Performance Evaluation of IEEE 802.11

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Abstract

This paper analyzes the performance of IEEE 802.11 MAC protocol under a disaster scenario. The performance is measured in terms of the recovery time and the throughput of the protocol when a network disaster occurs. To make the problem amenable to analysis, some approximations are used, and a new technique to collapse a very large state space is introduced. The analytical results are found to agree with simulations.

1. Introduction

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) multiple access control (MAC) protocol has been chosen by IEEE 802.11 workgroup for the Distributed Coordination Function (DCF) [1] of wireless LANs. Several performance analyses have been performed to evaluate the performance of the IEEE 802.11 MAC protocol [2, 3, 4]. The focus of this paper is the performance of the protocol in the event of a network *disaster* [5].

The *disaster scenario* is termed by IEEE 802.14 workgroup to describe a power up situation in the hybrid fiber coax (HFC) networks [5]. Since both the HFC and CSMA/CA MAC protocols are based on similar principles, it is interesting to investigate the response of CSMA/CA under such scenario. This situation is likely to occur following a major fault in a wireless local area network whereby many nodes start transmission at once.

Under the disaster scenario, all stations are assumed to transmit a packet each at the same time. Once the packet is transmitted, the station will remain idle. We will derive a method to evaluate how long it will take to clear the backlog, and what the system throughput is during that period.

In the next section, the operation of the IEEE 802.11 MAC protocol of the DCF is described. In Section 3, we present the disaster analysis of the IEEE 802.11 MAC protocol. Finally, in Section 4, the analytical results are verified by computer simulations.

2. The IEEE 802.11 MAC Protocol

According to IEEE 802.11, stations access the channel using a *basic access method*, or an optional *four-way handshaking access method* with an additional Request-To-Send/Clear-To-Send (RTS/CTS) message exchange (see Fig. 1). Under the basic access method, a station, when ready for a new packet transmission, first senses the channel status. If the channel is found to be busy, the station defers its transmission and continues to sense the channel until it is idle. After the channel is idle for a specified period of time called the distributed interframe space (DIFS) period, the station choose a random number as a backoff timer. Note that the time immediately after the DIFS period is slotted. As shown in Fig. 1, the timeslot duration is at least the time required for a station to detect an idle channel plus the time required to switch from listening to transmitting mode. The backoff timer is decreased by one for each idle slot, stopped if the channel is sensed busy, and then reactivated if the channel is idle again and remains idle for more than a DIFS time duration. When the backoff timer reaches zero, the packet is transmitted.

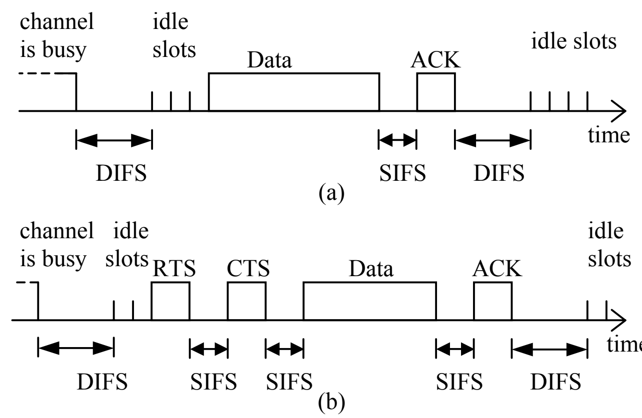

Fig. 1. IEEE 802.11 access methods: (a) Basic access method. (b) Four-way handshaking access method.

The choice of the random number for the backoff timer is based on the binary exponential backoff algorithm, where a station chooses any of the numbers between 0 and *CW*-1 randomly with equal probability. The Contention Window (*CW*) is set to be *CWmin* for every new packet transmission. *CW* is doubled each time when the transmission is unsuccessful, until it reaches *CWmax*, then it remains at *CWmax*. To determine whether a packet transmission is successful, after its completion, a positive acknowledge (ACK) is transmitted by the receiver. ACK is transmitted after a short interframe space (SIFS) period when successfully receiving the entire packet. If ACK is not detected within a SIFS period after the completion of the packet transmission, the transmission is assumed to be unsuccessful, and a retransmission is required.

In the case of the four-way handshaking access method, an additional operation is introduced on top of the basic access method before a packet transmission is taken place. When the backoff timer of a station reaches zero, instead of transmitting the packet as in the basic access method, the station with the four-way handshaking access method first transmits an RTS frame to request for a transmission right. Upon receiving the RTS frame, the receiver replies with a CTS frame after a SIFS period. Once the RTS/CTS is exchanged successfully, the sender then transmits its packet.

