NETWORK MANAGEMENT:
A REVIEW OF EMERGING CONCEPTS, STANDARDS, AND PRODUCTS

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The objectives of this report are (1) to identify and examine various divergent perspectives that exist about the technology termed network management; (2) to develop a conceptual definition and understanding of network management that is rational and comprehensive; and (3) to examine the questions of what is involved in supporting and controlling a network, what is being done or needs to be done to provide that support and control, and who is involved in doing it. Consistent with these objectives, the report presents a conceptual explanation of network management that is admittedly idealistic, describes the many organizations that are actively involved with the development of real-world, network management standards, examines the functional characteristics of a variety of network management products (available in 1991/92), and discusses some of the important issues and trends that are creating new requirements for network management.

Key words: network management, network management systems, standards

1. INTRODUCTION

The topic of this report is network management (NM)—what it is today, how it is evolving, who is working on it, and how it may change in the future. Many have asked, "What is network management?" and many answers have been given.

For example, a definition given by Freeman (1989), in discussion of data networks and their operation, is the following:

> "Network management means somewhat different things to different people. One can argue that the term is synonymous with technical control. For this discussion, consider the terms the same.
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> Many conjure up a view of technical control, a military communications term, as banks of patch panels where all circuits of interest can be bridged or terminated for testing. They also can be rerouted in case of poor performance or failure. Network management also includes the traffic flow function and its control, although this function is automated in some of the higher-level protocols and in

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> International Telegraph and Telephone Consultative Committee (CCITT) Signaling System No.7."

Terplan (1989), at a network management and control workshop[1] that primarily was concerned with networks to connect (and inter-connect) terminals and computers, gave the following definition for network management:

> "Network management means deploying and coordinating resources in order to plan, operate, administer, analyse, evaluate, design and expand communication networks to meet service level objectives at all times, at a reasonable cost, and with optimum capacity."

In the book entitled *Engineering and Operations in the Bell System* (Rey, 1983), network management is described as the function that keeps the network operating near maximum efficiency when unusual traffic patterns or equipment failures would otherwise cause network congestion and inefficiency. The Bellcore *Network Management Handbook* (1989) presents a very similar definition of network management:

> "Network management is the term used to describe a variety of activities associated with improving network traffic flow and customer service when abnormal conditions (unusual traffic patterns or equipment failures) ultimately may have resulted in a congested, inefficient network."

To provide perspective for the Bellcore definition of network management, we note that the Bell system book (Rey, 1983) devotes four chapters to telephone company operations, describing operations as being divided into three kinds of functions—provisioning, administration, and maintenance.

> "**Provisioning** is the process of making the various telecommunications resources (such as switching systems, transmission facilities, and operators) available for telecommunication services. Provisioning includes forecasting the demand for service, determining the additions (or changes) to the network that will be needed, determining where and when they will be needed, and installing them.
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> **Administration** covers a broad group of functions that sustain services once they have been provided. Administration generally consists of **network administration** and **service administration**. Network administration ensures that

[1] The Network Management and Control Workshop, held September 19-21, 1989, in Tarrytown, NY, and jointly sponsored by the (New York) Polytechnic University, the New York State Science and Technology Foundation and its Center for Advanced Technology in Telecommunications (CATT), NYNEX Corporation, and the IEEE Communications Society's Committee on Network Operations and Management (CNOM).

> the network is used efficiently and that grade-of-service objectives are met. Service administration includes such diverse functions as billing; collecting and counting coins from coin telephones; and, for customer switching system, giving engineering and service evaluation assistance and keeping detailed engineering records.
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> **Maintenance** operations ensure that network components work properly once they are installed. Maintenance includes the testing and repair activities that correct existing malfunctions (corrective maintenance) and those that prevent service-affecting malfunctions (preventive maintenance)."

A recent technical paper on the evolution of network management at the American Telephone and Telegraph (AT&T) Company (Wetmore, 1991) makes the following observation:

> "The practice of network management has undergone significant changes at AT&T over the last five years. ...the definition of the term "network management" has changed as well. **Today, this term is used to apply to many of the functions related to the operation, maintenance and administration of a telecommunication network.** (Emphasis added) That is why AT&T has begun using a more specific term—network traffic management (NTM)—to refer to the discipline formerly known as network management."

Wetmore's paper primarily discusses the changes that AT&T has implemented in developing their current practices of *network traffic management.*

Material that describes military telecommunication systems often uses the words (and acronyms) Administration, Operations, and Maintenance (AO&M) or Administration, Operations, Maintenance, and Provisioning (AOM&P) in discussing the telephone company operations functions defined above. These functions often, but not always, include the functions of network management.

Other views of network management, that often are similar to the definitions given above, have been expressed in the literature. (See, for example, Caruso, 1990; Flanagan, 1990; Herman, 1989; and Valovic, 1987.) The management associated with local area networks (LANs) is the basis for one of the most common and widespread interpretations of network management.

Organizations that have been and are developing standards for network management (see Section 3) also have defined network management. For example, management for Open Systems Interconnection (OSI) networks is defined by the International Organization for Standardization (ISO) in conjunction with the International Electrotechnical Commission (ISO/IEC) (1989) as:

> "The facilities to control, coordinate and monitor the resources which allow communications to take place in the OSI Environment."

There is no single, clear definition for network management given by the International Telegraph and Telephone Consultative Committee. For example, Recommendation X.200 (CCITT, 1989e) that defines the reference model of open systems interconnection for CCITT applications contains no explicit definition for network management. However, this Recommendation is closely aligned with the ISO 7498 Standard (1984) that defines the basic reference model for open systems interconnection for information processing systems. It seems reasonable, therefore, to conclude that a definition very similar to the ISO/IEC definition cited above for network management would apply.

Recommendation E.410 (CCITT, 1989b) presents general information concerning international network management and defines network management as:

> "... the function of supervising the ... network and taking action when necessary to control the flow of traffic."

Note the emphasis on traffic control in this definition.

Another view of network management is suggested in Recommendation M.30 (CCITT, 1989d) which presents principles for a Telecommunications Management Network (TMN) for international transmission systems and telephone circuits. Again, no explicit definition is given for network management, but text of the Recommendation indicates that the TMN provides an organized structure to achieve network management, and that management includes performance management, fault (or maintenance) management, configuration management, accounting management, and security management. These are the functions necessary to cover operations, administration, maintenance, and provisioning of a telecommunication network.

Finally, the CCITT definition given for network management in Volume I (CCITT, 1989a) that contains terms, definitions, abbreviations, and acronyms is:

> "The activity performed ... to regulate traffic flow."

This definition is referenced to and exactly the same as that given in Recommendation Z.337 (CCITT, 1989f) that is concerned with network management administration.

The definition that we offer that is broad and general and that will be followed in this report, unless explained otherwise, is developed from basic definitions for ***network*** and

management. This definition applies to all types of telecommunication networks and the services that these networks provide.

The Institute of Electrical and Electronics Engineers (IEEE) Standard Dictionary of Electrical and Electronics Terms (Jay, 1988) does not define network management, but it contains several definitions for ***network***. Pertaining to communications, particularly data transmission, ***network*** is defined as

> "A series of points interconnected by communication channels."

Pertaining to software, ***network*** is defined as

> "An interconnected or interrelated group of nodes."

Webster's Dictionary (Gove, 1976) defines ***network*** (in part) as

> "**2:** a system of lines or channels that interlace or cross like the fabric of a net **4:** a system of electrical conductors in which conduction takes place between certain points by more than one path."

Federal Standard 1037B (GSA, 1991) defines ***network*** as

> "**1.** An interconnection of three or more communicating entities and (usually) one or more nodes. **2.** A combination of passive or active electronic components that serves a given purpose."

In fact, there are many types of networks. These networks usually are classified by applying criteria, either independently or in combination, such as the service(s) offered, the geographic area(s) covered, the customers served, and the way in which the network is implemented.[2] In this report, a generic meaning for "the network" is intended unless a more specific definition is needed or clearly implied by the context of the discussion. From all of the definitions cited above, the generic definition for ***network*** that we use is

> An interconnected group of communicating entities and nodes (e.g., telephones, terminals, computers, circuits, and switches).

[2] Networks classified by the offered services may be grouped as voice networks, data networks, imagery networks, etc. Those classified by the area(s) to which services are provided include local, national, enterprise-wide, and global networks. Networks classified by the way in which the network has been implemented include, for example, circuit-switched, packet-switched, and message-switched networks. Networks often are classified as public or private networks, and whether the network is used for interconnecting computers, terminal operators, businesses, or other entities.

Before proceeding further with the definition of network management, some additional comments about the term "network" (or networks) are appropriate. The term is used frequently in this report with a rather broad range of meanings. Several formal definitions for network have been given, along with the generic definition that we prefer and use. The formal definitions of two closely related terms, taken from proposed Federal Standard 1037B (GSA, 1991) also are important to note:

> **network architecture** — 1. The design principles, physical configuration, functional organization, operational procedures, and data formats used as the basis for the design, construction, modification, and operation of a communication network. 2. The structure of an existing communication network including the facilities, operational structure and procedures, and the data formats.
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> **network topology** — The specific physical (real) or logical (virtual) arrangement of the elements of a network. Note: Two networks have the same topology if the connecting configuration is the same, although the networks may differ in physical interconnections, distance between nodes, transmission rates, and signal types.

These terms and other related terms are discussed in a report on telecommunication networks, services, architectures, and implementations by Linfield (1990).

Consistent with these definitions, the term "network" is used in many ways to describe networks from either the providers' or the users', or sometimes both, viewpoints. Some of the most common types of networks are identified below.

- The public switched telephone network or PSTN.
- The public data network or PDN.
- An integrated services digital network (ISDN), that may be either public or private, and that may include a local area network or wide area network. Such networks, today, exist only as "islands" of integrated services.
- (The networks identified above may be considered from either the providers' or users' viewpoints. The networks identified below most commonly are considered from the users' viewpoint.)
- A user's network that uses either the PSTN or the PDN and may include a local area network or wide area network.

- A user's private network that may include a local area network or wide area network.

- A user's private network that uses either the PSTN or the PDN. Such networks may include a local area network or wide area network.

Many other types of networks may be imagined that would use mixtures of components and involve either the public switched network, a private network, or both. An example would be a virtual private network (VPN), a service that is offered by an interexchange carrier (IEC) to provide customers the benefits of a premises-to-premises voice and data private tandem network without requiring private tie trunks across the network. A VPN exists as a private network embedded in the IEC's switched public network. The VPN is software defined and only appears to have dedicated switching and transmission facilities. These facilities, in fact, are physically shared with other public network users.

Our discussion of the network sometimes may represent the perspective of the provider and at other times the perspective of the user. Users' networks often are heterogeneous because of the several network architectures[3] that usually are involved. An example of a user's network that uses today's PSTN is illustrated in Figure 1. This network shows CPE at one node with a PABX connected through the PSTN to CPE utilizing Centrex services at the other node. The CPE at each of these network nodes includes a variety of terminal equipment such as telephones, personal workstations (WSs), facsimile equipment, and host computer systems serving remote terminals, as well as local area networks that can include additional, similar terminal equipment. We observe that such a network can include many separate network management capabilities. In principle, the user's network also may include satellite links as normal transmission capabilities or as back-up transmission capability for the terrestrial transmission network. In the near future, these satellite links may be provided by satellites, such as the Advanced Communications Technology Satellite (ACTS), that have on-board switching and narrow, directive antenna beam capabilities.

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[3] Various meanings of the general term network architecture are defined and discussed by Linfield (1990). Very briefly, one important distinction is that network architecture may be understood to be the physical arrangement and connectivity of the network elements, and this often is described as the physical network architecture. Another common understanding, however, of network architecture concerns the protocols that are used for communication, and this often is described as the functional network architecture.

