

**Figure 5.9** ♦ A four-node TDM and FDM example

A third channel partitioning protocol is **code division multiple access (CDMA)**. While TDM and FDM assign time slots and frequencies, respectively, to the nodes, CDMA assigns a different *code* to each node. Each node then uses its unique code to encode the data bits it sends. If the codes are chosen carefully, CDMA networks have the wonderful property that different nodes can transmit simultaneously and yet have their respective receivers correctly receive a sender's encoded data bits (assuming the receiver knows the sender's code) in spite of interfering transmissions by other nodes. CDMA has been used in military systems for some time (due to its anti-jamming properties) and now has widespread civilian use, particularly in cellular telephony. Because CDMA's use is so tightly tied to wireless channels, we'll save our discussion of the technical details of CDMA until Chapter 6. For now, it will suffice to know that CDMA codes, like time slots in TDM and frequencies in FDM, can be allocated to the multiple access channel users.

### 5.3.2 Random Access Protocols

The second broad class of multiple access protocols are random access protocols. In a random access protocol, a transmitting node always transmits at the full rate of the channel, namely,  $R$  bps. When there is a collision, each node involved in the collision repeatedly retransmits its frame (that is, packet) until its frame gets

through without a collision. But when a node experiences a collision, it doesn't necessarily retransmit the frame right away. *Instead it waits a random delay before retransmitting the frame.* Each node involved in a collision chooses independent random delays. Because the random delays are independently chosen, it is possible that one of the nodes will pick a delay that is sufficiently less than the delays of the other colliding nodes and will therefore be able to sneak its frame into the channel without a collision.

There are dozens if not hundreds of random access protocols described in the literature [Rom 1990; Bertsekas 1991]. In this section we'll describe a few of the most commonly used random access protocols—the ALOHA protocols [Abramson 1970; Abramson 1985; Abramson 2009] and the carrier sense multiple access (CSMA) protocols [Kleinrock 1975b]. Ethernet [Metcalfe 1976] is a popular and widely deployed CSMA protocol.

### Slotted ALOHA

Let's begin our study of random access protocols with one of the simplest random access protocols, the slotted ALOHA protocol. In our description of slotted ALOHA, we assume the following:

- All frames consist of exactly  $L$  bits.
- Time is divided into slots of size  $L/R$  seconds (that is, a slot equals the time to transmit one frame).
- Nodes start to transmit frames only at the beginnings of slots.
- The nodes are synchronized so that each node knows when the slots begin.
- If two or more frames collide in a slot, then all the nodes detect the collision event before the slot ends.

Let  $p$  be a probability, that is, a number between 0 and 1. The operation of slotted ALOHA in each node is simple:

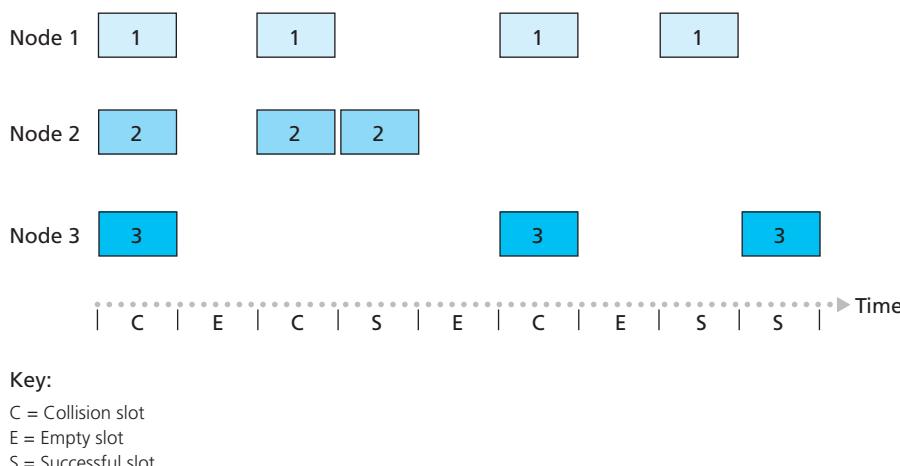
- When the node has a fresh frame to send, it waits until the beginning of the next slot and transmits the entire frame in the slot.
- If there isn't a collision, the node has successfully transmitted its frame and thus need not consider retransmitting the frame. (The node can prepare a new frame for transmission, if it has one.)
- If there is a collision, the node detects the collision before the end of the slot. The node retransmits its frame in each subsequent slot with probability  $p$  until the frame is transmitted without a collision.

