

Digital Communications

Fourth Edition

John G. Proakis



Copyright 2000 by The McGraw-Hill Companies, Inc.
All rights reserved. Printed in the United States of America.

NTT EX2010
MediaTek v. NTT
IPR2020-1404

system design methods that we have described for single-user communication are directly applicable and no new problems are encountered in a multiple access environment, except for the additional task of assigning users to available channels.

The interesting problems arise when the data from the users accessing the network is bursty in nature. In other words, the information transmissions from a single user are separated by periods of no transmission, where these periods of silence may be greater than the periods of transmission. Such is the case generally with users at various terminals in a computer communications network that contains a central computer. To some extent, this is also the case in mobile cellular communication systems carrying digitized voice, since speech signals typically contain long pauses.

In such an environment where the transmission from the various users is bursty and low-duty-cycle, FDMA and TDMA tend to be inefficient because a certain percentage of the available frequency slots or time slots assigned to users do not carry information. Ultimately, an inefficiently designed multiple access system limits the number of simultaneous users of the channel.

An alternative to FDMA and TDMA is to allow more than one user to share a channel or subchannel by use of direct-sequence spread spectrum signals. In this method, each user is assigned a unique code sequence or *signature sequence* that allows the user to spread the information signal across the assigned frequency band. Thus signals from the various users are separated at the receiver by cross-correlation of the received signal with each of the possible user signature sequences. By designing these code sequences to have relatively small cross-correlations, the crosstalk inherent in the demodulation of the signals received from multiple transmitters is minimized. This multiple access method is called *code-division multiple access* (CDMA).

In CDMA, the users access the channel in a random manner. Hence, the signal transmissions among the multiple users completely overlap both in time and in frequency. The demodulation and separation of these signals at the receiver is facilitated by the fact that each signal is spread in frequency by the pseudo-random code sequence. CDMA is sometimes called *spread-spectrum multiple access* (SSMA).

An alternative to CDMA is nonspread random access. In such a case, when two users attempt to use the common channel simultaneously, their transmissions collide and interfere with each other. When that happens, the information is lost and must be retransmitted. To handle collisions, one must establish protocols for retransmission of messages that have collided. Protocols for scheduling the retransmission of collided messages are described below.

15-2 CAPACITY OF MULTIPLE ACCESS METHODS

It is interesting to compare FDMA, TDMA, and CDMA in terms of the information rate that each multiple access method achieves in an ideal AWGN channel of bandwidth W . Let us compare the capacity of K users, where each

interpretation. We note that rate R_{2m} corresponds to the case in which the signal from user 1 is considered as an equivalent additive noise in the detection of the signal of user 2. On the other hand, user 1 can transmit at capacity C_1 , since the receiver knows the transmitted signal from user 2 and, hence, it can eliminate its effect in detecting the signal of user 1.

Due to symmetry, a similar situation exists if user 2 is transmitting at capacity C_2 . Then, user 1 can transmit up to a maximum rate $R_{1m} = R_{2m}$, which is illustrated in Fig. 15.2.4 as point B . In this case, we have a similar interpretation as above, with an interchange in the roles of user 1 and user 2.

The points A and B are connected by a straight line. It is easily seen that this straight line is the boundary of the achievable rate region, since any point on the line corresponds to the maximum rate $W \log_2 (1 + 2P/WN_0)$, which can be obtained by simply time-sharing the channel between the two users.

In the next section, we consider the problem of signal detection for a multiuser CDMA system and assess the performance and the computational complexity of several receiver structures.

15-3 CODE-DIVISION MULTIPLE ACCESS

As we have observed, TDMA and FDMA are multiple access methods in which the channel is partitioned into independent, single-user subchannels, i.e., nonoverlapping time slots or frequency bands, respectively. In CDMA, each user is assigned a distinct signature sequence (or waveform), which the user employs to modulate and spread the information-bearing signal. The signature sequences also allow the receiver to demodulate the message transmitted by multiple users of the channel, who transmit simultaneously and, generally, asynchronously.

In this section, we treat the demodulation and detection of multiuser CDMA signals. We shall see that the optimum maximum-likelihood detector has a computational complexity that grows exponentially with the number of users. Such a high complexity serves as a motivation to devise suboptimum detectors having lower computational complexities. Finally, we consider the performance characteristics of the various detectors.

15-3-1 CDMA Signal and Channel Models

Let us consider a CDMA channel that is shared by K simultaneous users. Each user is assigned a signature waveform $g_k(t)$ of duration T , where T is the symbol interval. A signature waveform may be expressed as

$$g_k(t) = \sum_{n=0}^{L-1} a_k(n)p(t - nT_c), \quad 0 \leq t \leq T \quad (15-3-1)$$

