NETWORK TOPOLOGY OPTIMIZATION

The Art and Science of Network Design

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Preface

Technology has changed much since the publication of the author's NETWORK SYSTEMS in 1982. The fields of telecommunications and networking have, in particular, witnessed more significant developments than any other field of human knowledge. This is primarily due to the fact that telecommunications is the engine that is driving the *information age* into our daily lives, as compared to the forces that brought us the agricultural and the industrial ages earlier.

One way to measure the progress in the field of telecommunications is to count the number of technical papers and books published during the last decade. That, however, may be an arduous task. A quick sampling of titles of these publications shows that the subject of designing private networks is still being neglected. Many of the books dealing with network design handle specialized areas such as voice and data, with hardly any information on network topology optimization. Most of the technical papers that dealt with the topological design of data networks were published during the late 1960s and early 1970s. No technical book has ever attempted to assess those papers in the light of the latest developments in the field of integrated corporate networks. A definite need for a book dealing with practical tools for the analysis and design of actual network systems, in addition to providing examples of actual network planning and design, has long existed. The author hopes that this book will meet that need.

The topology of a network system provides a great deal of insight into its behavior. To illustrate, most of the central offices of a public telephone network represents a star topology. Recently, well-publicized outages in Illinois and New Jersey disconnected many large corporations from the rest of the world. They lost millions of dollars in revenue. A redesign of their network topologies would have eliminated such catastrophies.

The recent popularity of T1 digital facilities has made strong impacts on the topologies of integrated corporate networks. Nowadays, one must be able to design mixed network topologies that allow the integration of voice, data, and video applications in a cost-effective manner. New technologies have also created the need for innovative network topologies. The introduction of Doelz's virtual packet and AT&T's ISN/Datakit network architectures requires the design of network links based on the "directed link" and "interconnected star" topologies, respectively. Many recent developments in IBM's System Network Architecture now allow an increasing amount of distributed intelligence within mixed topology networks. Several international standards related to the evolving Integrated Services Digital Network impose their own topological constraints.

It is the purpose of this book to describe well-proven algorithms for the analysis and synthesis of network topologies for voice, data, and integrated voice/data applications under one cover. To accomplish this task, the book is divided into ten chapters. The first chapter deals with basic networking concepts essential for designing cost-effective networks. Those who are well versed with these concepts may skip this chapter. The next three chapters deal with generalized tools for network analysis and design, and specialized tools for network analysis and the design of voice and data networks. These chapters provides a good deal of information for future use. The fifth chapter defines algorithms for synthesizing useful network topologies. The sixth chapter describes a state-of-the-art network design and analysis software package. The next three chapters describe the actual process of designing voice, data, and integrated voice/data network topologies, and presenting the results in a form that provides useful conclusions. The last chapter discusses how the tasks described in this book fit into the overall network planning process. Appendix B describing the evolving networking standards, is also included. The contents of Chapter 10 make copious use of the material presented in Appendix B. An undergraduate degree in telecommunications or equivalent experience in voice and data communications is recommended for full comprehension of the scope of this book.

The author is particularly indebted to a great pioneer, Mr. M. L. Doelz, for introducing the author to most of the key concepts of data communications during the development of the first modem, message switching system, economical networks, and protocol-independent, virtual packet switching. The author would also like to thank Mrs. Pamela Schemagin and Ms. Ajita Sharma for their painstaking help in performing many tedious numerical analyses, proofreadings, and improving the readability of this book.

The author can be reached at P.O. Box 822938, Dallas, TX 75382, or (214) 691-6790. Any questions or inquiries should be sent to above address.

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Basic Networking Concepts

1.1 INTRODUCTORY REMARKS

This book is primarily concerned with the design of telecommunications networks. It is the purpose of this book to use the principle of successive decomposition, or iterative modeling, as expounded in an earlier book, *Network Systems* (Sharma et al. 1982), to provide a balanced treatment of telecommunications network design.

