# Chapter 6
# Local Area Networks

*Success doesn't discriminate. It's an equal opportunity employer—available to everyone willing to pay the price.*

—Anonymous

When designing a local area network (LAN), establishing performance characteristics of the network before putting it into use is of paramount importance; it gives the designer the freedom and flexibility to adjust various parameters of the network in the planning rather than the operational phase. However, it is hard to predict the performance of the LAN unless a detailed analysis of a similar network is available. Information on a similar network is generally hard to come by so that performance modeling of the LAN must be carried out.

In this chapter we focus on the analytic models of four LAN important protocols: the token-passing access methods for the ring and bus topologies, the CSMA/CD for bus, and the star. The analytic models provide an insight into the nature of the networks. It should be emphasized that for each network, we do not provide all the details; that can be found in the references. We provide enough detail to understand the performance analysis, which is our focus.

Before we present the analytic model for each network, it is expedient that we consider the OSI reference model, which applies to LANs, MANs, and WANs.

## 6.1 OSI Reference and IEEE Models

An effective solution to communication between diverse equipment by numerous manufacturers is to have vendors abide by a common set of rules or data-exchange protocols. In 1973, the International Standards Organization (ISO) issued a recommendation for a standard network architecture. This is known as the Open System

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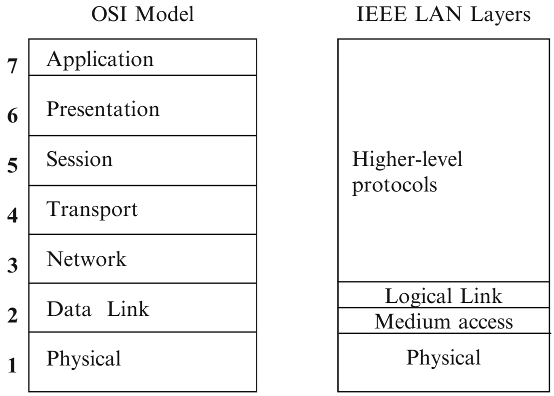


**Fig. 6.1** Relationship between the OSI model and IEEE LAN layers

Interconnection (OSI) reference model. "Open" refers to the ability to communicate with any other system obeying the same standards.

The OSI reference model is a structured model. It is divided into seven layers as shown in Fig. 6.1 and explained as follows.

The *application layer*, layer 7, is the one the user sees. It provides services directly comprehensible to application programs; login, password checks, network transparency for distribution of resources, file and document transfer, industry specific protocols.

The *presentation layer*, layer 6, is concerned with the interpretation of the data. It restructures data to/from standardized format used within network; text compression, code conversion, file format conversion, and encryption.

The *session layer*, layer 5, manages address translation and access security. It negotiates to establish a connection with another node on the network and then to manage the dialogue. This means controlling the start, stopping, and synchronisation of the conversion.

The *transport layer*, layer 4, performs error control, sequence checking, handling of duplicate packets, flow control, and multiplexing. Here it is determined whether the channel is to be point-to-point (virtual) with ordered messages, isolated messages with no order, or broadcast messages. It is the last of the layers which are concerned with communications between peer entities in the systems. The transport layer and above are referred to as the upper layers of the model, and they are independent of the underlying network. The lower layers are concerned with data transfer across the network.

The *network layer*, layer 3, provides a connection path between systems, including the case where intermediate nodes are involved. It deals with message packetization, message routing for data transfer between non-adjacent nodes or stations, congestion control, and accounting.

The *data-link layer*, layer 2, establishes the transmission protocol, the way in which information will be transmitted, acknowledgment of message, token possession, error detection, and sequencing. It prepares the packets passed down from the network layer for transmission on the network. It takes a raw transmission and transforms it into a line free from error. Here headers and framing information are added or removed. With these go the timing signals, check-sum, and station addresses, as well as the control system for access.

The *physical layer*, layer 1, is that part that actually touches the media or cable; the line is the point within the node or device where the data is received and transmitted. It sees to it that ones arrive as ones and zeros as zeros. It encodes and physically transfers messages (raw bits stream) between adjacent stations. It handles voltages, frequencies, direction, pin numbers, modulation techniques, signaling schemes, ground loop prevention, and collision detection in CSMA/CD access method.

A good way to remember the layers is this. Starting from the layer 1, one should remember the saying, "**P**lease **D**o **N**ot **T**hrow **S**ausage **P**izza **A**way."

The IEEE has formulated standards for the physical and logical link layers for three types of LANs, namely, token buses, token rings, and CSMA/CD protocols. Figure 6.1 illustrates the correspondence between the three layers of the OSI and the IEEE 802 reference models. The physical layer specifies means for transmitting and receiving bits across various types of media. The media access control layer performs the functions needed to control access to the physical medium. The logical link control layer is the common interface to the higher software layers.

## 6.2 LAN Characteristics

A local area network (LAN) is distinguished from other types of computer networks in that communication is usually confined to a moderate geographical area such as a building or a campus. It has the following characteristics:

- Short distance (up to 1 km)
- High speed (1–100 Mbps)
- Low error rate ($10^{-8}$ to $10^{-4}$)
- Ease of access

A LAN is usually owned by a single organization and it is designed for the purpose of sharing resources.

The topology of a network is the way in which the nodes (or stations) are interconnected. The basic forms of LAN topologies are shown in Fig. 6.2.

The type of technology used to implement LANs are diverse as the LAN vendors. Both vendors and users are forced to make a choice. This choice is usually based on several criteria such as:

– network topology and architecture
– access control
– transmission medium
– transmission techniques (baseband/broadband signaling)
– adherence to standards
– performance in terms of channel utilization, delay, and power

The primary performance criterion is the delay-throughput characteristics of the system.

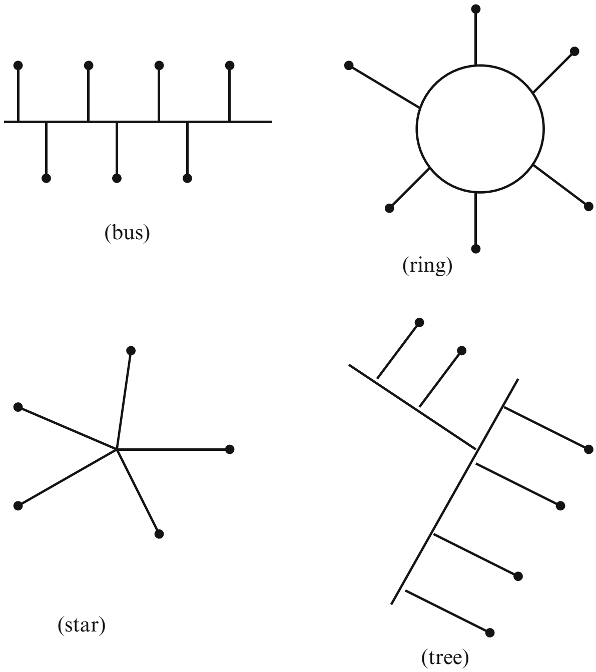


**Fig. 6.2** Typical LAN topologies

The **mean transfer delay** of a message is the time interval between the instant the message is available at the sending station and the end of its successful reception at the receiving station.

