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PERFORMANCE ANALYSIS OF THE IEEE 802.11 DISTRIBUTED COORDINATION FUNCTION WITH UNICAST AND BROADCAST TRAFFIC

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ABSTRACT

Most studies on performance of IEEE 802.11 DCF networks do not contemplate the existence of broadcast traffic. They model network behaviour in presence of unicast traffic alone. In a real scenario, broadcast frames exist, and they will influence the overall network behaviour. This work presents a new traffic generalized model for CSMA/CA saturated single-hop networks able to describe the network behaviour in presence of both unicast and broadcast frames. Interesting statistics like station transmission probability, average time needed to complete a frame transmission, and network aggregate throughput are deduced from the model. The paper compares the performance of our model with other models proposed only for unicast traffic. Our model is validated for broadcast and unicast traffic through simulations, using an IEEE 802.11 DCF network scenario. Results are presented and analysed for different scenarios of broadcast/unicast network loads, different number of nodes and different frame data lengths.

I. INTRODUCTION

IEEE 802.11 based Wireless LANs (WLANs) usually transport both broadcast and unicast traffic. Most applications rely on unicast traffic between two stations. Others, such as routing algorithms, service location algorithms rely on broadcast traffic. However, the models proposed so far for the IEEE 802.11 Distributed Coordinated Function (DCF) [1,2], analyse the network performance with unicast traffic only.

DCF is the Medium Access Control (MAC) protocol usually used by 802.11 stations. It runs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [3] protocol. Most of published works tackling IEEE 802.11 modelling assume a single-hop network. Usually they provide a bound for the packet transmission probability and the network throughput in the condition of traffic saturation [1,2]. The exponential backoff mechanism used in 802.11 Distributed Coordination Function (DCF) is modelled in order to achieve the network throughput only for unicast traffic. The work presented in [2] aims to compute the network throughput through the average contention time between two consecutives transmissions. This approach is denominated average *cycle time*. In each cycle, a station should make a successful transmission. Saturation is also assumed and the study is only valid for unicast traffic.

Our theoretical analysis builds on [1] to achieve the network aggregate throughput. It proposes a model able to describe both unicast and broadcast transmissions, from which the computation of the aggregate throughput can be possible. It uses the average *cycle time* approach to derive a generalized model of MAC 802.11 DCF networks. As far as we know, this is the first study that analyses the influence of broadcast transmissions in the unicast performance and vice-versa.

The next section describes the generalized model assumptions. The model is used to derive the individual station transmission probability, the average frame transmission time, and the network aggregate throughput, which is presented in section III. Our proposals are validated using a network simulator and the results are illustrated in section IV. Finally, some conclusions are taken in section V, where further work is also discussed.

II. TRAFFIC-GENERALIZED MODEL

In 802.11 DCF networks [3], frames exchanged between stations can be classified as broadcast or unicast if they are sent to all available neighbour stations, or, to a unique and specific station, respectively. For both cases, when the MAC layer receives a request to transmit a packet from the upper layer, the physical and the virtual carrier are sensed to observe if the channel is idle. If the channel is idle during a period greater than the *Distributed Inter-Frame Space* (DIFS) interval, the MAC begins the transmission. If the medium is in use during the DIFS interval, the MAC selects uniformly a backoff value from the interval $(0, W_i)$, where W_i is the current backoff stage contention window size. The backoff counter (BC) is decremented each time the channel is detected to be idle for an interval of a slot time. I.e., when busy slots are sensed, the BC is frozen. It is only decremented again after the channel is idle for a DIFS time interval (equals to 2.5 slots). A 2-ways handshaking (basic mode) or a 4-ways

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handshaking (RTS/CTS) can be used, depending on the frame's size to transmit. The backoff mechanism uses multiple backoff stages. When the BC expires in a given stage, the station tries a new transmission. As data reception is acknowledged, a station retries a transmission if the acknowledge is not received. When a retransmission is made, a station doubles the backoff window size, except for the last stage of backoff. When the retransmission at the last backoff stage is unsuccessful, the frame is discarded. For a broadcast transmission, only a single stage of backoff is used. When the BC expires, the data is sent without being acknowledged, which can lead to unrecoverable collisions if one or more stations start transmitting at the same slot. The different backoff behaviours (for unicast and broadcast transmissions) lead to distinct contention times. The model described below models these different behaviours.

A. Model assumptions

The proposed analytical model assumes a single-hop network where there are no hidden terminals present. It models the broadcast and the basic unicast transmission schemes, but the model is extensible to unicast transmissions using RTS/CTS handshaking. Saturated traffic is assumed. A fixed number of stations (*n*) compete to access the wireless medium, each having always a frame to transmit. The station transmits a broadcast or unicast frame according to a uniform probability density function.

