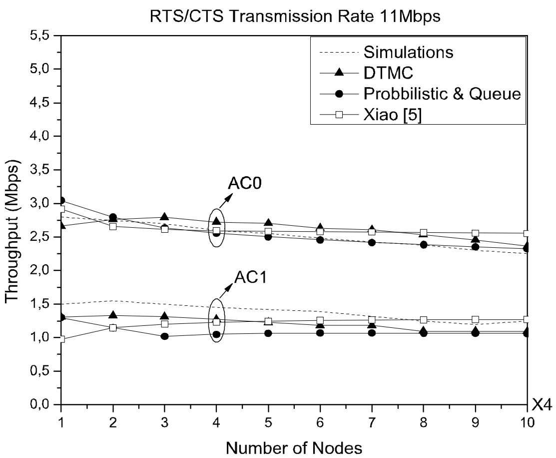

Fig. 3. Model comparison for saturation throughput using RTS/CTS access method in IEEE 802.11b/e and without errors.

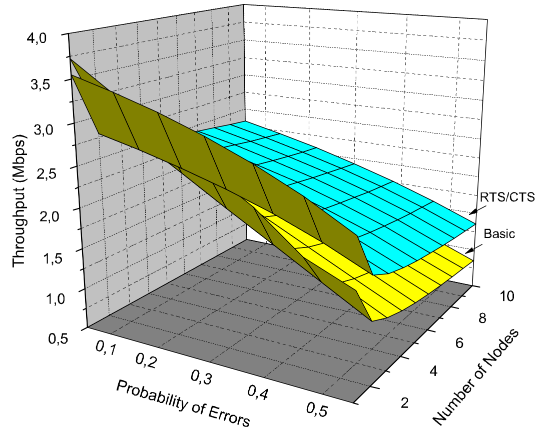

Fig. 4. Saturation Throughput using Basic and RTS/CTS Access Method in 11Mbps bandwidth and varriable probability of errors

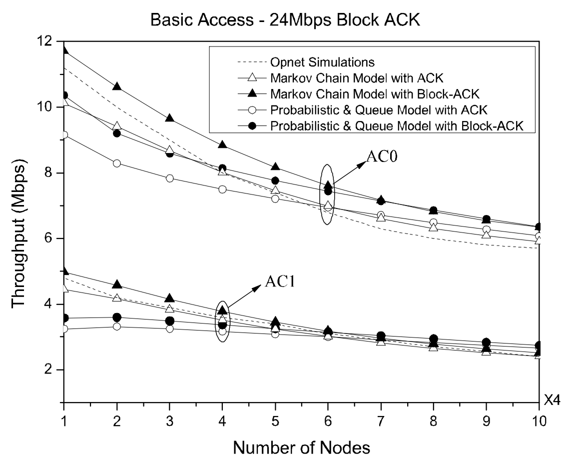

Fig. 5. Model comparison of saturation throughput with Block ACK enabled (F=64) in 24Mbps with IEEE 802.11a

IV. Validation and Results

For validating the correctness of the mathematical analysis, OPNET modeler^{TM} (version 12) was used with the HCCA simulation model incorporated. The two lowest ACs $i = \{2, 3\}$ are omitted due to the insignificant variation of their throughput compared to other ACs $i = \{0, 1\}$.

A. General Comparison Analysis

As regards the *accuracy*, the DTMC model offers better results, owing to the fact that more EDCA characteristics can be included. This leads to another advantage of the DTMC model which is its *flexibility*. The modelling of each independent state allows for extreme detail in modelling each specific characteristic of the MAC protocol, such as the absence of the first state and the correlation of each state with the previous slot. Moreover the DTMC can also be used as a *depiction of the states* of the MAC protocol.

On the other hand, the other two models demonstrate different advantages. They lead to approximate results bearing much *complexity* compared to the DTMC model, as shown in the next subsection. Moreover, they allow for *non-saturation conditions* of traffic, whereas in the DTMC model case this can be proved a very complex issue. The DTMC Model of Xiao [5] was also used as a benchmark.

Lastly it seems that the standard can partly coope with errors if RTS/CTS access method is used. The probability of errors is a derivation of cross layer architectures (coding, error correction etc.) and is that probabilty that the MAC layer finally sees. It is also shown the linear effect of probability error to the throughput performance of the MAC layer.

In Fig.5, IEEE 802.11a is modeled with a bandwidth of $24Mbps$. It is showcased that the Block-Ack mechanism can offer higher throughput at higher loads and can even provide better results in higher bandwidth occasions. This is due to the reduction of unnecessary ACKs. The reason for modeling IEEE 802.11a is that the new IEEE 802.11n (PHY/MAC layer) has similar characteristics. The above equations include the changes due to different transmission rates of 802.11a.

	DTMC	**Probabilistic**	**Queue**
accuracy	$high$	$medium$	$medium$
flexibility	$high$	$medium$	$medium$
complexity	$high$	low	low
nonsat	low	$medium$	low
depiction	$high$	low	$medium$

Table 1. Comparison of the proposed analyses

B. Complexity Analysis

Complexity is an important characteristic as regards mathematical analysis and algorithms. Comparing the three approaches in terms of complexity allows an insight in the usability and scalability of each one.

The DTMC model is obviously the most complex one. This is due to the independence of each state, which models a state of the BEB, and to the correlation with the state of the previous slot. However the state of the previous slot is hardly incorporated in models based on queueing theory or geometric distribution since it does not allow the flexibility to change Backoff Duration according to the simulation needs. A significant drawback of the proposed DTMC is that non-saturation throughput analysis becomes a complex problem, whereas in the other analyses the arrival rate could be changed very easily with simple algebra. On the other hand, the modeling of independent states makes easier to provide amendments in the analysis, such as the one given with the inexistence of the first state. Thus it is easy to observe that the analysis of this first model requires big DTMC and more mathematical formulas to be calculated.

Moreover, the addition of extra features and the incorporation of realistic modelling in this approach injects even more complexity in the final calculations. Apart from this heuristic approach, a computational complexity comparison can be performed in terms of big-o notation. Instead of computer instructions we use a simple formula calculation as the basic unit of complexity. Each algorithm's order of complexity can be estimated as a function of the number of calculation points N, the number of steps used in the fixed point iteration method M, the retry limits L_i and the number of ACs calculated i. Results show that all three algorithms have linear complexity relative to M and N, and that the DTMC model is approximately four times more complex than the other two approaches.

$$\text{DTMC} : O\left[NM\left(\sum_i (4L_i+1)\right)\right]$$

$$\text{Pr obabilistic/Queue} = O\left[NM\left(\sum_i (L_i+3)\right)\right]$$

Ordinary values for the parameters are: $N = 10$, $M = 20$, $L = 7$ and $i = 4$.

V. Conclusion

In this paper we compared the three main approaches of IEEE 802.11e modelling for performance analysis. The novelty of the paper is that we have chosen a different path for comparison analysis, instead of single enhancements on the well-known mathematical analyses. Moreover the general thinking and discussion offer insights regarding the correct method to analyze future standards, according to specific criteria. As a conclusion, we propose the DTMC analysis be used in cases where capturing all the effects of the medium and high accuracy are necessary. On the other hand, the other approaches, having the same results and complexity, offer faster results and higher scalability, appearing attractive when non-saturation conditions are used.

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