By retransmitting with probability  $p$ , we mean that the node effectively tosses a biased coin; the event heads corresponds to “retransmit,” which occurs with

probability  $p$ . The event tails corresponds to “skip the slot and toss the coin again in the next slot”; this occurs with probability  $(1 - p)$ . All nodes involved in the collision toss their coins independently.

Slotted ALOHA would appear to have many advantages. Unlike channel partitioning, slotted ALOHA allows a node to transmit continuously at the full rate,  $R$ , when that node is the only active node. (A node is said to be active if it has frames to send.) Slotted ALOHA is also highly decentralized, because each node detects collisions and independently decides when to retransmit. (Slotted ALOHA does, however, require the slots to be synchronized in the nodes; shortly we’ll discuss an unslotted version of the ALOHA protocol, as well as CSMA protocols, none of which require such synchronization.) Slotted ALOHA is also an extremely simple protocol.

Slotted ALOHA works well when there is only one active node, but how efficient is it when there are multiple active nodes? There are two possible efficiency concerns here. First, as shown in Figure 5.10, when there are multiple active nodes, a certain fraction of the slots will have collisions and will therefore be “wasted.” The second concern is that another fraction of the slots will be *empty* because all active nodes refrain from transmitting as a result of the probabilistic transmission policy. The only “unwasted” slots will be those in which exactly one node transmits. A slot in which exactly one node transmits is said to be a **successful slot**. The **efficiency** of a slotted multiple access protocol is defined to be the long-run fraction of successful slots in the case when there are a large number of active nodes, each always having a large number of frames to send.



**Figure 5.10** ♦ Nodes 1, 2, and 3 collide in the first slot. Node 2 finally succeeds in the fourth slot, node 1 in the eighth slot, and node 3 in the ninth slot

Note that if no form of access control were used, and each node were to immediately retransmit after each collision, the efficiency would be zero. Slotted ALOHA clearly increases the efficiency beyond zero, but by how much?

We now proceed to outline the derivation of the maximum efficiency of slotted ALOHA. To keep this derivation simple, let's modify the protocol a little and assume that each node attempts to transmit a frame in each slot with probability  $p$ . (That is, we assume that each node always has a frame to send and that the node transmits with probability  $p$  for a fresh frame as well as for a frame that has already suffered a collision.) Suppose there are  $N$  nodes. Then the probability that a given slot is a successful slot is the probability that one of the nodes transmits and that the remaining  $N - 1$  nodes do not transmit. The probability that a given node transmits is  $p$ ; the probability that the remaining nodes do not transmit is  $(1 - p)^{N-1}$ . Therefore the probability a given node has a success is  $p(1 - p)^{N-1}$ . Because there are  $N$  nodes, the probability that any one of the  $N$  nodes has a success is  $Np(1 - p)^{N-1}$ .

Thus, when there are  $N$  active nodes, the efficiency of slotted ALOHA is  $Np(1 - p)^{N-1}$ . To obtain the *maximum* efficiency for  $N$  active nodes, we have to find the  $p^*$  that maximizes this expression. (See the homework problems for a general outline of this derivation.) And to obtain the maximum efficiency for a large number of active nodes, we take the limit of  $Np^*(1 - p^*)^{N-1}$  as  $N$  approaches infinity. (Again, see the homework problems.) After performing these calculations, we'll find that the maximum efficiency of the protocol is given by  $1/e = 0.37$ . That is, when a large number of nodes have many frames to transmit, then (at best) only 37 percent of the slots do useful work. Thus the effective transmission rate of the channel is not  $R$  bps but only  $0.37 R$  bps! A similar analysis also shows that 37 percent of the slots go empty and 26 percent of slots have collisions. Imagine the poor network administrator who has purchased a 100-Mbps slotted ALOHA system, expecting to be able to use the network to transmit data among a large number of users at an aggregate rate of, say, 80 Mbps! Although the channel is capable of transmitting a given frame at the full channel rate of 100 Mbps, in the long run, the successful throughput of this channel will be less than 37 Mbps.

