Chapter 11
Modeling IEEE 802.11 (WiFi) Protocol

11.1 Introduction

The IEEE 802.11 (WiFi) is the most widely used medium access control protocol for wireless local area networks (LANs). Being a wireless protocol, it is based on p-persistent CSMA/CA discussed in Chap. 10. The only difference between WiFi and CSMA/CA is that when a user has a packet or frame to send and senses channel is free, it will unconditionally go through a random wait before it attempts a transmission. On the other hand, CSMA/CA under the same conditions will immediately send the frame. WiFi underwent several versions such as 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, 802.11ad, and 802.11ah. We shall discuss here simplified versions of the protocol since our intention is to illustrate how such protocol is using the features common in all versions. IEEE 802.11 wireless LAN standard is used for infrastructure as well as ad hoc networks.

Infrastructure wireless networks have a central controller called *access point* (AP) that coordinates medium access among the users. This part of the protocol is referred to as Point Coordination Function (PCF) and it occupies a short time period at the start of each transmitted frame as shown in Fig. 11.1. The frame starts with a PCF period which is a time period to enable prioritized access for control messages and time-critical traffic [1–3]. This form of *centralized medium access scheme* enables the IEEE 802.11 to offer some quality of service (QoS) guarantees through implementation of a *scheduling algorithm* at the AP.

Ad hoc wireless networks do not have a central controller. Instead, each node or user attempts to access the shared medium on its own. This part of the protocol is referred to as Distributed Coordination Function (DCF) and it follows the PCF period of each transmitted frame as shown in Fig. 11.1. This is a form of *distributed reservation scheme* that could provide statistical QoS guarantees.

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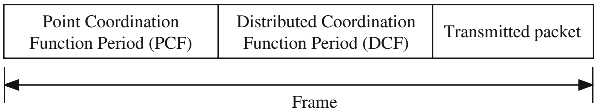


Fig. 11.1 Location of PCF and DCF periods in the frame of IEEE 802.11 protocol

11.2 IEEE 802.11: Basic DCF for Ad Hoc Wireless LANs

The DCF MAC part of IEEE 802.11 standard is based on CSMA-CA (listen-before-talk) with rotating backoff window [1]. When a node receives a frame to be transmitted, it chooses a random backoff value which determines the amount of time the node must wait until it is allowed to transmit its frame. A node stores this backoff value in a *backoff counter*. During periods in which the channel is clear, the node decrements its backoff counter. (When the channel is busy it does not decrement its backoff counter.) When the backoff counter reaches zero, the node transmits the frame. Since the probability that two nodes will choose the same backoff factor is small, collisions between frames are minimized. Collision detection, as is employed in Ethernet, cannot be used for the radio frequency transmissions of IEEE 802.11. The reason for this is that when a node is transmitting it cannot hear any other node in the system which may be transmitting, since its own signal will drown out any others arriving at the node.

In that sense, 802.11 could be classified as CSMA/CA but with provisions for reducing the chance of collisions through adoption of the reservation slots using the backoff counters. The slots have the effect of ensuring that a reduced number of users compete for access to the channel during any given reservation slot.

Figure 11.2 shows the DCF part of the IEEE 802.11 frame. After the PCF period (i.e., SIFS), there is the DCF period (i.e., DIFS) which is a contention window that is divided into reservation slots. The figure shows six such slots. The duration of a reservation slot depends on the propagation delay between stations. The rest of the frame is dedicated to transmitting the frames.

A station that intends to transmit senses if the channel is busy. It will then wait for the end of the current transmission and the PCF delay. It then randomly selects a reservation slot within the backoff window. The figure shows that a station in time reservation slot 2 starts transmitting a frame since the channel was not used during reservation slots 0 and 1.

Collisions occur when two or more stations select the same reservation slot. If another station started transmission at an earlier reservation slot, the station freezes its backoff counter and waits for the remaining contents of this counter after the current transmission ends.

The basic DCF uses a two-way handshaking data exchange mechanism shown in Fig. 11.3.

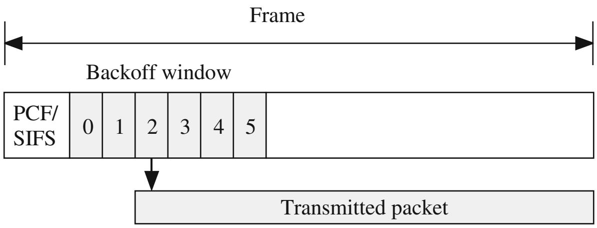


Fig. 11.2 Basic DCF of the IEEE 802.11 frame

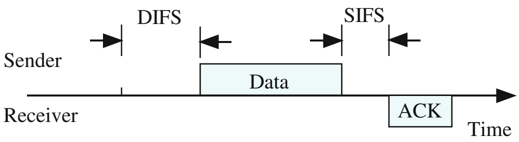


Fig. 11.3 Two-way handshaking data exchange mechanism for the basic DCF function of the IEEE 802.11 WiFi MAC protocol

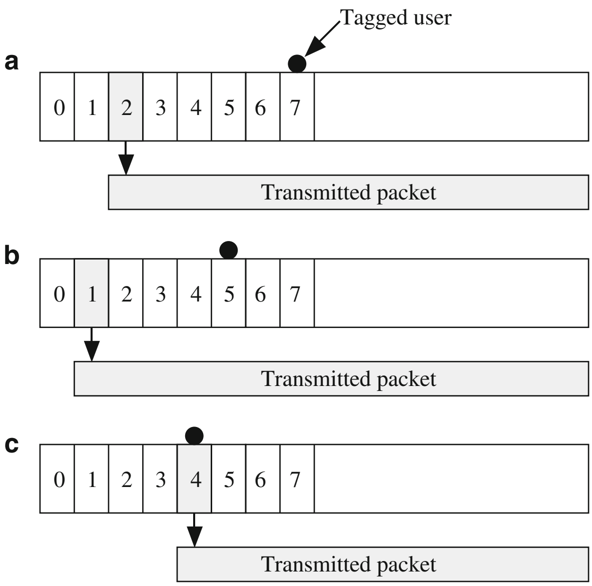


Fig. 11.4 IEEE 802.11 MAC scheme

11.2.1 Markov Chain Modeling of the Basic DCF

We consider the behavior of one user, which we term the tagged user. Figure 11.4 shows the IEEE 802.11 MAC scheme as viewed by a certain user (called the *tagged user*). Figure 11.4 indicates that the tagged user, as indicated by the black circle, randomly selected reservation slot 7 to start transmission. So its backoff counter contains the value 7 now. However, another user starts transmission at reservation slot 2 as indicated by the grey box. Since the channel was quite for two reservation slots (slot 0 and 1), the backoff counter of the tagged user will contain the value 5 at the end of the current frame.

Figure 11.4b shows next frame. However, another user at reservation slot 1 started transmission. Since the channel was quite for one reservation slots (slot 0), the backoff counter of the tagged user will contain the value 4 at the end of the current frame.

Figure 11.4c shows next frame. The tagged user is successful in starting transmission since the channel was quite for four reservation slots (0, 1, 2, and 3).

Modeling the behavior of the backoff counter can certainly be done using Markov chains. However, we can equally model such random behavior through a backoff, or persistence, probability p when the user is waiting for the channel to be free before attempting to transmit a packet. We will follow this approach in the following subsection.

11.2.2 IEEE 802.11: Basic DCF Model Assumptions

We employ the following simplifying assumptions.

1. Since the current state of the user depends only on its immediate past history, we can model the user using Markov chain analysis.
2. The states of the Markov chain represent the states of the user: idle, waiting, transmitting, and collided.
3. There are N equal priority users in the network. By network we mean a single-hop network or the nodes within the transmission range of a particular node.
4. We replace the waiting backoff window with a transmit probability p when the channel is sensed idle.
5. The duration of one time step in the contention window is roughly taken equal to the maximum expected propagation delay τ_p plus the time it takes a station to sense the presence of a carrier. This time is called the Distributed Interframe Spacing (DIFS).
6. The Markov chain time step is taken equal to the DIFS period.
7. The ratio of frame transmission delay to contention window delay is $n > 1$.
8. All frames have equal lengths such that a frame takes n time steps to be transmitted.
9. Probability that an idle station receives a frame for transmission during a frame period is a.
10. A station can have at most one message waiting for transmission.
11. Collided users employ a random backoff strategy with transmit probability γ when the channel is sensed idle.

Figure 11.5 shows the state transition diagram for the IEEE 802.11 WiFi tagged user when the basic DCF protocol is used. There are several transmitting states because the time required for transmitting one frame (τ_t) is bigger than the propagation delay τ_p. There are also several collided states since a user continues to transmit after a collision has taken place.

