Performance Analysis of IEEE 802.11 DCF with Data Rate Switching

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***Abstract*— In this letter, we propose a novel Markov chain model for IEEE 802.11 WLAN, considering a commonly used data rate switching mechanism. In the proposed model, both collision and transmission errors are considered. The performance of IEEE 802.11 DCF (Distributed Coordination Function) is analyzed using the proposed model. The accuracy of the proposed model is verified by simulation.**

***Index Terms*— 802.11, DCF, data rate switching, Markov chain.**

I. Introduction

MULTIPLE data rates are supported in IEEE 802.11 standard [1] although the mechanism how stations switch between multiple data rates is left for the equipment manufacturers. Some publications in this area, such as that in [2], have discovered that most commercial IEEE 802.11 products use a simple data rate switching (DRS) mechanism: if a station has U ($U \geq 1$) consecutive successful transmissions, it will increase its data rate to a higher data rate until the highest data rate has been reached. If the station suffers D ($D \geq 1$) consecutive unsuccessful transmissions, it will decrease its data rate to a lower data rate until the lowest data rate has been reached.

Despite extensive work on analyzing the performance of IEEE 802.11 DCF (Distributed Coordination Function), most of them consider stations use a single data rate only and the effect of using DRS has been largely ignored, such as those in [3], [4]. Meanwhile existing work on DRS mechanism for IEEE 802.11 WLAN only presents simulation or experiment results, such as that in [2], and an analytical approach is lacking. In this letter, we present a novel Markov chain model for DCF performance analysis, considering the aforementioned DRS mechanism. In our analysis, both collision and transmission errors are considered[1]. The rest of this letter is organized as the follows. In Section II, the proposed model is presented; In Section III, the saturated throughput is analyzed; Finally Section IV presents the simulation study and concludes this letter.

II. The Analytical Model

The following assumptions are used in the model.

- Traffic load is saturated.

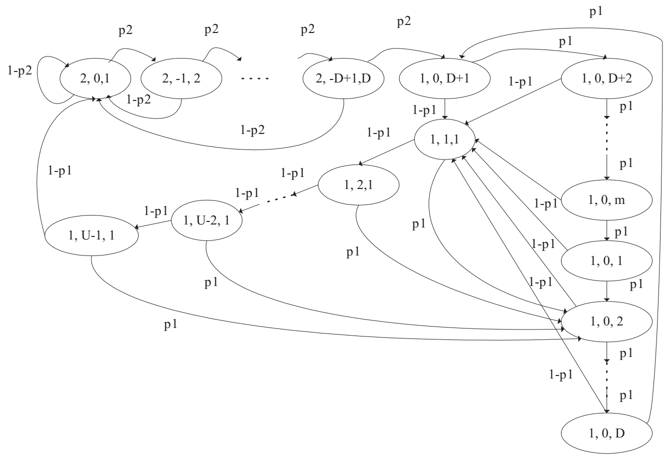

Fig. 1. The basic Markov chain model.

- The number of stations, n, is fixed and known.
- The transmission probability of a station in a generic time slot is a constant, denoted by τ. The value of τ is unknown and to be solved.
- Only two data rates, R2 and R1 ($R2 > R1$), are considered for simplicity. The maximum retransmission limit for sending a data frame, m, is set to be 7 [1, p. 361]. In this letter, we consider $m > D$. The proposed model can be easily revised for $m \leq D$.
- The transmission error is measured in frame error rate (FER). FERs at the data rates of R2 and R1 are set to be known constants, denoted by FER_2 and FER_1 respectively. The transmission error occurs on data frame only.

A. The Basic Markov Chain Model

The proposed Markov chain model is shown in Fig. 1. There are three state variables in the model, i.e., $w(t)$, $v(t)$, and $q(t)$. The first state variable, $w(t)$, models the current data rate of a given station, therefore $w(t) = 2$ (representing R2) or $w(t) = 1$ (representing R1). The second state variable, $v(t)$, models the number of consecutive successful and unsuccessful transmissions experienced by the station, which is explained in the following.

