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Performance Evaluation of Modulated Markov Process Models for Traffic on IEEE 802.11 Networks – Study of Case for the QRD Network[1]

Evaluación del Desempeño de los Modelos de Tráfico Modulados por Cadenas de Markov en Redes 802.11 – Caso de Estudio Red QRD

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***Abstract* - This paper evaluates the performance of Markov modulated processes models in IEEE 802.11 networks. This study is focused on the "Quindio Región Digital" (QRD) network. Performance evaluation of the traffic models is performed in three stages. In the first stage, we obtain the statistical characteristics of the current traffic on the QRD network. In the second stage, the most suitable traffic models are selected for the current characteristics of the QRD network such as out-of-saturation operation and management of heterogeneous traffic. In the third stage, we define a performance metric that is used to evaluate the traffic patterns through simulation.**

***Key Word* - QRD, WLAN, MAC, time slot, contention window, Markov chains, traffic, correlation, goodness of fit test, snnifer.**

***Resumen* - En este artículo se evalúa el desempeño de los modelos basados en procesos modulados por cadenas de Markov en redes IEEE 802.11. El estudio se centra en la red "Quindio Región Digital" (QRD). La evaluación del desempeño de los modelos de tráfico se desarrolla en tres etapas. En la primera etapa se obtienen las características estadísticas del tráfico real de la red QRD. En la segunda etapa, se realiza una selección de los modelos de tráfico que se adecuan mejor a las características reales de la red QRD tales como operación fuera de saturación y manejo de tráfico heterogéneo. En la tercera etapa, se define una métrica del desempeño, la cual se utiliza para evaluar los patrones de tráfico real y generado con el modelo a través de simulación.**

***Palabras Clave* - QRD, WLAN, MAC, ranura de tiempo, ventana de contienda, cadenas de Markov, trafico, correlación, prueba de bondad de ajuste, sniffer.**

I. Introduction

In the recent years, wireless networks have become popular for the design of access networks due to their potential benefits with respect to wired networks. Since the standard IEEE 802.11 has been widely accepted for the design of these networks, a detailed study of this standard provides useful tools to design and plan proper networks, and to meet user requirements with respect to information management and services.

This paper presents the performance evaluation of one popular method to model WLAN 802.11networks: Modulated Markov process. This model takes into account an exponential backoff protocol under non-saturated stations and heterogeneous-traffic-flow conditions to compute the throughput of the distributed coordination function (DCF) for basic access. Therefore, this model is suitable for the analysis of traffic frames in a real network. In this paper, the performance of this model is compared using actual data from the "Quindío Región Digital" (QRD) network [1].

The models under analysis assume that the probability of packet collision of a packet is constant and independent on

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the state and station regardless the number of retransmissions. This assumption, validated through simulations, shows high-accurate results even when the number of stations in the wireless LAN is greater than 10.

This paper is organized as follows. Section 2 defines the two medium access mechanisms used in DCF, basic mechanism and RTS/CTS (Request to send/Clear to send) mechanism, as well as a combination of both. Section 3 shows the results and statistics obtained for a real traffic in the QRD network. Sections 4 and 5 include the performance evaluation of the model under study, the modulated Markov process model, which takes into account real conditions such as non-saturated stations and heterogeneous traffic. Section 6 presents the simulation results that verify the performance of this model on the QRD network. Finally, Section 7 summarizes the results and discusses the performance of the model on real network data.

II. Distributed Coordination Function 802.11

This section presents an overview of the distributed coordination function (DCF), which is described by the IEEE 802.11 protocols. A detailed description is included in [1]-[5].

A station with a new packet to be transmitted senses the channel activity. If the channel is found inactive during a period of time equal to the distributed interframe space (DIFS), the station transmits. Otherwise, if the channel is found busy (immediately or during the DIFS), the station continuously senses the channel until it is found inactive during a DIFS. From this viewpoint, the station generates a random backoff interval before transmitting (i.e., performs an anti-collision protocol) to minimize the probability of collision within the packets transmitted by other stations. In addition, to avoid channel break, a station must wait for a random backoff time between two consecutive transmissions of a new packet even if the channel is found inactive during a DIFS. To improve efficiency, DCF uses a discrete backoff scale. The time following an inactive DIFS is sliced and a station can transmit only at beginning of each slot time. The size of the slot time "σ" is set equal to the time required by each station to detect the transmission of a packet from any other station.