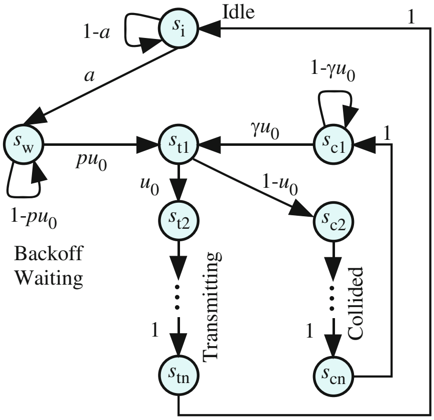


Fig. 11.5 State transition diagram for the IEEE 802.11 WiFi tagged user when the basic DCF protocol is used

In the figure u_0 denotes the probability that all $N-1$ users, apart from the tagged user, will not transmit when the channel is free. The probability that a user will not start transmission even when the channel is sensed free is given by:

$$p_{idle} = s_i + (1-p)s_w + (1-\gamma)s_{c_1} \tag{11.1}$$

where $a' = a/n$ is the probability that a station requests a transmission during a time step, p is the persistence probability when the user is waiting for the channel to be free, and γ is the probability that a collided user starts a transmission. Based on that, excepting the tagged user, the probability all untagged users will not start transmission is given by:

$$u_0 = [s_i + (1-p)s_w + (1-\gamma)s_c]^{N-1} \tag{11.2}$$

We organize the distribution vector at equilibrium as follows.

$$\mathbf{s} = \begin{bmatrix} s_i & s_w & s_{t_1} & s_{t_2} & \cdots & s_{t_n} & s_{c_1} & s_{c_2} & \cdots & s_{c_n} \end{bmatrix}^t \tag{11.3}$$

The corresponding transition matrix of the channel for the case when $n = 3$ is given by:

$$\mathbf{P} = \begin{bmatrix} 1-a' & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ a' & 1-pu_0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & pu_0 & 0 & 0 & 0 & \gamma u_0 & 0 & 0 \\ 0 & 0 & u_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-u_0 & 0 & 0 & 1-\gamma u_0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{11.4}$$

At equilibrium the distribution vector is obtained by solving the two equations

$$\mathbf{P}\,\mathbf{s} = \mathbf{s} \tag{11.5}$$

$$\sum \mathbf{s} = 1 \tag{11.6}$$

However, the terms in **P** depend on the state vector components. This constitutes a highly nonlinear set of equations. The solution for **s** is obtained through several techniques such as optimization or iterative techniques as follows:

1. Input the values of p, γ, a, N, and n.
2. Assume a trial value for state vector **s**.
3. Start the iterations by obtaining the probability u_0.
4. Substitute the value of u_0 to obtain an updated value $\mathbf{s}(updated)$.
5. Calculate the error $\mathbf{e} = \mathbf{s}(updated) - \mathbf{s}$ and the root mean square error e_{rms}.
6. Update the state vector

$$\mathbf{s} = \mathbf{s} + \alpha\,\mathbf{e}$$

   where α is the update step size which is usually taken equal to 0.1 or even smaller.
7. Repeat the iterations starting at Step 3 and stop when e_{rms} is below a certain value.

11.2.3 IEEE 802.11 WiFi: Basic DCF Protocol Performance

The throughput is given by the equation:

$$Th = nNT_n \tag{11.7}$$

Figure 11.6 shows the throughput of IEEE 802.11 WiFi for the IEEE 802.11/DCF protocol versus the average input traffic when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. The black line is the throughput of IEEE 802.11 WiFi, the blue line is the throughput of p-persistent CSMA/CA with the same parameters as the WiFi, the green line is the throughput of slotted ALOHA, and the red line is the throughput of pure ALOHA.

At low input traffic, the WiFi basic DCF protocol throughput is comparable to p-persistent CSMA/CA but then it becomes a bit smaller than it since users with a frame to transmit have to wait before accessing the channel.

Changing the value of p has little effect on the throughput. However, the collided backoff probability drastically affects the throughput. When γ is increased from 0.01 to 0.05, the throughput of both CSMA/CA and IEEE 802.11 is reduced. Increasing γ to 0.1 will reduce the IEEE 802.11 drastically, a very small value.

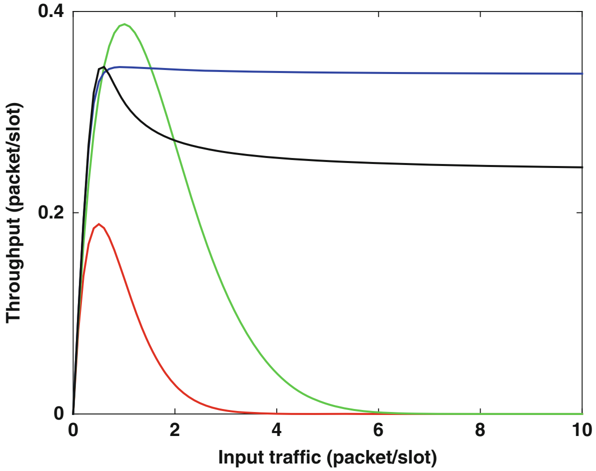
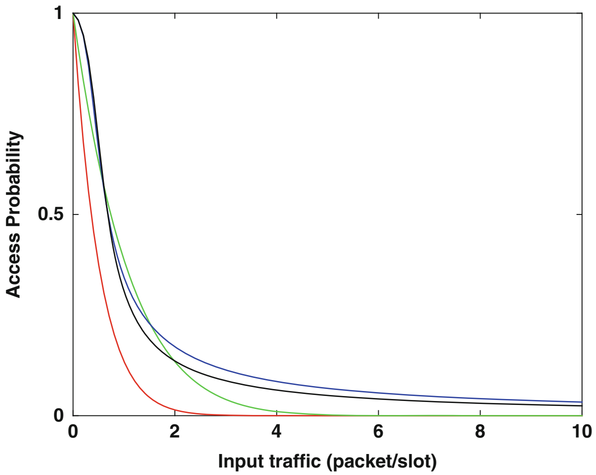


Fig. 11.6 Throughput for the IEEE 802.11/DCF protocol versus the average input traffic when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. The *black line* is the throughput of IEEE 802.11 WiFi, the *blue line* is the throughput of p-persistent CSMA/CA, the *green line* is the throughput of slotted ALOHA, and the *red line* is the throughput of pure ALOHA

Fig. 11.7 Access probability of IEEE 802.11 basic DCF when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. The *black line* is the access probability of IEEE 802.11 basic DCF, the *blue line* is the access probability of p-persistent CSMA/CA, the *green line* is the access probability of slotted ALOHA, and the *red line* is the access probability of pure ALOHA



The user access probability is given by:

$$p_a = \frac{Th}{Na} \tag{11.8}$$

Figure 11.7 shows the access probability of IEEE 802.11 when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. Again, we see that p_a for IEEE 802.11 basic DCF is equal to or a bit smaller than p_a for CSMA/CA.

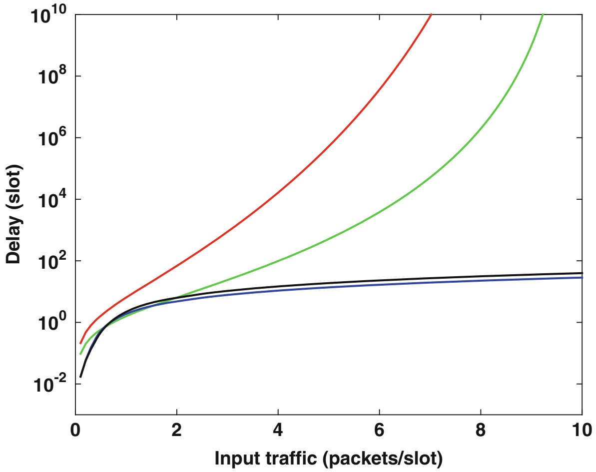


Fig. 11.8 Frame delay of IEEE 802.11 basic DCF when $n = 20$, $N = 10$, $p = 0.5$, and $\gamma = 0.01$. The *black line* is the delay of IEEE 802.11 basic DCF, the *blue line* is the delay of p-persistent CSMA/CA, the *green line* is the delay of slotted ALOHA, and the *red line* is the delay of pure ALOHA

The average number of attempts for a successful transmission is

$$n_a = \sum_{i=0}^{\infty} i \ (1 - p_a)^i \ p_a$$
$$= \frac{1 - p_a}{p_a} \tag{11.9}$$

Figure 11.8 shows the delay of the IEEE 802.11 basic DCF protocol when $n = 50$, $N = 10$, and $p = 0.5$ when $n = 20$, $N = 10$, $p = 0.5$, and $\gamma = 0.01$. The black line is the delay of IEEE 802.11 basic DCF, the blue line is the delay of p-persistent CSMA/CA, the green line is the delay of slotted ALOHA, and the red line is the delay of pure ALOHA.