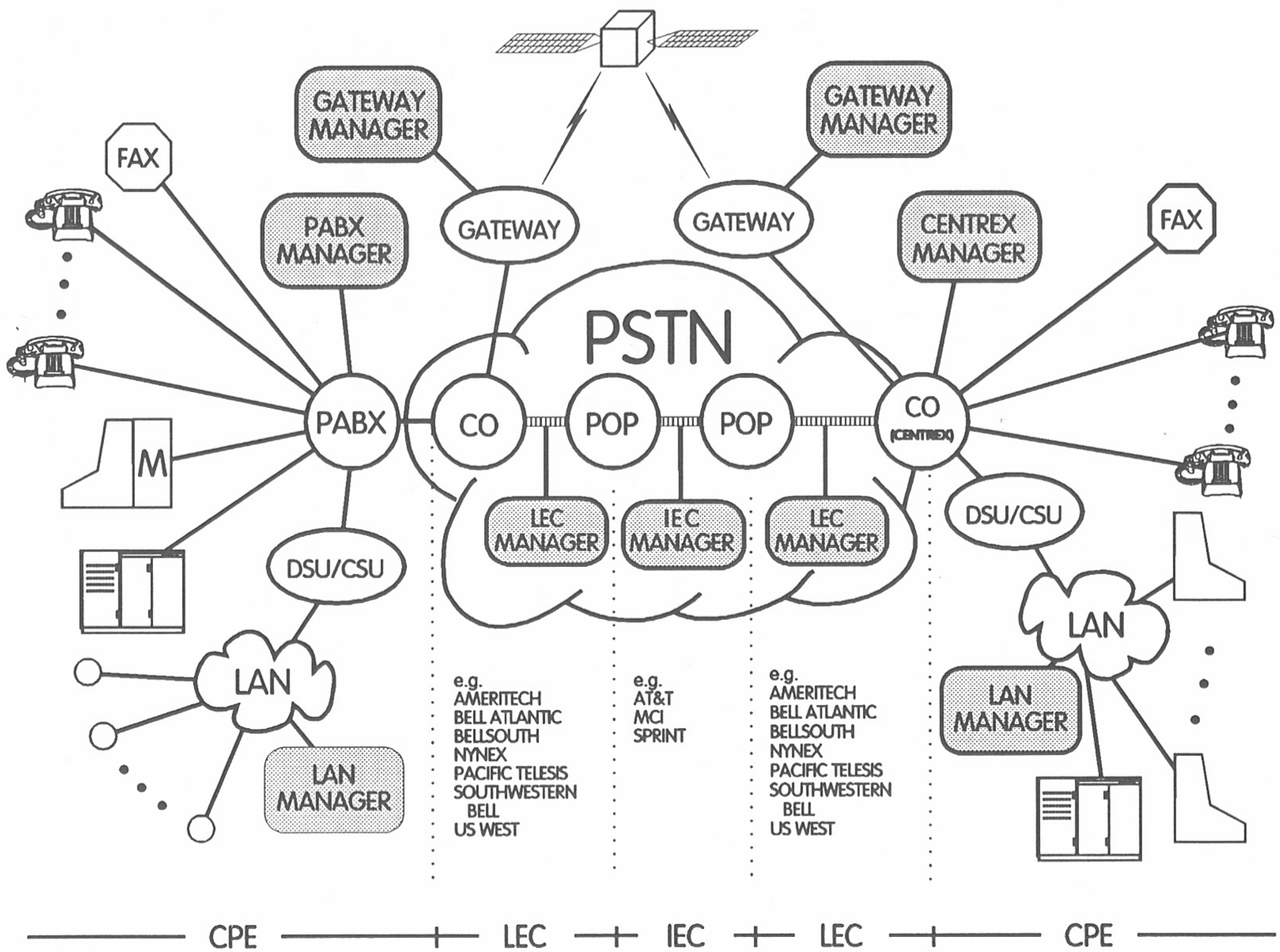

Figure 1. Illustration of a possible user's network that uses today's Public Switched Telephone Network.

A somewhat more abstract illustration (compared to Figure 1) of a possible user's network with an ISDN type of node added is shown in Figure 2. The "switched network" part of this illustration is composed of multiple switched networks that include local-exchange carriers (LECs) and IECs providing circuit-switched networks, packet-switched networks (for data), and the common-channel signaling network that also is packet-switched. This figure illustrates types, rather than representative numbers, of nodes and terminal equipment comprising the user's network. The heterogeneity of the network is illustrated by different functionality being defined for each node. Communication between the different functional architectures requires carrier-signal-type and protocol conversions. These conversions are provided by capabilities such as modems, data/channel service units (often referred to as DSU/CSUs[4]), special gateways, etc. or by other capabilities incorporated into the network nodes. Network management in this conceptual, user network would be integrated, distributed, and ubiquitous.

A possible, futuristic and more advanced concept for users' networks is shown in Figure 3, where several important ideas are illustrated. For example, the networks available to users at any given time would contain a spectrum of capabilities, ranging from Plain Old Telephone Service (POTS) to ISDN and, eventually, to broadband-ISDN (B-ISDN) and personal communication systems (PCSs) and Mobile Telephone Service (MTS). Such networks could include LANs, MANs, and WANs that provide integrated services using ordinary telephones and workstations as well as integrated workstations[5] (IWSs) at the users' locations, or customers' premises. Capabilities for B-ISDN and PCS are only in developmental stages, but some IWSs exist today. Similar to the conceptual network illustrated in Figure 2, network management in such an advanced network is expected to be highly integrated, distributed, and completely ubiquitous.

As for the management part of network management, Webster's Dictionary (Gove, 1976) defines ***management*** (in part) as

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[4] Strictly speaking, a CSU (channel service unit) is a hardware interface between a user's data terminal equipment and a digital link with a central office. The CSU provides line isolation, to protect the network from malfunctions in a user's equipment, and loopback capabilities for network testing. A DSU (data service unit) is a hardware device that provides digital interface between a digital line and an item of data terminal equipment. The DSU provides timing recovery, bipolar conversion, signal generation control, signal recognition, and synchronous sampling. Generally, the DSU includes the CSU functions, the devices often are referred to as DSU/CSU.

[5] Workstations that provide integrated services.

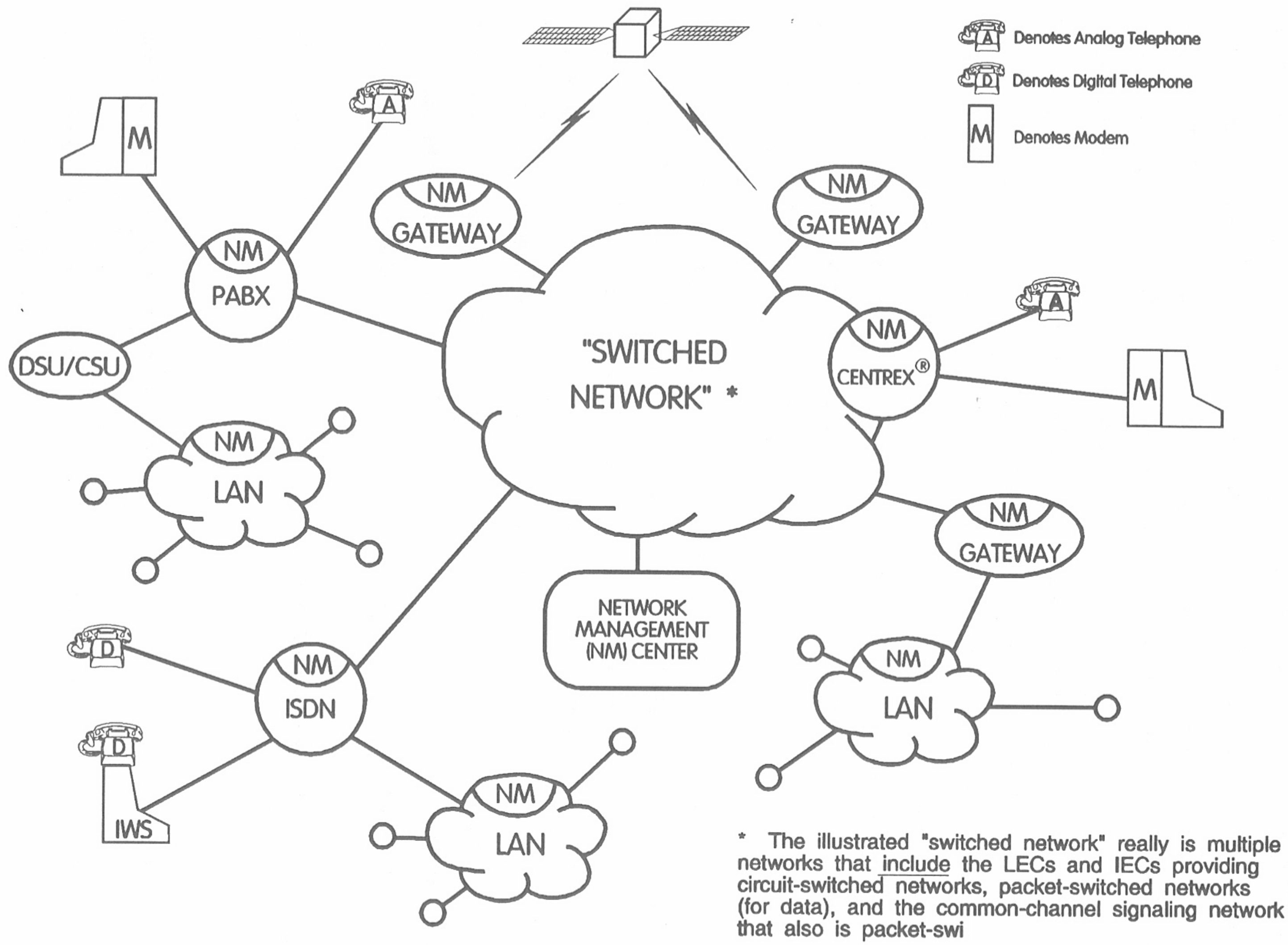

Figure 2. Illustration of another, possible user's network; expanded functionality with the ISDN node and more abstract when compared with Figure 1.

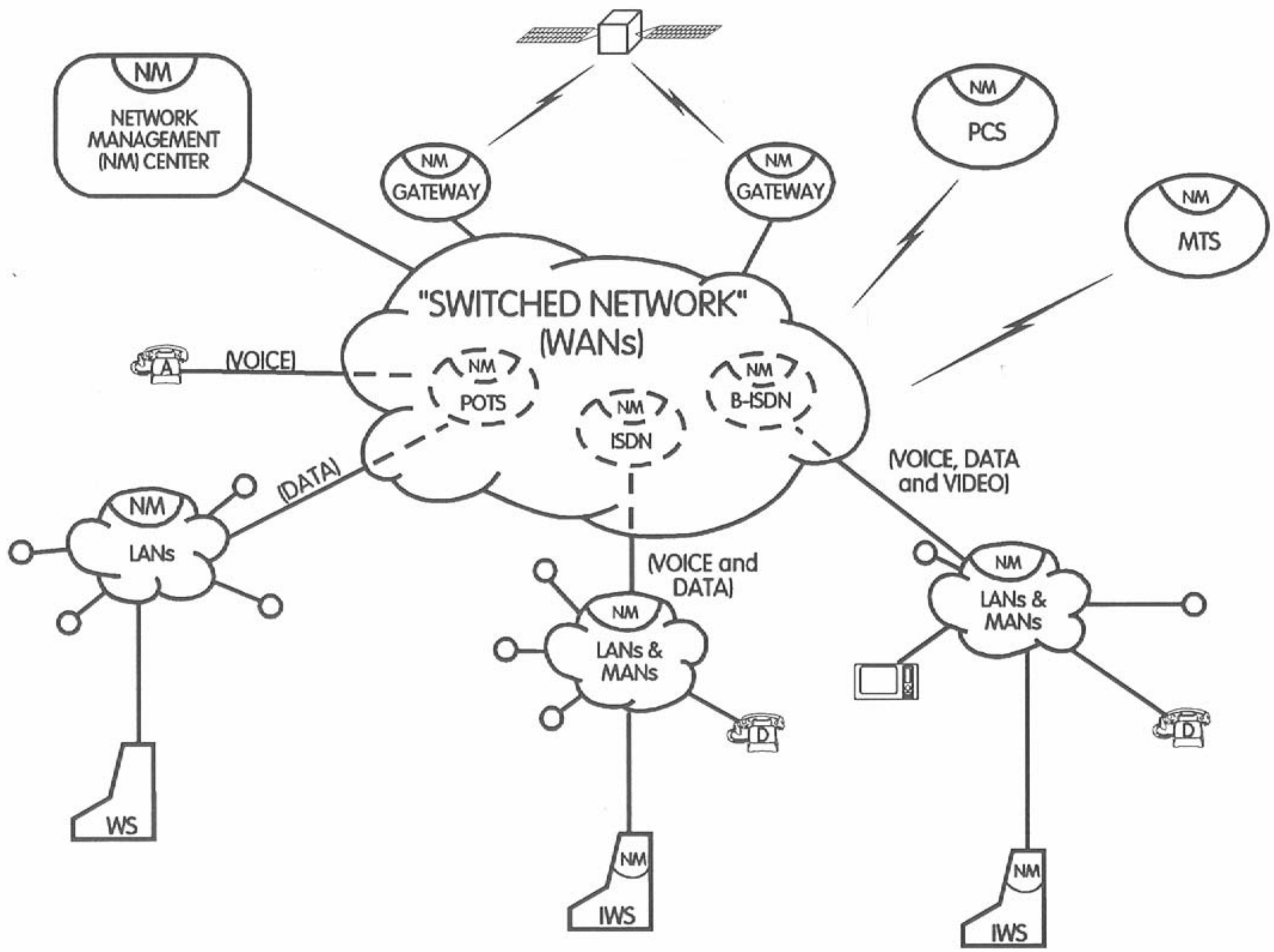

Figure 3. An example of a possible, futuristic and more advanced configuration for a user's network (than illustrated in Figure 2).

> "The act or art of managing as **a:** more or less skilled handling of something **c:** the conducting or supervising of something (as a business); especially, the executive function of planning, organizing, coordinating, directing, controlling, and supervising any industrial or business project or activity with responsibility for results."

From these various definitions for ***network*** and ***management***, we have formulated the following general definition for ***network management:***

> **The act or art, more or less skilled, of supporting and controlling an interconnected group of communicating entities and nodes (e.g., telephones, terminals, computers, circuits, and switches)[6]**

It should be recognized that the skill used in providing support to and control of the network management process may be direct human participation or it may be "skill" built into software and hardware that applies automation and even artificial intelligence (AI).

The threefold objective in this report, then, is

a) to sort through some of the divergent perspectives that exist (and that seem to cause confusion and misunderstanding) about network management

b) to develop a conceptional understanding of network management that is rational and comprehensive and that, intentionally, is not oriented exclusively to data networks or voice networks

c) to examine the questions of what is involved in supporting and controlling a network, what is being (or needs to be) done to provide that support and control, and who is involved in doing it.