It is convenient to regard the transfer delay as comprising of three components. The first component, W, is called the waiting time or access time. It is the time elapsed from the availability of a message in the source station transmit buffer until the beginning of its transmission on the channel. The second component, $T_p$, called the propagation time, is the time elapsed from the beginning of the transmission of the message until the arrival of the first bit of the message at the destination. The third component is the transmission or service time, S, which is the time elapsed between the arrival of the first bit of the message at the destination and the last bit. As soon as the last bit arrives at the destination, the transfer is complete. This implies that the transfer delay D includes the waiting time W (or queueing delay) at the sending station, the service (or transmission) time S of the message, and the propagation delay $T_p$, i.e.

$$D = W + S + T_p \tag{6.1a}$$

In terms of their expected values

$$E(D) = E(W) + E(S) + E(T_p) \tag{6.1b}$$

## 6.3 Token-Passing Ring

The token-passing ring, developed by workers at the Zurich Research Laboratories of IBM in 1972 and standardized as an access method in the IEEE Standard 802.5, is the best-known of all the ring systems. Here we are interested in its basic operation and delay analysis [3–4].

### 6.3.1 Basic Operation

In a token ring, the stations are connected as in all ring networks as illustrated in Fig. 6.3.

Access to the transmission channel is controlled by means of a special eight-bit pattern called a *token*, which is passed around the ring. When the system is initialized, a designated station generates a free token, such as 11111111. If no station is ready to transmit, the free token circulates around the ring. When a station wishes to transmit, it captures the free token and changes it to a busy token, such as 11111110, thereby disallowing other stations from transmitting. The packet to be transmitted is appended to the busy token. The receiving station copies the information. When the information reaches the sending station, the station takes it off the ring and generates a new free token to be used by another station who may need the transmission channel.

This operation can be described by a single-server queueing model, as illustrated in Fig. 6.4.

The server serves as many queues as stations attached to the ring. The server attends the queues in a cyclic order as shown by the rotating switch which

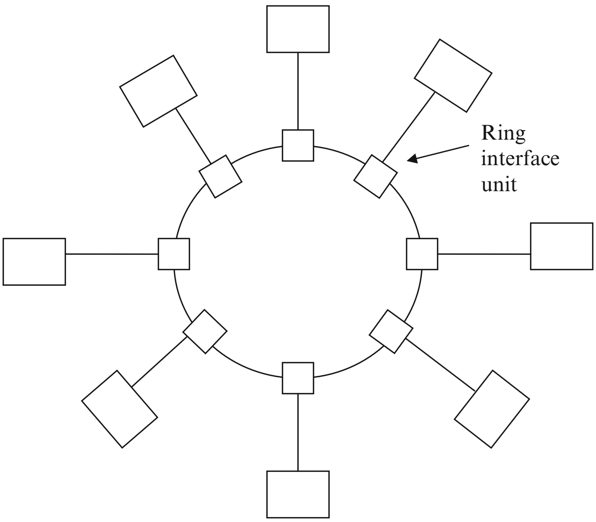


**Fig. 6.3** A typical ring topology

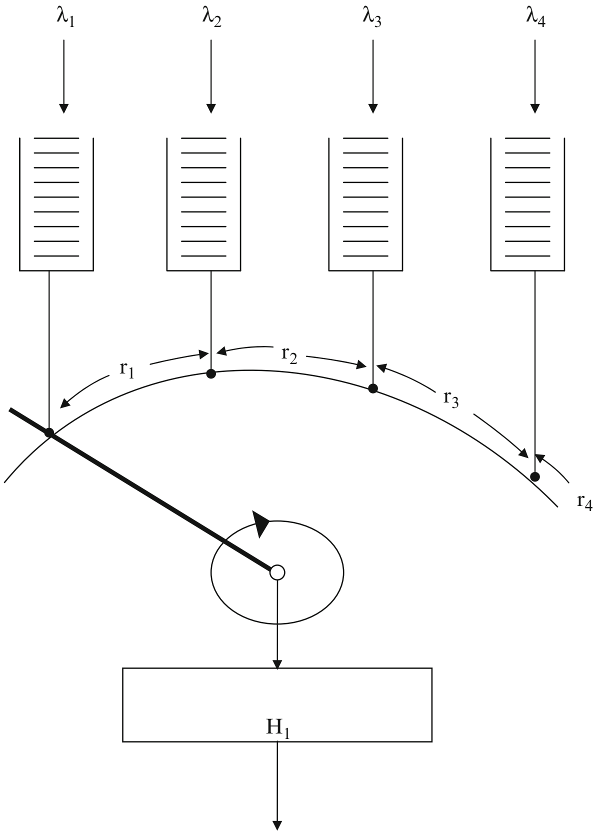


**Fig. 6.4** Cyclic-service queueing model

represents the free token. Once a station captures the token, it is served according to one of the following service disciplines:

- *Exhaustive service*: the server serves a queue until there are no customers left in that queue.
- *Gated service*: the server serves only those customers in a queue that were waiting when it arrived at that queue, i.e. when the server arrives at a queue, a gate is closed behind the waiting customers and only those customers in front of the gate are served.
- *Limited service*: the server serves a limited number of customers, say K (constant) or less, that were waiting when it arrived at the queue.

#### 6.3.1.1 Delay Analysis

Consider a single server serving N queues in a cyclic manner as shown in Fig. 6.4. Let $r_i$ denote a constant switchover time from queue i to queue i+1 and $R_o$ be the sum of all switchover times, i.e.

$$R_o = \sum_{i=1}^{N} r_i \tag{6.2}$$

We examine the M/G/1 model, that is, messages arrive at queues according to independent Poisson processes with mean rates $\lambda_1, \lambda_2, \cdots, \lambda_N$ and the service times $H_i$ of the messages from queue i are generally distributed with mean $E(S_i)$ and second moment $E(S_i^{\,2})$. We denote the utilization of queue i by

$$\rho_i = \lambda_i E(S_i) \tag{6.3}$$

and assume that the normalization condition:

$$\rho = \sum_{i=1}^{N} \rho_i < 1 \tag{6.4}$$

Let $V_i$ denote the intervisit time of queue i, also known as the server-vacation time, the time interval from the server's departure from the queue until its return to the same queue. The moment generating function for the statistical-equilibrium waiting time distribution is given by [5–7]:

Exhaustive service:

$$G_W^e(z) = E\left(e^{-zW_i}\right) = \frac{1-\rho_i}{E(V_i)}\,\frac{1-G_v(z)}{z-\lambda_i+\lambda_i G_s(z)} \tag{6.5}$$

Gated service:

$$G_W^g(z) = \frac{G_c(z)\lambda_i[1-G_s(z)]-G_c(z)}{E(V_i)[z-\lambda_i+\lambda_i G_s(z)]} \tag{6.6}$$

Limited service:

$$G_W^{\ell}(z) = \frac{1-\rho_i+\lambda_i E(V_i)}{E(V_i)}\,\frac{1-G_v(z)}{z-\lambda_i+\lambda_i G_s(z)G_v(z)} \tag{6.7}$$

where $G_v(z) = E(e^{-zV_i})$ is the generating function for the intervisit time;

$G_s(z) = E(e^{-zS_i})$ is the generating function for the service time, $G_c(z) = E\left(e^{-zC_i}\right)$ is the generating function for the cycle time.

