Modeling the IEEE 802.11 DCF with Hidden Stations

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Abstract. Many works have been put on analyzing the performance of the IEEE 802.11, but hidden station problem was seldom involved. In practice, the existing of hidden stations will lead heavy drop of system throughput. A novel model is proposed in this paper, which can be used to analyze the throughput of 802.11 DCF in presence of hidden stations under saturation condition. Different scenarios are used in simulation to validate it, and the results show that the model is accurate.

Keywords: IEEE 802.11, DCF, Saturation, Hidden stations.

1 Introduction

During the last few years, the IEEE 802.11 [1] has become the standard protocol for Wireless Local Area Network (WLAN) and has been widely deployed. The Medium Access Control (MAC) technique of 802.11 is called Distributed Coordination Function (DCF). Many models have been established to analyze the throughput of 802.11 DCF. Most research of DCF modeling focused on the maximum throughput or the saturated throughput.

Bianchi [2] presented a Markov chain model to compute the throughput under saturation condition, i.e., each station always has a frame available for transmission and the transmission queue of each station is assumed always nonempty. One of the main assumptions is that all stations are in the same radio proximity. This model then has refined in different ways, but the problem of hidden station was seldom dealt with. However, stations do not typically operate under the same radio proximity, and maybe some stations cannot hear the transmissions of other ones. RTS/CTS mechanism can reduce the effect of hidden stations [3], but it cannot eliminate it. So, recently, some research efforts have been devoted to the problem. In [4], an analytical model was derived from Bianchi's Markov model and Tobagi's hearing graph framework [5]. However, its results show that it is a little sketchy. Based on [2], Vassis [6] presented a model introducing the transmitting time, within which the transmitting station may experience collision because of hidden stations. Nevertheless, its theoretical results under usual number of stations do not match up to the simulation. Paper [7] proposed a model focusing on ad hoc networks with hidden

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terminals. The results showed in the paper are good, but the author gave some equations without clear proof. In this paper, we extend Bianchi's model and present a model applicable to the hidden station problem.

2 Saturated Model with Hidden Stations

In this section, we present a model suitable for analyzing the IEEE 802.11 DCF with hidden stations under saturated condition. In our scenario, total n stations around the AP are divided into J groups. Group j, $j \in [1, J]$, has n_j stations. Stations in one group are in the same radio domain, and they can hear each other. However, they cannot hear stations in other groups, and which indicates the hidden station problem. All stations can be heard by the AP, and they always have frames to send to the AP.

The main assumptions follow those in [2]. We assume that the channel is ideal (i.e. no link errors), and stations in same group are equally likely to access the channel. We also make the most of the same notations used in [2]. Equations (7) and (9) in [2] represent the saturated model without hidden stations, and they are rewritten here as equations (1) and (2) for purposes of completeness.

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \tag{1}$$

$$p = 1-(1-\tau)^{n-1} \tag{2}$$

In equation (1), transmission probability τ is expressed as functions of the conditional collision probability p. This equation is suitable for the scenario with hidden stations, and the only difference is using τ_j and p_j for group j. But equation (2) is not tenable when hidden stations are present. To deal with the hidden station problem, we now extend Bianchi's model and introduce more variables.

For group j, let Es_j be the expected time spent per state.

$$\begin{aligned}
Es_j &= Pi_j\sigma + Pa_jTa + Ps_jTs + Pc_jTc + Pb_jTb \\
Pi_j &= (1-\tau_j)^{n_j}(1-\sum_{k\neq j} Ps_k \frac{Es_j}{Es_k}) \\
Pa_j &= (1-\tau_j)^{n_j}\sum_{k\neq j} Ps_k \frac{Es_j}{Es_k} \\
Ps_j &= (1-(1-\tau_j)^{n_j})(1-p_j) \\
Pc_j &= 1-(1-\tau_j)^{n_j} - n_j\tau_j(1-\tau_j)^{n_j-1} \\
Pb_j &= (1-(1-\tau_j)^{n_j})p_j - Pc_j
\end{aligned} \tag{3}$$

In equation (3), σ is the time of an idle slot, and Pi_j is the probability that station in group j experiences idle, that is, none of the stations in the group transmits and

AP does not send anything either. Pa_j is the probability that all stations in group j do not transmit but they can hear an ACK (for basic access mechanism) or a CTS (for RTS/CTS mechanism) from AP caused by successful transmission in other groups, and Ta is the time taken for an ACK or a CTS. Ps_j is the probability that at least one station in group j transmits and succeeds, and Ts is the time taken for a successful transmission. Pc_j is the probability that more than one stations in group j are transmitting simultaneously, and Tc is the time taken for a collision between stations in same group. Pb_j is the probability that at least one station transmits and collides with transmission from other groups, and Tb is the time taken for a collision between stations in different groups.

We now consider the expected time Et_j between two successive transmission of DATA (for basic access mechanism) or RTS (for RTS/CTS mechanism) frames for a station in group j.

$$\begin{aligned}
Et_j &= Qi_j\sigma + Qa_jTa + Qs_jTs + Qc_jTc + Qb_jTb \\
Qi_j &= \sum_{i=0}^{m} \frac{W_i}{2} p_j{}^i \Big/ \sum_{i=0}^{m} p_j{}^i \\
Qa_j &= \sum_{k \neq j} Qs_k \frac{Et_j}{Et_k} \\
Qs_j &= n_j(1-p_j) \\
Qc_j &= n_j(1-(1-\tau_j)^{n_j-1})/2 \\
Qb_j &= n_j(p_j - (1-(1-\tau_j)^{n_j-1}))
\end{aligned} \tag{4}$$