III. NETWORK ANALYSIS

A. Markov Chain Model

The behaviour of a single station was studied using the Markov transmission model presented in Figure 1.

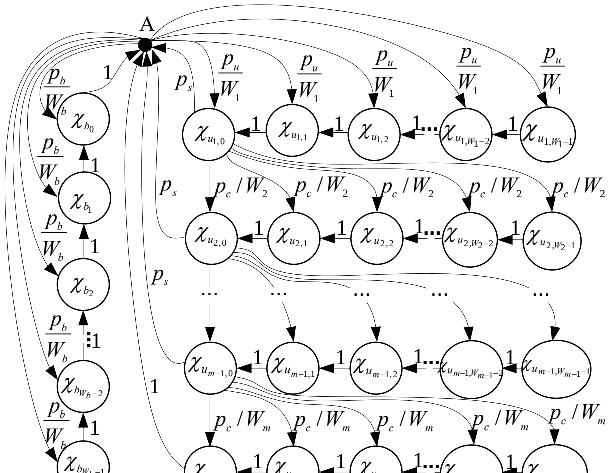

Fig. 1. Generalized Markov model for a single station.

The model extends [1] by introducing a set of markov states χ_{b_j} representing the unique BC stage used for broadcast transmissions. The markov states represented by $\chi_{u_{i,j}}$ denote the BC states used in a unicast transmission. j expresses the BC state in the i^{th} backoff stage. A station starts a BC to a broadcast transmission with probability p_b, or a BC to a unicast transmission with probability $p_u = 1 - p_b$. When the BC reaches a state $\chi_{u_{i,0}}$ or χ_{b_0} a transmission is started. It is assumed that each packet collides with constant and independent probability p_c, and is successful with probability $p_s = 1 - p_c$. [1] model for unicast was enhanced by considering that in the last state of the last backoff stage $\chi_{u_{m,0}}$, a node stops retrying transmissions. A represents the total flow of chains ending a frame transmission and starting a new transmission. If we assume m backoff stages for unicast, then according to the standard [3], we have

$$\begin{cases} W_i = 2^{i-1} W_1, 0 < i < m \\ W_i = W_{i-1}, i = m \end{cases} \quad \text{and} \quad W_b = W_1. \qquad (1)$$

B. Station transmission probability

The markov chain states' probability can be written in function of A. For state $\chi_{u_{i,0}}$ we have [1]

$$\chi_{u_{i,0}} = p_u (1 - p_s)^{i-1} A, \quad 0 < i \le m. \qquad (2)$$

Within the backoff stages, we have

$$\chi_{u_{i,k}} = \frac{W_i - k}{W_i} \chi_{u_{i,0}}, \quad 0 \le k \le W_i - 1 \qquad (3)$$

and

$$\chi_{b_k} = \frac{W_b - k}{W_b} p_b A, \quad 0 \le k \le W_b - 1. \qquad (4)$$

The probability of one station transmitting a unicast frame in a given slot is given by

$$\chi_u = \sum_{i=1}^{m} \chi_{u_{i,0}} = p_u \frac{1 - (1 - p_s)^m}{p_s} A. \qquad (5)$$

The total probability of a station starting a new transmission in a given slot is

$$\chi = \chi_u + \chi_{b_0}. \qquad (6)$$

Assuming a network composed by n stations, the probability of a successful transmission p_s is related with the probability of $n-1$ stations not beginning a transmission at the same slot:

$$p_s = (1 - \chi)^{n-1}. \qquad (7)$$

Using the normalization condition

$$\sum_{j=0}^{W_b-1}\chi_{b_j}+\sum_{i=1}^{m}\sum_{k=0}^{W_i-1}\chi_{u_{i,k}}=1, \tag{8}$$

the parameter A is defined as

$$A=\left(\frac{W_b+1}{2}+p_u\sum_{i=2}^{m}\frac{W_i+1}{2}(1-p_s)^{i-1}\right)^{-1}. \tag{9}$$

Finally, starting from (6) and using (1), (4), (5), and (9) we achieve

$$\chi=\left[p_u\frac{1-\left(1-(1-\chi)^{n-1}\right)^m}{(1-\chi)^{n-1}}+p_b\right]A. \tag{10}$$

(10) can be numerically solved in order to determine each station's transmission probability χ.