The average energy required to transmit a frame is estimated as

$$E = E_0 \sum_{i=0}^{\infty} (i + 1)(1 - p_a)^i \ p_a$$
$$= \frac{E_0}{p_a} \tag{11.10}$$

where E_0 is the energy required to send the one frame. In dB, the above equation can be written as

$$E/E_0 = -10 \log_{10} p_a \quad \text{dB} \tag{11.11}$$

Figure 11.9 shows the average energy needed to transmit a frame of the IEEE 802.11 basic DCF protocol when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. The black

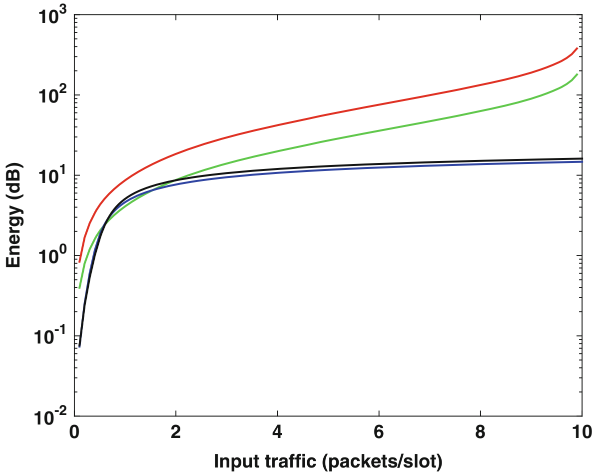


Fig. 11.9 Average energy to transmit a frame for the IEEE 802.11 basic DCF when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. The *black line* is the energy of IEEE 802.11 basic DCF, the *blue line* is the energy of p-persistent CSMA/CA, the *green line* is the energy of slotted ALOHA, and the *red line* is the energy of pure ALOHA

line is the energy of IEEE 802.11 WiFi, the blue line is the energy of p-persistent CSMA/CA, the green line is the energy of slotted ALOHA, and the red line is the energy of pure ALOHA.

11.3 IEEE 802.11: DCF Using RTS/CTS for Ad Hoc Wireless LANs (MACA)

As was mentioned in Sect. 11.2, the basic DCF function is based on CSMA/CA for MAC functionality. That is why we notice that the system throughput was equal to, or slightly below, the CSMA/CA throughput. We also saw that in Chap. 10 that CSMA/CD protocol has higher throughput compared to CSMA/CA. This is the main motivation for attempting to modify the IEEE 802.11 DCF function to incorporate the CSMA/CD protocol. This is achieved through the use of four-way handshaking protocol as shown in Fig. 11.10.

A station with a packet to send will first send a *request to send* packet (RTS) when it senses the channel is free for a minimum of DIFS time. If the RTS packet is successfully received without suffering collisions, the intended receiver will issue a *clear to send* packet (CTS). After this, the sender will commend to send the data and wait for an acknowledgment (ACK) for the receiver.

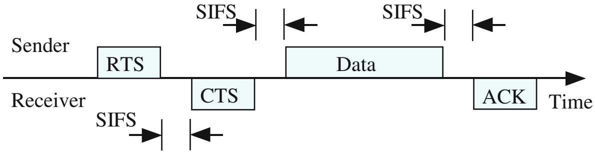
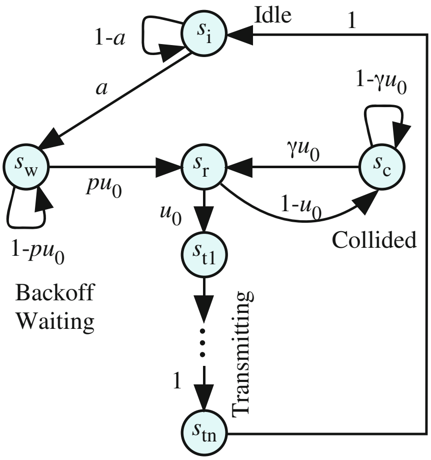


Fig. 11.10 Four-way handshaking RTS/CTS (MACA) protocol for IEEE 802.11 WiFi DCF function

Fig. 11.11 State transition diagram for the IEEE 802.11 WiFi tagged user when the RTS/CTS DCF protocol is used



11.3.1 Modeling DCF Using RTS/CTS

To derive a simple model for WiFi DCF using RTS/CTS, we employ a set of assumptions similar to those employed in Sect. 11.2.2. The only difference is that the RTS/CTS mechanism is used to start assure no collisions will take place. We note that the time a station requires to determine if a collision occurred is the duration of the RTS/CTS packets. This is definitely shorter than the data duration. Thus the RTS/CTS mechanism mimics the CSMA/CD and hopefully the performance will improve over that of the basic DCF function.

Figure 11.11 shows the state transition diagram for the IEEE 802.11 WiFi tagged user when the RTS/CTS DCF protocol is used. There are several transmitting states because the time required for transmitting one frame (τ_t) is bigger than the propagation delay τ_p. There is only one collided state since a user will not transmit after a collision has taken place.

In the figure u_0 denotes the probability that all $N-1$ users, apart from the tagged user, will not transmit when the channel is free. The probability that a user will not start transmission even when the channel is sensed free is given by:

$$p_{idle} = s_i + (1-p)s_w + (1-\gamma)s_{c_1} \tag{11.12}$$

where p is the persistence probability when the user is waiting for the channel to be free and γ is the probability that a collided user starts a transmission. Based on that, excepting the tagged user, the probability all untagged users will not start transmission is given by:

$$u_0 = [s_i + (1-p)s_w + (1-\gamma)s_c]^{N-1} \tag{11.13}$$

We organize the distribution vector at equilibrium as follows:

$$\mathbf{s} = \left[\, s_i \;\; s_w \;\; s_r \;\; s_c \;\; s_{t_1} \;\; s_{t_2} \;\; \cdots \;\; s_{t_n} \,\right]^t \tag{11.14}$$

The corresponding transition matrix of the channel for the case when $n = 3$ is given by:

$$\mathbf{P} = \begin{bmatrix} a & 1-pu_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & pu_0 & 0 & \gamma u_0 & 0 & 0 & 0 \\ 0 & 0 & 1-u_0 & 1-\gamma u_0 & 0 & 0 & 0 \\ 0 & 0 & u_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{11.15}$$

At equilibrium the distribution vector is obtained by solving the two equations

$$\mathbf{P}\,\mathbf{s} = \mathbf{s} \tag{11.16}$$

$$\sum \mathbf{s} = 1 \tag{11.17}$$

However, the terms in **P** depend on the state vector components. This constitutes a highly nonlinear set of equations. The solution for **s** is obtained through several techniques such as optimization or iterative techniques as follows:

1. Input the values of p, γ, a, N, and n.
2. Assume a trial value for state vector **s**.
3. Start the iterations by obtaining the probability u_0.
4. Substitute the value of u_0 to obtain an updated value $\mathbf{s}(updated)$.
5. Calculate the error $\mathbf{e} = \mathbf{s}(updated) - \mathbf{s}$ and the root mean square error e_{rms}.
6. Update the state vector

$$\mathbf{s} = \mathbf{s} + \alpha\,\mathbf{e}$$

   where α is the update step size which is usually taken equal to 0.1 or even smaller.
7. Repeat the iterations starting at Step 3 and stop when e_{rms} is below a certain value.

11.3.2 IEEE 802.11 WiFi: RTS/CTS Protocol Performance

The throughput is given by the equation:

$$Th = nNT_n \tag{11.18}$$

Figure 11.12 shows the throughput for the IEEE 802.11 RTS/CTS protocol versus the average input traffic when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The black line is the throughput of IEEE 802.11 RTS/CTS, the blue line is the throughput of p-persistent CSMA/CD, the green line is the throughput of slotted ALOHA, and the red line is the throughput of pure ALOHA.

At low input traffic, the WiFi RTS/CTS protocol throughput is comparable to p-persistent CSMA/CD but then it becomes a bit smaller than it since users with a frame to transmit have to wait before accessing the channel.

Changing the value of p has little effect on the throughput. However, the collided backoff probability drastically affects the throughput. When γ is increased from 0.01 to 0.05, the throughput of both CSMA/CD and IEEE 802.11 RTS/CTS is reduced.