TABLE 1.
Slot Time (ranura de tiempo), valores máximos y mínimos de la ventana de contienda para las tres especificaciones PHY del estándar 802.11: Frecuency Hopping Spread Spectrum (FHSS) Direct Sequence Spread Spectrum (DSSS), and Infrared (IR).

PHY	Slot Time (σ)	CWmin	CWmax
FHSS	50 µs	16	1024
DSSS	20 µs	32	1024
IR	8 µs	64	1024

As shown in Table 1, the size of the slot time "σ" depends on the physical layer, and it represents the propagation delay involved in switching from a reception state to transmission state (i.e., RX-TX time) as well as the time to signal to the MAC layer about the channel state (i.e., to detect a busy time). DCF adopts an exponential backoff behavior, in which the backoff time for each packet transmission is chosen to be uniform in the range (0,W-1), where W is called contention window, and this window depends on the number of failed transmissions for a given packet. In the first transmission attempt, W is set to be equal to the minimum contention window (CWmin). After each failed transmission, W is doubled until reach its maximum value CWmax = 2mCWmin. The values for CWmin and CWmax are reported in the final version of the standard [5].

The backoff time counter is stopped when a transmission is detected over the channel, and it is resumed when the channel is found inactive again for more than one DIFS. The station transmits when the backoff counter reaches zero. The Fig. 1 depicts this operation.

Since CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) is not based on the station capabilities to detect a collision by listening to their own transmissions, an affirmative acknowledge (ACK) is transmitted by target station to signal a successful packet reception. ACK is transmitted immediately following the packet reception, and this time interval is called short interframe space (SIFS). As long as the SIFS (in addition to the propagation delay) is shorter than a DIFS, none station is capable of detecting channel inactivity during a DIFS until the end of an ACK. If the transmitting station does not receive any acknowledge for a certain ACK waiting time, or a different transmission packet is detected over the channel, the transmission of packets is restarted according to the predefined backoff rules.

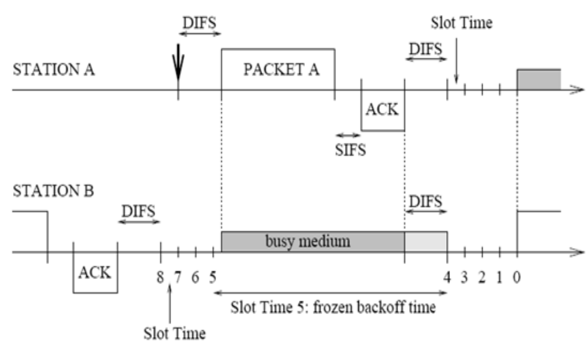

Fig. 1. Basic Access Mechanism

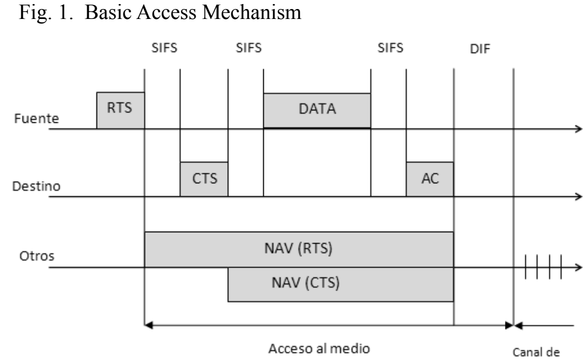

Fig. 2. RTS/CTS Mechanism

The previous two-way transmission approach is called basic access mechanism. DCF defines an additional and optional four-way transmission approach. This mechanism is called RTS/CTS, which is shown in Fig. 2. The station that requires a packet transmission must wait until the channel is found inactive during a DIFS, following the backoff rules explained above. Then, instead of transmitting the data packet, a preliminary short frame, called "request to send" (RTS) is transmitted. When the target station detects a RTS frame, it responses after a SIFS by sending a "clear to send" (CTS) frame. A station is allowed to transmit only if a CTS frame is received properly.