1) $v(t) = -i$, $i \geq 1$ represents that the station has suffered i consecutive unsuccessful transmissions before the current transmission.
2) $v(t) = i$, $i \geq 1$ represents that the station has experienced i consecutive successful transmissions before the current transmission.
3) $v(t)$ will be reset to 0 or it will remain 0 in three occasions: i) The station experiences a rate switching;

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[1]In this letter, collision is defined as two or more stations transmit at the same time and collide with each other, thefore all these transmissions are unsuccessful. Transmission errors are caused by poor radio channel conditions.

ii) The station experiences an unsuccessful transmission at R1; iii) The station experiences a successful transmission at R2. With such definition, we may avoid unnecessary Markov states to record the number of consecutive successful transmissions at R2 and the number of consecutive unsuccessful transmissions at R1, and it will simplify the Markov chain.

Finally, the third state variable, $q(t)$, models the number of the transmission attempts involved in sending a single data frame. $q(t) = j, j \geq 1$ means that the station is performing the j^{th} transmission attempt. When the maximum retransmission limit, m is reached, the frame will be dropped and $q(t)$ will be reset to 1, which means a new data frame will be transmitted.

Denote the steady state probability of the Markov chain by $s(w(t), v(t), q(t))$, the transition equations are given by:

$$s(2,0,1) = s(2,-j+1,j)(1-p_2), 1 \leq j \leq D \quad (1)$$
$$s(2,-j,j+1) = s(2,-j+1,j)p_2, 1 \leq j \leq D-1 \quad (2)$$
$$s(1,0,D+1) = s(2,-D+1,D)p_2, \quad (3)$$
$$s(1,0,j+1) = s(1,0,j)p_1, 1 \leq j \leq m-1, \quad (4)$$
$$s(1,0,1) = s(1,0,m)p_1, \quad (5)$$
$$s(1,1,1) = s(1,0,j)(1-p_1), 1 \leq j \leq m, \quad (6)$$
$$s(1,j,1) = s(1,j-1,1)(1-p_1), 2 \leq j \leq U-1, \quad (7)$$
$$s(2,0,1) = s(1,U-1,1)(1-p_1), \quad (8)$$

where p_2 and p_1 are the probabilities that a transmission from the station is unsuccessful at the data rates R2 and R1 respectively:

$$p_i = p_c + (1-p_c)FER_i, i = 1,2. \quad (9)$$

Here p_c is the probability that a transmission from the station collides with transmissions from other stations, given by $p_c = 1-(1-\tau)^{n-1}$.

The transition equations are explained as follows: Eq. (1) represents a successful transmission at R2; Eq. (2) represents an unsuccessful transmission at R2 and the next transmission should be at R2 because the limit of D consecutive unsuccessful transmissions at R2 is not reached yet; Eq. (3) represents a decrement of the data rate from R2 to R1 when the station experiences D consecutive unsuccessful transmissions at R2; Eq. (4) and Eq. (5) represent unsuccessful transmissions at R1; Eq. (6) and Eq. (7) represent successful transmissions at R1; finally (8) represents an increase of the data rate from R1 to R2 when the station experiences U consecutive successful transmissions at R1.

B. The Transmission Probability, τ

The Markov chain model in Fig. 1, however, does not allow us to relate the steady state probabilities to the transmission probability of a given station, τ, which must be found in order to determined the collision probability, p_c, in Eq. (9). To solve the problem, the evolution of the backoff counter in each state of the Markov model in Fig. 1 is modeled and shown in Fig. 2. In Fig. 2, the sub-state represents the value of the backoff counter of the station [3]. It varies between 0 and $CW(j)$, where $CW(j)$ is the congestion window size corresponding to the j^{th} transmission attempt from the station for sending a frame. The value of j is determined by the state variable $q(t)$ of the Markov model. The detail about how $CW(j)$ varies with j can be found in [1]. When the sub-state (0) is reached, a transmission will occur.