The user access probability is given by:

$$p_a = \frac{Th}{Na} \tag{11.19}$$

Figure 11.13 shows the access probability of IEEE 802.11 RTS/CTS when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The black line is the throughput of IEEE 802.11

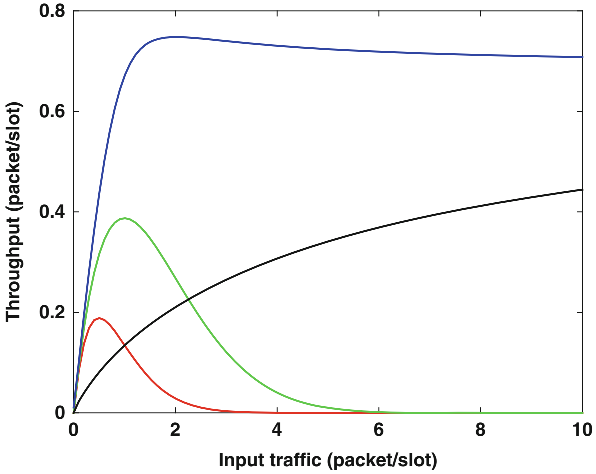


Fig. 11.12 Throughput for the IEEE 802.11 RTS/CTS protocol versus the average input traffic when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The *black line* is the throughput of IEEE 802.11 RTS/CTS, the *blue line* is the throughput of p-persistent CSMA/CD, the *green line* is the throughput of slotted ALOHA, and the *red line* is the throughput of pure ALOHA

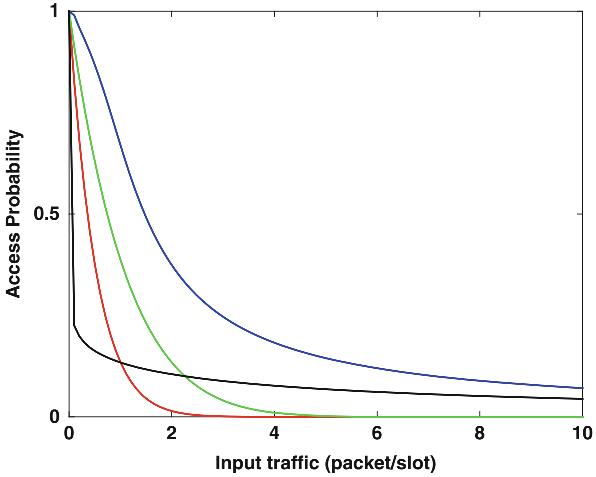


Fig. 11.13 Access probability of IEEE 802.11 RTS/CTS when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The *black line* is the throughput of IEEE 802.11 RTS/CTS, the *blue line* is the throughput of p-persistent CSMA/CD, the *green line* is the throughput of slotted ALOHA, and the *red line* is the throughput of pure ALOHA

RTS/CTS, the blue line is the throughput of p-persistent CSMA/CD, the green line is the throughput of slotted ALOHA, and the red line is the throughput of pure ALOHA. Again, we see that p_a for IEEE 802.11 RTS/CTS is almost equal to the access probability for the p-persistent CSMA/CD protocol.

The average number of attempts for a successful transmission is

$$\begin{aligned} n_a &= \sum_{i=0}^{\infty} i \, (1 - p_a)^i \, p_a \\ &= \frac{1 - p_a}{p_a} \end{aligned} \tag{11.20}$$

Figure 11.14 shows the delay of the IEEE 802.11 RTS/CTS protocol when $n = 50$, $N = 10$, and $p = 0.5$ when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The black line is the delay of IEEE 802.11 WiFi, the blue line is the delay of p-persistent CSMA/CD, the green line is the delay of slotted ALOHA, and the red line is the delay of pure ALOHA.

The average energy required to transmit a frame is estimated as

$$\begin{aligned} E &= E_0 \sum_{i=0}^{\infty} (i+1)(1 - p_a)^i \, p_a \\ &= \frac{E_0}{p_a} \end{aligned} \tag{11.21}$$

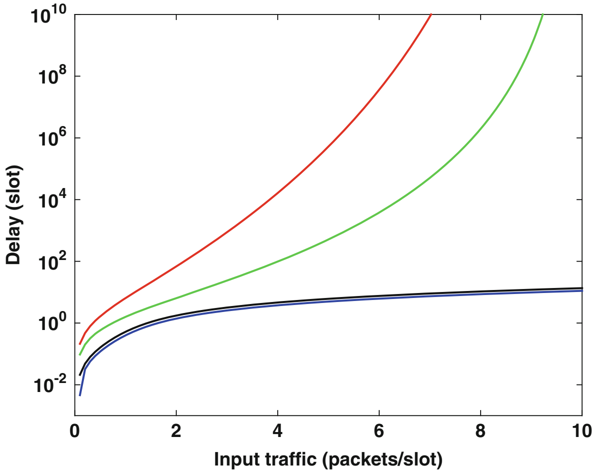


Fig. 11.14 Frame delay of CSMA/CA when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The *black line* is the delay of IEEE 802.11 RTS/CTS, the *blue line* is the delay of p-persistent CSMA/CD, the *green line* is the delay of slotted ALOHA, and the *red line* is the delay of pure ALOHA

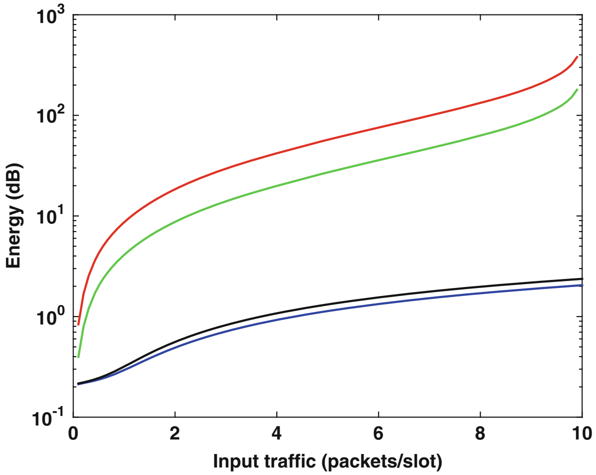


Fig. 11.15 Average energy to transmit a frame for the IEEE 802.11 RTS/CTS when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The *black line* is the energy of IEEE 802.11 RTS/CTS, the *blue line* is the energy of p-persistent CSMA/CD, the *green line* is the energy of slotted ALOHA, and the *red line* is the energy of pure ALOHA

where E_0 is the energy required to send the one frame. In dB, the above equation can be written as

$$E/E_0 = -10 \log_{10} p_a \quad \text{dB} \tag{11.22}$$

Figure 11.15 shows the average energy required to transmit a packet for the IEEE 802.11 RTS/CTS protocol when $n = 20$, $N = 10$, $p = 0.05$, and $\gamma = 0.01$. The

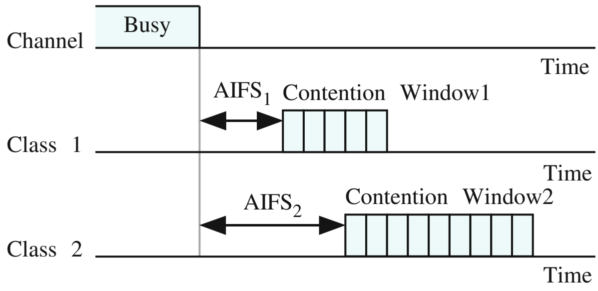


Fig. 11.16 AIFS channel access for the IEEE 802.11e EDCA (WMM)

black line is the energy of IEEE 802.11 RTS/CTS, the blue line is the energy of p-persistent CSMA/CD, the green line is the energy of slotted ALOHA, and the red line is the energy of pure ALOHA.

11.4 IEEE 802.11e EDCA (WMM) Protocol

The IEEE802.11e standard was introduced to support QoS. The new standard defines the Hybrid Coordination Function (HCF) for supporting QoS over the wireless communication. The HCF uses two access modes: the Enhanced Distributed Channel Access (EDCA) for ad hoc wireless networks and Hybrid Coordination function Control Channel Access (HCCA) for infrastructure wireless networks. The contention-based EDCA replaces the DCF of the standard 802.11 and the contention-free HCCA replaces the PCF of the standard 802.11. Sometimes EDCA is called WiFi Multi Media (WMM) and is essentially DCF with four priority classes: background, best effort, video, and audio.

The basic idea for QoS support is to provide different minimum and maximum backoff slots for the service classes. The minimum backoff value dictates a deterministic delay before the user is able to start the backoff timer access the channel. The minimum backoff delay is called Arbitration Inter-Frame Space (AIFS). Figure 11.16 shows the AIFS channel access for the IEEE 802.11e EDCA (WMM).

Note in the figure that Class 1 service is the higher priority class since its contention window starts earlier and the size of its backoff counter is smaller. Both these factors give class 1 service better chance of accessing the service before the lower priority class.