Telecommunications deals with the transmission, emission, or reception of signs, signals, written images, sounds, or intelligence of any nature by wire, radio, optical, or other electromagnetic means. A telecommunications network consist of two or more nodes that are interconnected through transmission links based on one or several of the many available technologies and network topologies. The network may be characterized by a hierarchy of nodes and/or links.

There are basically two types of telecommunications networks—switched and nonswitched. The most common variety of nonswitched system involves communications between two or more humans. Another common variety of the nonswitched system is a broadcasting network, which primarily involves the transmission of only one type of information at any one time from a single location (or several locations repeating the transmission to different areas of reception) and the reception of the same information by a large number of listeners. Other types of nonswitched networks deal with data processing and database management, and generally involve a single service node. This book does not cover nonswitched telecommunication networks. There are many examples of switched communication systems. The best example of a switched system is that of the public telephone network that allows subscribers to talk with one another. Public data networks also provide an excellent example of the switched system used for the interchange of messages or packets of data. Such networks allow the subscribers to fully share the network facilities. This book deals with the topological design of *switched communication networks* that provide a variety of services such as voice, data, and video to subscribers. In order to accomplish that task, one must first introduce basic networking concepts such as classes of communication networks, network components, attributes of network traffic, voice and data communication, and network architecture.

1.2 CLASSIFICATION OF SWITCHED COMMUNICATION NETWORKS

Switched communication systems can be understood only in terms of their roots. One can therefore classify switched communication networks as follows:

1. geographical coverage of the switched network
2. method of accessing the switched network
3. switching technique employed in the network

1.2.1 GEOGRAPHICAL COVERAGE

There are three types of networks characterized by their geographical coverage:

a. Local Area Networks (LANs): About 60 percent of all networks fall into the category of LANs, which span one or more buildings over a campus.
b. Metropolitan Area Networks (MANs): About 22 percent of all networks cover distances of about 50 miles and fall into the catagory of MANs.
c. Wide Area Networks (WANs): About 18 percent of all networks fall into the category of WANs, which cover distances of about 500 miles (10 percent) and larger (8 percent).

Some authors have defined a MAN as an interconnection of LANs, and a WAN as simply an interconnection of LANs and MANs.

1.2.2 METHOD OF ACCESSING

Each subscriber node must be designed to access the switched network for service. Basically, there are three distinct access methods:

1. Demand Access: This is generally employed in most voice and data communication networks. According to this interrupt-based technique, the subscriber goes off-hook to demand service. The service node provides a dial tone immediately after discovering the off-hook condition. The dial tone is an invitation for a further dialogue that ultimately results in a switched path between the calling and the called subscribers.

2. Polled Access: This is another popular method for allowing the computer-controlled switching node to interrogate each subscriber regarding the need for data interchange with another subscriber.

3. Multiaccess: A few WANs employ the ALOHA multiaccess technique, whereby a source node begins transmitting whenever it has a message or packet in its memory. If a collision occurs between two messages/packets transmitted by two sources, each node retransmits after waiting for a random period. In some ALOHA systems, a source will retransmit a message/packet if it does not receive a positive acknowledgment from the destination node within a certain period. The multiaccess technique is primarily employed by LANs. Many LANs employ the *carrier-sense-multi-access* (CSMA) technique, whereby each node senses the carrier on the shared bus before sending the message or packet. Collisions are handled in the same way as for ALOHA. The remaining LANs employ the *token access*, whereby a node can only transmit when it grabs a free token.

1.2.3 SWITCHING TECHNIQUES

Switching technology employed by the network determines the manner in which the network components or facilities are shared among the subscribers. Three types of switching techniques can be enumerated, as follows:

1. Circuit Switching (CS): Provides a private, hardwired connection through the network, between two or more subscribers, for the entire duration of the call. The flow of user information is completely transparent to the network nodes in the path of the call. The connection is brought down immediately after the calling party hangs up. The circuit-switched networks have mainly been employed for voice and video teleconferencing services. The use of the public telephone network for data communications has also been increasing ever since the advent of personal computers (PCs) and low-cost modems.