3. Disaster Scenario Analysis

Under the disaster scenario, there are r stations ready for new packet transmission at the same time. Each station has only one packet to transmit. In this paper, we assume that the packet size is fixed. The process for all r stations to successfully transmit their packets is defined as a *recovery process* of the disaster scenario. By the time the last station completes its packet transmission, the recovery process ends.

We adopt the technique used in [6] for analyzing the mean contention period for Ethernet and apply it here to analyze the mean time of the recovery process for IEEE 802.11 MAC protocol. The technique requires two steps: 1) The computation of the attempt probability, P_n, of a particular station, and 2) The mean time for all r stations to obtain a successful transmission each based on the P_n.

The Attempt Probability, P_n

As described earlier, a station, when ready for a new packet transmission, will backoff for a period of time based on a randomly chosen number between 0 and CW-1. The packet transmission is attempted when the backoff timer expires. If the attempt is unsuccessful, the value of CW is doubled as long as it is smaller than $CWmax$, and a new value of backoff timer is chosen.

Let n be the number of wasted slots (i.e. idle or collided slots) from the time when a station is ready. After n number of wasted slots, a station attempts to transmit its packet into the next slot only if the station experienced an unsuccessful attempt previously between slot n–min($CWmax$,$2^c CWmin$) and slot n–1 where c is the number of collisions experienced by that station at that slot. Thus the probability, P_n, that a particular station will attempt its packet transmission after n number of wasted slots can be computed by the following recursive equations:

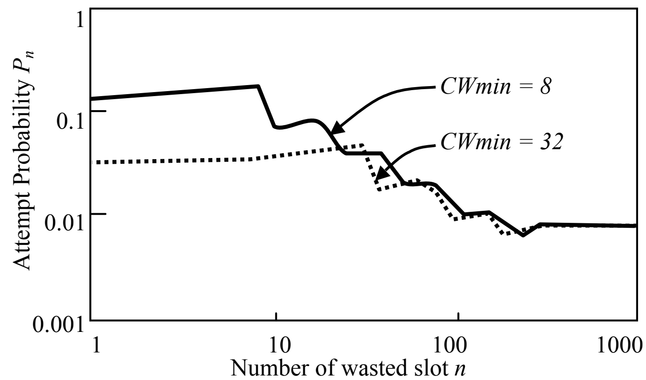

Fig. 2. Attempt probabilities of IEEE 802.11 MAC protocol

$$P_n = \sum_{c=0}^{n} P(n,c) \qquad , n = 0,1,2,... \qquad (1)$$

where

$$P(0,c) = 0 \qquad , c \geq 1$$

$$P(n,0) = \begin{cases} 0 & , n \geq CWmin \\ 1/CWmin & , otherwise \end{cases}$$

$$P(n,c) = \sum_{k=\max(0,n-bf)}^{n-1} \frac{P(k,c-1)}{bf} \qquad , n \geq 1, c \geq 1$$

$$bf = \min(CWmax, 2^c CWmin).$$

Fig. 2 presents the attempt probability, P_n, of a particular station versus the number of wasted slots, n. In the figure, two attempt probability curves are shown, each with $CWmax$=256 and different values of $CWmin$. Note the *distinctive saw tooth pattern* of the curves, this distinctive pattern is discussed in great details in [6].

The Mean Time of the Recovery Process

To model the disaster scenario, we first assume that after n number of wasted slots counting from the beginning of the process, all stations attempt their packet transmissions into the next slot according to the attempt probability given in (1) independently. It is demonstrated in [6] that this assumption is very accurate, especially when the number of stations is large. With this assumption, as shown in Fig. 3, we consider a two-dimensional state space $\{D_m, D_n\}$, where D_m is the number of stations at a particular state and D_n is the number of wasted slots occurred on the channel since the beginning of the recovery process.

In the model, the recovery process of r stations starts from state $\{r, 0\}$, and ends at the rightmost states with D_m=0. Transitions are only legal rightwards, henceforth called *rightward transitions*, and downwards, henceforth called *downward transitions*. It is because at any timeslot, either the number of stations is reduced by one as a result