Consistent with this objective, the report presents a conceptual explanation of network management in Section 2 that is recognized as idealistic in some cases. In addition to discussing the purpose and scope of network management, functions that are suitable for management are identified. Contrasting perspectives and factors that affect the development and implementation of network management and integrated network management systems are included.

In Section 3 the report discusses the various organizations that are actively involved with the development of network management standards. Typical products, i.e., the systems, that are

[6] In the discussion of network management fundamentals (Section 2), various statements are made concerning network management as it has been understood by others or as it may be understood in a particular situation. These statements are not intended as alternate definitions of network management. Rather, all of these statements should be understood to be covered by, and be a part of, this general definition for network management.

available to assist users and providers with network management are discussed in Section 4. The emphasis is on functional capabilities and capability differences in these products.

Section 5 summarizes the highlights of the report and identifies some issues and trends that are likely to influence the continuing development of network management. Advanced optical fiber technology, broadband integrated services digital networks, expert systems that incorporate artificial intelligence, the introduction and growth of personal communication systems, the diversity of standards, and government regulations are among the topics noted. The conclusions and recommendations that have emerged in conducting this study are collected in Section 6. References cited in the report are given in Section 7.

Three appendices supplement the material presented in the report. Appendix A contains an extensive identification of organizations that are involved with the development of network management standards, showing the inter-relationships between these organizations. Appendix B is a summary description of the OSI Reference Model, and Appendix C is a list of the OSI Network Management Standards.

2. FUNDAMENTALS OF NETWORK MANAGEMENT

For many years, network operations were quite focused. A user simply would specify his service needs to "the telephone company" and that company took the responsibility to plan, design, build, and maintain the necessary capabilities to satisfy those needs. The telephone company would follow its well-defined operations procedures for providing, administering, and maintaining the network and the telecommunications services it provided (briefly described in Section 1). These user-specified, telephone-company-managed, networks were relatively straightforward variations of networks to provide voice telephone service. Most users simply relied on "the telephone company" to take care of all of their service needs, fix their problems, provide the necessary expansions, install the upgrades, and insure quality.

In the 1960s and 1970s, data communications were introduced and information-processing networks, with varying requirements for network quality and capacity to support a variety of new voice-bandwidth services, began to evolve. As the technology matured, more user-controlled devices were connected to the network, and information-processing networking began to change from batch to real-time applications. Divestiture of the Bell System (the AT&T Divestiture Plan approved August 5, 1983 and effective January 1, 1984) substantially accelerated this trend. The old approach of relying on "the telephone company" to satisfy all networking requirements no longer was a viable option. "The telephone company" simply was not allowed to respond to every user request as before. In addition, the concept and benefits of dynamic network reconfiguration and control (some of the capability provided by network management) began to be realized, thus the need for user-controlled network management was becoming recognized. Though recognized as needed, network management systems that provide extensive user-control are still in the future.

The practices of network management, however, tended to be separated into one set of "standard practices" and capabilities, often utilized by users, for managing the data or information-processing networks and another set of "standard practices" and capabilities, administered by the local and inter-exchange carriers, for managing the voice (telephone) networks. Network management for data communications tended to place emphasis on monitoring and control so as to achieve high quality performance of the network. Network management for telephone networks, on the other hand, tended to place emphasis on administration of the network—"either it worked or it didn’t."

Several years ago, Gawdun (1987) reported that market research conducted by Bellcore had identified several functions that could give users additional management and control capabilities (sometimes provided by the carrier) over their network configuration and bandwidth. These included

- time-variant circuit connections
- time-variant bandwidth/bit rates
- real-time disaster recovery
- real-time performance information
- network status information
- reservation capabilities
- time-variant service options.

New technology and other user/business requirements are causing computing and information-processing capabilities to be transformed into distributed environments with requirements for sophisticated interconnecting networks; sometimes referred to as data networks or information-processing networks. This trend coupled with new technology and users' requests for new services provided by the network are causing Plain Old Telephone Service to be transformed into sophisticated telecommunication networks with considerable processing power[7]. Some examples of the services provided by these sophisticated networks include

- The Public Telephone Network "800" toll-free calling services that are supported by intelligent databases (and sometimes integrated with service to identify the calling party's telephone number—Automatic Number Identification or ANI)

- Virtual private network (VPN) service (an example of AT&T's Software Defined Network service) that provides customers with premises-to-premises integrated voice/data private tandem network service without the need for private tie trunks across the public inter-exchange network (IEC)

- Switched Digital Services to provide short-term, high-data-rate, digital connectivity, such as the Switched Multi-megabit Data Service (SMDS) offered by carriers

- A variety of Messaging Services such as facsimile, paging, and voice and electronic mail

- Common Channel Signaling (CCS) that allows faster and more complex signaling between different parts of the network to remotely control the switching and to support various other sophisticated, intelligent network services.

The distinction between telephone networks and data or information-processing networks is becoming more and more blurred. That trend is continuing as digital transmission services such as T1[8] and fractional T1 become widely available. The introduction of integrated services digital networks, and the planning for future broadband-ISDN, provide integrated access to voice, data, and video services and will further encourage and shape this transition. The "marriage" of telephone and information-processing networks to support this integration has led to the definition

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[7] The processing power spoken of here is within the network to support the transport function and intelligent services provided by the network. It is not the distributed computing and information-processing capabilities supported by network interconnections.

[8] In the strictest sense, transmission that used copper-based digital facilities to provide 24 simultaneous voice or data circuits at 64 kbps for each circuit (1.544 Mbps) was introduced as T1 (or T-carrier) service. Today, many T-carrier services are based on fiber optic transmission facilities, rather than copper. However, the term continues to be used and now is understood to refer to any digital carrier service.

of information networks[9] as enablers of the Information Age (Caruso, 1990). Networks to provide these services often include a wide assortment of equipment from a variety of vendors that may use different protocols and interfaces. Many of these diverse equipments often include some "management" capability or system, but only for that particular component.

In this environment, network management is one of the most important, but confusing and least understood, aspects of telecommunication networks. In summarizing users' needs, Caruso suggests that the highest-priority attributes of new network management systems are interoperability of products from different vendors and integration of the capabilities to manage a wide variety of individual network components into a single system-one interpretation of integrated network management. Caruso also notes that the Information Age offers many opportunities and challenges, but that perhaps the greatest challenge is that of managing the telecommunication network resources and services, a challenge that is real to the public carriers as well as each user[10] that has unique, user-defined networks. This is the challenge that has created the relatively new and evolving discipline called **network management**[11].

Day-to-day activities of many organizations are increasingly dependent upon a diversity of telecommunication services. Executives, for example, are discovering that creative use of telecommunication services is key to enhanced revenues and increased profits for their businesses. These usage and economic-importance trends, along with the growing complexity and sophistication of the network, all contribute to the strategic importance of network management.

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[9] Throughout this report, we use the terms "telecommunication" and "telecommunication networks" rather than "information" and "information networks", as suggested by Caruso (1990), in referring to or describing networks that provide both telephone and information-processing services. Such use is consistent with the definitions of "telecommunication" that are published by CCITT (1989a) and in FED STD-1037B (GSA, 1991).

[10] A "user" is a person, a human operator of a computer terminal, or a computer-application program that processes communicated information (see ANSI, 1983) that is connected to and uses the services provided by a telecommunication network. From a telecommunication network point of view, an "enterprise" is an organization or corporation where many "users" share services that are specified according to the enterprise's objectives and priorities and that are provided by the "enterprise's network".

[11] Some writers use the term, network management, in describing only those aspects of network management that pertain to the lower levels (i.e., the physical, data link, network, and, possibly, transport layers) of the OSI Reference Model (ISO, 1984). The term, integrated network management, often is used to describe network management performed with multi-vendor equipment or to describe the management of networks that provide integrated services. The conceptual definition of network management developed and presented in this report includes all of these aspects of management and, therefore, obviates any need for the term, integrated network management, except in discussion of products for performing network management.

Network characteristics such as high aggregate bandwidth channels with accompanying increased vulnerability to operational failures, increasingly heterogeneous mixes of network components—hybrid networks, etc., are examples of the growing complexity and sophistication of networks. These are the types of factors that are leading users to express their most urgent needs as being network management systems that will allow the interoperability of products from different vendors and the integration of diverse management capabilities.

Managing the telecommunication network resources is considered to be one of the greatest challenges that users and providers of these resources must face. Network management from the end-user's perspective may involve individual control in the use of available telecommunication services. For voice services, available features may include call forwarding, speed calling, multi-party calling, etc. Similar, but often more complex, features for data-communication services also may be available. Such features might include ability to update user profiles and provide real-time, interactive information to the network in order to define and control required data communication services.

Often, the end-users' requirements are aggregated and processed by an enterprise's communications manager. This manager's authority might include ability to reconfigure software-defined networks embedded in the Public Switched Telephone Network (PSTN), reconfigure private, leased-line networks, or make station rearrangements for the central rather than private switching services (e.g., Centrex[12] in lieu of a private branch exchange (PBX) or private automatic branch exchange (PABX)). Other responsibilities could include planning, ordering and installing, configuring, repairing, accounting and billing, reporting, and controlling network security.

The increasing complexity and sophistication of networks, the rising percentage of total business costs that derive from telecommunication services, as well as opportunities to reduce costs (for a provider) or expenses (for a user) and save dollars, all underscore the growing importance of network management. Many factors contribute to the complexity of network management from both the service-users' and the service-providers' perspectives; such factors

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[12] Centrex is a switching service provided by physical and logical partitions within the Central office so as to provide calling features normally provided by a PBX. These features may include ISDN, automatic callback, automatic redial, customer-originated trace, calling number delivery blocking, calling number display, voice messaging, station rearrangement, station message detail recording (SMDR), and Automatic Call Distribution (ACD).

include the many commercial information-processing standards and procedures and the multiplicity of networks, e.g., the public telephone network, packet-switched data networks, ISDN, and a variety of private, dedicated networks,

The need for network management is solidly established by the natural growth in size and complexity of networks and the expanding services provided by these networks, as well as the sharply increasing reliance of businesses on telecommunication services for meeting their profit objectives. But, the importance (and burden) of user participation in the management or control of the network also has increased dramatically since divestiture of the Bell System that led to the subsequent division of public telecommunication networks into the following four major domains:

- the inter-exchange (or long-distance) carriers (IECs)
- the intra-exchange (or local-exchange) carriers (LECs)
- the customers' premises, with customer premises equipment (CPE)
- the information service providers (who may include third-party network management service providers).

Summarized, the situation today is—

- increasing numbers of users
- increasing numbers and types of equipment (from many different vendors, with different interfaces and protocols) that users want to connect to their networks
- increasing opportunities to provide the telecommunication connections (networks) between this widely diverse equipment.

2.1 Purpose and Scope of Network Management

Caruso (1990) has noted that the telephone network provides the earliest example of network management, where telephone operators could detect network problems and initiate maintenance and repair efforts. The direct participation of operators in establishing each call dramatically changed in the 1950s, however, with the introduction of direct distance dialing. Then, stored-program-control switches (introduced in the 1960s) and computerized operations systems (introduced in the 1970s), with software- rather than hardware-controlled operation, provided the capability for sophisticated and centralized network monitoring, data collection, and network control, collectively called network management. This was network management from the perspective of the provider, and customers generally realized very high reliability and availability of the offered services. Then, as network services became more sophisticated, it was recognized that customers' business successes were critically dependent on judicious use of these new features, so services known as customer network management services became available. Some examples are a user's ability to change the call-forwarding number, the speed dialing selections, or to rearrange connectivity (a Centrex service feature).

As a result of the Bell-system breakup and the "digital revolution in network design" (Flanagan, 1990), there are strong, new trends in networking technology. For many years, most users' networks were voice-grade lines that may have carried voice or data (with the use of modems). However, since the introduction of digital carrier systems (in the early 1960s) and the offering of tarriffed digital services (e.g., T1 service in 1983), the separate operational domains for analog and digital services (that include voice service) have also resulted in separate network management systems for each domain. These individual-domain, network management systems and practices provide no single point from which it is certain that all of a user's network connections and services can be managed. There is no "single view" of the end-user's entire network, and, in fact, some portions of that network are completely unmanaged and inaccessible to be managed. In today's growing digital-networks environment, this is regarded as a very undesirable situation.

Noting that a variety of network management issues remain unresolved, Cassel et al., (1989) have identified four general issues that are relevant to all areas of network management. These general issues are:

> **What functionality is needed?** Different communities of interest continue to perceive different network management needs that require different solutions. In other words, what are the essential functions that must be provided in network management?
>
> **How far do we standardize?** Agreement on the functions that must be provided for management of the network does not solve all of the problems. In general, and for a variety of reasons, implementations of the same functionality will be done in different ways by different hardware and software developers. The result is network heterogeneity. Management of the network, however, requires direct access to detailed information about the network and the ability to manipulate

many network characteristics. Thus, the issues arise: What parts of the network must or should be standardized? And, where should the network allow for proprietary characteristics?

How well will the system scale? Much of the current interest in network management follows from the recognition that many "existing networking systems" are growing very rapidly (suggested to be in excess of 100% per year). This growth is challenging network users and providers alike to develop new management systems that will support very large networks (perhaps containing millions of nodes).

How fast can we expect existing networks to change? In general, the more complex and innovative the network management system, the longer it will take to upgrade an existing network to support it. An anticipated deficiency of information required by a more complex or innovative network management system can become the basis for using less complex systems that only address immediate and obvious needs, while less pressing needs may allow the freedom to develop complete systems. Note, however, that this general rule for matching networks and management systems is not hard and fast; complex and powerful management systems have been proposed for networks with immediate needs, and simple systems have been proposed for less developed networks.