Qi_j is the expected number of idle slots between two successive transmission. According to the different back-off stage it may stay, the expected number of idle slots is $W_i/2$ with probability $p_j{}^i$, where $i = 0, \ldots, m$. Qi_j is then calculated by the weighted average of them. Qa_j is the expected number of ACKs or CTSs caused by successful transmissions in other groups. Qs_j is the expected number of successful transmissions in the group. In Et_j, all stations in the group may transmit once on average. So totally n_j attempts of transmitting may happen. But some of them may collide with probability p_j; thus Qs_j equals to $n_j(1-p_j)$. Qc_j is the expected number of collisions with stations in same group. In n_j attempts of transmitting, some of them may fail because other stations in the group begin transmitting at the same time. When two stations in the group collide, they share the time of collision, so a coefficient 1/2 occurs in the expression of Qc_j. We ignore the probability of more than two stations transmitting at the same time because it is relatively smaller. Qb_j is then the expected number of collisions with stations in other groups. Finally, Et_j is calculated by summing up them.

For transmission probability τ_j is scaled in Es_j and Et_j is the time between two successive transmitting, this leads to

$$\tau_j = Es_j / Et_j \tag{5}$$

Equations (1), (3), (4) and (5), which describe the model, represent a nonlinear system with p_j, τ_j, Es_j and Et_j. It can be solved by numerical computation. In our study, we solve the model using the method *fsolve* implemented in the MATLAB optimization toolbox.

The model is suitable for both basic access and RTS/CTS mechanism. It is necessary only to specify corresponding values of Ta, Ts, Tc and Tb when different payloads and mechanisms are employed, and they are calculated in the same way as in [2].

3 Model Validation

To validate the model, we have compared its results with that obtained with NS-2. The results are based on basic access mechanism with 11 Mbps data rate and 500 bytes packet payload. Two scenarios, including different kinds of grouping schemes, are used for validation.

The first scenario includes three grouping schemes, i.e., n stations are equally divided into 2, 3 and 4 groups. The results are shown in Figs. 1 and 2. Fig. 1 shows how Et increases with n. Fig. 2 shows how normalized total throughput drops with n. From the figures, we see that, though stations transmit more quickly when they are divided into more groups, total throughput drops anyway. Smaller group lets stations get more chances to transmit, whereas experience more collisions because of more hidden stations.

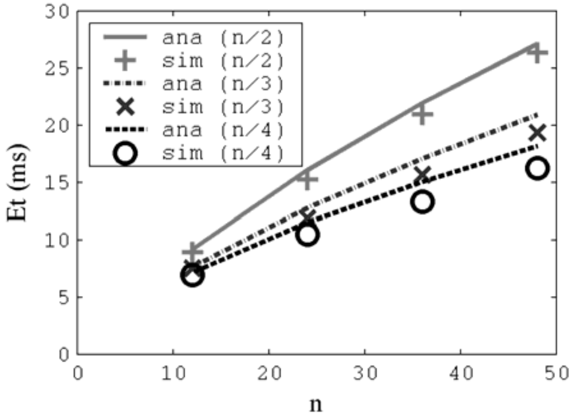

Fig. 1. Et vs. n

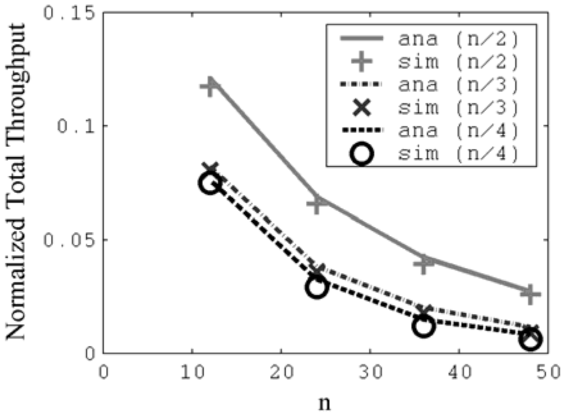

Fig. 2. Throughput vs. n

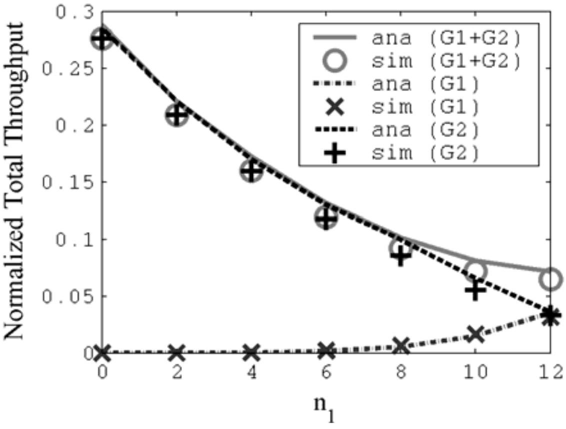

Fig. 3. Throughput vs. n_1

In the second scenario, 24 stations are divided into 2 groups, G1 and G2, which has n_1 and $24-n_1$ stations, respectively. Throughputs of G1 and G2, as well as their sum, are plotted in Fig. 3 versus the value n_1. It shows that group's throughput is not in proportion to its number and smaller group's throughput is extremely low when there is a big difference between the numbers of two groups. This is to some extent unfair to the minority. Moreover, the degradation of total throughput from no hidden stations case (n_1 = 0) is obvious, and it descends further as the proportion of hidden stations goes high.

4 Conclusions

In this paper, we have presented a novel model to analyze 802.11 DCF in presence of hidden stations under saturation condition. The model's analytical results are validated against simulations, and it shows that the model is extremely accurate. Future works will address RTS/CTS mechanism and real machine evaluation.

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