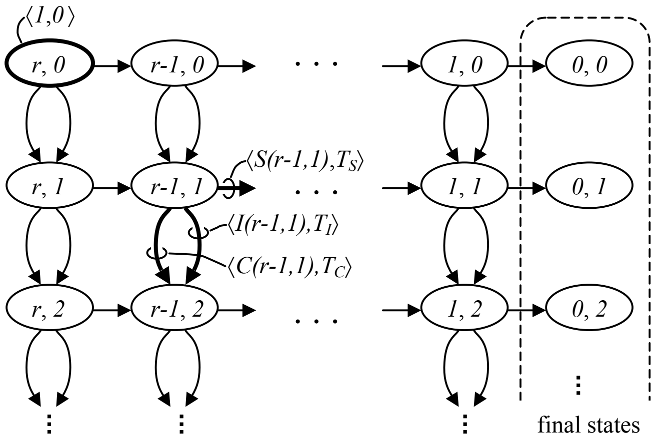

Fig. 3. Two-dimensional state space for recovery process under disaster scenario

of a successful transmission, or a slot is wasted so that the number of wasted slots is increased by one. While a rightward transition can occur only in one way when exactly one station accesses the channel yielding a successful transmission, a downward transition may occur in either one of the two cases: 1) no station accesses the channel resulting an idle period, or 2) two or more stations access the channel causing a collision. This is shown in Fig. 3 by two arrows for downward transitions and a single arrow for rightward transitions from any states excluding the final states. Therefore at any of those states, there are three one-step transitions. Note that for any of the states $\{1, D_n\}$, a collision occurs with probability zero.

Define *transition duration* as the time duration for a one-step transition either rightwards or downwards between any pair of adjacent states. Thus with each one-step transition, we associate two values: 1) a transition probability, and 2) a transition duration. Given that the system is in state $\{m, n\}$, let $S(m,n)$, $C(m,n)$, and $I(m,n)$ be the probabilities that the channel will obtain a successful transmission, a collision, and an idle period respectively.

The probability, $S(m,n)$, that a successful transmission will occur after n number of wasted slots with m active stations, can be viewed as the probability that only one out of m stations accesses the channel [6], thus:

$$S(m,n) = m \cdot P_n \cdot (1 - P_n)^{m-1} \tag{6}$$

where P_n is the attempt probability. The probability that the channel will be idle, $I(m,n)$, is the probability that all m stations choose not to attempt, which can be expressed as:

$$I(m,n) = (1 - P_n)^m \tag{7}$$

and the probability of the appearance of a collision on the channel, $C(m,n)$ is:

$$C(m,n) = 1 - [S(m,n) + I(m,n)]. \tag{8}$$

While the transition probabilities are functions of the state $\{m, n\}$, the transition duration is state independent, but it is different when the channel obtains a successful transmission, a collision, and an idle period. The duration of a successful transmission is equal to a packet transmission time, denoted T_S. The duration of a collision is denoted T_C, and let T_I be the duration of an idle period (see Table 3 in Section 4).

Our aim is to obtain the mean duration of the recovery process, $E[T_{disaster}]$, that is the total time duration required to transit from state $\{r, 0\}$ to any final state. Since the number of states is infinite and the total number of possible paths is huge, a brute force evaluation of the probability of each possible path is not practical.

Our technique used in this paper is based on the key idea that the number of possible paths can be significantly reduced by aggregating paths leading from state $\{r, 0\}$ to any state $\{m, n\}$, which have the same total duration. In other words, if there are j paths leading from the initial state $\{r, 0\}$ to a particular state $\{m, n\}$, and all j paths have duration, say d, we can add up their probabilities to obtain their total probability. There is no need for remembering the particular details of all j paths.

To apply our technique, every state is associated with a set of ordered pairs $\{\langle p_1, d_1\rangle, \langle p_2, d_2\rangle, \ldots, \langle p_j, d_j\rangle\}$, where each d_i represents the time duration that the process will transit into that particular state from the initial state, and p_i represents the probability of that transition. A convenient way to describe the technique is by the use of polynomials. The set of ordered pairs described above can be expressed by the polynomial as follows:

$$P_x(\{m,n\}) = p_1 x^{d_1} + p_2 x^{d_2} + \cdots + p_j x^{d_j}. \tag{2}$$

The initial state $\{r, 0\}$ is assigned with an ordered pair $\langle 1, 0\rangle$. It is because state $\{r, 0\}$ occurred with probability one and the time it takes to reach this state from the beginning of the recovery process is zero. Thus the initial state can be expressed as $P_x(\{r,0\}) = 1 \cdot x^0$.

As mentioned earlier each of the one-step transitions is already associated with a transition probability, p_t, and transition duration, d_t, hence it can also be expressed in a polynomial form as $p_t \cdot x^{d_t}$.