Generally stated, the purpose of network management is to help users efficiently and effectively use their diverse telecommunication resources so as to receive maximum service benefits and to help providers use their resources efficiently so as to enhance profitability. More specifically, the purpose of network management, for both users and providers, is to maximize availability and performance of the telecommunication resources within the scope of three basic functional areas suggested by Valovic (1987) as:

Monitoring and control: Observing the performance of the network equipment and making changes, as necessary in the operating parameters. These functions usually involve short-term or real-time adjustments to configuration of the network.

Administration: A wide range of day-to-day tasks such as adding new users to the network, maintaining accurate inventory of the network assets, billing for use of the network, dynamically reconfiguring the network, as required, etc. These functions usually involve medium-term, e.g., hourly or daily, adjustments to configuration of the network.

Planning and design: The on-going process of revising the design of the network, as may be required, and re-optimizing use of the network while giving consideration to the users' needs. These functions usually involve long-term, e.g., yearly, adjustments to configuration of the network.

One aspect of the scope of network management is that it is a multi-dimensional discipline that combines pre-implementation activities, such as planning, analysis, and design of the network, with many operational activities, that include administration, maintenance, and control. The historical responsibilities for managing the network within each of the domains noted earlier give rise to questions about other aspects of the scope of network management today and into the future. Such questions include: "How much control should an end-user have over a carrier's circuit and switches?"; "How can a user truly realize end-to-end management of his/her network?"; "How far into the customer's premises should a carrier's management capabilities extend?"; or "What options are available for a carrier to cope with disruptions to major sections of his network?"

Most networks will include many switching nodes and terminations. These nodes will contain a diverse mixture of different vendors' equipments (e.g., switching equipment, multiplexers, concentrators, computer terminals, etc.). The nodes are likely to be connected using a variety of transmission media (e.g., open-wire lines, paired and coaxial cables, fiber-optic cable, terrestrial microwave radio, satellite, etc.). The network may include LANs, a wide area network (WAN), a metropolitan area network (MAN), or any combination. Connections through the network could include, or be in addition to, normal connections to a private network or to the local- and inter-exchange carriers of the public network. Because of the diversity of equipment connected to the network and the diverse ways in which telecommunication connections may exist between the nodes, the users' equipment (e.g., host computers, terminals, PABXs, etc.) may be unable to inter-communicate. These mixed equipment need to be able to provide information to and receive instructions from a central computer that understands the "language" of each type of equipment and the topology of the entire network. Flanagan (1990) calls this central computer a "mediator," and suggests that the technology is available for "mediator" functionality that can extend network management capability to the ends of the network.

In effect, the concepts that we have just described explain one aspect of integrated network management[13]. Subsequent subsections examine how this scope for network management might be realized. A conceptual network-management architecture is illustrated in Figure 4. The network would consist of many users and a diverse mixture of different vendors' equipment using today's Public Switched Telephone Network to provide the telecommunication connections between customer premises equipment.

For an integrated network management capability, this architecture shows the network manager's (or users') access to and control of network elements in the customer premises, LEC, and IEC domains. The network management capability is connected directly to vendor-specific network management capabilities for the customer premises domain. It is connected to network management gateways for the local-exchange and inter-exchange carriers' domains. These gateways provide the connections or interfaces to the various vendor-specific network management capabilities and associated network elements in these domains. In addition, connections between vendor-specific network elements in the customer premises' and local-exchange carriers' domains are shown. Standard interfaces and protocols between the various network management systems and between the network management systems and the network elements would provide substantial improvement to interoperability.

The developing technology of advanced communications satellites[14] may offer significant new capabilities for augmentation and/or restoration of telecommunication services that are provided by the public switched telephone network, a network that today is largely made-up of terrestrial elements for switching and trunking. The concept of services provided by a hybrid network composed of both advanced-technology, terrestrial and communications-satellite components is described and discussed by Nesenbergs (1991). This revolutionary composition for a hybrid network, that could be either private or public, will require new interfaces, both

[13] Other aspects of integrated network management have to do with networks that are managed using the OSI/ISO-based methodology for packet-switched networks and the methodology recommended by the CCITT (1989d), namely Telecommunication Management Networks, for circuit-switched networks, as well as the management of networks that provide integrated services, e.g., voice, data, and video services.

[14] In the context of this report, on-board signal processing, rapidly switchable, spot-beam antennas, and the use of carrier frequencies in the 30/20-GHz band are the principle new technologies that are associated with advanced communications satellites. The on-board signal processing and spot-beam antenna technologies are most relevant to the development of a hybrid public switched network.

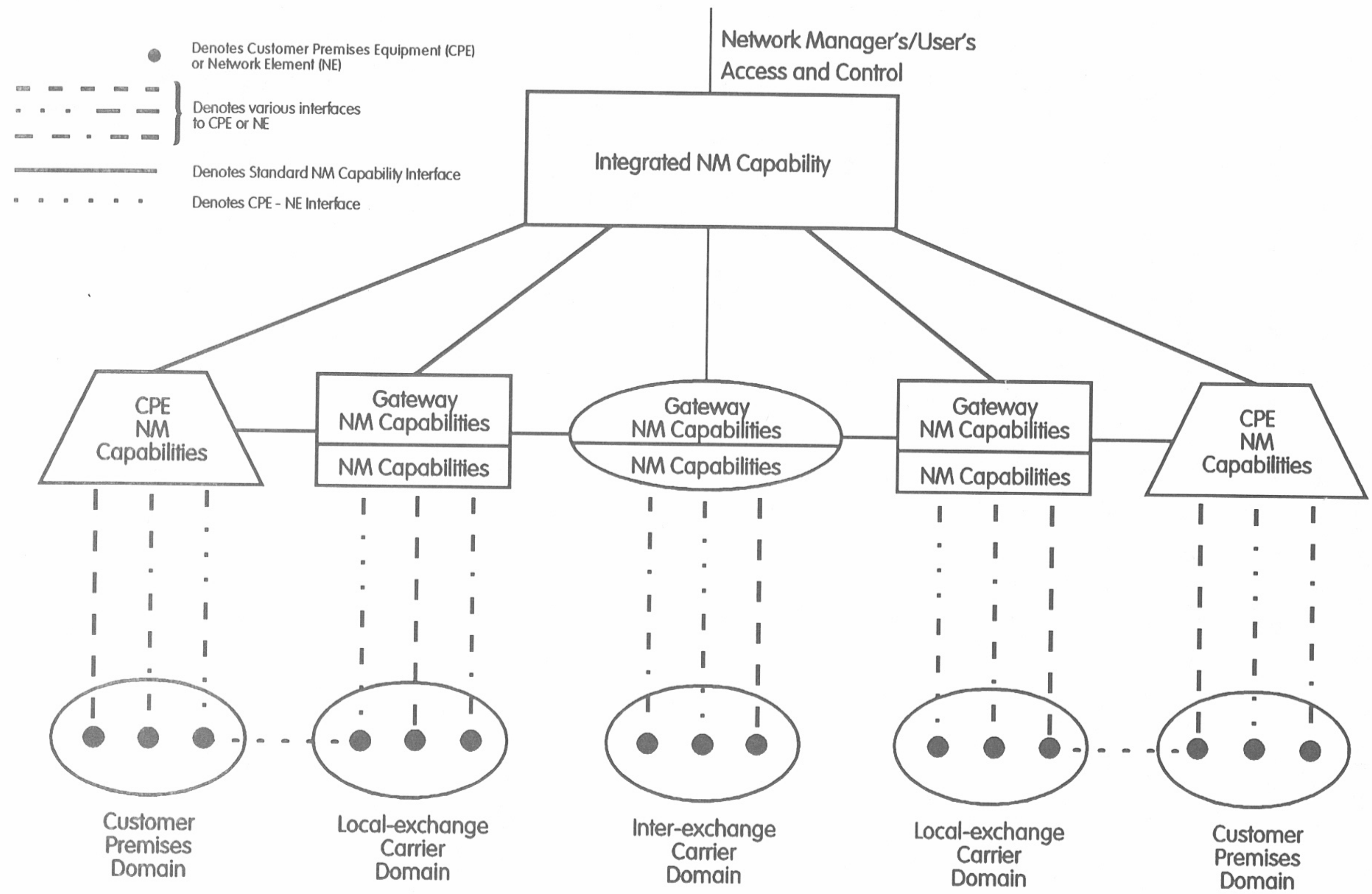

Figure 4. A conceptual network-management architecture (based on Caruso, 1990).

physical and functional, to be defined. New specifications and standards also will be required to define the inter-operation of these hybrid networks. These specifications and standards will need to interact and be aligned with existing network management practices and standards.

2.2 Basic Concepts of Network Management

Many people seem to believe that managing telecommunication resources requires only the right hardware and software; that is, get the "right tools" (Frank, 1988 and Herman, 1989). There may have been a time when that was possible, but the complex, dynamic networks that users demand and are using today cannot be managed adequately by simply connecting a bewildering array of "boxes that blink and buzz" (e.g., many separate, vendor-specific, network management tools) to the network. As Frank and Herman and others suggest, the discipline of network management is a multi-dimensional, continuing process; it is a series of actions, changes, and functions, repeated as often as necessary, that help users realize efficient and effective use of their telecommunication resources.

In this section of the report, we first define and discuss the overall process of network management, before we examine the specific functions that are involved. A complex process often is understood and defined most usefully by applying a systematic approach to the problem. Such an approach has been followed by others, and we use some of their ideas in this discussion (for example, see the papers by Willetts, 1988 and 1991, and Bohm and Ullmann, 1989). The approach is conceptual and based largely upon an application of management techniques rather than on applications of technology that have been (or could be) developed and offered specifically for network management. (Section 4 discusses network management systems and capabilities that are available today.)

The approach considers network management to be a management process that is applicable to all of the telecommunication resources (i.e., the network, the network elements, and the services provided by the network) independent of any specific network architecture. (Various architectures for implementing the network management process are defined and discussed before considering the functions that are suitable for management.) The approach allows us to define and describe a conceptual, network management capability, that is integrated by design, with the hope that such network management capability could replace the collection of discrete but individually-limited capabilities that often are being used today.

Every organization performs essential functions and has support requirements that we assume can be provided by an information processing system that is part of the total assets of the organization. The system may be large or small and provide multiple services or a single service, but just as for the other assets of the organization, it must be planned, designed, installed, used, repaired, modified as needs change, etc.; in other words, it must be managed. The information processing system would consist of hardware, software, and procedural facilities for which Böhm and Ullman (1989) have suggested the conceptual structure shown in Figure 5. The system would be divided into three, layered parts, each with its own management capabilities: (1) the application (sub)system, (2) the distributed, processing-support (sub)system, and (3) the communication (sub)system. The communication (sub)system is considered to be a general capability that provides both telephony and data communications.

The **application (sub)system** would consist of all the applications (pertaining to the information processing system) and the relationships between them that would result in interactions between the applications. These applications would be described in terms specific to the organization's interests or business. If the organization were a financial institution, the applications likely would include accounting and banking operations. If the organization were a research laboratory, the applications would include capabilities for developing and manipulating files of data. If the organization were a telecommunication carrier, the applications would include all of the operations required to provide high-quality, reliable services to customers at reasonable costs. Management of the application (sub)system would be required to coordinate and control the various (perhaps, many) applications.

Interactions between applications, regardless of location, would be supported by the **distributed, processing-support (sub)system**. This support could be direct for collocated applications, as indicated by connection "a" between applications 1 and 2. Or, the support could require use of the communication (sub)system for applications at different locations, as indicated by connection "b" between applications 2 and n.