2. Packet Switching (PS): Packet-switched networks permit the transfer of information between two subscribers through the routing of addressed packets of user data through the network. Unlike the circuit-switched network, each PS node employs the store-and-forward technique for switching each packet, for the purpose of routing it towards the destination on a virtual/permanent circuit established before the start of the transmission. In that sense, the PS node is not transparent to user data. Both the network links (virtual or permanent variety) and nodes are fully shared among all the subscribers. Most PS nodes use only the random-access memory, to minimize the switching delays. Some recently introduced PS systems employ very small packets and the technique of nodal bypassing (when the destination is somewhere else on the virtual circuit) to minimize the delays even further. In general, all packets are switched according to the first-in-first-out (FIFO) scheme, except when priorities are assigned to the packets.

3. Message Switching (MS): Message-switching networks employ a long-term store-and-forward (S/F) scheme for each received message. Each message is generally stored in full before forwarding it towards the destination. There are many variations of a message-switched network, depending upon the length of the message and/or the legal commitments related to the delivery of the message. Some message-switched systems provide a disk-based storage for a short-term retrieval and a magnetic tape storage for a long-term retrieval. Most message-switched networks segment the messages for high utilization of the storage media and fast retrievals from the storage media.

In general, a LAN, MAN, or WAN may employ any combination of the above-mentioned access methods or switching technologies.

1.3 COMPONENTS OF A TYPICAL NETWORK SYSTEM

The smallest switched network system must employ at least one switching (or service) node and several communication facilities known as subscriber lines (SLs) for connecting the on-net subscribers to the switching node(s). If there is more than one switching node, communication facilities known as access lines (ALs) and trunks are employed for interconnecting the various types of switching nodes. The links connecting a lower-level, privately owned, customer premise equipment (CPE) in the form of a Private Branch Exchange (PBX) or a data concentrator to tandem switching (TS) nodes are generally called access lines (ALs). The links that connect tandem switching nodes are called trunks (TKs). In case a private switched network provides communication services to the off-net subscribers (or public), one will need additional ALs for connecting a subset of its switching nodes to the Central Office (CO) switches of the public network. See Figure 1.1 for an illustration of a switched communication network and its major components, as discussed above.