The polynomials of subsequent states can be obtained by summing all the products of the polynomials of the previous states and the transition polynomials:

$$P_x(\{m,n\}) = \begin{cases} P_x(\{m+1,n\}) \cdot (S(m+1,n) \cdot x^{T_S}), \\ \qquad if\ (m=0)\ or\ (m=0,1,\ldots,r-1, n=0) \\ P_x(\{m,n-1\}) \cdot (I(m,n-1) \cdot x^{T_I} + C(m,n-1) \cdot x^{T_C}), \\ \qquad if\ m=r, n=1,2,\ldots \\ P_x(\{m,n-1\}) \cdot (I(m,n-1) \cdot x^{T_I} + C(m,n-1) \cdot x^{T_C}) \\ \quad + P_x(\{m+1,n\}) \cdot (S(m+1,n) \cdot x^{T_S}), \\ \qquad if\ m=1,2,\ldots,r-1, n=1,2,\ldots \end{cases} \tag{3}$$

The numerical computation can be performed by obtaining each $P_x(\{m,n\})$ from left to right, and then top to bottom starting from the initial state $\{r, 0\}$. Then the polynomial for all the final states can be obtained by:

$$P_x(\text{all the final states}) = \sum_{j=0}^{\infty} P_x(\{0, j\}) = \sum_{\text{all terms}} p_i \cdot x^{d_i} \quad (4)$$

where the sum of all obtained probabilities from the final state is one. That is:

$$\sum_{\substack{\text{all terms in}\\ \text{the final states}}} (p_i) = 1 .$$

The mean time for the recovery process, $E[T_{disaster}]$, is thus:

$$E[T_{disaster}] = \sum_{\substack{\text{all terms in}\\ \text{the final states}}} (p_i \cdot d_i) . \quad (5)$$

The Disaster Throughput

Having obtained the mean duration of the recovery process, $E[T_{disaster}]$, the disaster throughput, S_d, can be obtain by the following equation:

$$S_d = \frac{r \cdot T_{payload}}{E[T_{disaster}]} \quad (9)$$

where $T_{payload}$ is the time duration to transmit the payload and again r is the number of stations.

One key approximation in this model is we assume that at any state, say $\{m, n\}$, all m stations have experienced the same number of wasted slots and hence they attempt the next slot with the same probability, P_n. In Fig 5, we show that this assumption may introduce errors. The error occurs whenever there is a collision. In Fig 5, station *B* attempted its packet transmission at slot t_s=3 and a collision is assumed. While station *A* did not attempt at slot t_s=3 but it detected this collision, it then stopped its backoff timer during the collision period. When the collision is over, at slot $t_s=4$, station *A* may attempt its packet transmission with attempt probability P_n where n=3, whereas station *B* in this case may attempt with attempt probability P_n where n=4 because station *B* counts the previous collided transmission as a wasted slot. This error will be significant only if collisions are often and the attempt probabilities of the values of n and its neighbors are in great different. Nevertheless, it can be seen from Fig. 2 that the attempt probabilities for near values of n are

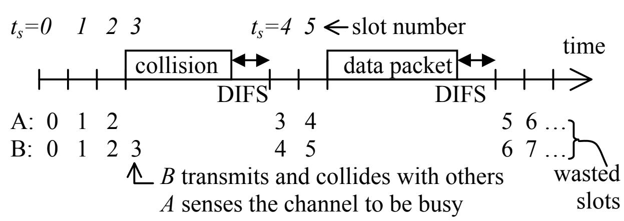

Fig. 5. The impact on collisions

similar, especially when n is large. Moreover, in the next section, we will demonstrate with simulation experiments that collisions under IEEE 802.11 are not often. Therefore, this assumption only produces insignificant errors.

4. Numerical and Simulation Results

In this section, we present the numerical as well as the simulation results. In our numerical computation and computer simulations, we have used the parameters in accordance with the specification of frequency hopping spread spectrum (FHSS) physical layer [1]. These parameters are:

Table 2. Parameters for numerical analysis and simulations

Channel bit rate	1 Mbit/s (1μsec bit time)
Propagation delay, τ	1 μsec
Slot time, T_{slot}	50 μsec
DIFS	128 μsec
SIFS	28 μsec
Station number, r	1,2,3,…,50
Packet payload	8184 bits
MAC header	272 bits
PHY header	128 bits
ACK frame size	112 bits + PHY header
RTS frame size	160 bits + PHY header
CTS frame size	112 bits + PHY header

Let T_H be the transmission time of the MAC and PHY headers, $T_{payload}$ be the transmission time of the packet payload. Let T_{ACK}, T_{RTS} and T_{CTS} be the transmission time of the ACK, RTS and CTS frames respectively. Therefore for both the basic and four-way handshaking access methods, T_S, T_I and T_C are given as follows:

Table 3. Time duration for a successful packet transmission, a collision and an idle period [2]

For basic access method:

$T_S = T_H + T_{payload} + \text{SIFS} + \tau + T_{ACK} + \text{DIFS} + \tau$
$= 8982$ μsec