From Eqs. (6.5)–(6.7), the mean waiting time of messages in queue i is determined by differentiating $G_W(z)$ and setting $z = 0$. The result is:

Exhaustive service:

$$E^e(W_i) = \frac{E(V_i)}{2} + \frac{Var(V_i)}{2E(V_i)} + \frac{\lambda_i E\left(S_i^2\right)}{2(1-\rho_i)} \tag{6.8}$$

Gated service:

$$E^g(W_i) = \frac{E(C_i)}{2} + \frac{Var(C_i)}{2E(C_i)} + \frac{\rho_i E(S_i^2)}{2(1-\rho_i)E(S_i)} \tag{6.9}$$

Limited service:

$$E^{\ell}(W_i) = \frac{\lambda_i E\left[(V_i + S_i)^2\right]}{2\left[1 - \rho_i + \lambda_i E(V_i)^i\right]} \tag{6.10}$$

Hence the mean waiting time can be found provided the first two moments of the intervisit times $V_i$ are known.

To find the first moment of $V_i$, let $C_i$ be the total cycle time (i.e. the time between subsequent visits of the server to queue i) and $T_i$ be the time spent by the server at queue i, then

$$E(V_i) = E(C_i) - E(T_i) \tag{6.11}$$

It is readily shown that [8]

$$E(C_i) = \frac{R_o}{1-\rho} \tag{6.12}$$

Since the traffic flow must be conserved, the average number of messages serviced during one visit of queue i is equal to the average number of arriving messages at that queue in one cycle time, i.e.

$$\frac{E(T_i)}{E(S_i)} = \lambda_i E(C_i)$$

or

$$E(T_i) = \lambda_i E(C_i) E(S_i) = \rho_i E(C_i) \tag{6.13}$$

Substituting Eqs. (6.12) and (6.13) into Eq. (6.11) gives the mean intervisit time of queue i as

$$E(V_i) = \frac{1-\rho_i}{1-\rho} R_o \tag{6.14}$$

Introducing Eqs. (6.12) and (6.14) in Eq. (6.8) leads to

$$E^e(W_i) = \frac{\mathrm{Var}(V_i)}{2E(V_i)} + \frac{1-\rho_i}{2(1-\rho)} R_o + \frac{\rho_i}{2(1-\rho_i)} \frac{E(S_i^2)}{E(S_i)} \tag{6.15}$$

for exhaustive service. Taking similar procedure for gated service discipline results in

$$E^g(W_i) = \frac{Var(V_i)}{2E(V_i)} + \frac{1+\rho_i}{2(1-\rho)} R_o + \frac{\rho_i}{2(1-\rho_i)} \frac{E\left(S_i^2\right)}{E(S_i)} \tag{6.16}$$

For limited service, we have an explicit solution for $E(W_i)$ only in the special case of statistically symmetric conditions and K = 1 for all stations [5, 7]. However, an upper bound for $E(W_i)$ for any K is presented in [9].

For symmetric traffic conditions (i.e. in the case of identical stations),

$$\lambda_1 = \lambda_2 = \cdots = \lambda_N = \frac{\lambda}{N} \tag{6.17}$$

$$r_1 = r_2 = \cdots = r_N = \frac{R_o}{N} = r \tag{6.18}$$

and the mean waiting time for all the queues becomes:

Exhaustive service:

$$E^e(W_i) = \frac{\delta^2}{2r} + \frac{Nr(1-\rho/N)}{2(1-\rho)} + \frac{\rho E\left(S^2\right)}{2(1-\rho)E(S)} \tag{6.19}$$

Gated service:

$$E^g(W_i) = \frac{\delta^2}{2r} + \frac{Nr(1+\rho/N)}{2(1-\rho)} + \frac{\rho E\left(S^2\right)}{2(1-\rho)E(S)} \tag{6.20}$$

Limited service:

$$E^e(W_i) = \frac{\delta^2}{2r} + \frac{Nr(1+\rho/N)+N\lambda\delta^2}{2(1-\rho-N\lambda r)} + \frac{\rho E\left(S^2\right)}{2(1-\rho-N\lambda r)E(S)} \tag{6.21}$$

where $\delta^2$ is the variance of the switchover time. An alternative, less rigorous means of deriving Eqs. (6.19–6.21) is the decomposition theorem [8]. Note that the only difference between Eqs. (6.19) and (6.20) is the ± signs in the terms $(1 \pm \rho)$ which implies that $E^e(W) \leq E^g(W)$. Thus, from Eqs. (6.19)–(6.21), we conclude that:

$$E^e(W) \leq E^g(W) \leq E^{\ell}(W) \tag{6.22}$$

The above derivations are for continuous-time systems. The corresponding derivations for discrete-time systems can be found in [5, 9–11].

The formulas in Eqs. (6.19)–(6.21) for the waiting time are valid for token ring and token bus. However, the mean value r of the switchover time and its variance $\delta^2$ differ for each protocol. Here we evaluate these parameters for the token ring.

The token passing interval or switchover time T is given by

$$T = T_t + T_{pt} + T_b \tag{6.23}$$

where $T_t$ is the token transmission time, $T_{pt}$ is the token propagation delay, and $T_b$ is the bit delay per station. Hence, the expected value r = E(T) is given by

$$r = E(T_t) + E\left(T_{pt}\right) + E(T_b) \tag{6.24}$$

and, since the random variables are independent, the variance Var (T) = $\delta^2$ is given by

$$\delta^2 = \mathrm{Var}(T_i) + \mathrm{Var}\left(T_{pt}\right) + \mathrm{Var}(T_b) \tag{6.25}$$

Assuming a constant token packet length $L_t$ (including preamble bits), for a network data rate R,

$$T_t = \frac{L_t}{R}$$

Its expected value is constant. Hence

$$E(T_t) = T_t = \frac{L_t}{R}, \quad \mathrm{Var}(T_t) = 0 \tag{6.26}$$

Assuming that the stations are equally spaced on the ring, the distance between any adjacent stations is identical to $\ell/N$, where $\ell$ is the physical length of the ring. If P is the signal propagation delay in seconds per unit length (the reciprocal of the signal propagation delay velocity u, i.e. P = 1/u), the token propagation delay is

$$T_{pt} = \frac{P\ell}{N}$$

Hence

$$E\left(T_{pt}\right) = T_{pt} = \frac{P\ell}{N}, \quad \mathrm{Var}\left(T_{pt}\right) = 0 \tag{6.27}$$

If $L_b$ is the bit delay caused by each station,

$$T_b = \frac{L_b}{R}$$

and

$$E(T_b) = \frac{L_b}{R}, \quad \mathrm{Var}(T_b) = 0 \tag{6.28}$$

We conclude from Eqs. (6.24)–(6.28) that

$$r = \frac{P\ell}{N} + \frac{L_b + L_t}{R}, \quad \delta^2 = 0 \tag{6.29}$$

The average propagation delay suffered from one station is the propagation delay halfway around the ring, i.e.

$$E(T_p) = \tau/2 \tag{6.30}$$

where τ is the round-trip propagation delay. Note that the sum of the switchover times (assumed to be constant) corresponds to the round-trip propagation delay and the sum of the bit-holding times at each station, i.e

$$Nr = P\ell + N(L_b + L_t)/R = \tau \tag{6.31}$$

Thus, for large N and symmetric traffic conditions, the mean transfer delay is obtained by substituting Eqs. (6.19)–(6.21), (6.29), and (6.30) in Eq. (6.1). We obtain:

Exhaustive service:

$$\boxed{E^e(D) = \frac{\tau(1-\rho/N)}{2(1-\rho)} + \frac{\rho E(S^2)}{2(1-\rho)E(S)} + E(S) + \tau/2} \tag{6.32}$$