### Aloha

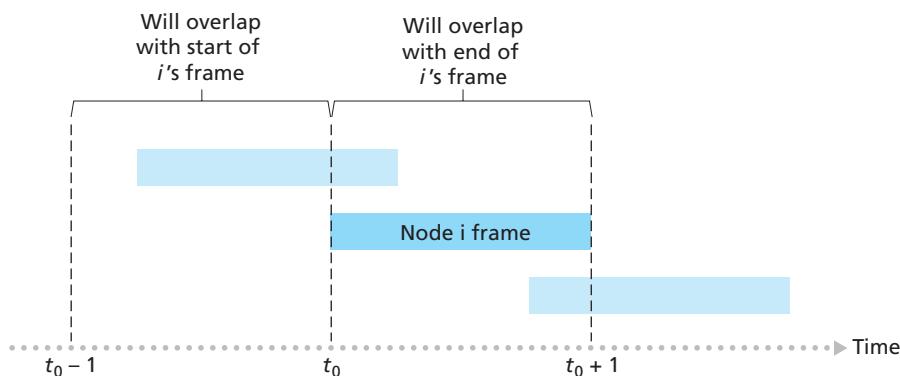
The slotted ALOHA protocol required that all nodes synchronize their transmissions to start at the beginning of a slot. The first ALOHA protocol [Abramson 1970] was actually an unslotted, fully decentralized protocol. In pure ALOHA, when a frame first arrives (that is, a network-layer datagram is passed down from the network layer at the sending node), the node immediately transmits the frame in its entirety into the broadcast channel. If a transmitted frame experiences a collision with one or more other transmissions, the node will then immediately (after completely transmitting its collided frame) retransmit the frame with probability  $p$ . Otherwise, the node waits for a frame transmission time. After this wait, it then

transmits the frame with probability  $p$ , or waits (remaining idle) for another frame time with probability  $1 - p$ .

To determine the maximum efficiency of pure ALOHA, we focus on an individual node. We'll make the same assumptions as in our slotted ALOHA analysis and take the frame transmission time to be the unit of time. At any given time, the probability that a node is transmitting a frame is  $p$ . Suppose this frame begins transmission at time  $t_0$ . As shown in Figure 5.11, in order for this frame to be successfully transmitted, no other nodes can begin their transmission in the interval of time  $[t_0 - 1, t_0]$ . Such a transmission would overlap with the beginning of the transmission of node  $i$ 's frame. The probability that all other nodes do not begin a transmission in this interval is  $(1 - p)^{N-1}$ . Similarly, no other node can begin a transmission while node  $i$  is transmitting, as such a transmission would overlap with the latter part of node  $i$ 's transmission. The probability that all other nodes do not begin a transmission in this interval is also  $(1 - p)^{N-1}$ . Thus, the probability that a given node has a successful transmission is  $p(1 - p)^{2(N-1)}$ . By taking limits as in the slotted ALOHA case, we find that the maximum efficiency of the pure ALOHA protocol is only  $1/(2e)$ —exactly half that of slotted ALOHA. This then is the price to be paid for a fully decentralized ALOHA protocol.

### Carrier Sense Multiple Access (CSMA)

In both slotted and pure ALOHA, a node's decision to transmit is made independently of the activity of the other nodes attached to the broadcast channel. In particular, a node neither pays attention to whether another node happens to be transmitting when it begins to transmit, nor stops transmitting if another node begins to interfere with its transmission. In our cocktail party analogy, ALOHA protocols are quite like



**Figure 5.11** ♦ Interfering transmissions in pure ALOHA



## CASE HISTORY

### NORM ABRAMSON AND ALOHANET

Norm Abramson, a PhD engineer, had a passion for surfing and an interest in packet switching. This combination of interests brought him to the University of Hawaii in 1969. Hawaii consists of many mountainous islands, making it difficult to install and operate land-based networks. When not surfing, Abramson thought about how to design a network that does packet switching over radio. The network he designed had one central host and several secondary nodes scattered over the Hawaiian Islands. The network had two channels, each using a different frequency band. The downlink channel broadcasted packets from the central host to the secondary hosts; and the upstream channel sent packets from the secondary hosts to the central host. In addition to sending informational packets, the central host also sent on the downstream channel an acknowledgment for each packet successfully received from the secondary hosts.

