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Local Area Networks and the Dynamic Hierarchy: A Tutorial*

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30 May 1986

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ABSTRACT

Effective research and development in communications networking continues to be a key to maximizing the benefits of a rapidly growing capability in information processing. The selection of a network architecture which will realize the highest gains for existing technology at minimum cost is critical. Certain specialized applications of the Local Area Network (LAN) suggest the need for an architecture which can be dynamically altered in significant ways. The purpose of this paper is to review the traditional network architectures and their characteristics and to discuss the limitations of these architectures in meeting the requirements of such specialized applications. Finally, the dynamic hierarchy is introduced as a network architecture which can better meet these unique requirements.

CR Categories and Subject Descriptors: C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design — *distributed networks, network topology;* C.2.4 [**Computer-Communication Networks**]: Distributed Systems; C.2.5 [**Computer-Communication Networks**]: Local Networks

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1. INTRODUCTION

The technology of the 1970's and 80's has introduced electronics equipment with capabilities that were not considered possible only a few short years ago. The impact has been widespread, providing innovations in business, professional, military, and government applications with considerable political, economic, and social ramifications. With the rapid increase in capabilities has come a corresponding growth in the need to better manage these high-tech resources in order to realize their potential. A primary key to achieving this end is the cost-effective, rapid, and reliable processing of information through networking.

Webster defines a network as a "fabric or structure of cords or wires that cross at regular intervals and are knotted or secured at the crossings". The definition is further narrowed to include an "interconnected or inter- related chain, group, or system" [8]. Networking can therefore be viewed as "interconnecting" communications devices using some type of medium ("cords or wires") for a communication path. If the devices are computers, the result is a computer network. Furthermore, when the network is within a small geographical area, the network can be described as a local network (as opposed to greater distance "long haul networks" or the very short range processor interconnections of "multiprocessor systems") [16, pp. 4-5].

A brief look at the network requirement characteristics of two specialized areas of network applications (within the nuclear power industry and a Naval task force at sea) provides evidence of the challenge facing today's network designers to choose suitable network architectures which will maximize benefits and resource utilization while minimizing costs.

Example One: A Nuclear Power Plant

First, a nuclear power plant network links several reactor vessels and supporting systems to a common control/ operations center. Such a network demands error-free performance to prevent severe reactor accidents and to maintain containment of the reactor vessel and supporting systems at all times. For example, critical plant parameters (reactor system temperature, pressure, etc.) and component status (valve position, rod position, pump speed) must be readily available at the operations center. Information response times must be short to allow for quick, easy identification of plant status and immediate response under time-sensitive emergency conditions. Redundant paths of information flow and redundant sources of condition status must exist to ensure the ultimate and certain delivery of status information to the operations center. Plant control and monitoring capability must also be possible from "alternate" operations centers.

Example Two: A Naval Task Force

A Naval task force at sea under wartime conditions represents a complex communications network. Command, control, and communications must be maintained throughout to ensure coordinated tactical operations and to guarantee the high likelihood of survivability and mission success. Similar networking constraints to that of the nuclear power plant are obvious — fast information response, redundancy of information flow, flexibility in the task force command center location, etc.

These two specialized applications suggest the need for a network architecture that can be dynamically altered in significant ways. The purpose of this paper is to review the traditional network architectures and their characteristics and to discuss the limitations of these architectures in meeting the requirements of the specialized applications. Finally, the dynamic hierarchy is introduced as a network architecture which can better meet these unique requirements.

2. NETWORK OVERVIEW

Expanding on a previous definition, the term local network can be more formally defined as "a communications network that provides an interconnection of a variety of data communicating devices within a small area" [15, p. 4]. To lay the groundwork for future discussion, a brief overview of the key characteristics, methods of message transmission, switching techniques, and categories of local networks is presented.

2.1. Characteristics

A properly designed local network exhibits specific characteristics which meet actual needs. A general summary of these (given below) is drawn from several references [4, 14, 15, 16], and represents a consensus of ideas.

1. *Sharability* - the sharing of critical or expensive resources to include data and software driving geographically separated components.
2. *Reliability* - the continuation of system performance through redundancy of components, multiple levels of backup.
3. *Maintainability* - the minimal disruption during repair, ease of modernization, and integration of components.
4. *Flexibility* - varied functional use of each device element.
5. *Accessibility* - greater access to users of multiple functional computing services with varying processor requirements. Wider access also improves communicability among users.
6. *Distribution of capability* - distribution of processing power, the practical result of local network utilization. The net gain is more capability per dollar spent. [See 3 for further discussion of distributed processing.]