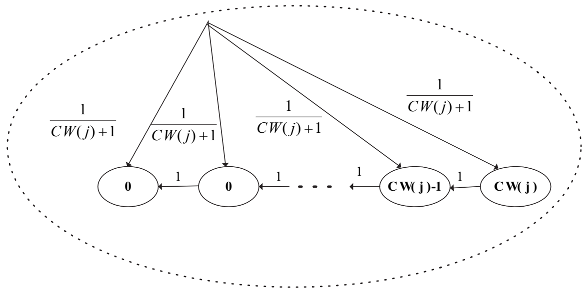


Fig. 2. The sub-states of a state in the basic Markov chain.

Let $s(i,k,j)$ be the steady probability of a given state in the Markov chain model shown in Fig. 1, and $b(r)$ be the steady probability of its sub-state (r), $0 \leq r \leq CW(j)$. Based on Fig. 2, it can be readily obtained that

$$b(0) = s(i,k,j)\frac{2}{CW(j)+2}. \quad (10)$$

As when the backoff counter reaches zero, a transmission will occur, the sum of $b(0)$s for all the states in the Markov chain model shown in Fig. 1 should be equal to the transmission probability τ:

$$\tau = \sum_{i,k,j} s(i,k,j)\frac{2}{CW(j)+2}. \quad (11)$$

C. Summary

Finally, considering that the sum of the steady state probabilities of a Markov chain is 1, we may obtain $\sum_{i,k,j} s(i,k,j) = 1$. Therefore a group of equations about τ can be obtained, and it will lead to the solution of τ, p_c, p_1, p_2, and eventually $s(i,k,j)$.

III. SATURATED THROUGHPUT

Within a generic time slot, one of the following four events may occur: (1) the channel remains idle; (2) a successful transmission starts; (3) an unsuccessful transmission due to transmission error occurs; (4) a collision occurs. The probability that the channel remains idle is given by

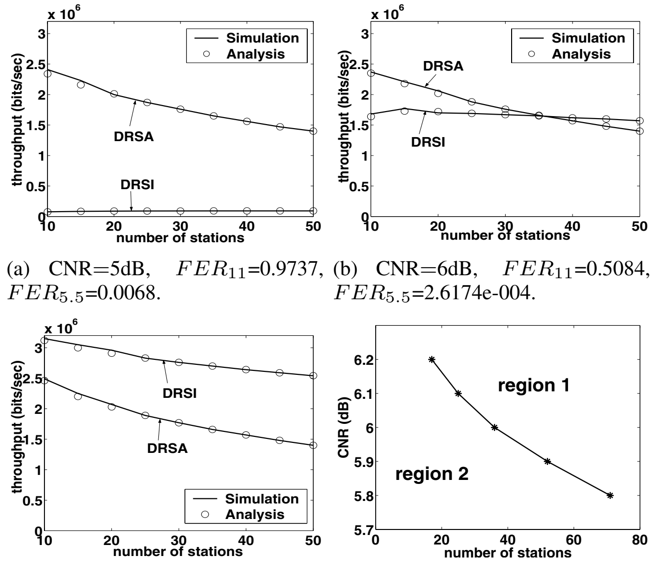
$$P_{idle} = (1-\tau)^n, \quad (12)$$

where τ has been solved in the last section.

Because a transmission will occur at either R2 or R1 which takes different amount of time, we calculate the conditional probabilities τ_2 and τ_1, representing that a transmission occurs at R2 and R1 respectively:

$$\tau_2 = \left[\sum s(2,i,j)\frac{2}{CW(j)+2}\right]/\tau, \quad (13)$$
$$\tau_1 = \left[\sum s(1,i,j)\frac{2}{CW(j)+2}\right]/\tau, \quad (14)$$

where parameters $s(2,i,j)$ and $s(1,i,j)$ have been solved in the last section.



(a) CNR=5dB, FER_{11}=0.9737, $FER_{5.5}$=0.0068.
(b) CNR=6dB, FER_{11}=0.5084, $FER_{5.5}$=2.6174e-004.
(c) CNR=7dB, FER_{11}=0.0868, $FER_{5.5}$=4.3223e-006.
(d) Threshold values for CNR and number of stations.

Fig. 3. The simulation and analytical results ("DRSA" means "data rate switching active", and "DRSI" means "data rate switching inactive").