C. Average frame transmission time

The time between the instant when a station has a frame to transmit and its actual transmission depends on the channel occupancy. During this period each station goes through a set of BC states, which can be modelled by the state transitions in Figure 1. Starting from point A, a station enters in one of the BC states χ_{b_j} or $\chi_{u_{1,j}}$, respectively for broadcast and unicast.

For nonzero j values of BC states stations are in receive mode, and the average transition time to the next BC state (T_x) depends exclusively on what the other n-1 stations do in the channel.

We define p_{b_s} and p_{u_s} as the probabilities of (any station except ours) having a successfully transmission of a broadcast or unicast frame, respectively:

$$p_{b_s}=(n-1)\chi_{b_0}(1-\chi)^{n-2}, \tag{11}$$

$$p_{u_s}=(n-1)\chi_u(1-\chi)^{n-2}. \tag{12}$$

The collision occurrence probabilities of only broadcast or only unicast frames are respectively given by

$$\begin{aligned}p_{b_c}&=\sum_{i=2}^{n-1}\left({}^{n-1}C_i\right)\chi_b{}^i(1-\chi)^{n-1-i}\\&=(1-\chi_u)^{n-1}-(1-\chi)^{n-1}-p_{b_s}\end{aligned}, \tag{13}$$

$$p_{u_c}=(1-\chi_b)^{n-1}-(1-\chi)^{n-1}-p_{u_s}. \tag{14}$$

The probability of having a collision with only mixed broadcast and multicast transmissions is given by

$$p_{m_c}=1-(1-\chi)^{n-1}-p_{b_s}-p_{u_s}-p_{b_c}-p_{u_c}. \tag{15}$$

The average contention time on each backoff state can be stated as (we will use T_x instead of $E[T_x]$ in order to simplify the notation)

$$\begin{aligned}T_\chi=(1-\chi)^{n-1}\sigma+p_{b_s}T_{bs}+p_{u_s}T_{us}\\+p_{b_c}T_{bc}+p_{u_c}T_{uc}+p_{m_c}T_{m_c}\end{aligned}. \tag{16}$$

Here, σ is the duration of an (empty) slot time. T_{b_s} and T_{u_s} are the average contention time sensed at this station due to a successful transmission from another station of a broadcast or a unicast frame, respectively. T_{b_c}, T_{u_c}, and T_{m_c} are the average contention time felt by a station due to a collision with broadcast transmissions, unicast transmissions, or both transmissions. Note that for each case the lengthiest frame in the collision sets the overall time. If we assume that all frames have the same average length and denote $E[P]$ as the average time to transmit them, then these average times are defined as

$$\begin{aligned}T_{b_s}&=E[P]+DIFS+\delta\\T_{u_s}&=E[P]+SIFS+DIFS+ACK+2\delta\\T_{b_c}&=T_{u_c}=T_{m_c}=E[P]+DIFS+EIFS+\delta\end{aligned}. \tag{17}$$

δ is the propagation delay and SIFS, EIFS and ACK are defined in [3]. A station waits for an Extended Interframe Space (EIFS) interval when a transmission error is detected (in this case a collision).

When the stations reach a transmission state ($\chi_{u_{i,0}}$ and χ_{b_0} in Figure 1), they change their air interface to transmission mode, transmit, and the probability of success is p_s, defined in (7).

The average transmission interval (*cycle time*) for broadcast frames is the probability of starting at a certain BC state times the expected *cycle time* given that the station is starting at that state:

$$\begin{aligned}T_b&=\sum_{j=0}^{W_1-1}P\{start\ \chi_{b_j}\}E\left[T_b\,|\,start\ \chi_{b_j}\right]\\&=\sum_{j=0}^{W_1-1}\frac{1}{W_1}\left(T_{b_s}+T_\chi j\right)=T_{b_s}+\frac{W_1-1}{2}T_\chi\end{aligned}. \tag{18}$$

We calculate the average transmission interval for unicast transmissions applying a similar expression to the previous one for each backoff stage that might be reached. Stage k is reached only if the k-1 previous stages failed. Note that in the unicast case the transmission time T_{u_s} for the sender (colliding or not) also includes the ACK transmission time.

$$T_u = \sum_{i=1}^{m} (1-p_s)^{i-1} \left(T_{u_s} + \frac{W_i - 1}{2} T_\chi \right). \quad (19)$$

Generalizing, the average time required to transmit a frame is given by

$$T_{tx} = p_b T_b + p_u T_u. \quad (20)$$

D. Station's Throughput

The station's throughput is a rate that measures the efficiency of the network as seen from one station. In average terms it is the ratio between a successful frame transmission time and the *cycle time*.