11.4.1 Modeling the IEEE 802.11e EDCA (WMM) Protocol

Let us make few simplifying assumptions:

1. All users can communicate together using one hop. This assumption eliminates the hidden terminal problem.

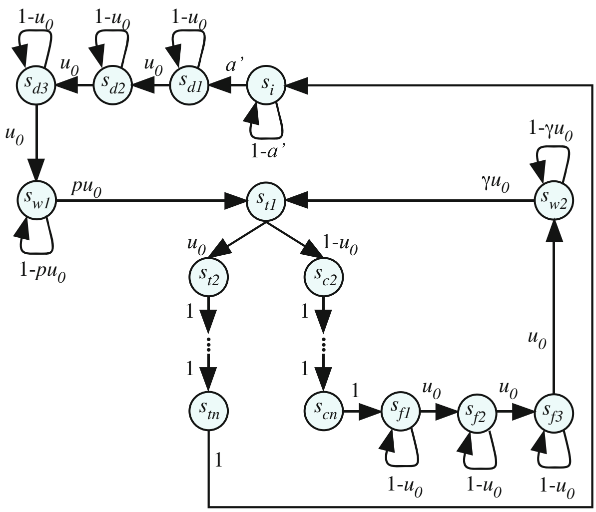


Fig. 11.17 State transition diagram for the tagged user in class 1 or class 2 when the IEEE 802.11.e EDCA (WMM) protocol is used

2. There are only two classes of service with class 1 being the higher priority class.
3. The number of users in class 1 is N_1 and the number of users in class 2 is N_2.
4. The probability that a class 1 user has a packet to send in one frame time is a_1. a_2 is a similar probability for class 2 users.
5. The AIFS delay for class 1 is d_1 slots and $d_2 > 1_1$ for class 2.
6. The transmit opportunity (TXOP) is the same for both classes of service which corresponds to same packet size n.
7. The probability that a class 1 uncollided user transmits when the channel is free is p_1 and p_2 for class 2.
8. A collided class 1 user attempts a retransmission with probability γ_1 and γ_2 for class 2 user.

Based on the above assumptions we can derive a state transition diagram for either class of service as shown in Fig. 11.17. The figure can be considered an extension of the IEEE 802.11basic DCF MAC protocol and bears some resemblance to the CSMA/CA protocol. However, to support QoS, there are two sets of delay states. The first set s_{d_i} $(1 \le i \le m)$ belongs to the idle users that just got a packet to send. This set of states provides a deterministic delay for the uncollided users before they even try to send a frame when the channel becomes free. Note that the delay counter is decremented only when the channel is sensed free.

The second set of delay states is s_{f_i} $(1 \le i \le m)$ provides a deterministic delay for the collided users before they even try to send a frame when the channel becomes free. Note that the delay counter is decremented only when the channel is sensed free. Without this delay, and at heavy traffic conditions, most users would be in the collided state and the system would revert to the basic DCF function.

In the figure u_0 denotes the probability that all users (except the tagged user) will not transmit when the channel is free. To derive this probability we need to find the probability that a user is idle and will not transmit. The probability that a user in class 1 or class 2 will not start transmission even with the channel is free is given by:

$$p_{idle} = s_i + \sum_{i=1}^{m} s_{d_i} + (1-p)s_{w_1} + \sum_{i=1}^{m} s_{f_i} + (1-\gamma)s_{w_2} \tag{11.23}$$

The probability that all users (excepting the tagged user) will not start a transmission is given by:

$$u_0 = p_{idle,1}^{N_1} \times p_{idle,2}^{N_2} \tag{11.24}$$

Assuming that AIFS $m = 2$ and $n = 3$, we organize the distribution vector at equilibrium as follows:

$$\mathbf{s} = \begin{bmatrix} s_i & s_{d_1} & s_{d_2} & s_{w_1} & s_{t_1} & s_{t_2} & s_{t_3} & s_{c_2} & s_{c_3} & s_{f_1} & s_{f_2} & s_{w_2} \end{bmatrix}^t \tag{11.25}$$

The corresponding transition matrix of the channel for the case when AIFS = 2 and $n = 3$ is given by:

$$\mathbf{P} = \begin{bmatrix}
1-a' & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
a' & 1-u_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & u_0 & 1-u_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & u_0 & 1-pu_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & pu_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \gamma u_0 \\
0 & 0 & 0 & 0 & u_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1-u_0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1-u_0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & u_0 & 1-u_0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & u_0 & 1-\gamma u_0
\end{bmatrix} \tag{11.26}$$

At equilibrium the distribution vector is obtained by solving the two equations

$$\mathbf{P}\,\mathbf{s} = \mathbf{s} \tag{11.27}$$

$$\sum \mathbf{s} = 1 \tag{11.28}$$

However, the terms in **P** depend on the state vector components. This constitutes a highly nonlinear set of equations. The solution for **s** is obtained through several techniques such as optimization or iterative techniques as follows:

1. Input the values of p_1, $p_2 \gamma_1$, γ_2, a_1, a_2, N_1, N_2, n, and m.
2. Assume a trial value for state vector **s**.
3. Start the iterations by obtaining the probability u_0.
4. Substitute the value of u_0 to obtain an updated value $\mathbf{s}(updated)$.
5. Calculate the error $\mathbf{e} = \mathbf{s}(updated) - \mathbf{s}$ and the root mean square error e_{rms}.
6. Update the state vector

$$\mathbf{s} = \mathbf{s} + \alpha\, \mathbf{e}$$

   where α is the update step size which is usually taken equal to 0.1 or even smaller.
7. Repeat the iterations starting at Step 3 and stop when e_{rms} is below a certain value.

11.4.2 IEEE 802.11.e EDCA (WMM) Protocol Performance

The throughput is given by the equation:

$$Th = \left[s_{t_1} + \sum_{i=2}^{n} s_{t_i} \right] N \tag{11.29}$$

Figure 11.18 shows the throughput of IEEE 802.11.e EDCA protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $n = 20$, $m_1 = 5$, $m_2 = 10$, $p_1 = 0.5$, $p_2 = 0.05$, $\gamma_1 = 0.01$, and $\gamma_2 = 0.001$. The top black line is the throughput of IEEE 802.11.e EDCA class 1, the bottom black line is the throughput of IEEE 802.11e EDCA class 2, the red line is the throughput of the IEEE 802.11 basic DCF protocol, the green line is the throughput of slotted ALOHA, and the blue line is the throughput of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol.

We note that the class 1 throughput is comparable to the basic DCF protocol and that at most traffic levels the throughput of both is close to the maximum value of the slotted ALOHA protocol. The chosen values for delay states d_i and f_i in Fig. 11.17 apparently have no significant effect on the class 1 performance in comparison with the basic DCF protocol.

The class 2 EDCA protocol has almost one-half the throughput of the class 1 protocol due to the chosen parameter values. That is why class 2 throughput is close to the peak of the pure ALOHA protocol.

The user access probability is given by:

$$p_a = \frac{Th}{Na} \tag{11.30}$$

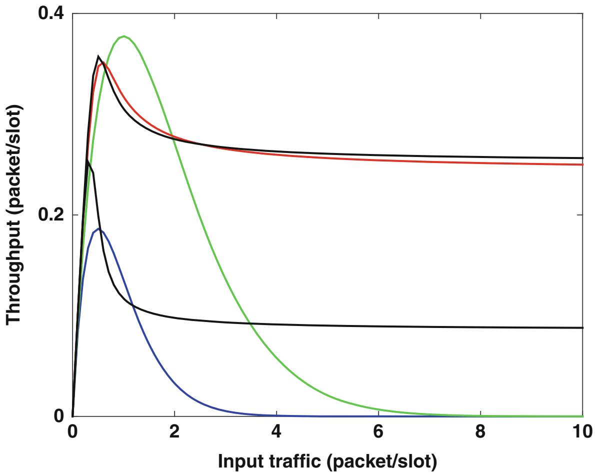


Fig. 11.18 Throughput of IEEE 802.11.e EDCA (WMM) protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $n = 20$, $m_1 = 5$, $m_2 = 10$, $p_1 = 0.5$, $p_2 = 0.05$, $\gamma_1 = 0.01$, and $\gamma_2 = 0.001$. The *top black line* is the throughput of IEEE 802.11.e EDCA class 1, the *bottom black line* is the throughput of IEEE 802.11e EDCA class 2, the *red line* is the throughput of the IEEE 802.11 basic DCF protocol, the *green line* is the throughput of slotted ALOHA, and the *blue line* is the throughput of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol

Figure 11.19 shows the access probability of IEEE 802.11.e EDCA protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10, n = 20$, $m_1 = 5$, $m_2 = 10$, $p_1 = 0.5$, $p_2 = 0.05$, $\gamma_1 = 0.01$, and $\gamma_2 = 0.001$. The top black line is the throughput of IEEE 802.11.e EDCA class 1, the bottom black line is the throughput of IEEE 802.11e EDCA class 2, the IEEE 802.11 basic DCF protocol red line almost coincides with the top black line, the green line is the throughput of slotted ALOHA, and the blue line is the throughput of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol. The higher p_a of class 1 compared to class 2 traffic is indicative of the higher QoS afforded through the use of different parameters for the two class.