Gated service:

$$\boxed{E^g(D) = \frac{\tau(1+\rho/N)}{2(1-\rho)} + \frac{\rho E(S^2)}{2(1-\rho)E(S)} + E(S) + \tau/2} \tag{6.33}$$

Limited service:

$$\boxed{E^\ell(D) = \frac{\tau(1+\rho/N)}{2(1-\rho-\lambda\tau)} + \frac{\rho E(S^2)}{2(1-\rho-\lambda\tau)E(S)} + E(S) + \tau/2} \tag{6.34}$$

Finally, the mean service time E(S) is given by

$$E(S) = \frac{L_p + L_h}{R} = \rho/\lambda \tag{6.35a}$$

where $L_p$ and $L_h$ are the mean packet length and header length respectively. For fixed messages (requiring constant service times),

$$E(S^2) = E^2(S) \tag{6.35b}$$

and for exponential service times,

$$E(S^2) = 2E^2(S) \tag{6.35c}$$

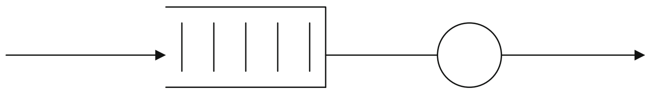


**Fig. 6.5** A switching node; for Example 6.1

*Example 6.1* Messages arrive at a switching node at the rate of 2 bits/min, as shown in Fig. 6.5. If the messages is exponentially distributed with an average length of 20 bytes and the node serves 10 bits/s, calculate the traffic intensity.

**Solution**

The arrival rate is the number of messages/second or packets/second.

$$\lambda = 2bits/\text{min}ute = \frac{2}{60}bps$$

The service time is the time taken to service 1 packet.

$$E(S) = \frac{L_p}{R} = \frac{20 \times 8}{10} = 16s$$

The traffic intensity is given by

$$\rho = \lambda E(S) = \frac{2}{60} \times 16 = 0.5333$$

*Example 6.2* A token-ring LAN has a total propagation delay of 20 μs, a channel capacity of $10^6$ bps and 50 stations, each of which generates Poisson traffic and has a latency of 1 bit. For a traffic intensity of 0.6, calculate:

(a) the switchover time,
(b) the mean service time,
(c) the message arrival rate per station,
(d) the average delay for exhaustive, gated, and limited service disciplines.

Assume 10 bits for overhead and 500 bits average packet length, exponentially distributed.

**Solution**

(a) If the end-to-end propagation time is $\tau = 20$ μs, then the switchover time $\tau$ is given by

$$r = \frac{\tau}{N} = \frac{20}{50} = 0.4\mu s$$

(b) The mean service time is

$$E(S) = \frac{L_p + L_h}{R} = \frac{500 + 10}{10^6} = 510\mu s$$

(c) Since $\rho = \lambda E(S)$, the total arrival rate is

$$\lambda = {}^{\rho}/_{E(S)}$$

Hence, the arrival rate per station is

$$\lambda_i = \frac{\rho}{NE(S)} = \frac{0.6}{50 \times 510 \times 10^{-6}} = 23.53\,\text{bps}$$

(d) For exponentially distributed packet lengths,

$$E\left(S^2\right) = 2E^2(S) = 52.02 \times 10^{-8} s^2$$

Using Eqs. (6.32)–(6.34), we obtain

$$\begin{aligned} E^e(D) &= \frac{20 \times 10^{-6}(1 - 0.6/50)}{2(1 - 0.6)} + \frac{0.6 \times 52.02 \times 10^{-8}}{2(1 - 0.6) \times 510 \times 10^{-6}} \\ &\quad + 510 \times 10^{-6} + 10 \times 10^{-6} \\ &= (24.7 + 765 + 520)\mu s = 1.3097\text{ms} \end{aligned}$$

for exhaustive service.

For gated service,

$$E^g(D) = \frac{20 \times 10^{-6}(1 + 0.6/50)}{2(1 - 0.6)} + (765 + 520)\,\mu s = 1.3103\,\text{ms}$$

For limited service,

$$\begin{aligned} E^l(D) &= \frac{20 \times 10^{-6}(1 + 0.6/50)}{2(1 - 0.6 - 0.02353)} + \frac{0.6 \times 52.02 \times 10^{-8}}{2(1 - 0.6 - 0.02353) \times 510 \times 10^{-6}} \\ &\quad + 510 \times 10^{-6} + 10 \times 10^{-6} \\ &= (26.881 + 812.81 + 520)\mu s = 1.3597\text{ms} \end{aligned}$$

Notice that

$$E^e(D) < E^g(D) < E^{\ell}(D)$$

as stated in Eq. (6.22).

## 6.4 Token-Passing Bus

The token-passing bus was inspired by the token ring and standardized in the IEEE Standard 802.4. The basic operation of the token bus LAN is fully discussed in [3, 12] while its delay analysis in [13].

### *6.4.1 Basic Operation*

The operation of the token bus is similar in many respects to that of the token ring. Although the token bus uses bus topology while the token ring uses ring, the stations on a token bus are logically ordered to form a *logical ring*, which is not necessarily the same as the physical ordering of the stations. Figure 6.6 shows a typical ordering of stations on bus with the sequence AEFHCA. Each station on the ring knows the identity of the stations preceding and following it. The right of access to the bus is controlled by the cyclic passing of a token among the stations in the logical ring. Unlike in a token ring where the token is passed implicitly, an explicit token with node addressing information is used. The token is passed in order of address. When a station receives the token, it may transmit its messages according to a service discipline (exhaustive, gated, or limited) and pass the token to the next station in the logical ring.

A token bus differs in some respects from token ring. Since token bus is a broadcast protocol, stations not in the logical ring can receive messages. Stations on a token bus are passive and thus create no station latency or delay unlike in token ring where the signal is regenerated at each station. Propagation delay on a token bus are generally longer because the token may have to travel longer distances to satisfy the logical ordering of the stations.

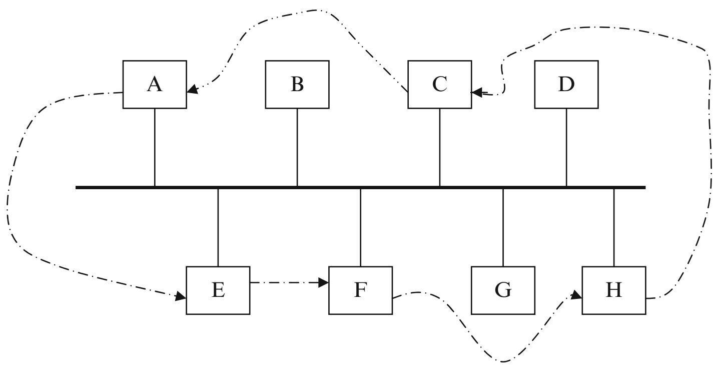


**Fig. 6.6** A typical logical ordering on a physical bus

### 6.4.2 Delay Analysis

As mentioned earlier, the expressions for waiting time (or queueing delay) in Eqs. (6.19)–(6.21) are valid for both token ring and token bus protocols except that the mean value of r of the switchover time and its variance $\delta^2$ are different for the two protocols. We now evaluate these parameters as they apply to the token bus.