Because the secondary hosts transmitted packets in a decentralized fashion, collisions on the upstream channel inevitably occurred. This observation led Abramson to devise the pure ALOHA protocol, as described in this chapter. In 1970, with continued funding from ARPA, Abramson connected his ALOHAnet to the ARPAnet. Abramson's work is important not only because it was the first example of a radio packet network, but also because it inspired Bob Metcalfe. A few years later, Metcalfe modified the ALOHA protocol to create the CSMA/CD protocol and the Ethernet LAN.

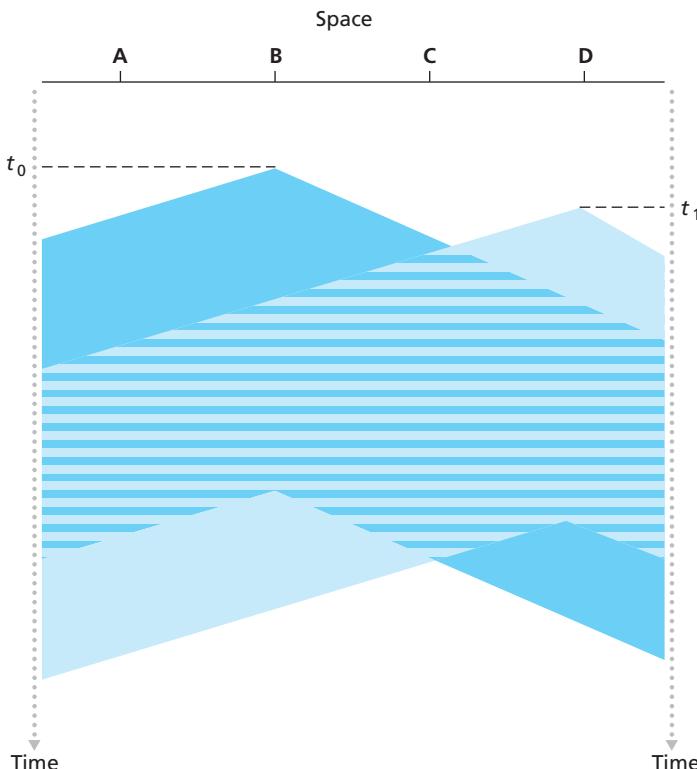
a boorish partygoer who continues to chatter away regardless of whether other people are talking. As humans, we have human protocols that allow us not only to behave with more civility, but also to decrease the amount of time spent “colliding” with each other in conversation and, consequently, to increase the amount of data we exchange in our conversations. Specifically, there are two important rules for polite human conversation:

- *Listen before speaking.* If someone else is speaking, wait until they are finished. In the networking world, this is called **carrier sensing**—a node listens to the channel before transmitting. If a frame from another node is currently being transmitted into the channel, a node then waits until it detects no transmissions for a short amount of time and then begins transmission.
- *If someone else begins talking at the same time, stop talking.* In the networking world, this is called **collision detection**—a transmitting node listens to the channel while it is transmitting. If it detects that another node is transmitting an interfering

frame, it stops transmitting and waits a random amount of time before repeating the sense-and-transmit-when-idle cycle.

These two rules are embodied in the family of **carrier sense multiple access (CSMA)** and **CSMA with collision detection (CSMA/CD)** protocols [Kleinrock 1975b; Metcalfe 1976; Lam 1980; Rom 1990]. Many variations on CSMA and CSMA/CD have been proposed. Here, we'll consider a few of the most important, and fundamental, characteristics of CSMA and CSMA/CD.

The first question that you might ask about CSMA is why, if all nodes perform carrier sensing, do collisions occur in the first place? After all, a node will refrain from transmitting whenever it senses that another node is transmitting. The answer to the question can best be illustrated using space-time diagrams [Molle 1987]. Figure 5.12 shows a space-time diagram of four nodes (A, B, C, D) attached to a linear broadcast bus. The horizontal axis shows the position of each node in space; the vertical axis represents time.