The average number of attempts for a successful transmission is

$$
\begin{aligned}
n_a &= \sum_{i=0}^{\infty} i \; (1 - p_a)^i \; p_a \\
&= \frac{1 - p_a}{p_a}
\end{aligned}
\tag{11.31}
$$

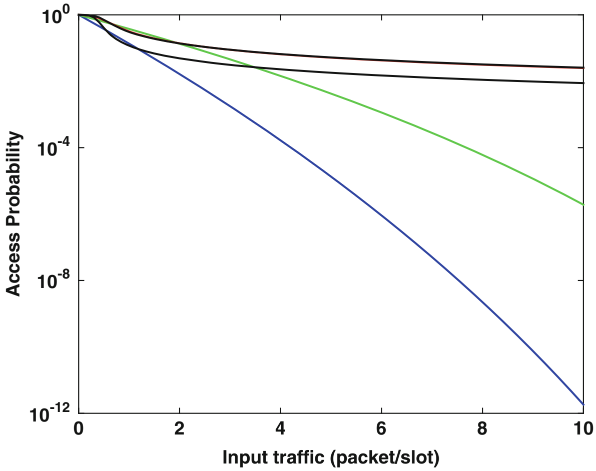


Fig. 11.19 Access probability of IEEE 802.11.e EDCA (WMM) protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $n = 20$, $m_1 = 5$, $m_2 = 10$, $p_1 = 0.5$, $p_2 = 0.05$, $\gamma_1 = 0.01$, and $\gamma_2 = 0.001$. The *top black line* is the throughput of IEEE 802.11.e EDCA class 1, the *bottom black line* is the throughput of IEEE 802.11e EDCA class 2, the IEEE 802.11 basic DCF protocol *red line* almost coincides with the *top black line*, the *green line* is the throughput of slotted ALOHA, and the *blue line* is the throughput of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol

Figure 11.20 shows the delay of the IEEE 802.11.e EDCA protocol when $n = 50$, $N = 10$, and $p = 0.5$ when $n = 20$, $N = 10$, $p = 0.5$, and $\gamma = 0.01$. The bottom black line is the delay of IEEE 802.11.e EDCA class 1, the top black line is the delay of IEEE 802.11e EDCA class 2, the IEEE 802.11 basic DCF protocol red line almost coincides with the top black line, the green line is the delay of slotted ALOHA, and the blue line is the delay of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol.

The average energy required to transmit a frame is estimated as

$$\begin{aligned} E &= E_0 \sum_{i=0}^{\infty} (i+1)(1-p_a)^i \; p_a \\ &= \frac{E_0}{p_a} \end{aligned} \tag{11.32}$$

where E_0 is the energy required to send the one frame. In dB, the above equation can be written as

$$E/E_0 = -10 \log_{10} p_a \quad \text{dB} \tag{11.33}$$

Figure 11.21 shows the average energy required to transmit a packet for the IEEE 802.11.e EDCA protocol when $n = 20$, $N = 10$, $p = 0.5$, and $\gamma = 0.01$. The

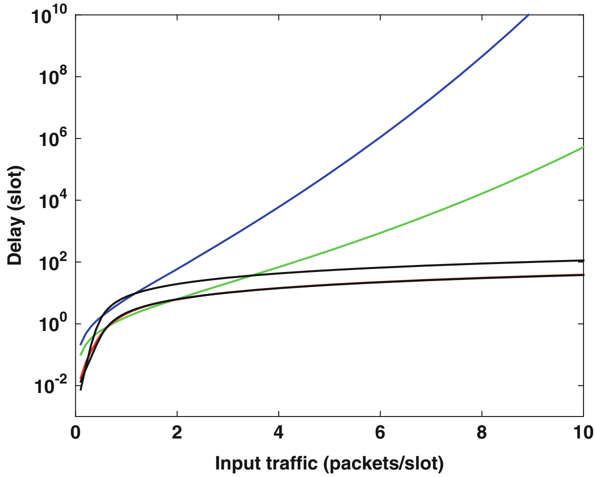


Fig. 11.20 Frame delay of IEEE 802.11.e EDCA when $n = 20$, $N = 10$, $p = 0.5$, and $\gamma = 0.01$. The *bottom black line* is the delay of IEEE 802.11.e EDCA class 1, the *top black line* is the delay of IEEE 802.11e EDCA class 2, the IEEE 802.11 basic DCF protocol *red line* almost coincides with the *top black line*, the *green line* is the delay of slotted ALOHA, and the *blue line* is the delay of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol

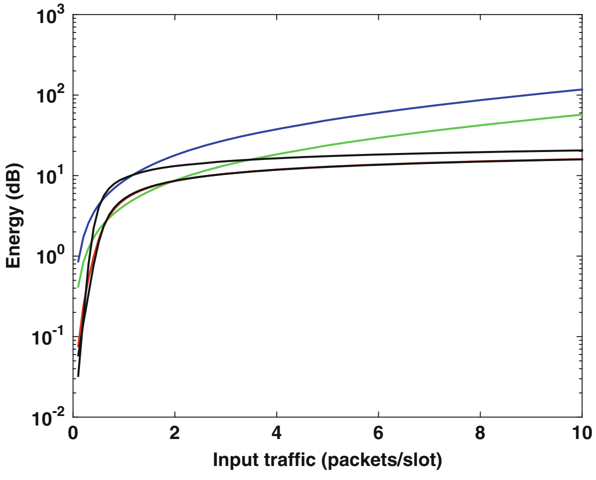


Fig. 11.21 Average energy to transmit a frame for the IEEE 802.11 EDCA protocol when $n = 20$, $N = 10$, $p = 0.8$, and $\gamma = 0.01$. The *bottom black line* is the energy of IEEE 802.11.e EDCA class 1, the *top black line* is the energy of IEEE 802.11e EDCA class 2, the IEEE 802.11 basic DCF protocol *red line* almost coincides with the *top black line*, the *green line* is the energy of slotted ALOHA, and the *blue line* is the energy of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol

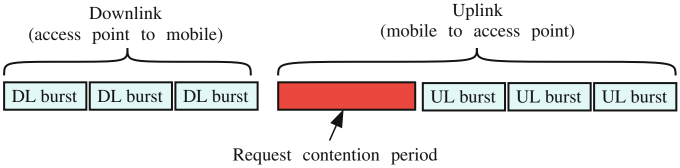


Fig. 11.22 The IEEE 802.11e HCCA frame structure

bottom black line is the energy of IEEE 802.11.e EDCA class 1, the top black line is the energy of IEEE 802.11e EDCA class 2, the IEEE 802.11 basic DCF protocol red line almost coincides with the top black line, the green line is the energy of slotted ALOHA, and the blue line is the energy of pure ALOHA. The parameters for basic DCF protocol were the same as the parameters for the class 1 EDCA protocol.

11.5 IEEE 802.11e HCCA Protocol

The HCCA is an evolution of the IEEE 802.11 basic PCF protocol. The HCCA is the most advanced coordination function and requires the availability of an Access Point (AP) to coordinate the medium access. Another name for AP is Hybrid Controller (HC). HCCA is not mandatory in IEEE 802.11e.

Figure 11.22 shows a simplified view of how HCCA divides the time into frames. Each frame is composed of a downlink subframe followed by an uplink subframe. The downlink subframe is composed of several downlink data bursts sent by the access point. The burst is composed of downstream data and control messages informing each user or station if they are allowed to send data in the uplink subframe.

The HCCA standard does not specify how the upstream request contention period operates. This period is shown as the red block in Fig. 11.22. Several modes of sending a station request could be used:

1. Using an ALOHA-type protocol, users could transmit their requests and hope there are no users that simultaneously send their requests. The chance of collided requests increases with increasing number of users and with increased traffic. QoS support could be established using different persistence and backoff probabilities. We expect that at heavy traffic conditions the number of transmitted requests will drop off in a manner similar to the exponentially decreasing throughput of the ALOHA protocol, refer to Eq. (10.21) on page 344 or the S-ALOHA protocol, refer to Eq. (10.46) on page 350.
2. The access point could poll the users in a round robin fashion. Request collisions will not take place but still not all requests will be granted due to the limited uplink duration and TXOP limitations. QoS could be supported by

controlling the round robin frequency and allocation of bandwidth. However, maintaining fairness and QoS requires accurate control of the polling sequence. The performance of the individual users will be drastically affected by the polling sequence.

3. Any multiple access multiplexing technique could be used to reduce the chance of request collisions. Examples include: time division multiple access (TDMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA), etc. This approach starts to look similar to the IEEE 802.16 (WiMax) protocol discussed in Chap. 12.