2.2. Methods of Network Message Transmission

There are two primary methods of network message transmission. In the *point-to-point* network, each network device receives, processes (to some extent) every message on the network, and then forwards the message (This method is also known as "store-and-forward") [16, p. 8]. *Broadcast* networks employ a common transmission medium for all connected network devices and are considered "multipoint" [14, p. 56]. Message processing at each device is simplified in that messages not addressed to a device can be disregarded. "Forwarding" is not required.

2.3. Switching Techniques

Message handling within the various network types can be categorized by three basic switching techniques [14, pp. 27-32; 12, pp. 10-11]:

1. Circuit switching produces a dedicated channel or communications path between two network stations.
2. Message switching is a store-and-forward implementation whereby a message transits through the network, node to node. Delays occur due to individual node processing times and messages are often permanently filed.
3. Packet switching varies from message switching in that the data unit is now called a "packet", packet length is now restricted, and packets are generally not filed. It should be noted that variations exist (datagram, virtual circuit, etc.) [14, pp. 31-32; 16 (Chap. 5)].

2.4. Classifications

Local networks can be classified into three (3) groups or categories [15, pp. 8,9]:

1. The Local Computer Network (LCN) or High Speed Local Network (HSLN) is primarily a network among the devices of a single computer room or system. Its purpose is to provide fast throughput using high speed devices such as mainframes and mass storage devices. Typical functions of such a network are system backup, and file and data manipulations.
2. Computerized Branch Exchange (CBX) is a form of the Private Branch Exchange (PBX). CBX is an onsite digital network and is used to transfer voice and data information.
3. Local Area Network (LAN) can link together a broader population of device types (including the ever-popular personal computer), and for this reason is a general purpose local network. The LAN typically can transfer video and graphics information in addition to the normal voice and data. Because of its flexibility, the LAN is the most widely used network today.

Although generally applicable to local networks, the following review of traditional network architectures and their characteristics is directed toward the LAN. The specific issues of combined data and other communications (voice, video, etc.) are not considered.

3. SURVEY OF TRADITIONAL NETWORK ARCHITECTURES AND THEIR CHARACTERISTICS

Networks come in all shapes and sizes. However, three basic structures can be identified. The star, ring, and bus/tree topologies are summarized, specifically highlighting inherent characteristics. Transmission media, communications protocols, and common applications are discussed. Other network topologies do exist, (mesh [12, pp. 15-17], loop/intersecting loop [16, p. 9,10], etc.), but most are only variations on, or combinations of, the basic structures.

3.1. Topologies

To generate an initial perspective, star and ring networks are typically point-to-point while bus/tree networks are broadcast [14, p. 55, 56].

Star

In a star configuration, all network devices are connected to a central node or switch. The central node manages the communications links among network devices, primarily employing circuit switching. An inherent difficulty with the star is that failure of the central switch can cripple the entire network [12, p. 11]. In addition, network data rate is limited by the central switch's capacity. However, the central switch handles most of the processing functions, thereby simplifying the communications protocol and network duties of peripheral stations [14, pp. 55].

Ring

Simply stated, a ring network consists of devices called repeaters, which are connected so as to form a complete circle or ring. An individual network station is linked to the ring via its repeater. Repeaters have two modes of operation — listen and transmit. Since data packets include an address field which identifies the destination station, the repeater must "listen" to the network, inspecting the packet to determine if the address corresponds to an attached station. Packet delivery is accomplished by sending it to the attached station while retransmitting a modified version onto the ring. The modification provides an acknowledgement of receipt. While transmitting for an attached station, the repeater must buffer incoming packets for later processing [15, pp. 17-18].

Certain glaring problems exist with this type of network architecture. Packet processing requirements are dispersed among network devices. The communication protocols are therefore necessarily more complex. Although packet insertion and removal difficulties are handled fairly well by medium access protocols, (which are briefly discussed later) significant drawbacks include cable vulnerability and repeater failure. Malfunctions of either type could end functionality of the entire network. Enhanced architectures utilizing ring wiring concentrators and bypass relays help minimize these problems, but do not overcome them [15, p. 19].

Bus/Tree

The basic structure of a bus network is a single transmission medium to which all network devices are joined. Thus, a single transmission on the network can be received by multiple stations at a time without rebroadcast. The tree network is essentially a bus network with branching transmission lines. A transmission disperses a packet through the network trunk and branches, so that it is received by all individual stations, yet retained only by those addressed. Only one station may transmit at a time [12, pp. 13-15; 15, p. 6-7].