The **communication (sub)system** would provide communication facilities for applications at different locations, usually based on specific network architectures. Management of the communication (sub)system is the process that Böhm and Ullman (1989) identify, conceptually, to be network management. Network architectures of such communication (sub)systems and their associated network management systems, as well as the protocols used in exchanging the

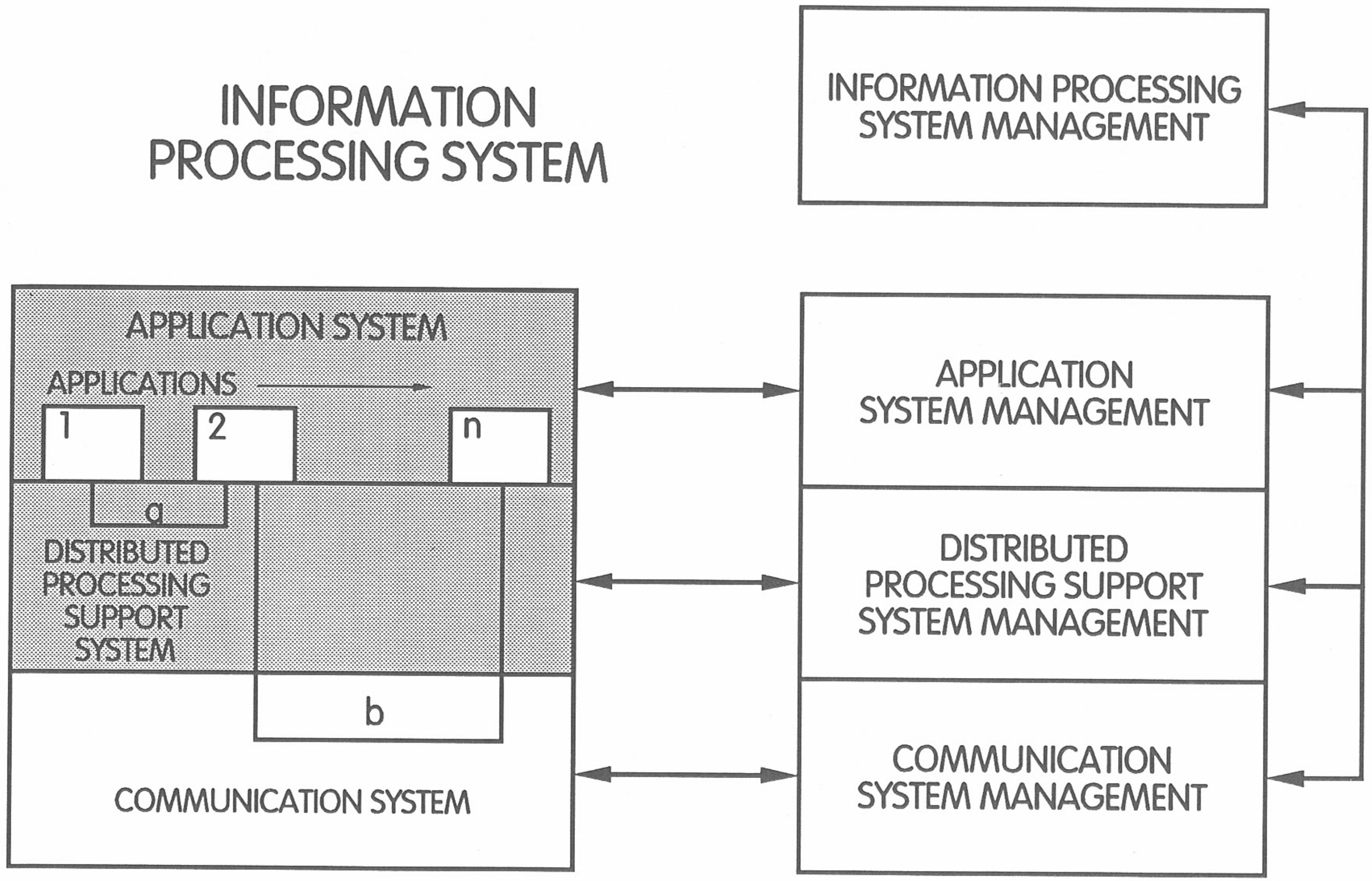

Figure 5. Conceptual structure for an information-processing system (Böhm and Ullmann, 1989).

information that is essential for doing network management, are being developed and refined by standards organizations. These network management standards efforts are discussed in Section 3.

Network managers would view networks such as those illustrated in Figures 1, 2, and 3 as being many network elements connected by some defined transmission capacity that collectively provide the desired telecommunication services, i.e., a domain of objects that they would want to manage. From a fundamental management perspective, however, the network could be considered to be a collection of managed elements (MEs) that may be divided into two classes—passive and active (Böhm and Ullmann, 1989 and Feridun et al., 1988). The passive managed elements could not be managed remotely. Such entities might include simple devices such as cables, dumb modems, and terminals or complex systems such as some PABXs that can only be managed locally. The active managed elements would include such items as intelligent modems, PABX networks, or protocol converters with internal management capabilities that enable them to be managed remotely using communication links. The capability that enables one to manage these elements may be defined as managed element management (MEM). Such capability must be suitable for monitoring and controlling all the intelligent devices and complex systems that comprise the network. Figure 6 shows a hierarchial management perspective for a network such as the one illustrated in Figure 2 (this and other management perspectives are discussed in Section 2.3).

Network management, in the context of this discussion that emphasizes the management perspective, is management of the managed elements, a process that may be performed by a network management center. For example, Figure 6 shows a network management center (NMC) that is controlling three MEM capabilities:

- a common-protocol capability for managing the 1...m managed elements in the PABX or private network

- a second, common-protocol capability for managing the 1...n managed elements in the ISDN network (that may be an ISDN island)

- a third, common-protocol capability for managing the 1...p managed elements in the Centrex or public network.

We now turn to discussion of the functions that need to be performed through the process of network management. In this discussion of functionality, several somewhat different

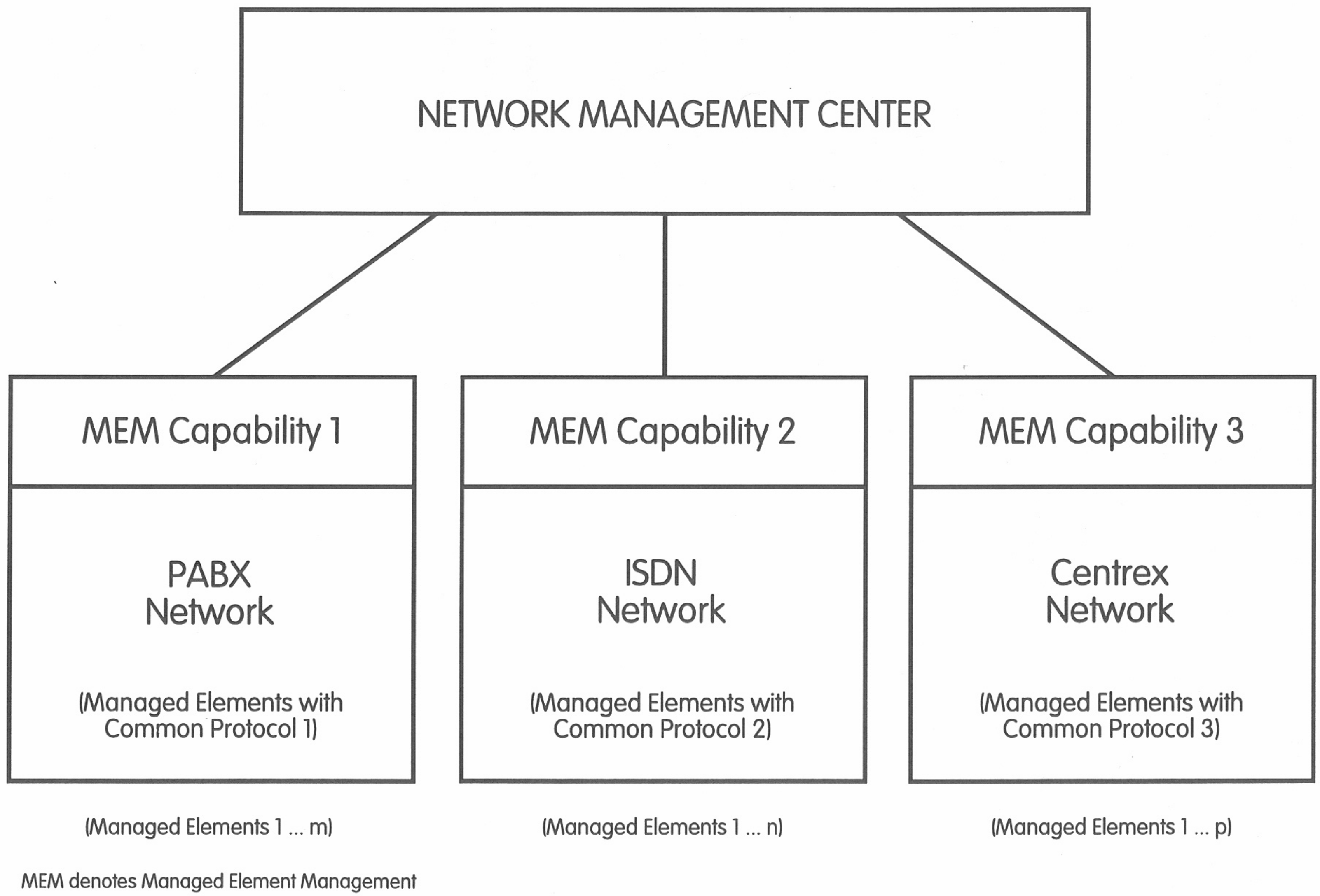

Figure 6. A user's network such as illustrated in Figure 2 from a hierarchial management perspective.

perceptions of network management are revealed. These differences reflect a refinement in understanding necessary functionality as the network management discipline has been evolving, differences associated with data-services users versus voice-services users, and differences associated with users' versus carriers' perspectives.

Earlier, in Section 2.1, we noted that Valovic (1987) has suggested three basic functional areas that relate to network management, namely monitoring and control, administration, and planning and design. Somewhat different expectations of network management tend to be held by users (or organizations, and the communications managers that represent these users) and the local and inter-exchange carriers that provide services for the users.

Some of the functions that users generally require in network management, as defined by Pyykkonen (1989), are identified in Figure 7. He notes that all of these functions are related to both physical and logical network management, but in practice, many of the functions are viewed as either physical or logical (but not both), largely due to the different views of voice and data (or management-information systems—MIS) users. Another view of network management functional categories (Caruso, 1990), that is quite complementary to Pyykkonen's view, is shown in Table 1. Each of these views presents eight functions or functional categories. One begins to see common functional areas that are included in each of these lists.

In recent development by a European telecommunications carrier of a capability for comprehensive, integrated network management, seven functional categories have been used to encompass the variety of communications management functions and services that are provided (Willetts, 1991). These categories and a brief description of each are shown in Table 2.

The Bellcore Network Management Handbook (1989) notes that "network management is responsible for supervising the performance of the network and controlling the flow of traffic ... to obtain the maximum use of network capacity." This responsibility is defined further to include the following seven specific functions:

- Monitor the flow of traffic in the network on a real-time basis.
- Collect and analyze network performance data.
- Identify abnormal network situations.
- Investigate and determine the reasons for network traffic problems.

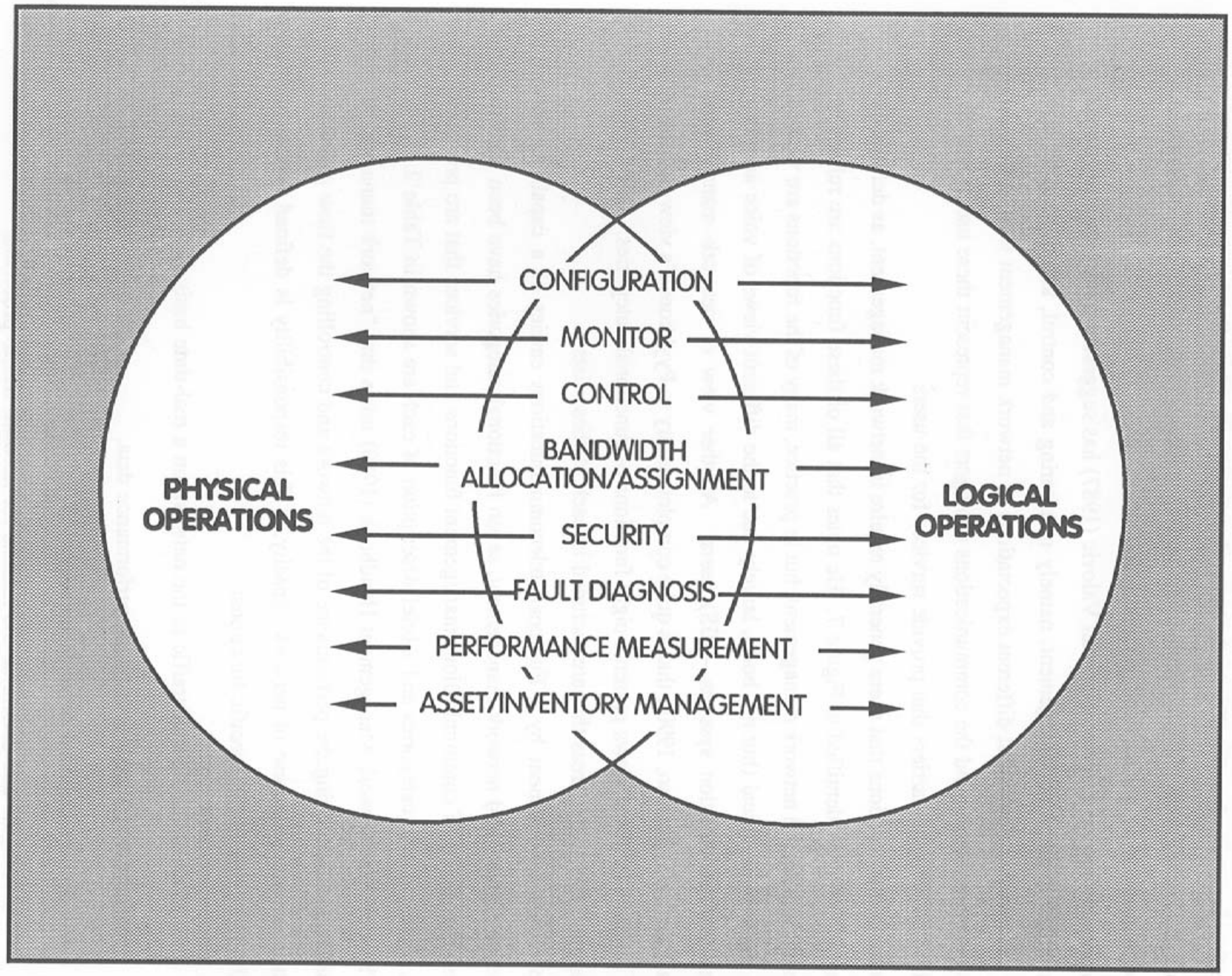

Figure 7. Functions, involving both physical and logical network operations, that users generally require in network management (Pyykkonen, 1989).