RTS and CTS frames carry out information about the length of the packet to be transmitted. This information can be read by any other listening transmitters, which update the network allocation vector (NAV) that stores information about the period of time when the channel is busy.

RTS/CTS mechanism is efficient in terms of system performance since it reduces the length of the frames involved in a contention process. In fact, even assuming perfect channel detection by each station, collision may occur when two or more packets are transmitted on the same slot time. If the two transmission stations employ a RTS/CTS mechanism, a collision is produced only in the RTS frame. However, this issue can be detected quickly by all transmission stations due to the lack of a CTS frame [6].

III. Acquisition of a Real Traffic

This section shows the data obtained from a real traffic in the QRD network, and the statistics performed on this data.

A. *Capture of traffic in the QRD network and statistics estimation*

A protocol analyzer was used to capture information about packets [7]. This information is grouped according to the arrival time and length of each packet. In this way, histograms and goodness of fit tests are used to estimate the statistics that characterize the traffic and features of the QRD network [1].

B. *Identification of the distribution function*

The methodology of goodness fit test proposed by Kolmogorov-Smirnov [8] is used to determine the distribution functions for the arrival-packet time and packet length. As a result of this test, the distribution function for the arrival-packet time is found to be exponential as shown in Fig. 3. With respect to the packet length (or equivalently, the average service time), the distribution function is uniform as shown in Fig. 4.

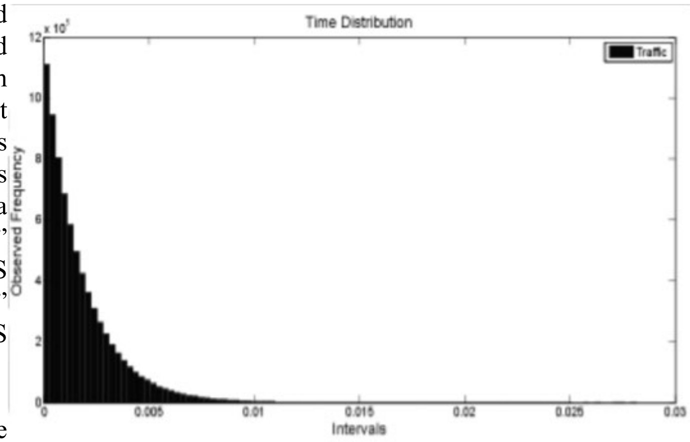

Fig. 3 Exponential distribution for the arrival-packet time on January 26, 2011.

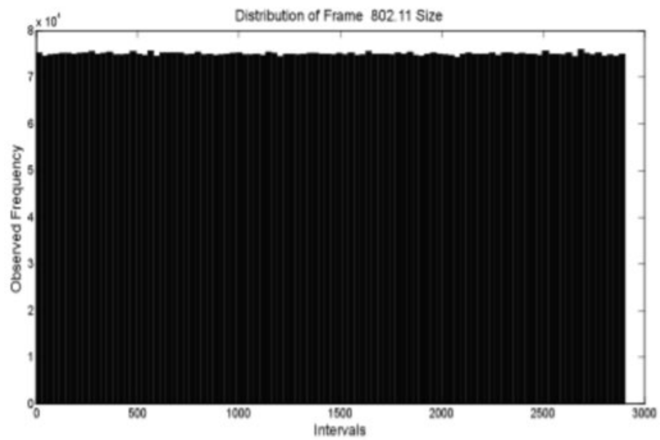

Fig. 4. Uniform distribution for the packet length

IV. Modulated Markov Process Models

References [6], [2] and [3] describe the model used to evaluate the throughput of a WLAN network under the standard IEEE 802.11 by a Markov modulated process. This random process was initially proposed by [6]. However, it is not convenient to perform an evaluation based on this model since the throughput is modeled under saturation conditions, and these conditions does not occur frequently in a real network such as QRD. On the other hand, a more realistic model for performance evaluation is described in [3]. This model provides more accurate results with a real traffic since it was proposed for non-saturation conditions, although it is limited exclusively for speech communication. A third model described in [2] matches the requirements for performance evaluation in 802.11g networks under working conditions such as the QRD network. This model takes into account a set of real conditions, providing an open framework to obtain general features of WLAN 802.11 networks. First, this model is designed to work with heterogeneous flows, i.e., it takes into account all kind of traffic. Second, this model works in real conditions since it considers non-saturation conditions. Third, this model describes accurately the behavior of a real traffic. The latter is verified through simulations shown in this paper.