Bus/tree networks utilize baseband and broadband transmission techniques. Baseband LANs use digital signals that are formed by using the entire frequency spectrum. Broadband LANs use analog signals, and frequency division multiplexing is possible to form separate transmission channels [15, pp. 10-15]. Baseband transmission is bidirectional and requires a bus topology. Bidirectional transmission is not suitable across the "splitters and joiners" of a tree [15, p. 11]. On the other hand, broadband transmission is unidirectional and is possible for both bus and tree topologies. Properties of baseband and broadband techniques produce very unique and varying performance considerations. Considerable debate is ongoing as to which is the better technique [6; 15, p. 16]. However, the problem of deciding when a station may have transmission rights is common to both techniques and is dealt with in the medium access control protocol strategies.

Reliability problems are of a much smaller magnitude with bus/tree networks since a single node can be effectively removed without interference to the network. In rare cases, however, traumatic disruptions to the transmission medium could disable (remove) stations that are downstream of the disturbance, thus essentially removing entire portions of the network [12, p. 15].

3.2. Transmission Media

Three media are germane to local networks: twisted pair wire, coaxial cable, and optical fiber. Although twisted pair wire is low in cost and easy to install, it is susceptible to interference. Having a low data rate and relatively high transmission loss, it is most frequently used in networks with low distance, low traffic requirements. Coaxial cable provides a performance improvement over twisted pair wire with capability for high data rates, distances, and resistance to noise but at higher cost. Finally, optical fiber represents state-of-the-art with far superior data rates and extremely low vulnerability to noise/interference. However, because of the high cost, difficult installation, and some technical limitations, it is currently not practical for most LANs [15, p. 7; also 12, 13, 14].

3.3. Medium Access Control Protocols

The strategy of granting access to the transmission medium is a critical concern in bus/tree and ring LANs. Although there are many protocols in existence, the most prevalent medium access control protocols are Carrier Sense Multiple Access (CSMA), CSMA with Collision Detection (CSMA/CD), and token bus (for bus/tree networks) and token ring, register insertion, and slotted ring (for the ring network). It is not so important for the purpose of this paper to understand the specifics of each protocol. Rather, the importance lies in the understanding that studies [15, p. 33-37] have shown that these protocols provide a wide performance range, each with its own merits and demerits. Despite the immense popularity of CSMA/CD, alternatives do exist. These alternatives have yet to play a major role [For further information on protocols, see 4 (Chapter 3); 12, pp. 17-18; 15, pp. 21-32.].

3.4. Common Applications

Stallings [15] gives an excellent summary of common network applications with general criteria for the selection of the most effective topology and media. The following is a recasting of key points.

Star networks tend to be the most economical, employing the twisted-pair wire media, which is perfectly suited for low capacity, low data, point-to-point communications. Star networks are generally CBX rather than LAN. Ring networks are perhaps the most versatile in their use of transmission media. Twisted pair wire, coaxial cable, or optical fiber can be used. Tree networks can only effectively utilize broadband coaxial cable or twisted-pair wire. Twisted pair wire and coaxial cable are suitable for bus networks. Computer room networking (typically HSLN) generally requires high-speed coaxial cable bus where high-speed peripheral device operations (file transfer, backup) are performed.

The most common LAN applications of media and topology combinations are:

1. For general office, business networking requirements
    a. Baseband coaxial cable bus or ring or
    b. Twisted pair bus or ring.

    (Selection of a. or b. is dependent on cost, number of devices, and communications distance. Of course, a. provides communication to a larger number of devices at greater distance whereas b. is much lower in cost.)
2. For general purpose networks
    a. Broadband coaxial cable bus (for the greatest flexibility in number of devices, system loading, and distance).

4. ARCHITECTURE EVALUATION

LANs are comprised of a complex variety of architectures, transmission media, and communications protocols which provide information support to a wide range of applications (business, home, military, etc.). In building a network, the supervising manager (or similar title) must choose a suitable architecture to meet specific requirements. In other words, the network architecture of choice should be highly dependent upon the end application. The specialized applications discussed earlier in the introduction require an architecture which can deliver fast information response, redundancy of information flow, and more importantly, the ability to be dynamically alterable. The data transfer requirements of this type of application can be more meaningfully grouped in terms of the capability requirements of surface combat systems: capability, operability, reliability, maintainability, survivability, and adaptability [11].

The traditional architectures provide varying measures of performance capability and operability. The review of their characteristics, however, has shown them to have significant weaknesses in the areas of reliability, maintainability, survivability, and adaptability. In addition, the most effective information architecture for a particular application is one whose structure physically parallels that of the decision-making process. Whether in a nuclear plant operations center (monitoring plant status to the lowest level) or in a Naval task force (where each unit commander has a clear span of control), the decision-making process follows a purely hierarchical path. Traditional network architectures are therefore not desirable. A "dynamic hierarchical" architecture is suggested.

