deterministic, meaning that it is possible to calculate the maximum and minimum amount of time it will take before any end computer will be able to transmit. This, as well as other reliability-increasing features such as fault managment mechanisms, makes token ring networks a good choice for real-time applications such as factory automation.

Token ring was developed around 1980 at an **IBM** research facility in Zurich, Switzerland. There is also an **Institute of Electrical and Electronics Engineers** (IEEE) specification (IEEE 802.5) that is very similar to and completely compatible with IBM's token ring network. One difference is that IBM token ring networks are specified using a star topology: All end computers are attached to a device called a *media access unit* (MAU). The IEEE 802.5 standard does not depend on a particular network topology. The term *token ring* is generally used to refer to both IBM's token ring network and IEEE 802.5 networks.

IBM introduced the first token ring product, a network adapter for the IBM **personal computer** (PC), in October 1985. The first token ring adapters operated at 4 megabits per second (Mbps); the speed of token ring networks was improved in 1989 when IBM introduced the first 16 Mbps token ring hardware. After this the 802.5 standard was also extended to support operation at the new speed. In 1994, the leading token ring vendor companies formed the Alliance for Strategic Token Ring Advancement and Leadership (ASTRAL) to promote token ring technology in the face of increasing popularity of (and competition from) the Ethernet standard.

In 1997 the draft for the IEEE 802.5r standard became available which defined the dedicated token-ring (DTR) operation. This doubled the transfer rate by allowing full duplex transmissions (this means that each computer is able to transmit and receive separate data streams concurently).

In the same year the High Speed Token Ring Alliance (HSTRA) was formed "to rapidly develop the technologies, standards and products necessary to deliver 100 Mbit/s token ring to the still very sizeable token ring customer base." One year later the draft IEEE 802.5t standard became available defining a 100 Mbps operation speed for token ring. The first 100 Mbps token ring adapters were introduced in the same year.

IEEE 802.5v, which standardizes the gigabit token ring, is currently under development.

FURTHER READING

Bird, David. *Token Ring Network Design.* Wokingham, Berkshire, England, and Reading, Mass.: Addison-Wesley, 1994.

Carlo, James T., et al. *Understanding Token Ring Protocols and Standards.* Boston: Artech House, 1998.

Dell'Acqua, Alexa A., and John F. Mazzaferro. *IBM's Token-Ring Network.* Charleston, S.C.: Computer Technology Research Corporation, 1992.

Held, Gilbert. *Token-Ring Networks: Operation, Construction, and Management.* Chichester, West Sussex, England, and New York: Wiley, 1994.

—*Gerald Friedland*

Topology, Network

When computers are interconnected in a **network**, there are different ways of setting up the communication paths between them. The specific arrangement of the computers in relation to the communication medium is the network topology, the shape of the network at hand.

The purpose of computer networks is to allow sharing of information across different machines. Two main issues are the type of communication protocol and the layout of the communication lines between the machines in the network. For example, point-to-point communication between all computers is possible if each machine has a private line to any other. This is too expensive, and therefore a cheaper alternative is *broadcasting networks*, in which any message from a computer can be received by any other. **AlohaNet**, one of the first packet networks, used a radio link with the same frequency for all computers connected. This is a classic example of a broadcasting topology. The principal commercial network topologies are bus, ring, star, and general graph arrangements.

In a *bus topology*, all computers are connected to a single cable that is used for all the data traffic between the machines. The arrangement is similar to that of the AlohaNet, but using an electrical medium. To avoid transmission collisions, the use of the bus has to be managed in some way. This can be done by assigning time slots to the computers, which can only transmit in round-robin fashion. The first computer can transmit in the first time slot, the second in the second time slot, and so on. Of course, the time slots are short enough to avoid long delays when a machine wants to transmit. Although this scheme is very simple, it is also very inefficient, because a machine with much data to be transmitted is allocated only a small portion of the total bandwidth, even if the other machines are idle.

A usual alternative to time slots is to use collision detection in bus networks. Since all machines tap the transmission line, before attempting to send a message, each of them first "hears" if the bus is available. If not, it waits. When the bus becomes available, the transmission is started. It is possible that two machines start transmitting almost at the same time, and a collision occurs. In that case, both machines detect that the data on the bus is being scrambled, stop transmitting, and back off for a short, random amount of time. After waiting, they try to transmit again. The idea of the random waiting time is to avoid consecutive collisions that would block the bus.

Ethernet is a bus network invented in the early 1970s by **Robert Metcalfe** (1946–) and David Boggs (1950–). Ethernet uses CSMA/CD (carrier-sense multiple access with collision detection), a transmission protocol roughly similar to the technique described above. Ethernet also uses *exponential back-off*, which means that after consecutive collisions the interval of time from which the random waiting time is chosen is doubled. In this way, if many computers collide in the bus, the period doubling takes them apart and allows orderly access of the bus.

Ethernet networks have been successful because the bus topology is very simple and it can be used with inexpensive cabling, such as **twisted-pair cable** telephone lines. Ethernet also runs on a number of different media such as coaxial cable and optical lines. Ethernet cards have steadily been improved, going from transmission speeds of 10 megabits per second (Mbps) to the current gigabit speeds.