11.5.1 A Simple Markov Model for IEEE 802.11 HCCA

In order to derive a simple model for the WiMax protocol we make several assumptions as follows:

1. All users can communicate with the access point using one hop. This assumption eliminates the hidden terminal problem.
2. The states of the Markov chain represent the states of the user: idle, waiting, transmitting, and collided.
3. There are only two classes of service with class 1 being the higher priority class.
4. The number of users in class 1 is N_1 and the number of users in class 2 is N_2.
5. The probability that a class 1 user has a packet to send in one frame time is a_1. a_2 is a similar probability for class 2 users.
6. The transmit opportunity (TXOP) is the same for both classes of service which corresponds to same packet size n.
7. The probability that a class 1 uncollided user transmits when the channel is free is p_1 and p_2 for class 2.
8. A collided class 1 user attempts a retransmission with probability γ_1 and γ_2 for class 2 user.
9. We use a shared multiple access request multiplexing scheme where there are $K < \min(N_1, N_2)$ contention slots. The duration of each contention slot is sufficient to send a request.
10. There are enough bandwidth to allow up to K successful users to transmit in the next uplink subframe.

The restriction $K < \min(N_1, N_2)$ guarantees that there will be no idle contention slots when most of the users are active.

Each user can be in one of three states as shown in Fig. 11.23. The figure can be considered an extension of the IEEE 802.11basic DCF MAC protocol and bears some resemblance to the CSMA/CA protocol.

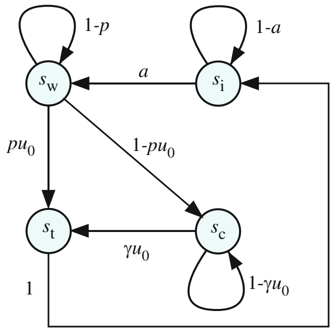


Fig. 11.23 The IEEE 802.11e HCCA Markov chain model for a user

A tagged user's request will not collide with another user under two conditions: either the other user is not attempting a transmission or the other user has selected another contention slot. The probability of this event happening is given by:

$$x = s_i + (1-p)s_w + (1-\gamma)s_c + (ps_w + \gamma s_c)(1 - 1/K) \tag{11.34}$$

The value of p and γ will depend on the user's class of service which will lead to two probabilities x_1 and x_2 for users in class 1 or class 2, respectively.

The probability that the tagged user's request will not suffer a collision and will receive an acknowledgement is given by:

$$u_0 = x_1^{N_1} \times x_2^{N_2} \tag{11.35}$$

We organize the distribution vector at equilibrium as follows.

$$\mathbf{s} = \begin{bmatrix} s_i & s_w & s_t & s_c \end{bmatrix}^t \tag{11.36}$$

The corresponding transition matrix of the channel is given by:

$$\mathbf{P} = \begin{bmatrix} 1-a & 0 & 1 & 0 \\ a & 0 & 0 & 0 \\ 0 & pu_0 & 0 & \gamma u_0 \\ 0 & 1-pu_0 & 0 & 1-\gamma u_0 \end{bmatrix} \tag{11.37}$$

At equilibrium the distribution vector is obtained by solving the two equations

$$\mathbf{P}\,\mathbf{s} = \mathbf{s} \tag{11.38}$$

$$\sum \mathbf{s} = 1 \tag{11.39}$$

However, the terms in $\mathbf{P}$ depend on the state vector components. This constitutes a highly nonlinear set of equations. The solution for $\mathbf{s}$ is obtained through several techniques such as optimization or iterative techniques as follows:

1. Input the values of p, γ, a, N, and K.
2. Assume a trial value for state vector $\mathbf{s}$.
3. Start the iterations by obtaining the probability u_0.
4. Substitute the value of u_0 to obtain an updated value $\mathbf{s}(updated)$.
5. Calculate the error $\mathbf{e} = \mathbf{s}(updated) - \mathbf{s}$ and the root mean square error e_{rms}.
6. Update the state vector

$$\mathbf{s} = \mathbf{s} + \alpha\, \mathbf{e}$$

where α is the update step size which is usually taken equal to 0.1 or even smaller.

7. Repeat the iterations starting at Step 3 and stop when e_{rms} is below a certain value.

11.5.2 IEEE 802.11.e HCCA Protocol Performance

The throughput for each class of service is given by the equation:

$$Th = s_t\, N \tag{11.40}$$

Figure 11.24 shows the throughput of IEEE 802.11.e HCCA protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The top black line is the throughput of IEEE 802.11.e HCCA class 1, the bottom black line is the throughput of IEEE 802.11e HCCA class 2, the blue line is the throughput of slotted ALOHA, and the red line is the throughput of pure ALOHA.

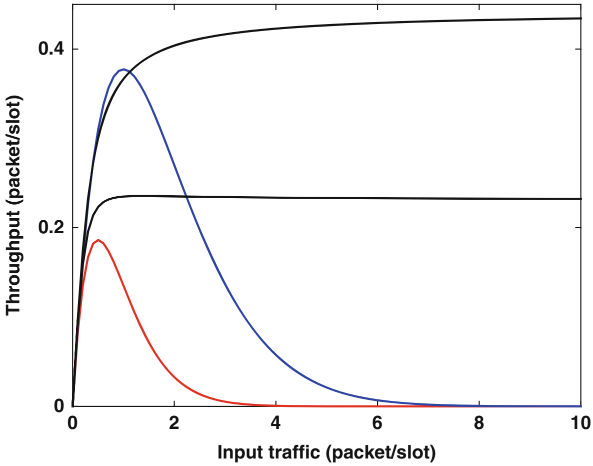


Fig. 11.24 Throughput of IEEE 802.11.e HCCA protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The *top black line* is the throughput of IEEE 802.11.e HCCA class 1, the *bottom black line* is the throughput of IEEE 802.11e HCCA class 2, the *blue line* is the throughput of slotted ALOHA, and the *red line* is the throughput of pure ALOHA

We note that the class 1 throughput is close to the maximum value of the slotted ALOHA protocol. Reducing the value of the persistence probability p results in reduced throughput. The highest throughput was achieved when $p = 1$. However, service differentiation and optimization of the throughput is accomplished by the proper choice of γ. Small or large values of γ reduce the throughput.

The class 2 EDCA protocol has almost one-half the throughput of the class 1 protocol due to the chosen parameter values. That is why class 2 throughput is close to the peak of the pure ALOHA protocol.

The user access probability is given by:

$$p_a = \frac{Th}{Na} \tag{11.41}$$

Figure 11.25 shows the access probability of IEEE 802.11.e HCCA protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The top black line is the access probability of IEEE 802.11.e HCCA class 1, the bottom black line is the access probability of IEEE 802.11e HCCA class 2, the blue line is the access probability of slotted ALOHA, and the red line is the access probability of pure ALOHA. The higher p_a of class 1 compared to class 2 traffic is indicative of the higher QoS afforded through the use of different parameters for the two classes.

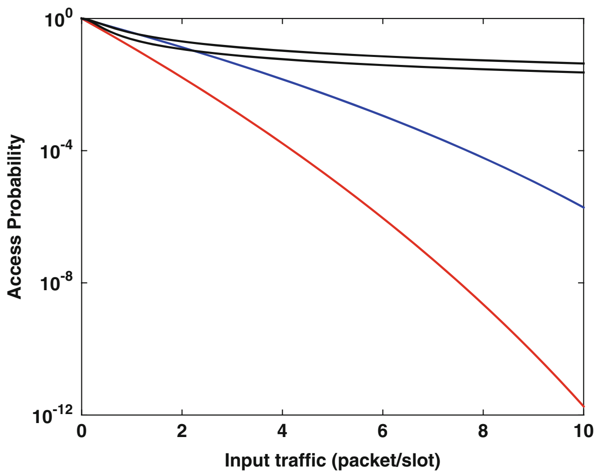


Fig. 11.25 Access probability of IEEE 802.11.e HCCA protocol versus the average input traffic for two classes of service when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The *top black line* is the access probability of IEEE 802.11.e HCCA class 1, the *bottom black line* is the access probability of IEEE 802.11e HCCA class 2, the *blue line* is the access probability of slotted ALOHA, and the *red line* is the access probability of pure ALOHA

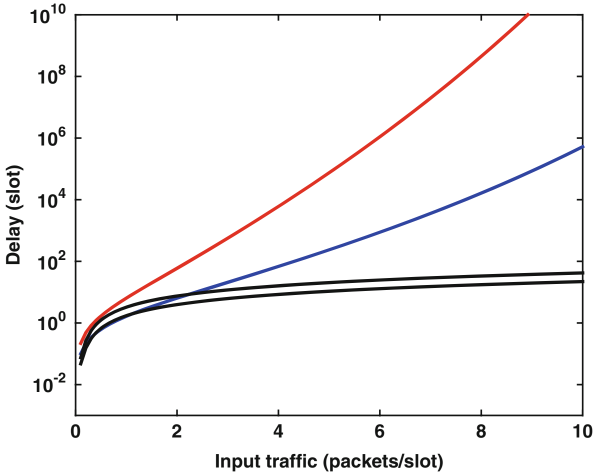


Fig. 11.26 Frame delay of IEEE 802.11.e HCCA when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The *bottom black line* is the delay of IEEE 802.11.e HCCA class 1, the *top black line* is the delay of IEEE 802.11e HCCA class 2, the *blue line* is the delay of slotted ALOHA, and the *red line* is the delay of pure ALOHA

The average number of attempts for a successful transmission is

$$n_a = \sum_{i=0}^{\infty} i\ (1 - p_a)^i\ p_a$$
$$= \frac{1 - p_a}{p_a} \tag{11.42}$$

Figure 11.26 shows the delay of the IEEE 802.11.e HCCA protocol when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The bottom black line is the delay of IEEE 802.11.e HCCA class 1, the top black line is the delay of IEEE 802.11e HCCA class 2, the blue line is the delay of slotted ALOHA, and the red line is the delay of pure ALOHA.