Unlike token ring, the token bus requires that the complete token packet be transmitted, received, and identified before a data packet can be generated and transmitted. Therefore, the token passing transmission time $T_t$ is a significant delay in token bus protocol. According to Eq. (6.26),

$$E(T_t) = T_t = \frac{L_t}{R}, \quad \mathrm{Var}(T_t) = 0 \tag{6.36}$$

Assuming bus length $\ell$, uniform distribution of N stations, and an equal probability of communication between any two stations, the distance between station i and its logical successor j is given by

$$d_{ij} = jd = \frac{j\ell}{N-1}, \quad 1 \le j \le N-1 \tag{6.37}$$

The probability of station i having the token and passing it to station j is given by

$$P_{ij} = \frac{1}{\binom{N}{2}} = \frac{2}{N(N-1)} \tag{6.38}$$

If X is the token propagation distance, the expected token propagation delay is

$$E(X) = \sum d_{ij}P_{ij} = \sum_{i=1}^{N}\sum_{j=1}^{i-1} \frac{2\ell j}{N(N-1)^2} = \frac{(N+1)\ell}{3(N-1)} \tag{6.39}$$

where the identities

$$\sum_{i=1}^{n} i = \frac{n}{2}(n+1)$$

and

$$\sum_{i=1}^{n} i^2 = \frac{n}{6}(n+1)(2n+1)$$

have been applied. Corresponding to the bus length $\ell$, we have an end-to-end propagation delay $\tau$. Therefore, the expected token propagation delay is

$$E\left(T_{pt}\right) = \frac{(N+1)\tau}{3(N-1)} \tag{6.40}$$

The variance of X is given by

$$\begin{aligned} \mathrm{Var}(X) &= E\left(X^2\right) - [E(X)]^2 = \sum d_{ij}^2 P_{ij} - [E(X)]^2 \\ &= \frac{(N+1)\ell^2}{3(N-1)^3} - \frac{(N+1)^2\ell^2}{9(N-1)^2} \end{aligned} \tag{6.41}$$

where the identity

$$\sum_{i=1}^{n} i^3 = \frac{n^2}{4}(n+1)^2$$

has been incorporated. Thus the variance of the token passing propagation delay is

$$\mathrm{Var}\left(T_{pt}\right) = \frac{(N+1)(N-2)\tau^2}{18(N-1)^2} \tag{6.42}$$

The bit delay per station adds to the token passing time a delay corresponding to token handling and address recognition. In IEEE 802.4, for example, a buffer of four or five bits may be required depending on the size of the address field. If $L_b$ is the bit delay caused by each station,

$$T_b = \frac{L_b}{R}$$

and

$$E(T_b) = \frac{L_b}{R}, \quad \mathrm{Var}(T_b) = 0 \tag{6.43}$$

Substitution of Eqs. (6.36), (6.40), (6.42), and (6.43) into Eqs. (6.24) and (6.25) yields

$$r = \frac{(N+1)\tau}{3(N-1)} + c, \quad \delta^2 = \frac{(N+1)(N-2)\tau^2}{18(N-1)^2} \tag{6.44}$$

with limiting values ($N \to \infty$) of

$$r = \frac{\tau}{3} + c, \quad \delta^2 = \frac{\tau^2}{18} \tag{6.45}$$

where

$$c = T_t + T_b = \frac{L_t + L_b}{R}$$

The packet propagation delay is the same as the token propagation delay so that for large N,

$$E(T_p) = \tau/3 \tag{6.46}$$

If we assume large N and symmetric traffic conditions, the mean transfer time is obtained by substituting Eqs. (6.19)–(6.21), (6.45), and (6.46) into Eq. (6.1).

Exhaustive service:

$$\boxed{E^e(D) = \frac{\tau^2}{36(\tau/3 + c)} + N(\tau/3 + c)\frac{(1 - \rho/N)}{2(1 - \rho)} + \frac{\rho E(S^2)}{2(1 - \rho)E(S)} + E(S) + \tau/3} \tag{6.47}$$

Gated service:

$$\boxed{E^g(D) = \frac{\tau^2}{36(\tau/3 + c)} + N(\tau/3 + c)\frac{(1 + \rho/N)}{2(1 - \rho)} + \frac{\rho E(S^2)}{2(1 - \rho)E(S)} + E(S) + \tau/3} \tag{6.48}$$

Limited service:

$$\boxed{\begin{aligned} E^\ell(D) = &\frac{\tau^2}{36(\tau/3 + c)} + \frac{N(\tau/3 + c)(1 + \rho/N)}{2[1 - \rho - N\lambda(\tau/3 + c)]} \\ &+ \frac{\rho E(S^2)}{2[1 - \rho - N\lambda(\tau/3 + c)]E(S)} + E(S) + \tau/3 \end{aligned}} \tag{6.49}$$

where the mean service time E(S) is given by Eq. (6.35) and the end-to-end propagation delay by

$$\tau = P\ell \tag{6.50}$$

## 6.5 CSMA/CD Bus

Multiple access local area network (LAN) protocols divide broadly into two classes [14]: *random* (or *contention* ) access protocols and *controlled access* protocols. In random access protocols, transmission rights are simultaneously offered to a group of stations in the hope that exactly one of the stations has a packet to send. However, if two or more stations send packets simultaneously on the channel, these messages interfere with each other and none of them are correctly received by the destination stations. In such cases, a collision has occurred and stations retransmit packets until they are successfully received by the destination stations.

Controlled-based access mechanism is one in which a token is first secured by a node in order to transmit its messages through the medium. Controlled access protocols, such as token ring and token bus considered in Sections 6.3 and 6.4 respectively, avoid collisions by coordinating access of the stations to the channel by imposing either a predetermined or dynamically determined order of access. Access coordination is done by use of the channel itself. Each station indicates with a short message on the channel whether or not it wants access. This polling mechanism consumes some channel capacity regardless of whether stations require access or not. While such protocols are efficient when traffic is heavy, under light traffic conditions they result in unnecessary packet delays as stations that want to transmit wait their turn.

In contrast, random access protocols exhibit small packet delays under light traffic conditions: stations transmit as soon as they want access to the channel, and the probability of a collision is low when traffic is light. Another attractive aspect of random access protocols is their simplicity, making them easy to implement at the stations [15].

The ALOHA family of protocols is popular due its seniority because it was the first random access mechanism to be introduced. In this type of protocols, the success of a transmission is not guaranteed in advance. When two or more packets overlap in time, even by a bit, all are lost and must be retransmitted. The carrier sense multiple access (CSMA) reduces the level of interference caused by overlapping packets by allowing users to sense the carrier due to other users' transmissions and aborting transmission when the channel is sensed busy. In CSMA, all nodes listen constantly to the bus and only transmit if there is no transmission already on the bus. This is the *carrier sense* aspect of the name. If there is no transmission on the bus, any node with available data can transmit immediately, hence the term *multiple access*. Beside the ability to sense carrier, some LANs have an additional feature of being able to detect interference among several transmissions while transmitting and abort transmission when there is collision. This additional feature produces a variation of CSMA that is known as CSMA-CD (Carrier Sense Multiple Access with Collision Detection). Because of its simplicity, CSMA-CD is perhaps the most popular contention-based protocol. It operates on a bus-type network and is sometimes referred to as the 'Ethernet' protocol.

