A Finite Load Analytical Model for the IEEE 802.11 Distributed Coordination Function MAC

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Abstract— **CSMA/CA protocols such as IEEE 802.11b are considered to be attractive MAC protocols for wireless LANs. In this paper, we extend a saturation throughput model for the IEEE 802.11 Distributed Coordination Function (DCF) MAC protocol to finite loads. The analytical model can help in the optimization of the protocol parameters as well as leading to the performance modeling of multi-hop ad hoc networks. The model is verified using simulations, and it is shown that the model is extremely accurate.**

I. INTRODUCTION

There have been various attempts to model and analyze the *saturation* throughput of the IEEE 802.11 DCF protocol ([1-3]), but there has been no comprehensive model that is applicable to arbitrary traffic loads yet. Such a model is an important first step towards a general model for a multi-hop network using this MAC protocol. A model for analyzing the binary exponential backoff mechanism of 802.11 DCF was introduced in [1]. Yet another model for predicting the saturation throughput of 802.11 DCF in broadcast networks is presented in [2]. In this paper, we present an extension of the model in [1] to the case of finite loads. An outline of the model is presented in the next section, and some simulation results to validate the model are presented in Section III.

II. IEEE 802.11 DCF ANALYTICAL MODEL

We refer to [4] for details of the operation of the DCF mode of 802.11. An *n*-station broadcast network is considered. Each of the stations (STAs) accesses the common channel using the 802.11 DCF MAC protocol. The operation of an STA is modeled as a Markov chain. The state diagram of the model for a single STA is shown in Figure 1. Packets arrive to the STA according to a Poisson process with rate λ packets/sec. Each STA is assumed to have an infinite buffer. The probability of failure given that an STA transmits a packet is assumed to be independent of the state of the STA and is denoted by p. A perfect error-free channel is assumed.

The proposed model state diagram consists of an aggregation of states that a node can reside in, from a transmit point of view. Each STA transmits and receives packets, but success or failure of receiving a packet from a receiver point of view is captured as a state of the channel in this model. The "*No-TX*" state is the state in which the node does not have any packet to transmit. The "*First-TX*", represents the first transmission of a packet after the "*No-TX*" state if the channel is sensed idle immediately after receiving a packet. The backoff states are denoted by (i,w), where i defines the contention window (W_i) as $W_i=2^i\, W$ (W denotes minimum contention window) for $0 \le i \le m'$, and $W_i=2^{m'}W$ for $m' \le i \le m$, where m is the maximum number of retransmissions. w is the backoff counter number. These backoff states are the same as in [1]. $(0',w)$ are backoff states entered when the STA's transmit buffer is empty after a successful transmission. (We have deviated slightly from the standard in order to simplify the model. If the buffer is empty after a successful transmission, we assume that the backoff counter number is selected from the range $(1,W)$ instead of $(0,W-1)$ as specifies by the standard.)

Transitions from state to state occur at the ends of *channel slots*. We define three types of channel slots, each of different duration: idle, fail, or success, depending on whether a slot on the channel is idle, a collision between two or more transmissions happened during the slot, or whether a packet was successfully transmitted during the slot, respectively. The duration of a channel slot is the period of time that the channel stays in one state: idle, fail, or success. An idle channel slot is a slot in which nobody attempts to transmit a packet and its duration is equal to one system slot, denoted by σ here. A successful channel slot occurs when just one node attempts to transmit a packet and a failed channel slot occurs when more than one node transmits. The average lengths of successful and failed slots are denoted by Ts and Tc, respectively.

The transition probabilities for the Markov chain are shown in Figure 1 except following transition probabilities.

$$NO\text{-}TX \rightarrow First\text{-}TX = (1-P_{tr(n-1)})\,(1-e^{-\lambda\sigma}) \quad (1)$$

$$NO\text{-}TX \rightarrow Backoff = P_{tr(n-1)}P_{s(n-1)}\,(1-e^{-\lambda Ts}) + P_{tr(n-1)}\,(1-P_{s(n-1)})(1-e^{-\lambda Tc}),$$

where $P_{tr(n-1)}$ is the probability that at least one STA out of $n-1$ transmits and $P_{s(n-1)}$ is the probability that one of the other $(n-1)$ STAs transmits a packet successfully. The transition probabilities in the backoff states are given in [1]. q is the probability that the transmit queue is empty when a node finishes a successful packet transmission after being in backoff. In other words, q is the probability that the node enters backoff with exactly one packet to transmit, and no new packets arrive until the packet is transmitted successfully. If the expected value of the time that the packet spends in backoff before successfully transmitting the packet is denoted by $E(S_b)$, then q is given by

$$q = e^{-\lambda E(Sb)}\ Prob\ (entering\ backoff\ with\ one\ packet). \quad (2)$$