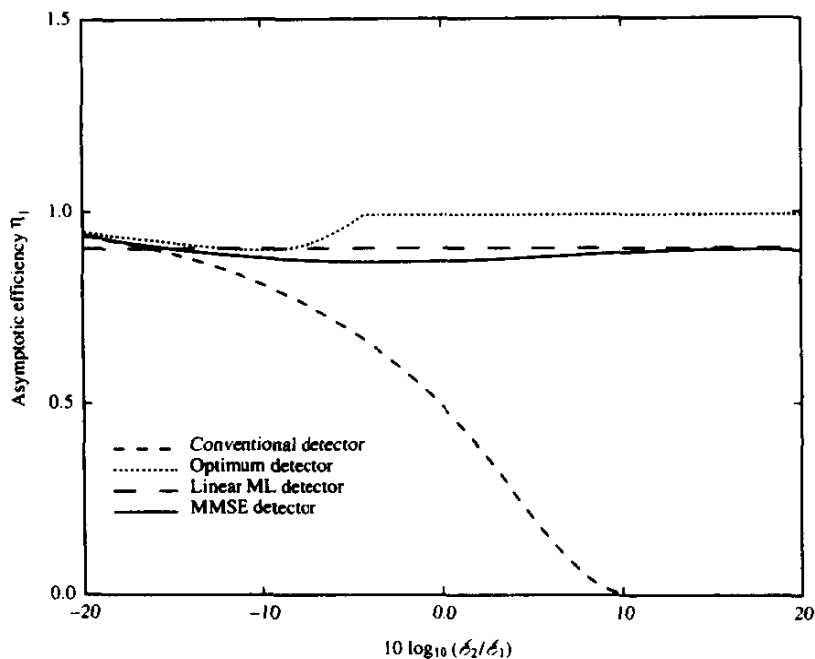


FIGURE 15-3-2 Asymptotic efficiencies of optimum (Viterbi) detector, conventional detector, MMSE detector, and linear ML detector in a two-user synchronous DS/SSMA system. [From Xie *et al.* (1990), ©IEEE.]

(1989), and Xie *et al.* (1990). Figure 15-3-2 illustrates the asymptotic efficiencies of these detectors when $K = 2$ users are transmitting synchronously. These graphs show that when the interference is small ($\mathcal{E}_2 \rightarrow 0$), the asymptotic efficiencies of these detectors are relatively large (near unity) and comparable. As \mathcal{E}_2 increases, the asymptotic efficiency of the conventional detector deteriorates rapidly. However, the other linear detectors perform relatively well compared with the optimum detector. Similar conclusions are reached by computing the error probabilities, but these computations are often more tedious.

15-4 RANDOM ACCESS METHODS

In this section, we consider a multiuser communication system in which users transmit information in packets over a common channel. In contrast to the CDMA method described in Section 15-3, the information signals of the users are not spread in frequency. As a consequence, simultaneous transmission of signals from multiple users cannot be separated at the receiver. The access methods described below are basically random, because packets are generated according to some statistical model. Users access the channel when they have one or more packets to transmit. When more than one user attempts to transmit packets simultaneously, the packets overlap in time, i.e., they collide,

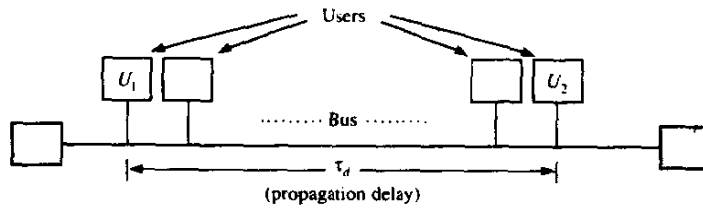


FIGURE 15-4-4 Local area network with bus architecture.

access protocols that yield higher throughput. An example of such a protocol is *carrier sensing with collision detection*, which is used as a standard Ethernet protocol in local area networks. This protocol is generally known as *carrier sense multiple access with collision detection* (CSMA/CD).

The CSMA/CD protocol is simple. All users listen for transmissions on the channel. A user who wishes to transmit a packet seizes the channel when it senses that the channel is idle. Collisions may occur when two or more users sense an idle channel and begin transmission. When the users that are transmitting simultaneously sense a collision, they transmit a special signal, called a *jam signal*, that serves to notify all users of the collision and abort their transmissions. Both the carrier sensing feature and the abortion of transmission when a collision occurs result in minimizing the channel down-time and, hence, yield a higher throughput.

To elaborate on the efficiency of CSMA/CD, let us consider a local area network having a bus architecture, as shown in Fig. 15-4-4. Consider two users U_1 and U_2 at the maximum separation, i.e., at the two ends of the bus, and let τ_d be the propagation delay for a signal to travel the length of the bus. Then, the (maximum) time required to sense an idle channel is τ_d . Suppose that U_1 transmits a packet of duration T_p . User U_2 may seize the channel τ_d s later by using carrier sensing, and begins to transmit. However, user U_1 would not know of this transmission until τ_d s after U_2 begins transmission. Hence, we may define the time interval $2\tau_d$ as the (maximum) time interval to detect a collision. If we assume that the time required to transmit the jam signal is negligible, the CSMA/CD protocol yields a high throughput when $2\tau_d \ll T_p$.

There are several possible protocols that may be used to reschedule transmissions when a collision occurs. One protocol is called *nonpersistent CSMA*, a second is called *1-persistent CSMA*, and a generalization of the latter is called *p-persistent CSMA*.

Nonpersistent CSMA In this protocol, a user that has a packet to transmit senses the channel and operates according to the following rule.

- (a) If the channel is idle, the user transmits a packet.
- (b) If the channel is sensed busy, the user schedules the packet