### *6.5.1 Basic Operation*

In a LAN employing CSMA-CD protocol, each node listens during, as well as before, transmitting its packet. Variations within the CSMA-CD protocols center about the operation mode of the station when the medium is sensed busy or idle. The most popular operation modes are [15, 16]:

- nonpersistent,
- 1-persistent, and
- p-persistent protocols

In the nonpersistent CSMA-CD scheme, a node with a packet ready for transmission senses the channel and acts as follows.

1. If the channel is sensed idle, the node initiates transmission of the packet.
2. If the channel is sensed busy, the node schedules the retransmission of its packet to some later time. It waits for a random amount of time and resenses the channel.
3. If a collision is detected during transmission, the node aborts its transmission, and schedules the retransmission of the packet later.

In the 1-persistent CSMA-CD protocol (which is a special case of the p-persistent), a node which finds the channel busy persists on transmitting as soon as the channel becomes free. If it finds the channel idle, it transmits the packet immediately with probability one. In other words, a ready node senses the channel and proceeds as in nonpersistent CSMA-CD, except that, when the channel is sensed busy, it monitors the channel until it is senses idle and then with probability one initiates transmission of its packet.

In the p-persistent protocol, a ready node senses the channel and proceeds as in non-persistent protocol except that when the channel is sensed busy, the node persists until the channel is idle, and

(i) With probability p it initiates transmission of the packet
(ii) With probability 1-p it delays transmission by $\tau$ seconds (the end-to-end propagation delay).

If at this instant, the channel is sensed idle, then the node repeats steps (i) and (ii); otherwise it schedules retransmission of its packet later.

Note that in all CSMA-CD protocols, given that a transmission is initiated on an empty channel, it takes at most one $\tau$ seconds for the packet transmission to reach all nodes. Beyond this time the channel will surely be sensed busy for as long as data transmission is in process. A collision can only occur if another transmission is initiated before the current one is sensed, and it will take at most additional $\tau$ seconds before interference reaches all devices. Moreover, Ethernet has a collision consensus reinforcement mechanism by which a device, experiencing interference, jams the channel to ensure that all other interfering nodes detect the collision.

In addition to the variations in the protocols, the transmission medium may be slotted or unslotted.

### *6.5.2 Delay Analysis*

A widely used analytic model of CSMA-CD networks was developed by Lam [17, 18]. The analysis of the M/G/1 queue using embedded Markov chain led to a closed-form expression for the mean delay E(D). The underlying assumptions are close to the standardized CSMA-CD protocol, and the results are simple to evaluate numerically.

The underlying assumptions in Lam's model are as follows. The network consists of an infinite number of stations connected to a slotted channel in which stations can begin transmissions only at the start of a time slot. The traffic offered to the network is a Poisson process with a constant arrival rate λ. Each state is allowed to hold at most one message at a time. Message transmission times are generally distributed. The system operates under the p-persistent protocol. Following a successful transmission, all ready stations transmit within the next slot. Following a collision, stations use an adaptive retransmission algorithm such that the probability of a successful transmission within any of the slots subsequent to a collision is constant and equal to 1/e (=0.368).

Under these assumptions, the mean delay was found by Lam and later modified by Bux [4, 19] for non-slotted channel as:

$$\boxed{\begin{aligned} E(D) = {} & \frac{\lambda\left[E\left(S^2\right) + (4e+1)\tau E(S) + 5\tau^2 + 4e(2e-1)\tau^2\right]}{2(1-\lambda[E(S)+\tau+2e\tau])} \\ & - \frac{\left(1-e^{-2\lambda\tau}\right)(e+\lambda\tau-3\lambda\tau e)}{\lambda e\left[F(\lambda)e^{-(1+\lambda\tau)}+e^{-2\lambda\tau}-1\right]} + 2\tau e + E(S) + \tau/3 \end{aligned}} \tag{6.51}$$

where τ is the end-to-end propagation delay as in Eq. (6.50), E(S) and $E(S^2)$ are respectively the first and second moments of the message transmission (or service) time as given by Eq. (6.35). The term τ/3 is the mean source-destination propagation time $E(T_p)$. It is heuristically taken as τ/2 in other works, but we have used τ/3 to be consistent with the derivation in Eq. (6.46). The function F(λ) is the Laplace transform of the message transmission time distribution, i.e.

$$F(\lambda) = \int_0^\infty f(t)e^{-\lambda t}dt \tag{6.52}$$

For constant message lengths,

$$F(\lambda) = e^{-\rho}, \quad E\left(S^2\right) = E^2\left(S\right) \tag{6.53}$$

where ρ = λE(S). For exponentially distributed message lengths,

$$F(\lambda) = \frac{1}{1+\rho}, \quad E\left(S^2\right) = 2E^2(S) \tag{6.54}$$

It is important to note the two limiting cases of operation of CSMA/CD from Eq. (6.51). The mean delay becomes unbounded as the traffic intensity ρ approaches the maximum value of

$$\rho_{\max} = \frac{1}{1+(2e+1)a} = \frac{1}{1+6.44a} \tag{6.55}$$

where $a = \tau/E(S)$. Also as the traffic intensity ρ approaches zero, the mean delay approaches the minimum value of

$$E(D)_{\min} = E(S) + \tau/3 \tag{6.56}$$

*Example 6.3* A CSMA/CD network with a channel bit rate of 1 Mbps connects 40 stations on a 2-km cable. For fixed packet length of 1,000 bits, calculate the mean transfer delay. Assume propagation delay of 5 μs/km and an average arrival rate/station of 0.015 packets/s.

**Solution**

The mean service time is

$$E(S) = \frac{L_R}{R} = \frac{1,000}{10^6} = 10^{-3}s$$

The mean arrival rate for each station is

$$\lambda_i = 0.015 \times 1,000 \text{ bits/s} = 15 \text{ bps}$$

Hence, the total arrival rate is

$$\lambda = N\lambda_i = 40 \times 15 = 600 \text{ bps}$$

The traffic intensity is

$$\rho = \lambda E(S) = 10^{-3} \times 600 = 0.6$$

The end-to-end propagation delay is

$$\tau = \frac{\ell}{u} = \ell P = 2 \text{ km} \times 5\mu s/\text{km} = 10\mu s$$

For constant packet lengths,

$$F(\lambda) = e^{-\rho}, \quad E\left(S^2\right) = E^2(S) = 10^{-6}$$

Applying Eq. (6.51), we obtain the delay as

$$\begin{aligned}
E(D) &= \frac{600\left\{10^{-6} + \left[(4e+2) \times 10^{-5} \times 10^{-3}\right] + 5 \times 10^{-10} + \left[4e(2e-1) \times 10^{-10}\right]\right\}}{2\left\{1 - 600\left[\left(10^{-3} + 10^{-5} + \left(2e \times 10^{-5}\right)\right]\right\}} \\
&\quad - \frac{\left(1 - e^{-2x6x10^{-3}}\right)\left[e + 6 \times 10^{-3} - \left(3e \times 6 \times 10^{-3}\right]\right.}{600e\left[e^{-0.6}e^{-\left(1+6x10^{-3}\right)} + e^{-12x10^{-3}} - 1\right]} + 2e \times 10^{-5} + 10^{-3} + \frac{10^{-5}}{3} \\
&= (761.35 - 103.87 + 1005.77)\mu s \\
&= 1.663 \text{ ms}
\end{aligned}$$

## 6.6 STAR

Due to their simplicity, the star networks evolved as the first controlled-topology networks. They are regarded as the oldest communication medium topologies because of their use in centralized telephone exchanges. As we shall see, the star topology has some disadvantages which led to its apparent unpopularity in local area networks. While the control of traffic is distributed in both the bus and the ring topologies, it is concentrated in the star.