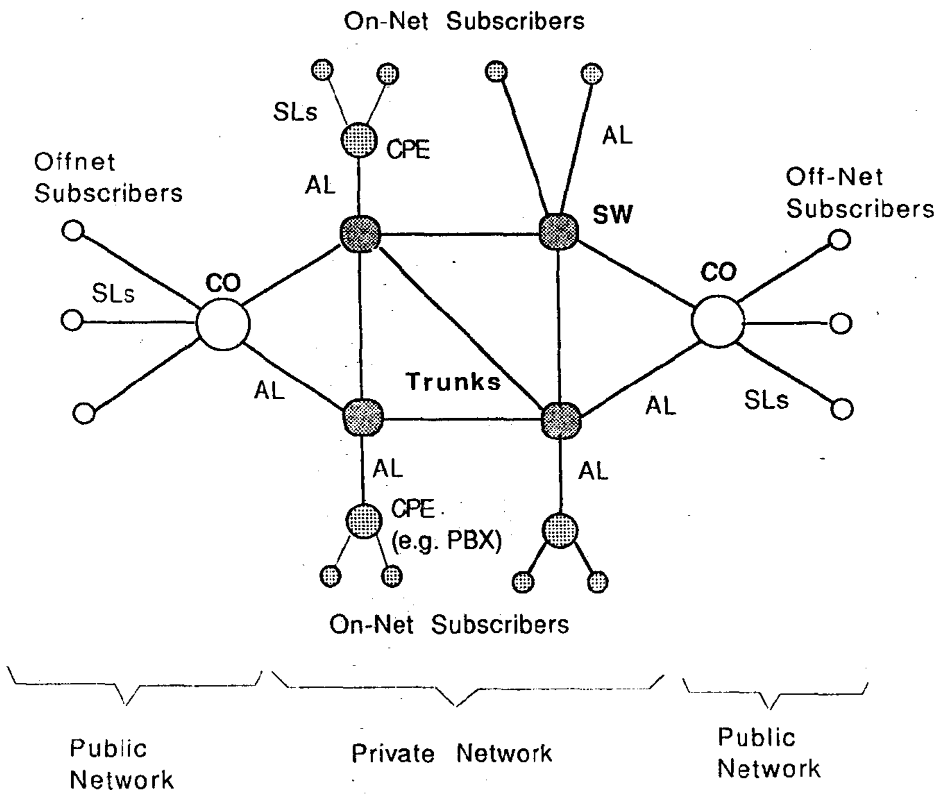

Figure 1.1. Components of a switched communication network.

1.4 BASIC TRAFFIC ATTRIBUTES

A network system exists primarily to provide useful services to a set of subscribers. These services involve many forms of information exchange between network service nodes and subscriber nodes. Several traffic attributes characterize such services. These attributes and their underlying concepts are enumerated in the following paragraphs.

A *telephone/data call* is an unstructured sequence of intelligence flowing in both directions beween the calling and the called subscribers. For circuit-switched voice networks, a call requires the establishment of a reserved, unshared path between the subscribers. A polite conversation between two persons in a voice network implies that intelligence flows in only one of the two directions. This results in a 50 percent utilization of network resources (except for the 2-wire subscriber links). A full duplex data call may not suffer from this constraint. For a packet-switched network, a shared virtual circuit is established before any data packets can be sent.

A *data message* represents the user's data directed from an originating subscriber towards a destination subscriber. Depending upon the switching technique, the message may or may not be transparent to the network node. Since a circuit-switching node does not alter or analyze the contents of the information flowing through the network, it is transparent to the users. Since a message-switching or a packet-switching node, on the other hand, must analyze a packet or a message before routing it to the destination, it therefore does not provide a transparent service to the users. An *input message* is generally called an *inquiry* and an *output message* is generally called a *response*. Many types of *control messages* flow between nodes to perform essential supervisory and signaling functions required by the various services. A message generally consists of many user-defined fields, each clearly demarcated to denote such items as originating and destination addresses, user data, and cyclic redundancy check (CRC) code for error detection. A packet may also consist of similar fields, but their size and contents (except for the user data) is generally defined by a standard or a proprietary protocol. Several packets may be required to transmit a message.

A *transaction* generally involves a series of messages in both directions relative to the user and the network node. A transaction is simply a characteristic of the particular application or service. For example, a Binary Synchronous Communication (BSC) protocol involves a sequence of messages between the data terminal and a host before receiving a response message from the host.

A *session* is almost identical to a transaction except that it may involve one or more transactions. A transaction or a session can not commence until a permanent or a temporary virtual circuit has been established.

The *expected call duration* (ECD) is defined by the duration of a single voice session. Some analysts substitute call holding time for ECD. A *message length* is generally determined by the number of bits or characters in the message. The *expected message duration* (EMD) can also be defined as the message length divided by the link capacity denoted in terms of bits or characters per second. Call or message duration may be characterized by randomness. For that case, a call/message duration distribution with at least a mean (μ) and a standard deviation (σ) must be defined before computing system resource utilizations and response times. A random distribution of call/message duration also results when many types of fixed length messages travel randomly over a shared virtual circuit, each consisting of one or more physical links.

Call or message arrival rate (λ) defines the rate at which the calls or messages are presented to a network resource/server. Traffic intensity (A) is generally defined as the product of arrival rate and the expected call duration of ECD. Therefore, $A = \lambda * \text{ECD}$ erlangs. Call intensity is measured in terms of erlangs, named after the famous Danish mathematician. Call intensity determines the average number of servers (e.g., links) concurrently occupied. In some quarters, hundred call seconds (CCSs) determines the call intensity. However, it does not have any physical meaning. CCSs can easily be divided by 36 to compute erlangs. Call intensity is an important concept that is employed for computing the number of servers (or links/trunks) required to provide a desired performance level.