$T_I = T_{slot} = 50$ μsec

$T_C = T_H + T_{payload} + \text{DIFS} + \tau = 8713$ μsec

For four-way handshaking access method:

$T_S = T_{RTS} + \text{SIFS} + \tau + T_{CTS} + \text{SIFS} + \tau + T_H + T_{payload} + \text{SIFS} + \tau + T_{ACK} + \text{DIFS} + \tau$
$= 9568$ μsec

$T_I = T_{slot} = 50$ μsec

$T_C = T_{RTS} + \text{DIFS} + \tau = 417$ μsec

Fig. 6 compares the numerical (shown in solid lines) and the simulations (shown in symbols) results of the duration for the recovery process for *CWmin*=8 and *CWmax*=256. Each of the numerical results is obtained until the final probability reaches 0.99. Notice the strong agreement between the two results. In fact, the numerical results overestimate the time duration by a few milliseconds due to a slight weakness of Molle's approximation [6] for a small number of stations. This is the reason why the throughput curve from numerical

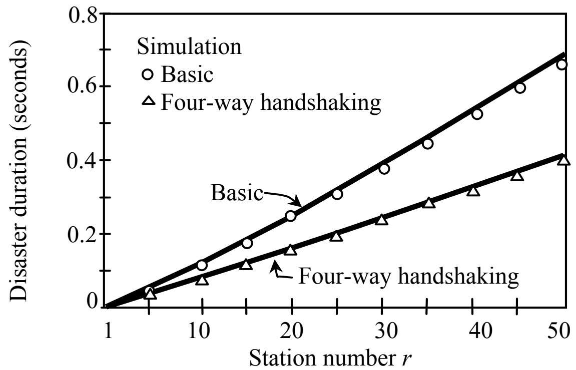

Fig. 6. The disaster duration of IEEE 802.11 for *CWmin*=8 and *CWmax*=256

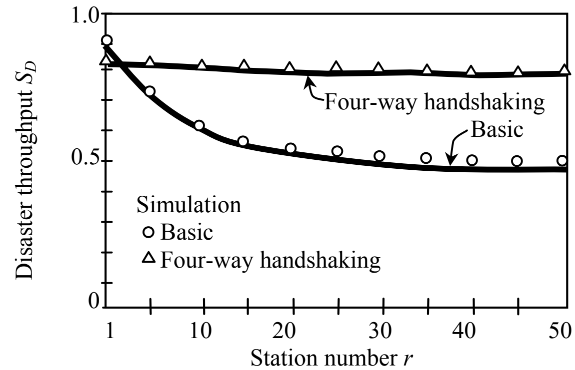

Fig. 7. The disaster throughput of IEEE 802.11 for *CWmin*=8 and *CWmax*=256

results shown in Fig. 7 is slightly lower than that from the simulation results in the beginning part when station number is small.

As can be seen from the results, the four-way handshaking access method in IEEE 802.11 MAC protocol guarantees a higher throughput under disaster scenario in most cases. However, when the number of stations is small, its throughput level is slightly under the basic access method because of the additional RTS-CTS exchange overhead.

In Fig. 8, we present the simulation results of the idle and collision probabilities when a slot is known to be wasted under the disaster scenario. We observe that the idle probability is much higher than the collision probability. This result again confirms the achievement of the *collision avoidance* in IEEE 802.11 MAC protocol.

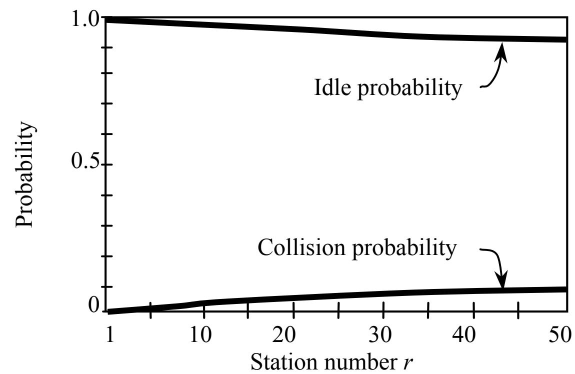

Fig. 8. The idle and collision probabilities for *CWmin*=8 and *CWmax*=256

5. Conclusion

In this paper, we have analyzed the DCF function of IEEE 802.11 MAC protocol under a disaster scenario. As part of the analysis, a new technique was introduced to collapse a very large state space and some approximations were used and later justified. The numerical results were then compared with simulations to show the accuracy of our model. Our results confirmed that the four-way handshaking access method offers better performance than the basic access method in most cases.

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