### *6.6.1 Basic Operation*

A star topology usually consists of a primary node (hub) and secondary nodes (the nodes on the periphery). The primary node is the central node which acts like a switch or traffic director. Communication between any two nodes is via circuit switching. When a peripheral node has data to transmit, it must first send a request to the central node which establishes a dedicated path between the node and the destination node. All links must therefore be full duplex to allow two-way communication between the primary and secondary nodes as shown in Fig. 6.7.

The use of a central node to perform all routing provides a fairly good mapping of technology, but at the expense of creating a complex routing station. The central node is a complex one from a hardware standpoint. It is also a limiting element in the star growth because it requires the hub to have a spare port to plug a new link. The delay caused by the hub affects the performance of the network. Because of the problems associated with the central switch, the star network exhibits growth

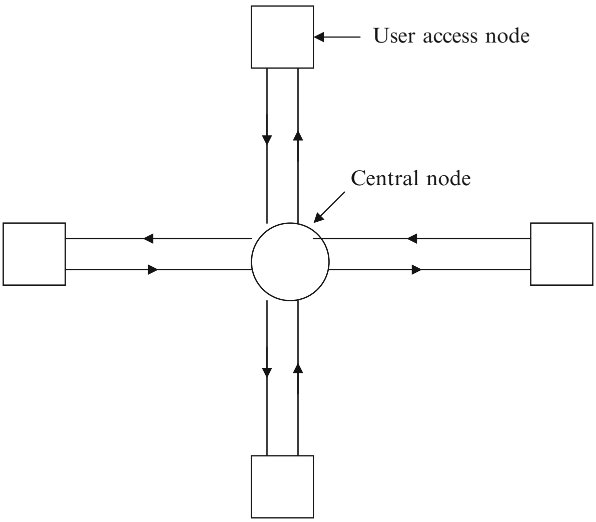


**Fig. 6.7** A typical star network

limitations, low reliability, poor expandability, and a complex central node. In spite of the bottleneck caused by the central node, however, the star is one of the common topologies commonly in use. Although the star may not be as effective as the bus or ring in terms of routing, the star is effectively used for other reasons.

The star networks offer positive features that many other networks lack. For example, the interconnection in star networks is point to point which makes them suitable for optical fiber-based implementation. That is, in fiber-optic systems, star-shaped topologies are usually preferred because they allow the interconnection of more nodes, are less prone to catastrophic failure, and are relatively flexible and expandable. In fact the first optical fiber networks were built in the star configuration [20]. Also, the throughput of star networks is usually very high and can easily approach unity, which means that the bandwidth is effectively utilized. Very high data rates can be sustained on star networks. Star systems allow simple modular expansion, and their performance is in general better than the performance of other networks [21].

### *6.6.2 Delay Analysis*

Delay analyses of star networks have been carried out by Kamal [21] and Mehmet-Ali, Hayes and Elhakeem [22]. Here we adopt the approximate analysis in [22].

The underlying assumptions of the analysis are as follows. Messages are assumed to arrive at each source node according to Poisson process with an average arrival rate of $\lambda_i$ and have an arbitrary length distribution. Messages arrive to the system at one of the N nodes and are switched to one of the other (N − 1) nodes. It is assumed that the source-destination line pair must be free before a message can be transmitted and that the probability that a message will have its destination as its source is zero. It is also assumed that messages are transmitted from the source queues strictly in their order of arrival. Finally, it is assumed that the traffic is symmetric. With each source modeled as an M/G/1 queue, the waiting time or queueing delay is obtained as [22]:

$$E(W) = \hat{y} + \frac{\lambda \hat{y}^2}{2(1-\rho)} \tag{6.57}$$

where

$$\hat{y} = [1 + (N-2)\rho G]E(S) \tag{6.58a}$$

$$\hat{y}^2 = 2\left[1 + 2(N-2)\rho G + (N-2)(N-3)\rho^2 G^2\right]E\left(S^2\right) \tag{6.58b}$$

$$\rho = \frac{\lambda E(S)}{1 - (N-2)G\lambda E(S)} \tag{6.58c}$$

$\lambda = \lambda_i$, and G = 1/(N − 1) is the probability that a message from source i will have node j as its destination. From Eq. (6.57), the stability requirement $\rho \leq 1$ implies that $\lambda E(S) \leq (N-1)(2N-3)$. For large N, this implies $\lambda E(S) \leq 1/2$.

The source-destination propagation time $E(T_p)$ is given by

$$E(T_p) = \tau \tag{6.59}$$

where τ is the round-trip or two-way propagation delay between any node and the central hub.

By substituting Eqs. (6.57) and (6.59) into Eq. (6.1), we obtain

$$\boxed{E(D) = \hat{y} + \frac{\lambda \hat{y}^2}{2(1-\rho)} + E(S) + \tau} \tag{6.60}$$

E(S) and $E(S^2)$, the first and second moments of the message service time, are given by Eq. (6.35).

## 6.7 Performance Comparisons

Having examined each LAN protocol separately, it is instructive that we compare the protocols in terms of their performance under similar traffic conditions. We compare Eqs. (6.32), (6.47), (6.51), and (6.60) and present typical performance results for the four protocols. As expected, the components of the mean delay that depend on the propagation delay make a negligible contribution towards total delay. The queueing delay, on the other hand, contribute heavily to the total delay.

Figures 6.8 and 6.9 compare the delay characteristic of the four protocols. In both figures, the ordinate represents the mean delay normalized to the mean service time, E(D)/E(S), while the abscissa denotes the traffic intensity or offered load, $\rho = \lambda E(S)$. In both figures, we consider:

N (no. of stations) = 50
$\ell$ (cable length) = 2 km
Packet length distribution: exponential
$E(L_p)$ (mean packet length) = 1,000 bits
$L_h$ (header length) = 24 bits
$L_b$ (bit delay) = 1 bit
$L_t$ (token packet length) = 0
P (propagation delay) = 5 μs/km

Figure 6.8 shows the curves plotted for the four protocols when the transmission rate, R, is 1 Mb/s. It is apparent from Fig. 6.8 that the star has the worse performance; the token ring performs less well than the token bus over the entire throughput range; and the token bus and CSMA-CD protocols track one another closely over most of the throughput range.