Table 1. Network Management Functional Categories Suggested by Caruso (1990)

CATEGORY	EXAMPLES
Fault Management	Fault detection, trouble reports.
Performance Management	Performance monitoring, alerts.
Configuration Management	Network topology database, band-width allocation, routing changes.
Accounting Management	Traffic usage statistics, billing reports.
Security Management	Secured access, intrusion detection/recovery.
Capacity Management	Forecasting, engineering.
Provisioning Management	Service ordering/tracking, pre-service testing.
Administration Management	Customer-controllable service profiles, management reports.

Table 2. Network Management Functional Categories Selected by a European Telecommunications Carrier (Willets, 1991)

Event management: deals with events occurring on the network (such as alarms) and the processes required to cope with them.
Performance management: ensures that the network is tuned to achieve optimum response times, utilization, and loading patterns.
Configuration management: covers how resources are configured into complete networks and includes disaster routing and provision for changes and expansion of the network.
Resource management: embraces the physical and logical construction of the network.
Financial management: deals with billing and costing, capital plant depreciation, and invoice reconciliation.
Access and security management: covers who is allowed to do what on the network and when.
Planning and design management: includes the series of functions required to plan new networks or extensions to existing networks, optimal routings and loadings, and fall-back strategies.

- Activate network controls or other corrective actions.
- Participate in joint planning sessions with inter-exchange carriers, local exchange carriers, and other telephone companies, and exchange information on matters of common interest.
- Coordinate activities with facility and switching system maintenance personnel to minimize the impact of outages.

Essentially, the sixteen sections of the Bellcore Handbook are detailed descriptions of these network management functions, with at least one section devoted to each function.

In the study performed by Linfield and Nesenbergs (1985), they applied the concept of telephone company operations (that is defined and discussed extensively by Rey, 1983) and the Bellcore concept of network management (Bellcore, 1989) to their discussion of Administration, Operations, and Maintenance and Network Management (AO&M/NM). Their study identifies and describes seven functional network operations as shown in Table 3. Most of these functions fall within the scope of network management presented in this report.

Many organizations are working on the development of standards for network management, and Section 3 presents a comprehensive discussion of that topic. Without providing the detailed, supporting information here, suffice it to note that (at the highest organizational levels) the Internet Activities Board (IAB)[15], the American National Standards Institute

[15] The IAB, through the work of its various subsidiary organizations, has developed the Internet suite of protocols for data communication and the associated Simple Network Management Protocol (SNMP) for network management. *The Simple Book, An Introduction to Management of TCP/IP-based Internets* (Rose, 1991) provides a thorough description of SNMP.

Table 3. Functional Examples of Telephone Network Operations
Described by Linfield and Nesenbergs (1985)

OPERATION	TYPICAL TIME SCALE	DESCRIPTIVE SYNOPSIS
Network Management (NM)	In Near-Real Time	Controls overload by alternate routing and reassignment of traffic to already-installed equipments. If local, NM is the same as technical control.
Network Administration	Hourly - Daily	Monitors traffic, keeps busy hour (BH) statistics, flags office (switch) degradations, plans and executes line/trunk assignments. Initiates installation requests.
Operator Administration	Daily - Monthly	Forecasts and provides operator service forces necessary for each hour, half hour, and if need be for each quarter hour of the day.
Long-Range Planning	Up to 20 years	Establishes most economic network growth and replacement strategies.
Network Design	Within 5 years	Estimates where, when, and how much of specific network elements will be needed.
Implementation	From Days to Years	Makes stress-dependent (changes) ASAP and slower planned economical changes, field construction, testing, and dismantling.
Maintenance	Continuous, Varied Pace	Repair, replacement, diagnostic testing, sometimes routine, otherwise under stress.

(ANSI)[16], the ISO in conjunction with the ISO/IEC[17], and the International Telegraph and Telephone Consultative Committee[18] are the leading organizations.

However, a study performed by the National Institute of Standards and Technology (NIST) (Aronoff et al., 1989) to determine functional requirements in the management of networks based on open systems interconnection standards asserts that a distinction must be made between network management, as commonly understood in the telecommunications industry, and the "management of OSI-based networks." These authors conclude, however, that while distinctions must be made, they believe that OSI management can be applied to the management of telecommunication networks beyond the focus of OSI management standardization and that such application is, in fact, being made in the United States (U.S.) to telephony elements by the American National Standards Institute in work within Technical Subcommittee (SC) T1M1. (See Section 3 for additional discussion of this specific point.)

There is at this time no generally-accepted, theoretical or practical, complete implementation of standards for network management. However, functional areas have been defined (ISO/IEC Standard 7498-4, 1989) that are widely accepted. Within the functional areas, numerous specific management functions also have been defined[19]. The five functional areas are shown in Table 4 with brief, paraphrased statements to describe what each area includes. (More thorough discussion and definition of these functional areas is included in Section 3.

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[16] The work of ANSI is developing network management standards is conducted by a Technical Subcommittee of Committee T1 known as T1M1. That Subcommittee is responsible for developing standards relating to internetwork operations, administration, maintenance, and provisioning of telecommunications networks. At the end of 1991 there were 18 draft standards either completed or in the process of being approved. There were an additional 10 draft standards under development in T1M1.

[17] The International Organization for Standardization (ISO) in conjunction with the International Electrotechnical Commission (IEC) have developed for information processing systems the Basic Reference Model for Open Systems Interconnection (OSI) (ISO, 1984). The framework for OSI Management is defined in Part 4 of the Basic Reference Model Standard (ISO/IEC, 1989).

[18] The results of work and agreements within the CCITT are contained in Recommendation X.200 (CCITT, 1989e) for open systems interconnection, in Recommendation E.410 (CCITT, 1989b) for international network management, and in Recommendation M.30 (CCITT, 1989d) for a telecommunications management network.

[19] For example, the OSI Network Management Forum (NMF) is following the ISO/IEC and CCITT standards in developing specifications for network management implementations (OSI/Network Management Forum, 1990), e.g., interoperable interface protocols, management services, a framework for modeling the communications network for management purposes, the architectural framework of interoperable network management agreements, etc.

Table 4. Network Management Functional Areas that are Widely Accepted by Users, Telecommunication Service Providers, and Standards-Making Organizations

Fault management: responsibility for and actions to detect, isolate, and control abnormal network behavior, such as excessive line outages (**what** "is the network doing?).
Accounting management: responsibility for and actions to collect and process data related to resource consumption in the network (**when** is the network used?).
Configuration management: responsibility for and actions to detect and control the state of the network for both logical and physical configurations (**where** is everything in the network?).
Performance management: responsibility for and actions to control and analyze the throughput and error rate of the network, including historical information (**how** is the network doing?).
Security management: responsibility for and actions to control access to network resources through the use of authentication techniques and authorization policies (**who** can use the network?).

Returning to our development of the management perspective for network management, we now expand the discussion of managed elements and relations between them (discussed earlier in this section and illustrated initially in Figure 6). A simple network is illustrated in Figure 8. This illustration, selected as a "cut" through the network illustrated in Figure 1, shows only a workstation and modem at one node connected, through a gateway and LAN, to a host computer at the other node. In reality, the network is composed of physical components (e.g., hardware devices, cables, etc.) and logical components (e.g., various software-defined services provided by the network). Each of these physical and logical components may be represented as a managed element, and the relationships between components may be represented as relationships between the managed elements. These concepts are illustrated in the simple network depicted in Figure 8. Each managed element, then, may be described using parameters, such as name, state, physical location, last maintenance date, etc., that collectively will comprise a database that describes the entire network. We have, in fact, just described the configuration management functional area defined in Table 4. The full representation of all managed elements, their relationships, and their descriptive parameters become a model of the network's managed objects—the configuration model and associated configuration database.

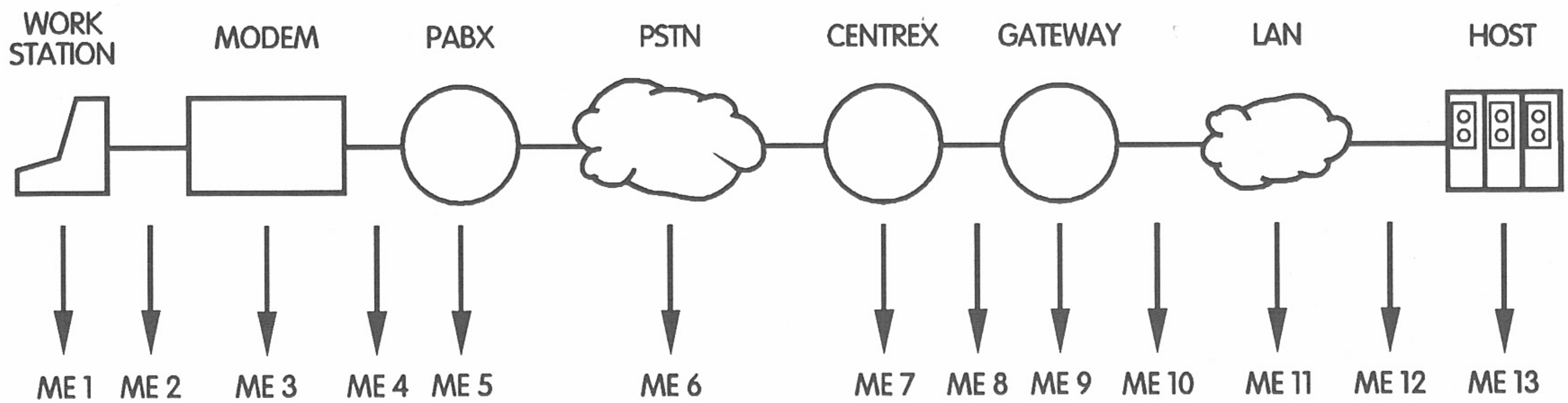

Figure 8. A simple, conceptual network, extracted from the user's network shown in Figure 3, illustrating the concept of managed elements.

We have noted that there are several possible approaches to management of the managed elements, or generic network management. The network configuration model just described must be suitable to support any of these approaches or architectures for network management. That is the subject of discussion in the next sub-section.

2.3 Approaches for Designing Network Management

A broad and very general definition for **network** is given in Section 1. The reality is that in practice many different types of telecommunication networks must interoperate and be managed for these networks to provide efficient and effective telecommunication services. The various types of networks (which may be public and private, national and international) likely will include voice networks; computer networks, such as packet-data networks, LANs, WANs, etc.; and networks for a variety of video services. In general, the communications resources of a business or organization include much more than just the physical and logical network of circuits and switches. Therefore, we use the term network management to describe the broader notion of managing all of the communication resources.

The introductory material for Section 2 gives some early, general-perspective information about network management. The historical reality, however, has been that each of the various types of networks noted above likely was established using systems (hardware and software) from a wide variety of developers and implementors, each with its own network management system (or capability). Interoperation[20] between the many individual network management capabilities now is essential, however, if overall effectiveness and efficiency are to be realized in managing and using the network. Managing these networks is more than a technical problem, however; the environment for managing telecommunication networks is, in fact, a combination of human, social, organizational, and technological components (or factors). Therefore, management of these networks to provide efficient and effective services must involve a combination of human, software, and hardware resources.

[20] Interoperation (a topic unto itself) of network management capabilities is the goal of proponents for open systems and the specific objective of the many network management standards organizations that are identified and discussed in Section 3. The concept of interoperation (or open systems) is that one tool (or set of tools that work together) can be used to manage all of the communication resources of a business or organization. Such capability often is referred to as integrated network management. (See, for example, Joseph and Muralidhar, 1990.)

As discussed above, the communications resources provided by telecommunications earners or other suppliers and used by businesses and other organizations generally are complex and heterogeneous. But, as noted by Joseph and Muralidhar (1990), these resources tend to fit into two main categories: resources that provide **interfacility** networks, such as circuit- and packet-switched telecommunications networks; and resources that provide **intrafacility** networks, such as the various forms of local area networks. The tools available today for managing networks in each of these two categories are quite different. For example, tools for managing interfacility networks focus on managing the physical and logical networks and sub-networks that are made-up of circuits, switches, and trunks (Aronoff et al., 1989), whereas, tools for managing intrafacility networks are very diverse, ranging from relatively simple modem managers to relatively complex LAN management systems. From the perspective of user control, relatively less effort is being devoted to development of tools for interfacility network management, and relatively more effort is being devoted to development of tools for intrafacility network management. The availability of user-controlled tools for managing networks in each of these categories is about proportional to the development effort in each. And, the network that needs to be managed typically is a complex mix of resources and services—a combination of many interfacility and intrafacility networks and sub-networks for which users feel there needs to be a common network management capability.

Basically, there are three main approaches that may be followed to develop and provide this common network management capability. These are the centralized approach illustrated in Figure 9, the distributed approach illustrated in Figure 10, and the hierarchical approach illustrated in Figure 11. There also would be various combinations of these approaches that could be used.