**Figure 5.12** ♦ Space-time diagram of two CSMA nodes with colliding transmissions

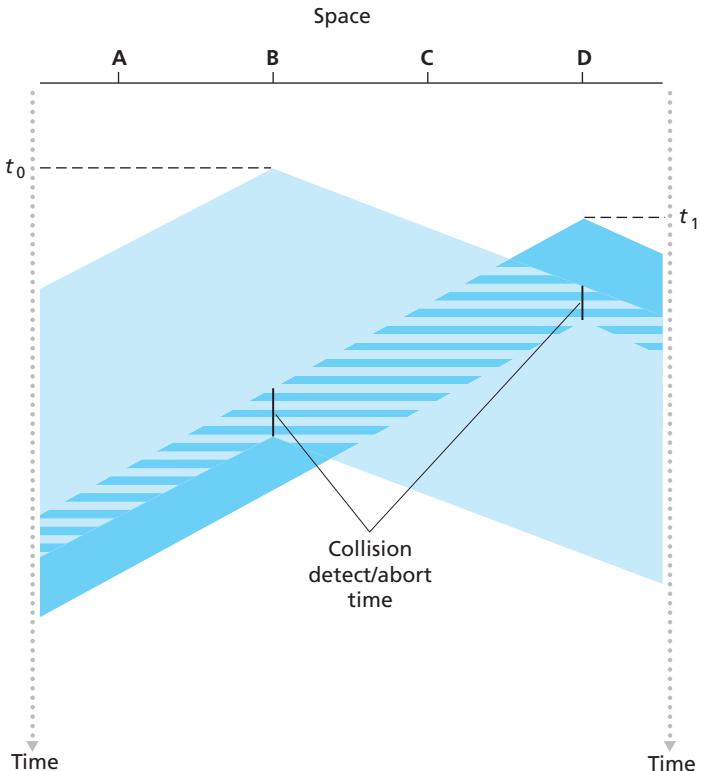
At time  $t_0$ , node B senses the channel is idle, as no other nodes are currently transmitting. Node B thus begins transmitting, with its bits propagating in both directions along the broadcast medium. The downward propagation of B's bits in Figure 5.12 with increasing time indicates that a nonzero amount of time is needed for B's bits actually to propagate (albeit at near the speed of light) along the broadcast medium. At time  $t_1$  ( $t_1 > t_0$ ), node D has a frame to send. Although node B is currently transmitting at time  $t_1$ , the bits being transmitted by B have yet to reach D, and thus D senses the channel idle at  $t_1$ . In accordance with the CSMA protocol, D thus begins transmitting its frame. A short time later, B's transmission begins to interfere with D's transmission at D. From Figure 5.12, it is evident that the end-to-end **channel propagation delay** of a broadcast channel—the time it takes for a signal to propagate from one of the nodes to another—will play a crucial role in determining its performance. The longer this propagation delay, the larger the chance that a carrier-sensing node is not yet able to sense a transmission that has already begun at another node in the network.

### Carrier Sense Multiple Access with Collision Detection (CSMA/CD)

In Figure 5.12, nodes do not perform collision detection; both B and D continue to transmit their frames in their entirety even though a collision has occurred. When a node performs collision detection, it ceases transmission as soon as it detects a collision. Figure 5.13 shows the same scenario as in Figure 5.12, except that the two nodes each abort their transmission a short time after detecting a collision. Clearly, adding collision detection to a multiple access protocol will help protocol performance by not transmitting a useless, damaged (by interference with a frame from another node) frame in its entirety.

Before analyzing the CSMA/CD protocol, let us now summarize its operation from the perspective of an adapter (in a node) attached to a broadcast channel:

1. The adapter obtains a datagram from the network layer, prepares a link-layer frame, and puts the frame adapter buffer.
2. If the adapter senses that the channel is idle (that is, there is no signal energy entering the adapter from the channel), it starts to transmit the frame. If, on the other hand, the adapter senses that the channel is busy, it waits until it senses no signal energy and then starts to transmit the frame.
3. While transmitting, the adapter monitors for the presence of signal energy coming from other adapters using the broadcast channel.
4. If the adapter transmits the entire frame without detecting signal energy from other adapters, the adapter is finished with the frame. If, on the other hand, the adapter detects signal energy from other adapters while transmitting, it aborts the transmission (that is, it stops transmitting its frame).
5. After aborting, the adapter waits a random amount of time and then returns to step 2.