A. *Throughput of the model based on Markov chains*

A model for mobile stations is presented in [2]. Since this model considers all nodes having a similar behavior, this model is not affected by the number of nodes as long as the number of nodes is greater than 10.

B. *Mobile station*

The MAC layer of a mobile node is modeled by a M/M/1/Q queue, where Q is the queue length (in packets) [9], [10]. The traffic (in the network layer) provided by the MAC layer is given by (1):

$$\mathrm{U_k(n)} = \lambda_k \mathrm{X_k(n)} \qquad (1)$$

Where $X_k(n)$ and λ_k are the service time and the arrival-packet rate, respectively, in the K-th node for N nodes in the network (the size of the node set ψ is N). n is defined as a vector of length N, where nk is referred to a mobile node K, with K ψ. The network traffic at the K-th node is given by (2):

$$\rho_k(\mathrm{n}) = \lambda_k \left(1 - \mathrm{P_{b,k}(n)}\right) \mathrm{X_k(n)} \qquad (2)$$

Where $\mathrm{P_{b,k}(n)}$ s the probability of blocking for a M/M/1/Q queue, computed by

$$\mathrm{P_{b,k}(n)} = \frac{\left(1 - \mathrm{U_k(n)}\right)\mathrm{U_k(n)^Q}}{1 - \mathrm{U_k(n)^{Q+1}}} \qquad (3)$$

For the special case where $\mathrm{U_k(n)} = 1$ the probability of blocking is $\mathrm{P_{b,k}(n)} = 1/(Q+1)$. Note that the probability of a node to have at least a stored packet is equal to the queue utilization parameter $\rho_k(\mathrm{n})$.

Defining the traffic throughput as the length in bytes of the transmitted payload by the service time,

$$\mathrm{S} = \frac{\mathrm{E[information\ per\ slot\ time]}}{\mathrm{E[length\ of\ the\ slot\ time]}} \qquad (4)$$

$$\mathrm{S_k(n)} = \frac{\rho_k(\mathrm{n})}{\mathrm{X_k(n)}} \mathrm{L_k} \qquad (5)$$

Equation (5) will be used to compare both models, the model based on Markov chains and the self-similar model, with actual data, where
$S_k(n)$ is the throughput
$\rho_k(n)$ is the offered traffic
$X_k(n)$ is the service time
$L_k(n)$ are the transmitted payload bits

To obtain the service time, we use the following expression

$$W_{backoff} = (1-p)\frac{W}{2} + p(1-p)\frac{2W}{2} + \cdots + p^{m+1}\frac{2^m W}{2} = \frac{1-p-p(2p)^m}{1-2p}\frac{W}{2} \qquad (6)$$

Where $\mathrm{W_{backoff}}$ is the mean backoff window length.

The backoff timer is decreased after each slot time except under a contention. Hence, any transmission by another station may cause the timer to be suspended and this contention divides the mean backoff window length by (ncontention + 1) in T slices [1].

$$(n_{contention} + 1)T_{slice} = W_{backoff} * T_{slot} \qquad (7)$$

Now, we will discuss the probability of contention caused by the station C transmitting while the station B is in backoff. Under saturation, the state of each station is alternated between transmission and backoff. Hence, when the timer for the station B is decreased, C is in backoff as show in Fig. 5, and the average residual lifetime for this timer is Wbackoff / 3. The expected residual lifetime is expressed in m2 / 2m1, where mi is the i-th moment of the timer distribution. For an uniform distribution, m2 = Wbackoff2 / 3 y m1 = Wbackoff / 2. Now, the contention in C is present if only if the timer in the station B expires after the station C. Then, this contention has a probability given by

$$1 - \frac{W_{backoff}/3}{W_{backoff}} = \frac{2}{3} \qquad (8)$$

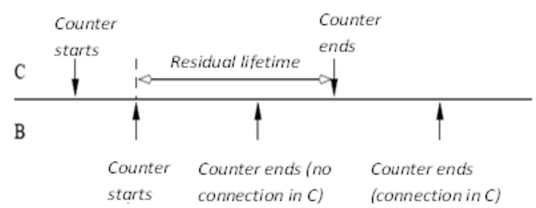

Fig. 5. Contention in station C during the backoff state of the station B.