A broadcast frame will succeed on the first attempt or fails. The average successful frame transmission time is $E[P]$ times the probability of success per *cycle time*. A unicast frame has more attempts, but it can also fail. The probability of success per *cycle time* takes into account the various possible BC stages.

$$\begin{aligned} T_{s_b} &= p_s E[P] \\ T_{s_u} &= \left(1-(1-p_s)^m\right) E[P] \end{aligned} \quad (21)$$

The average station's throughput is

$$S_{indv} = \frac{p_u T_{s_u} + p_b T_{s_b}}{T_{tx}}. \quad (22)$$

IV. MODEL VALIDATION

We used the ns-2 [4] simulator version 2.28 to validate our model. We made some changes in the IEEE 802.11 MAC layer implemented in the simulator, in order to have the desired saturation behaviour: all existing queues from upper layers were eliminated, and a new frame was generated after finishing the previous frame transmission. All frames have the same size. For each node, we count the time between two consecutive successful transmissions T_{wasted} and the amount of time T_{access} that channel is effectively used to successfully transmit the frame. Comparing with the approach in subsection D above, T_{wasted} can correspond to more than one *cycle time* if certain frames are unsuccessfully transmitted. Assuming k successful frame's transmissions during all simulated time, the average station's throughput is

$$S_{indv} = \sum_{i=0}^{k} T_{access} \Big/ \sum_{i=0}^{k} T_{wasted}. \quad (23)$$

The aggregate throughput is the summation of all station's throughputs. We validate the model assuming the parameters presented in Table 1. The model is validated using IEEE 802.11b. But we should note that it is also valid for higher performance versions of 802.11 like 802.11g, as the ratio between all time parameters and the slot time is constant.

Table 1. Validation parameters used.

SIFS	10 µs	Channel bit rate	1 Mbit/s
DIFS	50 µs	MAC+PHY header	416 bits
EIFS	364 µs	ACK	304 bits
Slot Time (σ)	20 µs	Propagation delay (δ)	2 µs
BC stages (m)	7	ACK_TIMEOUT	304 µs
W_1	32	Simulated Time	1500 s

In a first experiment we used only unicast traffic ($p_b = 0$) to compare our model to the ones of [1] and [2]. Figure 2 presents the average simulation results, and the numerical solutions computed using the three models. Two different frame payload sizes were simulated. Our model exhibits a good performance when compared to the simulation results. The results achieved with the other two models have lower accuracy. This is partially justified by the fact that we have a limit for the number of transmission retries at the last stage ([1] and [2] have infinite retries). We also use the Extended Inter-frame Space (EIFS) interval in case of errors in the transmission (as in [2]).

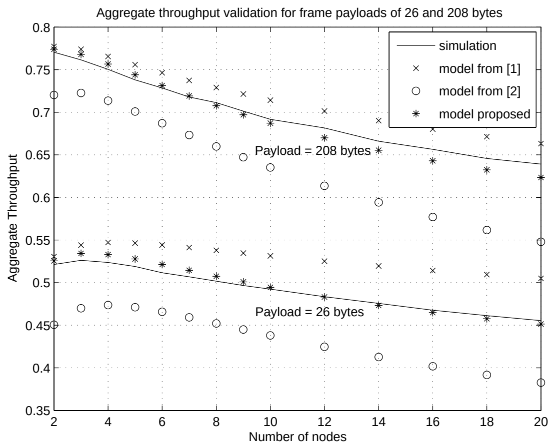

Fig. 2. Comparative throughput results for unicast.

As a second experiment we made simulations for 11 different values of p_b and for six different frame lengths in order to validate the model. Figure 3 illustrate the validation results for 3 values ($p_b=0$, $p_b=0.5$, $p_b=1$) for a frame length of 26 bytes. The simulation results were obtained with a standard deviation below 3.5%. The solutions given by the model are contained in the simulation error interval for all simulated values of p_b, which successfully validates the model.

V. PERFORMANCE ANALYSIS

The third experiment led to the aggregate network throughput, considering a variable number of nodes, different amounts of broadcast traffic, and different frame lengths. Figures 4 and 5 represent the surfaces. The aggregate network throughput increases with the frame length for identical values of the other variables. This is expectable as the network gets more efficient and can also be seen in Figure 2.