Accordingly, we may obtain the following probabilities:

$$P_{suc\_2} = n\tau(1-\tau)^{n-1}\tau_2(1-FER_2), \quad (15)$$
$$P_{suc\_1} = n\tau(1-\tau)^{n-1}\tau_1(1-FER_1), \quad (16)$$
$$P_{FER\_2} = n\tau(1-\tau)^{n-1}FER_2\tau_2, \quad (17)$$
$$P_{FER\_1} = n\tau(1-\tau)^{n-1}FER_1\tau_1, \quad (18)$$
$$P_{col\_2} = \sum_{i=2}^{n}\binom{n}{i}\tau^i(1-\tau)^{n-i}\tau_2^i, \quad (19)$$
$$P_{col\_1} = \sum_{i=2}^{n}\binom{n}{i}\tau^i(1-\tau)^{n-i}(1-\tau_2^i). \quad (20)$$

Eq.(15) and Eq.(16) calculate the probabilities that a successful transmission occurs at R2 and R1 respectively; Eq.(17) and Eq.(18) calculate the probabilities that an unsuccessful transmission caused by transmission error occurs at R2 and R1 respectively; Eq.(19) calculates the probability that a collision occurs and all stations involved transmit at R2; finally Eq.(20) calculates the probability that a collision occurs and at least one station involved transmits at R1, which will result in a longer duration for the collision than that in Eq.(19).

Finally, the overall throughput can be obtained:

$$Throughput = [(P_{suc\_1} + P_{suc\_2})PL]/EL, \quad (21)$$

where PL is payload size of the data frame, and EL is the average time duration required for the four possible events, given by $EL = \sum P_{event}T_{event}$. Here P_{event} is the probability for the four aforementioned events, given in Eq.(12), (15)-(20), and T_{event} is the duration for each event, whose values can be found in [3].

IV. Simulation Study and Conclusion

In our simulation using OPNET [5], IEEE 820.11b DSSS (direct sequence spread spectrum) physical layer is used. The payload size of the data frame is 4000 bits. Stations will transmit the payload at two data rates: 11Mbps and 5.5Mbps. In our simulation, DQPSK (Differential Quadrature Phase Shift Keying) is used at both data rates [1, pp. 195-223], and all stations use the identical transmission power under the same additive white Gaussian noise (AWGN) channel condition at both data rates. Therefore the carrier to noise ratio (CNR) is the same at both data rates. Accordingly, bit error rate (BER) at both data rates can be obtained [6]. With BER, FER for data frame can be obtained by $FER = 1 - (1 - BER)^{PL}$. We set $U = 8$, $D = 3$ following the setting in [2]. Frame header and ACK frame are always transmitted at 1Mbps.

The results for different channel conditions are shown in Fig. 3(a)- 3(c), where we observe that the analytical results generally agree very well with the simulation results. For comparison, we also simulate the scenarios that the data rate is fixed at 11Mbps, shown in Fig. 3(a)- 3(c) as well[2].

Because IEEE 802.11 standard does not differentiate whether an unsuccessful transmission is caused by either transmission error or collision, the effect of using DRS is determined by both CNR and the number of competing stations. When CNR$\leq$5dB, the transmission error is large and has a dominant impact, consequently using DRS always results in an improved throughput compared with the scenario not using the DRS, as illustrated in Fig. 3(a). When CNR$\geq$7dB, the transmission error is small, and most transmission failures are caused by collision. It is always beneficial for stations to transmit at a higher data rate, and using DRS will result in a reduced throughput, as shown in Fig. 3(c). When 5dB$<$CNR$<$7dB, the impacts of transmission error and collision are close. When the number of stations is large, collision will have a dominant impact and it is beneficial for stations to transmit at a higher data rate and the converse, as shown in Fig. 3(b). In Fig. 3.(d), two regions are marked according to CNR and the number of stations: in region 2, using DRS can increase the throughput, and in region 1, using DRS will reduce the throughput.

The analytical model developed in this letter will be helpful for designing guidelines assisting the decision on whether or not to use DRS in a specific wireless environment, without resorting to lengthy simulations and experimentation.

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