A station in backoff time can wait approximately 2/3(n-1) interruptions by another n-1 stations. This value is underestimated as long as the timer in the station B can be interrupted more than once by station C, then

$$n_{contention} = \frac{2}{3}n \qquad (9)$$

Replacing (9) in (7),

$$\left[1 + \frac{2}{3}n\right] T_{slice} = W_{backoff} * T_{slot} \qquad (10)$$

As long as the probability of collision p is less than 0.5, larger transmissions are priority attended after the carrier detection. Therefore, larger collisions may occur because a station senses the channel as inactive in the slot time just before the transmission. For this reason, p can be approximated by Tslot / Tslice. However, this value is an underestimate because it excludes all transmissions belonging to the current station.

Then, the no transmission factor is given by:

$$p = \frac{n-1}{n}\frac{T_{slot}}{T_{slice}} \qquad (11)$$

The above expression is similar to the Schwitzer approximation for queue networks, giving the correct value of p = 0 for n = 1. Removing Tslice and Wbackoff terms from (11),

$$p\frac{1-p-p(2p)^m}{1-2p} = \frac{2}{W}\left[1+\frac{2}{3}n\right]\frac{n-1}{n} \qquad (12)$$

Having knowledge about W, m and n, this equation can be solved for p, where p is the square root of the approximation given by (12).

Using this value of p, the service time in (6) can be described by

$$X_{k(n)} = (2-p)\left(T_{PHY} + T_{SIFS} + T_{ACK} + T_{DIFS} + \frac{W}{n+1}\sigma\right) \qquad (13)$$

Table 2 shows all parameters used to run the simulations performed in this paper. These parameters are based on recommendations of the standard IEEE 802.11.

TABLE 2.
MAC PARAMETERS FOR IEEE 802.11

Parameter	Value
SIFS	10 µs
DIFS	50 µs
σ (SLOT)	20 µs
CWmin, CWmax, m	32, 256, 3
MACheader	240 bits + 32 bits
PHYheader	192 bits
Lk	1452.76 bytes
LACK	112 + PHYheader
Rdata	2 Mbps
Rbasic	1 Mbps

The Markov Modulated Process Model throughput in Mbps as function of the number of stations is presented in Fig. 6. This plot follows an increasing exponential shape, where the throughput between the first and tenth stations increases by a 0.7 Mbps rate, and after the tenth station, the throughput reaches a steady value. In this case, increasing the number of stations does not vary quickly the throughput as the case for a small number of stations. The latter suggests that the model is stable for a number of stations in the network greater than 10.

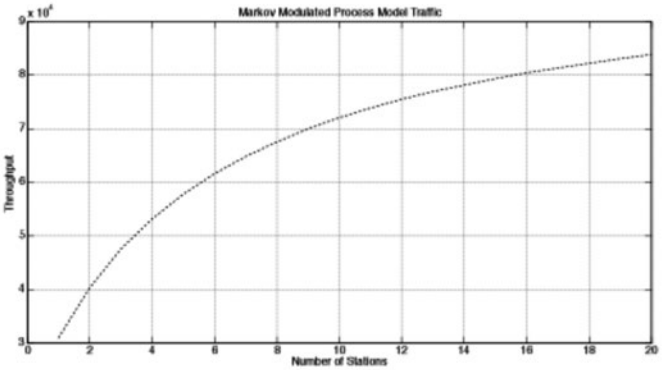

Fig. 6. Throughput in the model based on a Markov modulated process

C. *Throughput for the real traffic*

From the QRD data, the mean average of the packets is 0.0076 seconds, which suggests that the actual offered traffic is λk = 7.6ms.