Traffic flow is a measure of the traffic intensity on any directed path consisting of an order sequence of network nodes. A sequence of two nodes implies a single circuit bundle connecting the two nodes. A sequence of N nodes implies a directed path of $(N - 1)$ intervening links, each consisting of several physical circuits. Most well-designed network systems provide some traffic flow control to prevent congestion that may result in system failures. There are many ways to achieve flow control. Access limiting and dynamic routing of traffic are some of the many popular methods.

The concept of switched systems and the associated traffic attributes, as introduced above, can be further expanded by discussing the well-known voice and data communication systems.

1.5 CONCEPTS OF VOICE COMMUNICATIONS

Voice communications are synchronous with telephony, which began with Alexander Graham Bell's invention of the telephone in 1876. The first mechanical circuit switch was installed in 1878 in New Haven, Connecticut. The first automatic, step-by-step Strowger switch was installed in 1892 in La Porte, Indiana. The first crossbar-type electromechanical switch was installed in 1938 in the U.S.A. Direct distance dialing (DDD) as based on the 7 digit code was introduced in 1947 in the U.S.A. The first stored program controlled (SPC) No. 1 ESS circuit switch (CS) was installed in 1965 in the U.S.A. A deregulation of the customer-premise-equipment began in 1968, as a result of the Carterfone decision. This gave impetus to the development of private automatic branch exchange (PABX) and privately owned tandem switches required for a private network. The first digital circuit switch employing pulse code modulation (PCM) and 255 μ-Law was commercially announced by Collins Radio Company in 1971. The divestiture of AT&T took place in 1984, which created about 250 Local Access and Transport Areas (LATAs) and resulted in seven Regional Bell Holding Companies (RBHCs) to handle local access and intra-LATA services, and many other common carriers (OCCs), such as the new AT&T, MCI, and U.S. Sprint, to handle inter-LATA and long-distance services and the leasing of long-haul analog/digital circuits. At present much activity is taking place in introducing No. 5 Electronic Switching System (ESS) Central Office (CO) switches capable of handling Integrated Services Digital Network (ISDN) based services. See Appendix B for a description of the ISDN-related standards and network topologies.

Voice communication networks are generally classified by the type of switching nodes employed. The first generation of voice switches used dumb Strowger switches. In the second generation of voice switches, SPC-type circuit switches were employed. The third generation of voice switches generally used digital CSs. In the fourth generation of voice switches, each switch can handle both voice and data. That, in turn, implies the capability to provide concurrent access to both voice and data terminals at each subscriber location and to share a modem pool for WAN applications. In addition to providing a traditional integrated voice and data (IVD) capability, an ISDN switch provides higher data rates and greater intelligence than the fourth generation circuit switch. For that reason, an ISDN switch may be called the fifth generation switch. In short, the various generations of voice switches can be characterized by an increasing amount of nodal and/or network intelligence required for cost effective network management and technical control (NM/TC).

Voice communication networks were originally characterized by analog transmission facilities with only space division multiplexing (SDM). With time, frequency division multiplexing (FDM) became the most cost-effective method of carrying a large number of voice conversations over a coaxial cable. For example, the L1, L3, L4, and L5 type carrier systems could carry 600, 1860, 3600, and 10800 voiceband channels, and were introduced in 1946, 1953, 1967, and 1974, respectively. Later analog and digital microwave systems (also called radio systems) became cost effective for long- and medium-haul routes for a medium number of voice channels. The T-carrier systems employing digital PCM-based multiplexing techniques became cost-effective in the early 1960s for short-haul routes. With the advent of fiber optics, the repeaterless distance and the number of voice channels carried by digital transmission systems, known as T-carriers, has increased rapidly. One can now state without equivocation that digital transmission is the only cost-effective means of carrying a large number of voice conversations and/or data traffic over all ranges of distance.