**Figure 5.13** ♦ CSMA with collision detection

The need to wait a random (rather than fixed) amount of time is hopefully clear—if two nodes transmitted frames at the same time and then both waited the same fixed amount of time, they'd continue colliding forever. But what is a good interval of time from which to choose the random backoff time? If the interval is large and the number of colliding nodes is small, nodes are likely to wait a large amount of time (with the channel remaining idle) before repeating the sense-and-transmit-when-idle step. On the other hand, if the interval is small and the number of colliding nodes is large, it's likely that the chosen random values will be nearly the same, and transmitting nodes will again collide. What we'd like is an interval that is short when the number of colliding nodes is small, and long when the number of colliding nodes is large.

The **binary exponential backoff** algorithm, used in Ethernet as well as in DOCSIS cable network multiple access protocols [DOCSIS 2011], elegantly solves this problem. Specifically, when transmitting a frame that has already experienced

$n$  collisions, a node chooses the value of  $K$  at random from  $\{0, 1, 2, \dots, 2^n - 1\}$ . Thus, the more collisions experienced by a frame, the larger the interval from which  $K$  is chosen. For Ethernet, the actual amount of time a node waits is  $K \cdot 512$  bit times (i.e.,  $K$  times the amount of time needed to send 512 bits into the Ethernet) and the maximum value that  $n$  can take is capped at 10.

Let's look at an example. Suppose that a node attempts to transmit a frame for the first time and while transmitting it detects a collision. The node then chooses  $K = 0$  with probability 0.5 or chooses  $K = 1$  with probability 0.5. If the node chooses  $K = 0$ , then it immediately begins sensing the channel. If the node chooses  $K = 1$ , it waits 512 bit times (e.g., 0.01 microseconds for a 100 Mbps Ethernet) before beginning the sense-and-transmit-when-idle cycle. After a second collision,  $K$  is chosen with equal probability from  $\{0, 1, 2, 3\}$ . After three collisions,  $K$  is chosen with equal probability from  $\{0, 1, 2, 3, 4, 5, 6, 7\}$ . After 10 or more collisions,  $K$  is chosen with equal probability from  $\{0, 1, 2, \dots, 1023\}$ . Thus, the size of the sets from which  $K$  is chosen grows exponentially with the number of collisions; for this reason this algorithm is referred to as binary exponential backoff.

We also note here that each time a node prepares a new frame for transmission, it runs the CSMA/CD algorithm, not taking into account any collisions that may have occurred in the recent past. So it is possible that a node with a new frame will immediately be able to sneak in a successful transmission while several other nodes are in the exponential backoff state.

### CSMA/CD Efficiency

When only one node has a frame to send, the node can transmit at the full channel rate (e.g., for Ethernet typical rates are 10 Mbps, 100 Mbps, or 1 Gbps). However, if many nodes have frames to transmit, the effective transmission rate of the channel can be much less. We define the **efficiency of CSMA/CD** to be the long-run fraction of time during which frames are being transmitted on the channel without collisions when there is a large number of active nodes, with each node having a large number of frames to send. In order to present a closed-form approximation of the efficiency of Ethernet, let  $d_{\text{prop}}$  denote the maximum time it takes signal energy to propagate between any two adapters. Let  $d_{\text{trans}}$  be the time to transmit a maximum-size frame (approximately 1.2 msec for a 10 Mbps Ethernet). A derivation of the efficiency of CSMA/CD is beyond the scope of this book (see [Lam 1980] and [Bertsekas 1991]). Here we simply state the following approximation:

$$\text{Efficiency} = \frac{1}{1 + 5d_{\text{prop}}/d_{\text{trans}}}$$

We see from this formula that as  $d_{\text{prop}}$  approaches 0, the efficiency approaches 1. This matches our intuition that if the propagation delay is zero, colliding nodes will abort