Increasing the transmission rate to 10 Mb/s while keeping other parameters the same, we obtain the curves in Fig. 6.9. It is evident from this figure that the

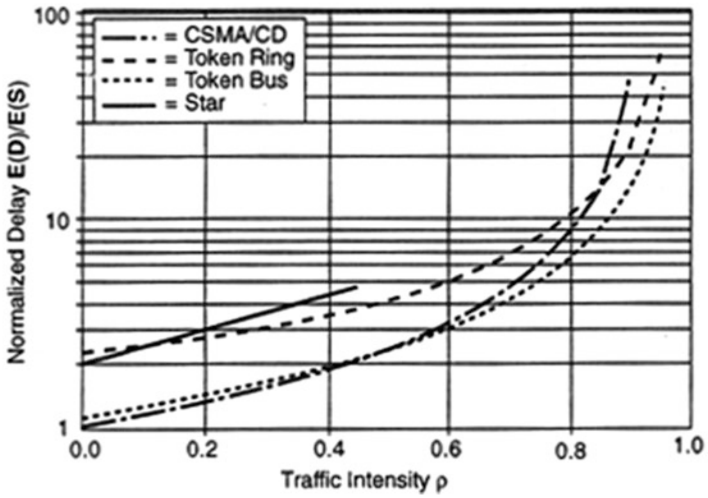


**Fig. 6.8** Normalized delay versus traffic intensity at R = 1 Mbps

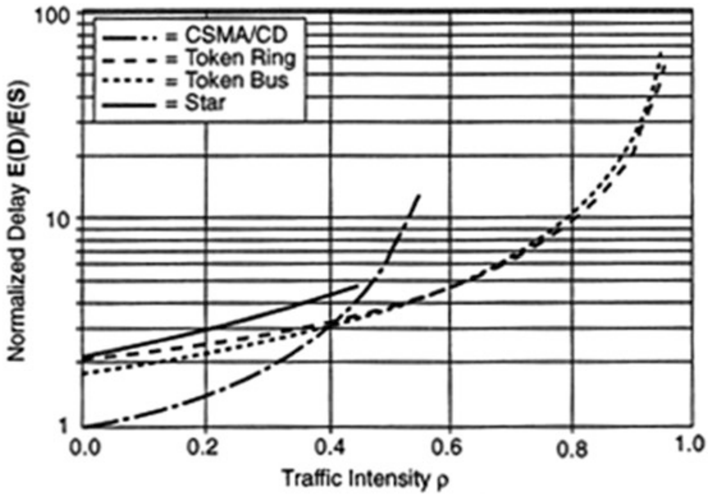


**Fig. 6.9** Normalized delay versus traffic intensity at R = 10 Mbps

performance of the star is still worst, the performance of both token-passing protocols is only slightly affected by the increased network rate, thus showing little sensitivity to this parameter. However, the CSMA-CD scheme is highly sensitive to the transmission rate. This should be expected because with increase in the transmission rate, relatively more collisions take place and more transmission attempts result in collisions.

From performance grounds, CSMA-CD is better at light loading. For heavy loading, token ring seems to be more desirable than token bus, and certainly more desirable than CSMA-CD networks. Performance, however, may not be the only consideration in selecting a LAN technology. From a reliability viewpoint, for example, token ring presents problems: whenever a station attached to the ring fails, the whole network fails since the message must be retransmitted at each station. Also considering the ease of maintenance, availability, extendibility, and complexity of a physical layer design, a bus architecture has some advantages over ring.

## 6.8 Throughput Analysis

Our major concern in the previous sections has been on using delay as the major performance criterion of the LANs. In this section, we will use throughput as the major performance measure. The throughput of a LAN is a measure in bits per second of the successful (or error-free) traffic being transmitted between stations.

The **throughput** is the fraction of time that is used to transmit information.

Since the information can be corrupted as it travels from one station to another, it is conventional to count only the error-free bits when measuring throughput.

To find the channel throughput S, we let E(U) be the average time that the channel is used without collisions, E(B) be the average busy period, and E(I) be the average idle period. The throughput is given by

$$S = \frac{E(U)}{E(B) + E(I)} \tag{6.61}$$

This is based on the assumption that the stations are statistically identical and that the network has reached steady state. The throughput is usually expressed in terms of the offered traffic rate G and the parameter *a*

$$a = \frac{\text{propagation delay}}{\text{packet transmission delay}} = \frac{\tau}{T_p} \tag{6.62}$$

The parameter a corresponds to the vulnerable period during which a transmitted packet can experience a collision. It is usually a small quantity, say 0.01.

For unslotted nonpersistent CSMA/CD, the throughput is given by [15]

$$S = \frac{Ge^{-aG}}{Ge^{-aG} + bG(1 - e^{-aG}) + 2aG(1 - Ge^{-aG}) + 2(2 - e^{-aG})} \tag{6.63}$$

where b is the jamming time or the length of the jamming signal. For slotted nonpersistent CSMA/CD,

$$S = \frac{aGe^{-aG}}{aGe^{-aG} + bG(1 - e^{-aG} - aGe^{-aG}) + a(2 - e^{-aG} - aGe^{-aG})} \tag{6.64}$$

## 6.9 Summary

1. In this chapter, we examined the delay-throughput characteristics of four local area networks: token ring, token bus, CSMA-CD bus, and star.
2. In order to make a valid comparisons between the schemes, we presented analytical models based on similar sets of assumptions. Assuming an M/G/1 queueing model for each station in the network, we obtained closed form approximate formula(s) for the mean delay for each protocol. The protocols were then compared under the same traffic conditions.
3. Throughput analysis of CSMA/CD was also considered.

The performance analysis of LANs is presented in [23].

## Problems

6.1 Describe briefly the seven layers of the OSI model.

6.2 Compare and contrast controlled access and random access protocols.

6.3 Explain how token ring works.

6.4 In a Cambridge ring with a data rate of 5 Mbps, each slot has 37 bits. If 50 stations are connected to the ring and the average internodal distance is 20 m, how many slots can the ring carry? Assume a propagation speed of $2.5 \times 10^8$ m/s and that there is a 1-bit delay at each station.

6.5 For a token-passing ring, assume the following parameters:

| | | |
|---|---|---|
| No. of stations | = | 50 |
| Transmission rate | = | 1 Mbps |
| Mean packet length | = | 1,000 bits (exponentially distributed) |
| Length of the ring | = | 2 km |
| Token length | = | 24 bits |
| Header length | = | 0 bit |
| Bit delay | = | 1 bit |
| Propagation delay | = | 5 μs/km |

Calculate the mean delay of a message for exhaustive service discipline for $\rho = 0.1, 0.2, \ldots, 0.9$.

6.6 For both constant exponential packet distributions, calculate the mean delay for a token bus LAN with the following parameters:

| | | |
|---|---|---|
| No. of stations | = | 50 |
| Transmission rate | = | 5 Mbps |
| Mean packet length | = | 1,000 bits |
| Bus length | = | 1 km |
| Token length | = | 96 bits |
| Header length | = | 0 bit |

(continued)

| | | |
|---|---|---|
| Bit latency | = | 1 bit |
| Propagation delay | = | 5 μs/km |

Try cases for ρ = 0.1, 0.2, . . ., 0.9 and assume exhaustive service discipline.

6.7 Explain how CSMA/CD protocol works.

6.8 Repeat problem 6.6 for the CSMA/CD protocol.

6.9 (a) Assuming an exhaustive service discipline, calculate the average transfer delay of a token bus with the following parameters.

| | | |
|---|---|---|
| No. of stations | = | 40 |
| Transmission rate | = | 1 Mbps |
| Mean packet length | = | 500 bits (exponentially distributed) |
| Cable length | = | 4 km |
| Token length | = | 96 bits |
| Header length | = | 0 bit |
| Bit delay | = | 1 bit |
| Propagation delay | = | 2 μs/km |
| Traffic intensity | = | 0.4 |

(b) Repeat part (a) for a CSMA/CD bus LAN.

6.10 Rework Problem 6.6 for the case of a constant packet length of 1,000 bits.

6.11 Verify Eqs. (6.55) and (6.56).

6.12 For the unslotted nonpersistent CSMA/CD, plot the throughput S versus offered local G. Take a = 0.01 and b = 5a.

6.13 Repeat 6.12 for slotted nonpersistent CSMA/CD.

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