As an approximation, we assume that the probability of entering backoff with one packet is one. For light loads, this is a reasonable assumption because backoff states are rarely visited, and the probability of entering backoff with more than one packet is expected to be insignificant. For heavy loads, q is almost zero because of large λ, and is therefore insensitive to the probability of entering backoff with exactly one packet. We will see later that this assumption does not result in any significant model inaccuracy. Hence, we set

$$q = e^{-\lambda E(Sb)}. \quad (3)$$

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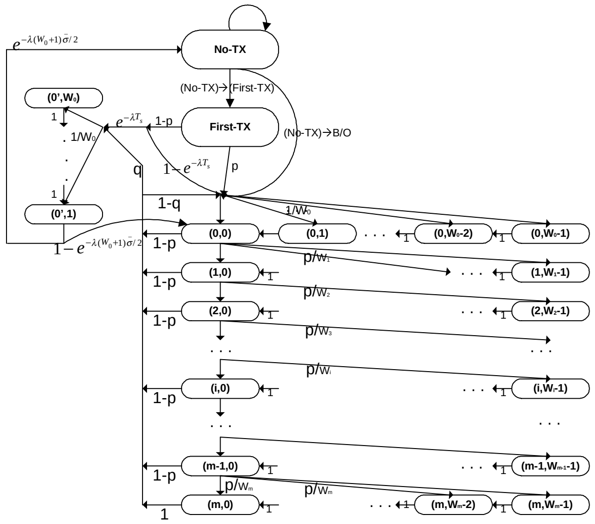

Figure 1 IEEE 802.11 DCF state model.

The backoff service time, S_b, is the duration of time that is spent in backoff states before a packet is transmitted successfully, given that backoff mode is entered by an STA for this packet's transmission.

$$E(S_b) = (1-p^{m+1})\left[T_s + \frac{T_c p - \bar{\sigma}/2}{1-p}\right] + \left(\frac{\bar{\sigma}}{2}\right)\left[\sum_{i=0}^{m} W_i p^i\right]. \qquad (4)$$

$\bar{\sigma}$ is the average time between successive counter decrements,

$$\bar{\sigma} = (1-p_{tr(n-1)})\sigma + p_{tr(n-1)} p_{s(n-1)}(T_s+\sigma) + p_{tr(n-1)}(1-p_{s(n-1)})(T_c+\sigma). \qquad (5)$$

We now solve the balance equations in order to find the stationary distribution of the Markov chain as a function of p, and then find the probability, τ, that a station transmits in a randomly chosen idle slot as $\sum b(i,0)+b(First\text{-}TX)$. We remark here that under heavy loads, q is close to zero, and this model reduces to the saturated load model of [1]. We next find an expression for the channel throughput.

We consider a network of heterogeneous users, i.e., whose traffic loads are different. Let us assume that there are k different arrival rates (loads) within a network and we denote the corresponding parameters by adding an index i, $1 \le i \le k$. Let there be n_i nodes with arrival rate λ_i, $\Sigma n_i = n$. Then the probability of packet failure for a node with arrival rate λ_i can be written as follows:

$$p_i = 1-(1-\tau_i)^{n_i-1}\prod_{j=1, j\neq i}^{k}(1-\tau_j)^{n_j} \qquad (6)$$

The probability that at least one STA transmits is

$$P_{tr(n)} = 1-\prod_{j=1}^{k}(1-\tau_j)^{n_j}, \qquad (7)$$

and the probability that the transmitted packet is successful is

$$p_{s(n)} = \frac{\sum_{i=1}^{k}\left(n_i\tau_i(1-\tau_i)^{(n_i-1)}\prod_{j=1, j\neq i}^{k}(1-\tau_j)^{n_j}\right)}{p_{tr(n)}}. \qquad (8)$$

Then, the network throughput, S, can be calculated as follows:

$$S = \frac{p_{tr(n)}\, p_{s(n)}\, E[P]}{(1-p_{tr(n)})\sigma + p_{tr(n)}\, p_{s(n)}\, T_s + p_{tr(n)}(1-p_{s(n)})T_c}. \qquad (9)$$

$E[P]$ denotes average payload size. The throughput expression is applicable to both the basic and the RTS/CTS modes of the MAC standard. The only difference is in the expressions for Ts and Tc. Ts and Tc for RTS/CTS and Basic modes are as follows:

RTS/CTS: $Ts = RTS + 3\ SIFS + CTS + E[P] + ACK + DIFS$,
$Tc = RTS + DIFS$ (10)

Basic: $Ts = E[P] + SIFS + ACK + DIFS$, $Tc = E[P] + DIFS$

III. Numerical Results

We validate the model by comparing model results with simulation results. The simulations were done using the Frequency Hopping Spread Spectrum (FHSS) system parameters [4] of 802.11 DCF and a packet length of 8184 bits. Each STA can be a receiver or a transmitter but not both simultaneously. The buffer size is set to a large number (forty packets in the simulations) in order to approximate an infinite buffer.

The throughput results when all STAs have the same traffic load are plotted against the offered load (per STA) in Figure 2 for the RTS/CTS mode. Throughputs for a heterogeneous network are shown in Figure 3. Two arrival rates (indicated in parentheses next to the curves) were chosen with half of the nodes (randomly picked) having one arrival rate and the remaining half the other. As can be seen from these results, the proposed model is quite accurate.

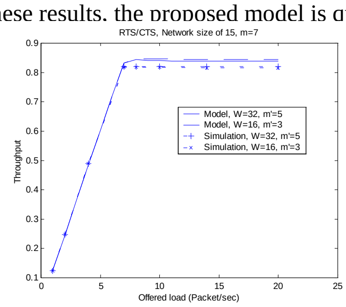

Figure 2 Throughput versus offered load per STA; RTS/CTS mode, n=15.

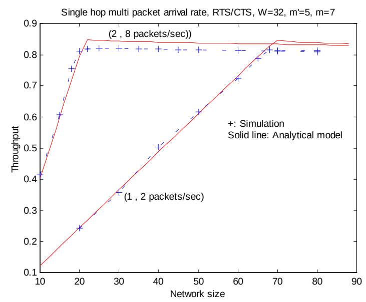

Figure 3 Heterogeneous network throughput versus network size.

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