In the centralized approach (Figure 9), all management entities are connected directly to the network management center which carries out all management functions. That is to say, the management entities have little or no inherent management capabilities, and all management data are exchanged directly between the network management center and the respective management entities, using appropriate protocols. This approach to network management tends to be the most economical to implement because a single location gathers, processes, and stores all the data required to control the network. However; the collection of data from many management entities and the distribution of control instructions throughout the network can consume significant

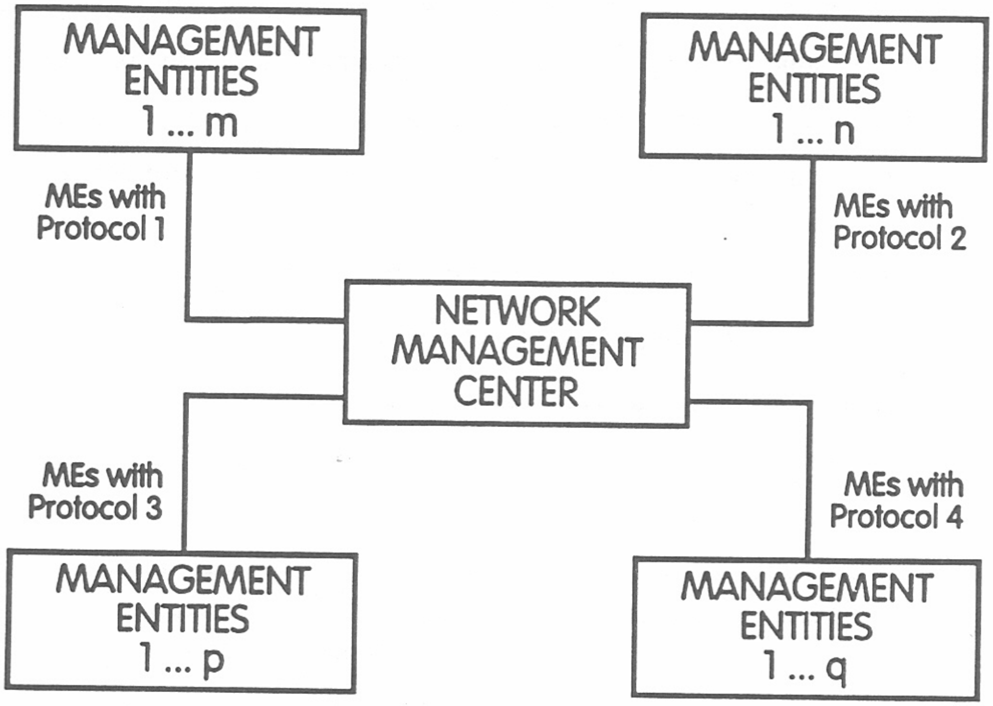

Figure 9. Centralized approach to network management.

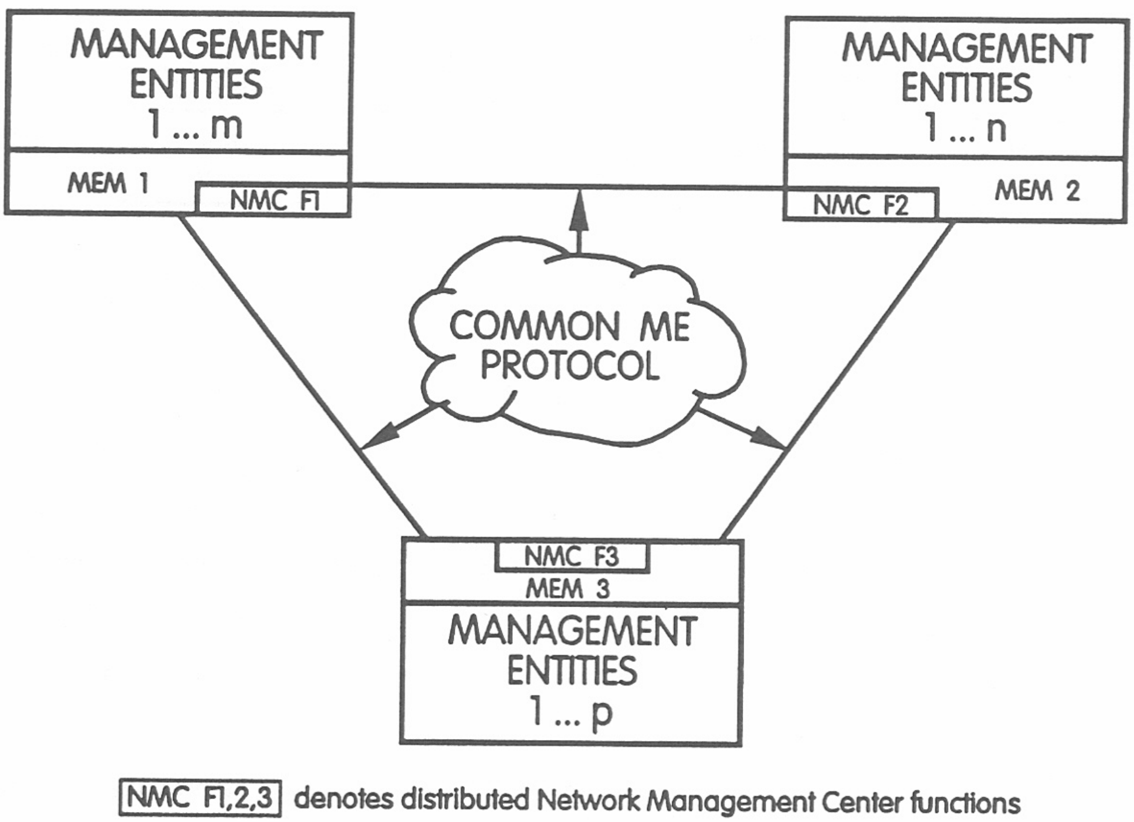

Figure 10. Distributed approach to network management.

portions of the network capacity, particularly for large networks, thus effectively reducing the network resources available for supporting the users' communications requirements. A single location for all data processing and storage also introduces a single point for failure. If the network management center fails, all management capability for the entire network is lost.

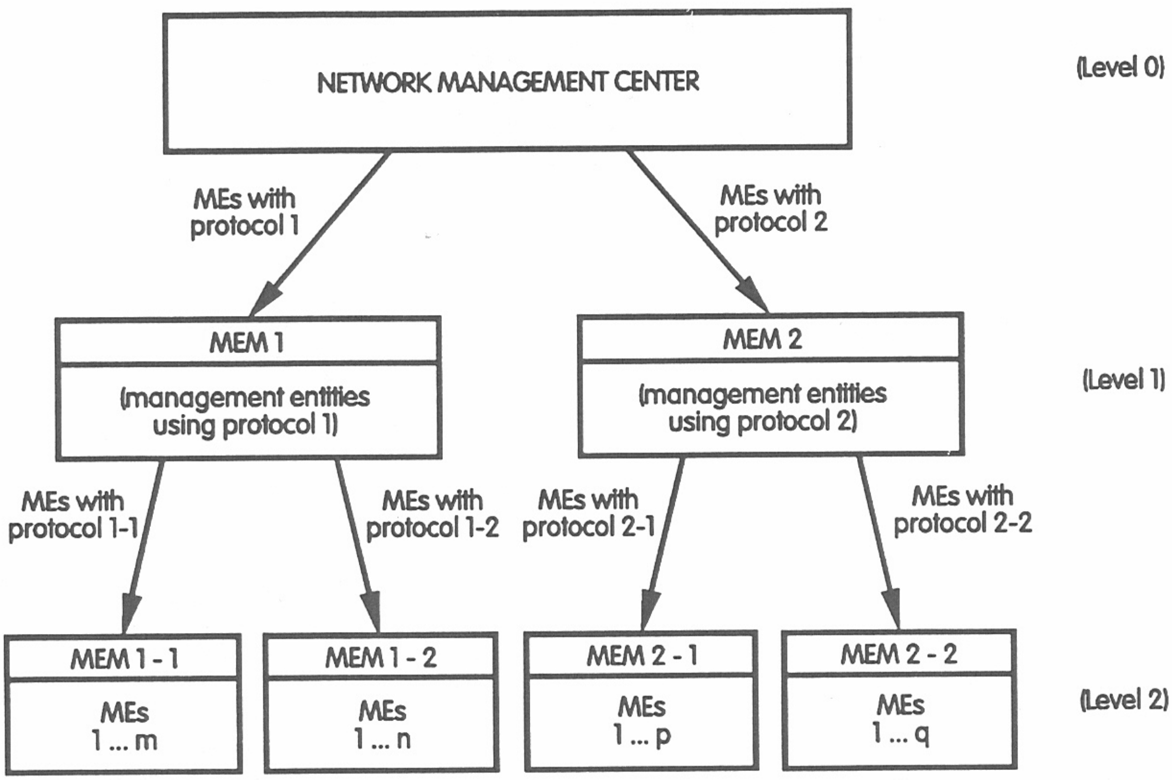

Figure 11. Hierarchical approach to network management.

In Figure 10, the network management functionality is distributed throughout the network. In this distributed approach, all MEM capabilities are interconnected, and all management entities can communicate with one another, provided the required condition of a common management protocol being used throughout the network is satisfied. (This requirement points directly to the benefit of open systems and standards for network management, features that are discussed in Section 3.) The distributed approach is more expensive than centralized network management because it requires every location to have network management capability, i.e., computer processing power and memory for storage, but there are at least two features that contribute to better performance. If one management entity manager fails, only part of the total network management capability is impaired. Considerable management functionality still is available for the remainder of the network. Secondly, with management functionality distributed throughout the network, there is less need for large amounts of management data to be exchanged over the network. Therefore, a larger portion of the network resources is available to support the users' communications requirements.

Several levels of management functionality in the hierarchical approach are illustrated in Figure 11. All management entities have some management capability that supports the collection and issuance of management information (or data). The network management center manages the next lower level of MEM capabilities and that level may manage still another, lower level of MEM capabilities. If the network management center fails, the highest level of management functionality is lost, but the next lower level of management functionality can take over to keep the network in operation. Some of the same advantages and disadvantages of the distributed network management approach also apply to the hierarchical approach, e.g., improved performance when compared to the centralized approach, but higher costs for implementation because of the redundant capability required for hierarchical network management.

Joseph and Muralidhar (1990) also identify three approaches to (or implementations for) network management as being centralized network management, distributed hierarchical network management, and distributed peer network management. These approaches are illustrated in Figure 12, where we see many similarities with the approaches discussed earlier and illustrated in Figures 9-11.

The different approaches to network management that have been illustrated and discussed are not exhaustive, but form the basis for many specific, network-management implementations. Some of these implementations are discussed in Section 4 where various specific and, sometimes, proprietary, network management systems are identified and discussed.

Meanwhile, the next step in describing fundamentals of network management is to consider the architecture for network management. Every organization concerned with providing or using telecommunication services should formulate its own management strategy consistent with its objectives and installed base of communication and information systems equipment. Any of the approaches discussed above, or derivatives of those basic approaches, may be followed to develop an architecture that will provide the features that are important to users and providers in their network management systems. The architecture should identify the major system

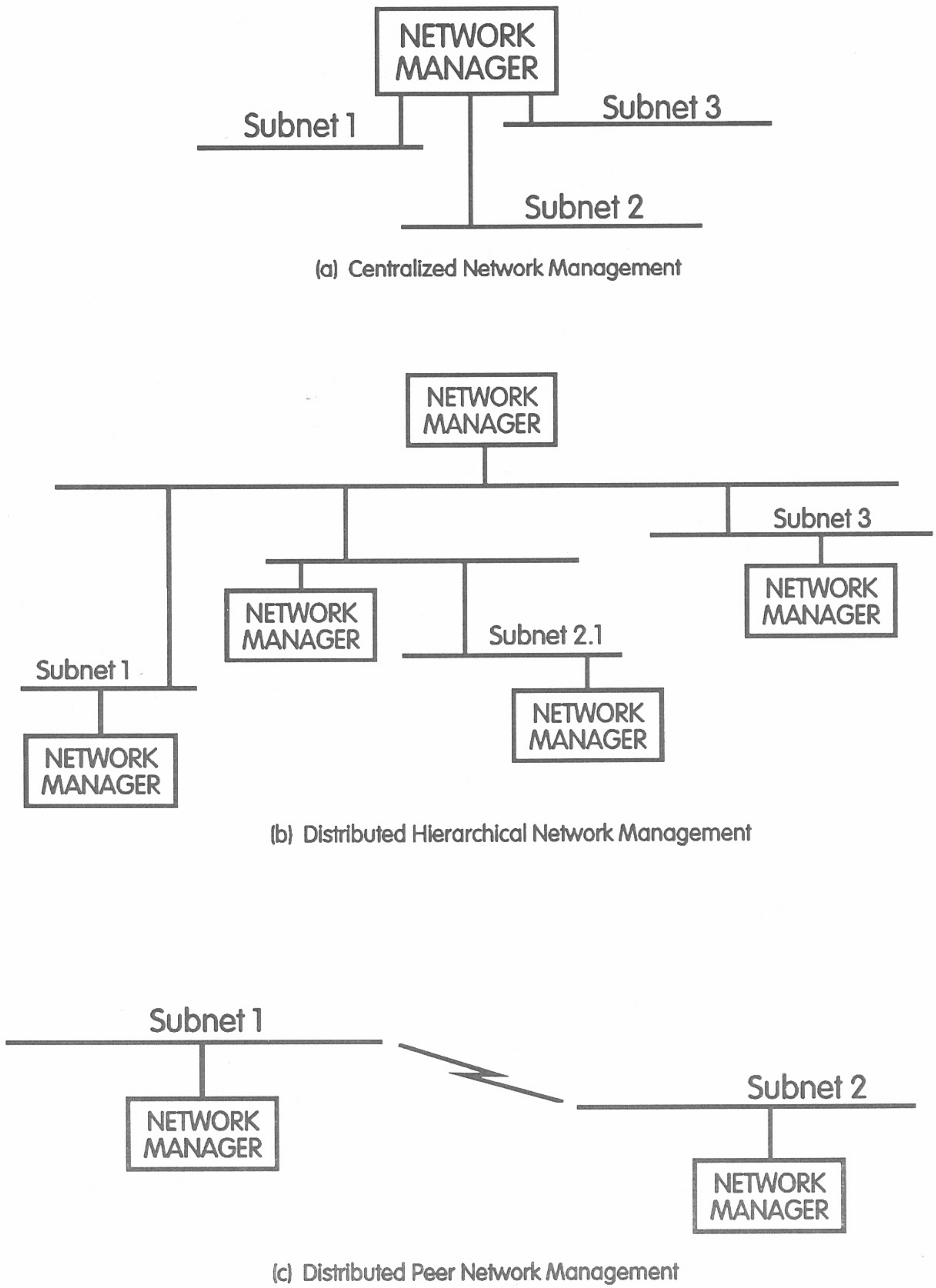

Figure 12. Possible network management implementations suggested by Joseph and Muralidhar (1990).

building blocks and specify the relationships that must exist between them so as to define a high-level framework that can be followed during detailed system design and implementation. The management architecture also should describe the organization of people, functions, and computer-support systems that will be needed to plan, operate, and administer the network and all of the network services. Some important characteristics of the architecture are that it utilize common descriptions of all the network components and capabilities and that it specify the minimum management functionality that is required in each network component to satisfy the overall management requirements. In summary, the architecture (or architectural design) becomes a way to identify and define the management functions that are needed, by applying management techniques rather than being limited to capabilities that are offered by technology available in 1991/92 or expected to become available as long as a "piece-wise approach" to network management is followed. That is to say, developing the network management architecture should be treated as a "systems problem" rather than as a "tools issue". Then, the architecture is a set of guidelines and ground rules that ensure that all of the constituent parts of the complex system will work together.