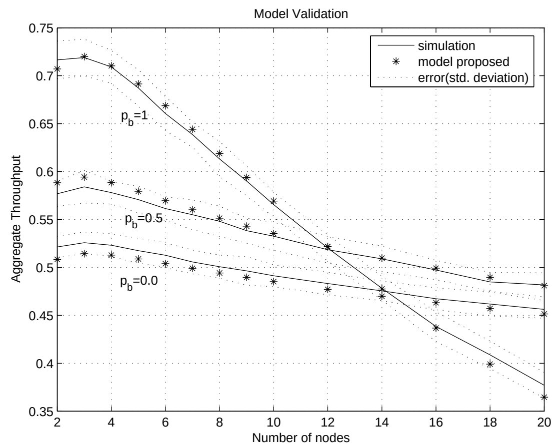

Fig. 3. Throughput validation for different p_b values.

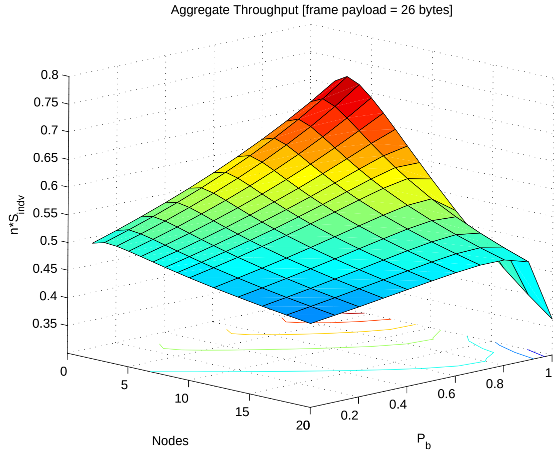

Fig. 4. Saturation broadcast/unicast throughput using frames with 26 bytes of payload.

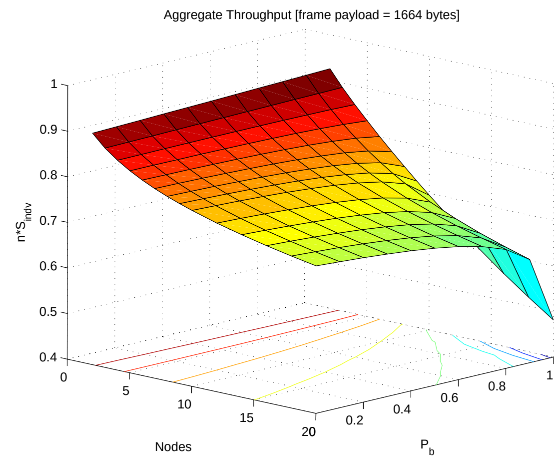

Fig. 5. Saturation broadcast/unicast throughput using frames with 1664 bytes of payload.

More interesting is the analysis of the impact of broadcast traffic (as it can be used as the base of multiple services). For small data frames (Figure 4), and assuming a small number of nodes, the network throughput increases as the relative amount of broadcast traffic increases. A combination of low *cycle time*, T_b, (due to not having the ACK time) and low collision rate (due to the small number of nodes) benefits the broadcast throughput. As the number of nodes grows, there is a threshold (aprox. 10 nodes in Figure 4) from which the throughput stops increasing with p_b. As the number of node increases the maximum aggregated throughput value happens for smaller and smaller values of p_b. For instance, for a 10 node system a value of 0.8 for p_b maximizes the throughput. In such a system (using also small frames) broadcast services are very efficient. As the number of nodes increases, or the broadcast traffic gets very heavy, the system/network degrades very abruptly. This is due to the increase of the collision probability that results from having a unique BC stage for broadcast traffic.

For larger frames (Figure 5) and when few nodes are considered, the throughput is almost constant and independent of p_b. There is again the effect of low *cycle time* and low collision probability, but this time the larger size of frames turns the effect of the ACK time less important. For networks with more nodes, the network throughput decreases as the broadcast traffic increases.

VI. Conclusions

In this paper, we present a model for IEEE 802.11 DCF networks. The model extends the work presented in [1], assuming the existence of both broadcast/unicast traffic in a saturated single-hop network. The model is used to derive the individual station transmission probability, the average frame transmission time, and the network aggregate throughput. We compare the numerical results given by our model with the results from two other proposed models and a set of simulations. Our model evidences a satisfactory accuracy when compared to the simulation results, and a better accuracy than [1] and [2] models.

We conclude that as long as the number of nodes on the coverage area remains small the total network throughput tolerates well the presence of broadcast traffic (it can even improve), and this is even independent from the frame size. When the networks become very dense care must be taken on the usage of broadcast traffic and structured algorithms must be devised.

Future work includes the modelling of non-saturated networks and multi-hop networks. This model will also be very valuable as a tool to develop and assess new network algorithms for mobile ad hoc networks.

References

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