At present, the availability of cost-effective digital switching and transmission techniques is quickening the pace towards a fully integrated digital network (FIDN). Since ISDN still employs CS for voice and CS and/or PS for data, we are still far from realizing an FIDN. But with the recent development of fast-packet switching technology (using small packets, fast routing analysis, and nodal-bypass mechanism), packetized voice is not far away. When packetized voice becomes economically feasible, the FIDN will finally become a reality, resulting in large economies-of-scale and a fully integrated network.

1.6 CONCEPTS OF DATA COMMUNICATIONS

Data communications is much older than voice communications, despite notions to the contrary. The earliest versions involved coded messages using drum sounds, smoke signals, and semaphore devices. The modern variety of data communications began with the invention of telegraphy in 1835. However, the biggest impetus to data communications came from the development of the first commercial modem by the Collins Radio Company in 1955. Such a modem soon became the foundation for several coded-feedback communications systems used for tape-to-tape and card-to-card data transport. A portion of the data was first divided into blocks, before their transmission. Each block had an overhead code for detecting any errors caused through transmission. A number of data blocks could be outstanding until feedback information regarding their correctness was received and before continuing the transmission of additional blocks. The next epoch occurred with the development of the first microprogrammable front-end (FE) communications processor in 1960. Later, Collins Radio Company made this processor the basis of the first SPC message switching system, ultimately replacing all of the existing torn-tape teletype systems by 1964. In 1968, Collins Radio Company also developed the C-System, which was a large LAN consisting of mainframes, minicomputers, and input/output devices, interconnected via time-division multiplexed (TDM) loops, capable of providing both message and packet-switching services to a large number of subscribers. The first Advanced Research Project Agency (ARPA) sponsored packet-switched network became operational in 1969 with only four nodes. The first public PS data network, as operated by Telenet Corporation, became operational in 1975.

The data switching nodes can also be characterized by several generations of development. The first generation switches were those that provided interchange of data between the host and terminals using the mechanism of polled access. The second generation of data switches were the SPC message switches nodes. The third generation of data switches were based on packet switching. The fourth generation of data switches attempt to integrate voice and data on transmission links only.

The technologies related to voice and data are becoming integrated, first in terms of transmission, and eventually switching technologies. A complete integration will imply a great deal of savings to the users. A fully integrated digital network will eventually become as basis of an emerging utility that will provide unfettered sharing of information to all subscribers with diverse bandwidth requirements. This would be very similar to the existing electric and water utilities, which provide any amount of utility through a simple wall outlet or a faucet. Unfortunately, it will take some time. Experience shows that it took six years to make packet switching commercially available after one could prove its cost-effectiveness. Several products based on packetized-voice finally appeared in late 1986. This came almost ten years after packetized voice was shown to be commercially feasible. The more complex the system, the longer is the delay between those two events. Based on that assumption, FIDN-based information utilities should be available by 2000 A.D. FIDNs will be fully integrated in terms not only of services, but also network management and control (NMC) functions. They will employ expert systems (ESs) to achieve self-healing.

1.7 CONCEPTS OF NETWORK ARCHITECTURE

A network architecture is generally characterized by three networking attributes:

1. Network Topology. This defines the manner in which the network nodes are interconnected. Generally, there is a hierarchy associated with the network nodes and/or links.
2. Transmission and Multiplexing Technique. This defines the modulation, encoding, transmission/reception, and multiplexing techniques employed to synthesize links for interconnecting the various network nodes. Issues such as analog or digital transmission, coaxial cable or optical fibers, and single or multiplexed streams of data are resolved.
3. Network Management and Control (NMC) Technique. This technique is involved with the switching technology, traffic flow control, and methods of distributing and controlling intelligence in the network.

Each of these concepts is elaborated upon in the following sections, using the principle of successive decomposition.

1.7.1 NETWORK TOPOLOGIES

The basic topologies that have proven useful for telecommunications networking can be classified as follows:

1. mesh topology—fully connected or partially connected varieties
2. minimal spanning tree or multidrop topology
3. directed link topology
4. star topology