Desikan (1990) has described network management system architecture as consisting of four major components: managed objects, a management information network, a communications processor, and a manager. A conceptual illustration of this network management system architecture is illustrated in Figure 13.

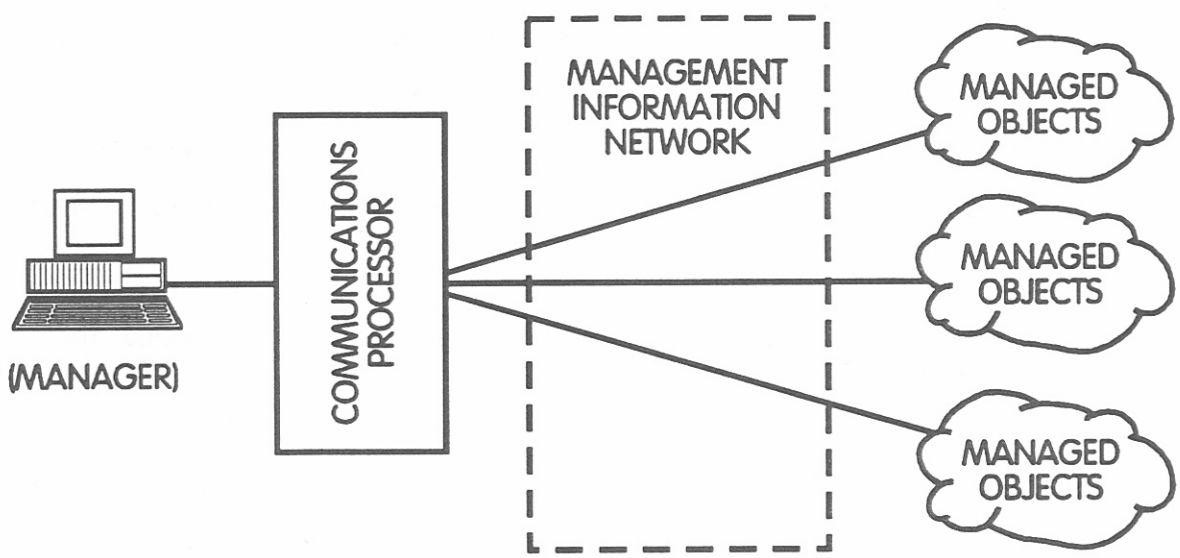

Figure 13. A conceptual illustration of network management system architecture.

Managed objects are components that generate events and reports and that are controlled by the network management system manager. Examples of managed objects include T1 multiplexers, local area network bridges and routers, matrix switches, and element management systems that are part of other network management systems.

The management information network is a data communications network that is used to transport management information, e.g., events, reports, etc., between the managed objects and the communications processor. This network may be a virtual network that is derived from the user's physical network. The TMN that has been defined by the CCITT (1989d) to support the management of telecommunications networks is an example of such a network.

A communications processor may or may not be required. When required, it multiplexes messages from the managed objects into a single data stream for transmission to the manager and provides protocol conversions that may be required between the managed objects and the manager. An ideal network management system would use a common protocol throughout the network and, therefore, not require any protocol conversion. However, many of the network management systems that are in-service and being placed into service today use proprietary protocols for exchanging information (data) between the managed objects and the manager. The management information network may have sufficient capability to perform any required protocol conversions and multiplex the messages between the managed objects and the manager.

The manager is a computer-based system that interprets information (data) from the managed objects, provides instruction (or control) responses back to the managed objects, and presents results, either graphically or in a text format, to the operator via an appropriate interface. For small networks, the manager may be a personal computer (PC); for larger networks, the manager may be a workstation, minicomputer, or main-frame computer, as appropriate.

According to Ben-Artzi et al., (1990), there are two models for network management that are used widely:

- **Polling-based management** where managed objects are polled for information of interest and this information is synchronously returned to the manager.

- **Event-based management** where managed objects asynchronously send pre-configured information of interest to the manager.

The Simple Network Management Protocol (SNMP), for Transmission Control Protocol/Internet Protocol (TCP/IP) based networks, is an example of polling-based management, whereas the Common Management Information Protocol (CMIP), for ISO/OSI-based networks, is an example of event-based management.

The functional capabilities that must be provided, regardless of the network management architecture that is used, are the capabilities discussed in Section 2.2. Today, there are no single network management systems that provide all of the functional capabilities described there or that have an architectural design to allow use of common protocols throughout the entire network (often referred to as open network architecture (ONA)). Open network architecture and full-capability, network management functionality are the general objectives of various standards organizations.

Characteristics of various network management protocols and the work being done by many standards organizations are described in Section 3. The network management systems that are in service and available to be placed in service are discussed in Section 4, along with some discussion of the efforts that are being directed to the realization of interoperation between the various systems that otherwise cannot interoperate.

2.4 Factors Influencing Development of Network Management

The concepts of network management that have been developed thus far in Section 2 are idealistic. Several factors must be recognized and taken into account as we progress from these idealistic concepts to discussing the development of standards for network management and the development and use of network management systems. These factors include

- the diversity of efforts that are being directed to the definition and development of standards for network management

- the reality that development and introduction of network management systems are evolutionary processes that began with conceptually simple objectives and systems, but are now progressing rather rapidly toward complex processes and sophisticated network management systems

- the dilemma that arises because market competition and regulations on the telecommunications market may combine, though not as an intentional plan, to discourage the development and implementation of integrated capabilities for network management.

2.4.1 Multiple Standards

Extensive information concerning standards for network management is presented in Section 3 and Appendix A. The comments that follow depend on that information for basis but are included here because they represent a significant factor that is affecting the development of network-management practices and systems.

The Internet community has for several years directed considerable effort into the development of standards for data networks and services and the management of these networks. This work has been (and continues to be) coordinated by the IAB which has two principal task forces: the Internet Engineering Task Force (IETF) and the Internet Research Task Force (IRTF). The IETF is responsible for defining architecture and protocols and for developing standards, including standards for network management, that are recommended for IAB approval. Their work has included development of the TCP/IP-based SNMP and the definition of an associated Management Information Base (MIB). Work also continues to be directed to the definition and development of a framework for common management information services (CMIS) and protocols that are compatible with the ISO/OSI-based standards. The Common Management Information Services and Protocol over TCP/IP (CMOT) is the principal network management product from this effort.

The SNMP and associated MIB are criticized by many as too limited in the capabilities offered for network management. Proponents and users of SNMP argue, however, that it is available now, it works, and it provides an adequate capability that satisfies their requirements for network management.

The international efforts in developing standards for network management are very diverse. For example, the ISO has developed and promoted such standards as CMIS and CMIP and defined an associated MIB for data networks. Much of this work (but not all) has been endorsed and adopted by the CCITT. In addition, the CCITT has defined International Network Management, for telephone service including ISDN, and the TMN, that include definitions of many management functions. Many other international and national groups, such as the OSI Network Management Forum (NMF), the Accredited Standards Committee T1 and. Technical Subcommittee T1M1, and groups accredited by the American National Standards Institute also are providing support to the development of international standards.

The international standards that are emerging are broad, not entirely consistent, and, often, too general. These characteristics of the standards cause difficulty when attempting to develop and market network management products that conform to the standards. They also foster reluctance by both users and product developers to attempt to conform with the standards, since the generality and lack of total consistency mean there is no guarantee that products from different developers/vendors will interoperate or provide exactly the same functionality. The positive side of international standards, however, is that such standards do tend to promote system interoperability and conformance to open network architecture objectives and the standards are supported widely outside of the United States. For these reasons, U.S. products in the international markets must conform with these standards to be successful. In addition, the international standards, generally speaking, have greater functional capability than most other standards, for example, the IAB or INTERNET standards. This last point is discussed more completely in Section 3.

Considerable effort is being directed by several National (United States) organizations (see Section 3.2.2) to developing network management standards. Much of their efforts have the dual objectives of developing National standards, and resolving vague and ambiguous features of international standards, and contributing to the development of international standards.

The United States Government also has become involved in developing standards for network management with issuance of the Government Network Management Profile (NIST, 1991). This profile was written because the Government has urgent needs for products to manage networks composed of multi-vendor components, and it recognizes that existing ISO/OSI based standards still are at an intermediate stage of development.

Finally, there are numerous product developers/vendors who have developed their own proprietary "standards" for the products that they market. Several of these standards have, for a time at least, been accepted by many users as de facto standards for the products used in their networks. Examples include the Systems Network Architecture (SNA) developed and used by International Business Machines Corporation (IBM), the Open View network architecture developed and used by Hewlett-Packard Company (HP), the DECNet architecture developed and used by Digital Equipment Corporation (DEC), etc. Fortunately, most of the companies that have been developing and using these proprietary, de facto standards now are attempting to achieve compatibility and inter-operability with equipments and systems that conform with either the SNMP or CMIS/CMIP standards, or both.

2.4.2 Evolutionary Processes

We have described how the telephone company provided the earliest network management. Then, as data communications developed and opportunities to provide new services were recognized following divesture of the Bell System, the requirements and capabilities for network management also expanded. These, of course, were (and continue to be) evolutionary processes that first provided simple management for individual elements of the network. As the number and complexity of the elements increased, the requirements for and complexity of network management systems also have increased. Now, we are hearing managers and providers of networks and network services expressing their needs for comprehensive, or integrated, network management.

The development of standards for network management and inter-operability of the network management systems is an integral and essential part of these evolutionary processes for developing and marketing management products. But, a reality in the process is that increased synergy among the standards, widespread conformance with the standards, and the ultimate capability of truly integrated network management with systems inter-operability will occur only as it becomes economically viable. Users of TCP/IP and SNMP, for example, are likely to continue to request SNMP products as long as such products are the least expensive and satisfy their management requirements. Products that conform with ISO/OSI standards for interoperability and integrated network management will be developed and available to users only as developers/vendors perceive an economically-viable demand. That demand will arise only when managers recognize their existing management capabilities to be inadequate to satisfy their (increasing) requirements and such products are available at reasonable cost.

2.4.3 Market Competition and Regulation

Both favorable and unfavorable influences arise from market competition and telecommunication regulation on the development of network management standards and systems. For example, competition continually stimulates the development of new and innovative technology that benefits users with more and easier-to-use capabilities and services at competitive prices. There is debate, however, concerning the effectiveness of competition in assuring high reliability for these services. Competition may influence a developer to market a product before it has been thoroughly tested. Some analysts speculate that regulation may be necessary to assure acceptable reliability and that some regulation to require that certain basic technologies be available for users at reasonable prices may be beneficial. Many, general examples could be cited, however, to argue that regulation often stifles innovation, reliability, and economy.

On the other hand, the development of standards is, in fact, a process that is supported extensively by organizations that provide network facilities and services, as well as organizations that develop and market both hardware and software for network management. The necessity of competition in the market place may influence and even restrict their willingness to completely and cooperatively support the agreements that would provide for "ideal" standards that would be completely consistent and sharply focused.

3. NETWORK MANAGEMENT STANDARDS

What are standards? Who needs them? Who makes them? How? What about network management standards? What are the current NM activities? What are the future issues and trends in standards for network management? The purpose of this section is to address these questions.

Standards for telecommunications have been evolving for many years. However, in the 1980’s, the demand for standards increased as divestiture became reality and technology advanced, network users increased, and networks took on global statures. The expanding technical innovations resulting from the convergence of telecommunications and computer technologies also played a key role.

In order to meet the need for standards, there are numerous organizations dedicated to standards development. The complex nature of these global, regional, and national organizations involved with information processing and telecommunications standards is depicted in Figure 14, developed by A. M. Rutkowski of the International Telecommunications Union (ITU) (Knight, 1991). Table 5 provides definitions of the many acronyms used in Figure 14. The arrows between organizations indicate the relative information flows and interworking.

Until recently, most participants in the standards-setting organizations were representatives of the telecommunications providers. Users were seldom represented. Participants came together