The Fig. 4 shows a uniform distribution for the length of the payload bits in the packets. The mean value is 1452.76 bytes, i.e., Lk = 1452.76 bytes. Hence, the throughput in Mbps against the number of network stations is shown in Fig. 7. From this figure, it is possible to determine the maximum throughput of a network with different number of terminals by dividing this value by the number of terminals. Thus, if packets with an average length of 1452.76 bytes are transmitted to any rate such as 1, 2, 11 or 54 Mbps, the maximum throughput is 90 kbps (Fig. 7). Assuming 20 terminals for the QRD network, the effective transmission rate by terminal are 4.5 kbps. This result is very accurate due to this analysis takes into account the time involved in solving collisions.

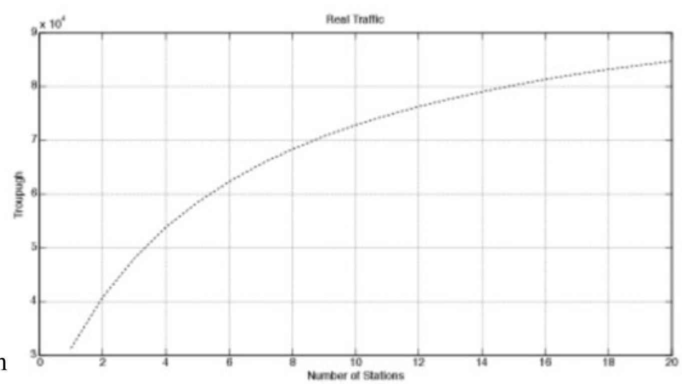

Fig. 7. Throughput in the QRD network as a function of the number of stations

V. RESULTS

The graphical results for the two models under study for the QRD network (a WLAN IEEE 802.11g network) as well as the real traffic are shown in Fig. 8. In this figure, throughput for the real traffic is shown in red, throughput for the modulated Markov process in discontinuous line.

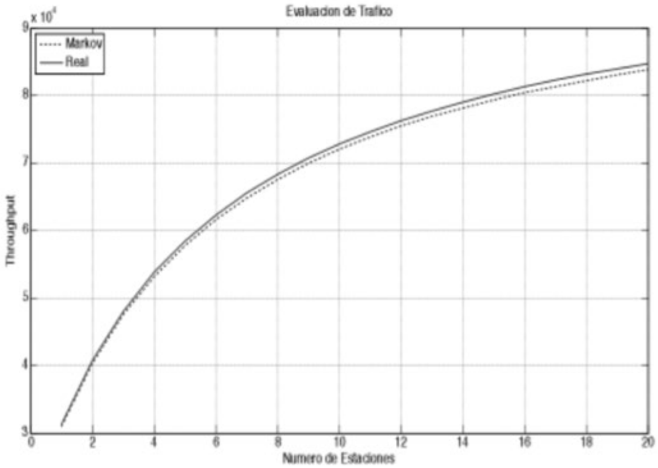

Fig. 8. Throughput for the modulated Markov process and real traffic.

From this figure, we can say that the model describes the conditions of real traffic. To support this claim, a numerical analysis based on correlation provides more accurate information than a graphical analysis. Correlation results for model and the real traffic on the QRD network, is shown below.

Correlation coefficient for the real traffic and the modulated Markov process:

Since the correlation coefficient is close to one, it is concluded that the model provide a strong correlation with the real data. The previous results allow us to conclude that the Modulated Markov Process model describes the features of IEEE 802.11 network traffic.

VI. Conclusions

In this paper, one popular traffic model for IEEE 802.11 wireless networks was evaluated. The model is based on queue theory, defining a simple but powerful model that captures all characteristics of the medium access control (MAC), the modulated Markov model. It is important to highlight that this model depends exclusively on the distribution of packet arrivals obtained for the QRD network. If arrivals were not assumed a Poisson process, the assumption about a memoryless process would not be possible, and a modulated Markov process would be immediately discarded. It is possible to conclude that the actual traffic in the WLAN QRD network is described by a model based on modulated Markov process. Under the assumptions about a memoryless Poisson process for the arrival time and the probability of packet collision independently on the previous state, it was possible to obtain a simulated throughput that matches the throughput obtained from a real traffic.

The most important reason why the model was selected for this study is the ability of these models to describe real conditions in non-saturated networks and heterogeneous traffic, i.e., streaming and elastic flows. Hence, it was feasible to perform a comparison under normal conditions, and these simulation results are close to real data.

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