In a *ring topology*, all computers are connected to a common bus, which is then closed to form a loop. **Token ring** networks work using this arrangement. Collisions are avoided by using a different approach as in Ethernet networks. In a token ring, a special packet, the *token*, is always circulating in the network. Each computer receives and passes it along the ring. If a computer wants to transmit, it absorbs the token, starts transmitting packets, and releases the token when it is done. The token-holding time is limited, so that every computer in the ring has a chance to send information.

Although collisions are avoided with this approach, *starvation* can happen if the token is absorbed by a machine that does not release it again because of failure. In this case, after waiting for some period of time, a machine generates a new token randomly and sends it to the other computers. The token ring protocol then makes sure that not more than one token has been generated. When two or more tokens are in the ring, the extra tokens are absorbed and transmission resumes in the normal way.

Another problem that can affect a token ring is the failure of one segment of the communication ring. If this happens, the ring is broken and the token cannot circulate. To provide fault tolerance, a token ring can be built as a double ring. If one segment in one ring fails, the second ring is used in a special way. One notable example of a token ring network with high transmission speed is the FDDI (**fiber distributed data interface**) standard, which is used over optical data lines providing 100 Mbps speed. FDDI networks are typically used as backbones for wide-area networks. Token ring network research was pursued primarily by **IBM**, who published a specification in 1981.

A *token bus network* is a type of hybrid between a bus network and a token ring. The computers communicate through a bus, but use a token, such as in a token ring, to avoid contention for the bus. Token bus networks are covered by the IEEE 802.4 standard.

A *star topology* is used when a central machine or hub is connected through private lines to many other machines. This is the typical topology of mainframes and their terminals. The **mainframe** is the center of the star and the terminals are situated at the tips of the rays. The main advantage of a star topology is that every computer or terminal can use the full speed of the communication channel.

Star networks have made a comeback in the realm of **local area networks**. A hub is placed at the center of the star and receives the data from many computers. Each computer has a private line of, for example, 10 Mbps to the hub. The hub can route messages from one computer to the other and can also connect the star to a very fast communication channel, with a speed of, for example, 1000 Mbps. In this way, each workstation needs only cheap twisted-pair cabling, while the communication out of the star is made using a more powerful network (e.g., gigabit Ethernet running over optical links). This would be an example of a hybrid topology, in which different segments of the network use different standards and transmission speeds as well as topology.

The most all-purpose type of network topology is a *general graph*, in which any node can be connected to any other node using private lines. This is the architecture of the **Internet**, in which local area networks are connected together in a general graph without any special structure. When a packet is to be sent over the network, it has to be routed by the computers at the nodes, which collaborate at this task. One approach that can be used to route packets over general graphs is to superimpose a *virtual topology* on the real network. A protocol is started at the nodes, and through the exchange of some messages, a *spanning tree* is found. This is a structure in which one node (the root) communicates with some children nodes, which in turn have other children nodes, and so on. In a tree, there is only one communication path from each node to any other (the packet from one node goes up to a common parent and then down to the destination node). The tree is spanning, because it covers all nodes in the network. Using this approach, once the spanning tree has been built, it is very easy to route messages. If one communication link fails, the spanning tree has to be rebuilt.

In the case of clusters of processors used for parallel computing, there are many other types of network topologies such as *mesh*, *torus*, and **hypercube**. Computers connected in a mesh are arranged in a quadratic grid, with the machines sitting at the crossings of the communication lines. If the upper and lower boundary, as well as the left and right boundary, are glued together, we obtain a torus, a doughnut-shaped structure. In a hypercube, the computers sit at the corners of three-dimensional cubes and the edges are the communication lines. Cubes in higher dimensions (hypercubes) provide more communication paths and place for more machines.

Further Reading

Metcalfe, Robert, and David Boggs. "Ethernet: Distributed Packet Switching for Local Computer Networks." *Communications of the ACM*, Vol. 19, 1976, pp. 395–404.

Sharma, Roshan Lal. *Network Topology Optimization: The Art and Science of Network Design*. New York: Van Nostrand Reinhold, 1990.

Stallings, William. *Data and Computer Communications*. New York: Macmillan; London: Collier Macmillan, 1985; 6th ed., Upper Saddle River, N.J.: Prentice Hall, 2000.

Tannenbaum, Andrew. *Computer Networks*. Englewood Cliffs, N.J.: Prentice-Hall, 1981; 2nd ed., Upper Saddle River, N.J., 1996.

—*Raúl Rojas*

Torres Quevedo, Leonardo

1852–1936

Spanish Engineer

Leonardo Torres Quevedo is the most renowned Spanish engineer of the twentieth century. He made important contributions to **cybernetics** and to the emerging field of computing; he is especially remembered for his **analog computers** and for his written description of a plausible **digital computer**.

Torres Quevedo published his first scientific paper in 1891 and began a 30-year period of intense activity in which he worked on many different projects. He conceived a new type of Zeppelin and, in 1905, built the first Spanish prototype. He experimented with radio control of boats and machines, a technique he called *Telekino*. Torres Quevedo also built several analog computing devices. One of them was his *algebraic machine*, an analog device that could find the roots, real or complex, of algebraic equations of up to eight terms. Moving parts were used to represent numbers in scales that could be linear or logarithmic.

The automatic chess player built by Torres Quevedo in 1912 aroused great interest across Europe. It could