The average energy required to transmit a frame is estimated as

$$E = E_0 \sum_{i=0}^{\infty} (i + 1)(1 - p_a)^i\ p_a$$
$$= \frac{E_0}{p_a} \tag{11.43}$$

where E_0 is the energy required to send the one frame. In dB, the above equation can be written as

$$E/E_0 = -10 \log_{10} p_a \quad \text{dB} \tag{11.44}$$

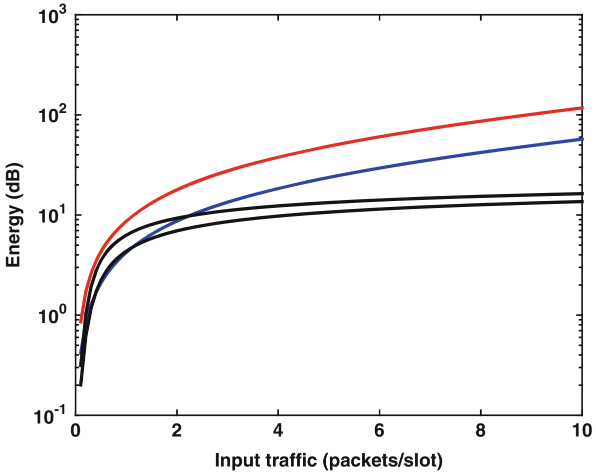


Fig. 11.27 Average energy to transmit a frame for the IEEE 802.11e HCCA protocol when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The *bottom black line* is the delay of IEEE 802.11.e HCCA class 1, the *top black line* is the delay of IEEE 802.11e HCCA class 2, the *blue line* is the delay of slotted ALOHA, and the *red line* is the delay of pure ALOHA

Figure 11.27 shows the average energy required to transmit a packet for the IEEE 802.11e HCCA protocol when $n = 50$, $N = 10$, and $p = 0.5$. Figure 11.21 is the case when $N_1 = N_2 = 10$, $p_1 = 1$, $p_2 = 1$, $\gamma_1 = 0.1$, and $\gamma_2 = 0.05$. The bottom black line is the delay of IEEE 802.11.e HCCA class 1, the top black line is the delay of IEEE 802.11e HCCA class 2, the blue line is the delay of slotted ALOHA, and the red line is the delay of pure ALOHA.

11.6 IEEE 802.11 Final Remarks

The DCF mode of the IEEE 802.11 protocols has been studied by many researchers. We tried to present here a simple model to start the reader in the area of modeling protocols. However, there are many ripe areas that have not been adequately explored for this protocol and for others also. We enumerate some of these directions:

1. Channel errors have not been considered. This is a physical layer problem but could also be considered in a cross-layer modeling. What matters here is to obtain the probability that a frame or packet is in error.
2. Channel fading has not been considered. This is called cross-layer modeling. It becomes useful when adaptive modulation and decoding are used. Chapter 13 attempts to provide a simple discussion of modeling channel fading.
3. Simple backoff strategies were used here in order to obtain simple expressions. Adopting binary exponential backoff (BEB) strategy would result in a more realistic model.
4. Perhaps the most serious deficiency in the models in this chapter is the implicit assumption that no new traffic arrives while the user is attempting to access the channel. This amounts to assuming the *transmit* buffer has a single storage location only. Using a more realistic buffer would require solving two queuing systems.

5. It was implicitly assumed that the transmit antennas were omnidirectional. The author's group, as well as others, have dealt with the interesting case of using directional antennas and its concomitant *deafness* problem.
6. It was implicitly assumed that all N users in our system can talk to each other through one hop. Using a multi-hop network would improve the performance even with the *hidden terminal* problem.

11.7 Problems

IEEE 802.11 Basic DCF

11.1. Explain what is meant by the following PHY layer terms:

1. Frequency-hopping spread spectrum (FHSS),
2. Direct-sequence spread-spectrum (DSSS) link layer,
3. Orthogonal Frequency Division Multiple Access (OFDM).

11.2. Explain what is meant by infrastructure wireless networks and relate that to the concepts of Ad-Hoc networks and base stations.

11.3. Explain what is meant by ad hoc wireless networks.

11.4. Explain what is meant by wireless sensor networks. How these differ from ad hoc networks.

11.5. Explain the operation of the DCF and indicate the type of LAN that uses it (infrastructure or ad hoc)?

11.6. Explain how DCF reduces the probability of collisions.

11.7. Is the basic DCF function close to CSMA/CA or CSMA/CD? Explain your answer.

11.8. Simulate the performance of the IEEE 802.11 basic DCF protocol for different values of the persistence probability p.

11.9. The analysis of the IEEE 802.11 basic DCF protocol assumed equally likely assignment of users to the w reservation slots. Develop a model of the channel when the assignment of active users to reservation slots follows a distribution different from the uniform distribution.

11.10. The analysis of the IEEE 802.11 basic DCF protocol assumed that the backoff counters of active users decrement by one when the channel is free. Develop a model of channel when the backoff counters assume a new random value each time the channel is busy. Only users that can transmit a frame are the ones that happen to have a backoff counter value of 0.

11.11. In an attempt to improve the performance of the IEEE 802.11 basic DCF protocol let us assume that an idle user will *immediately* attempt a transmission when the channel is sensed idle. Analyze this situation.

11.12. Model the IEEE 802.11 basic DCF protocol when truncated binary backoff strategy is employed. In other words when the collided user attempts m retransmission attempts before declaring the channel unavailable.

IEEE 802.11 RTS/CTS

11.13. Is the RTS/CTS mechanism of the IEEE 802.11 close to CSMA/CA or CSMA/CD? Explain your answer.

11.14. Simulate the performance of the IEEE 802.11 RTS/CTS protocol for different values of the persistence probability p.

11.15. Simulate the performance of the IEEE 802.11 RTS/CTS protocol for different values of the backoff probability γ.

11.16. The actual implementation of the IEEE 802.11 RTS/CTS protocol assumed that backoff is accomplished using a counter that decrements by one when the channel is free. Develop a model of system.

11.17. In an attempt to improve the performance of the RTS/CTS protocol let us assume that an idle user will *immediately* attempt an RTS transmission when the channel is sensed idle. Analyze this situation.

11.18. Model the IEEE 802.11 RTS/CTS protocol when truncated binary backoff strategy is employed. In other words when the collided user attempts m retransmission attempts before declaring the channel unavailable.

IEEE 802.11 EDCA

11.19. Model the EDCA protocol when the TXOP for the two classes of service is not equal. The higher value of XTOP is assigned to the higher priority class.

11.20. How will the EDCA model in Sect. 11.4 change if four classes of service are modeled? How will you ascertain that there is service differentiation for the developed model?

IEEE 802.11e HCCA

11.21. Explain the operation of the PCF and indicate the type of LAN that uses it (infrastructure or ad hoc).

11.22. Explain if IEEE 802.11e HCCA eliminates collisions.

11.23. Investigate the types of scheduling protocols that could be used in the HCCA portion of the IEEE 802.11e protocol.

11.24. Develop a discrete-time Markov chain model for the IEEE 802.11e user when the access point uses polling.

11.25. Assume the IEEE 802.11e HCCA protocol that serves 10 customers and the channel speed is 1 Mbps. Each customer is assumed to issue requests at a rate of 100 requests/s and the average length of a frame is 5.12 kb. Obtain the performance of this system.

11.26. Analyze the IEEE 802.11e HCCA protocol in which there are two customer classes. Class 1 has N_1 customers and class 2 has N_2 customers. Users in class 1 can access the channel when they issue a request, while users in class 2 can only access the channel when none of the users of class 1 has a request.

11.27. In the analysis of the IEEE 802.11e HCCA protocol, where users had transmit buffers, it was assumed that requests arriving at a given time step are processed in that time step. Develop a new analysis that processes these requests at the next time step.

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