5. THE DYNAMIC HIERARCHY

The dynamic hierarchy is defined by Moose [10]:

> The dynamic hierarchy is a generalization of the centralized, tree structured network. It shares with its conventional counterpart the characteristic that, at any given time, a single node resides at the logical apex of the hierarchy. The remaining nodes are configured in a tree structured topology. If, in addition, we allow the apex to vary, the result is a dynamic hierarchical network. This is suitable for an application in which there exists multiple external situations. For each situation, an apex node is designated as the most beneficial for the particular situation. At any given time, the network conforms to one of the specified topologies. When a situation change occurs, the network undergoes a transition, with the appropriate node becoming the logical apex of the hierarchy corresponding to the reconfigured topology.

The dynamic hierarchy should be distinguished from the dynamic non-hierarchical structure which has been implemented by AT&T Communications in a "new approach to call-routing, called Dynamic Nonhierarchical Routing (DNHR). The system is called dynamic because the predetermined routing paths of calls can be changed up to ten times a day. It is called non-hierarchical because it eliminates the traditional structured, hierarchical routing system by using the computer-controlled intelligence that AT&T has built into its switching and trunking network. This permits calls to be routed more efficiently based on forecasted and measured calling patterns" [1; also see 9 for additional information].

5.1. Significance of the Dynamic Hierarchy Concept

The dynamic hierarchy is an architectural concept for a LAN that is embedded within an application system displaying the following characteristics:

(1) real-time or time-critical response is mandatory
(2) demands on the application system can vary and alter the load placed on

individual elements of the embedded LAN (the message traffic and the processing requirements)

(3) the encapsulating system has stringent requirements for high capability, reliability, adaptability, and survivability that must be imparted as requirements of the LAN

As previously suggested a nuclear power plant or a Naval combat system is one example of an application system that subjects an embedded LAN to the requirements stated above.

5.2. Time-critical Response

Timing constraints for action or response by the encapsulating system forces timing conditions (timeouts and defaults) for computer communications in the embedded LAN. Such conditions cannot be relegated to low level functions in the link of the Open System Interconnection Model [5], but must be treated at the transport or session layers so that timing constraints can be represented at the proper design level (see Marlow [7] for an example; for additional explanation, see Davidoff, et al [2]).

The dynamic hierarchy increases the flexibility and capability available to the application system designer. Reconfiguration through apex reassignment brings critical LAN nodes effectively closer through *increased bandwidths* on connecting links. Consequently, more design alternatives are provided to meet timing constraints imposed by the encapsulating system.

5.3. Varying Demands

Changes in the demands on the encapsulating system can come from external stimuli, e.g. identification of an air threat, or from internal conditions, e.g. detection of an incorrect valve setting. Similarly, the embedded LAN must react to demands that are external (but internal as well as external to the encapsulating system) or internal (eg., a failed processor board). Demands can take both synchronous and asynchronous forms, with the latter being very troublesome in capacity planning.

The dynamic hierarchy provides high level reconfigurability to changing demand, permitting both processing and data resources to be reallocated or redistributed. Relationships among nodes of the LAN are redefined to render the necessary support to application functions.

5.4. Stringent Requirements

The severe requirements for fault-tolerance, high availability, degraded mode operation, etc. placed on the encapsulating system impose even more stringent criteria on the LAN designer, who must insure that the network reliability, for example, is sufficiently high to meet the application system requirements for capability, reliability, and survivability. In essence, the LAN design responsibilities include the requirements imposed by the encapsulating system *and* the requirements on LAN performance in order to meet them.

The dynamic hierarchy concept is quite supportive of survivability and reliability, offering forms of recovery and degraded operation that are not possible otherwise. Increased capability is achieved through "tuning" to meet the specific application demands more effectively than is possible with a static topology. Performance criteria such as operability (see [11, p. 18]) and security can potentially be increased as well.

6. CONCLUSION

Nance characterizes the data transfer requirements in such terms as data transfer "speed", structure "paralleling" the chain of command (or decision-making process), "redundancy", "distribution" of function, and "reconfigurability" [11]. Although suitable in many applications, the inherent static nature of the traditional architectures represents a compromise with dynamic requirements of the specialized applications. The characteristics of the dynamic hierarchy are admirably suited to meet these requirements. Research is currently ongoing to investigate dynamic and static hierarchical systems through mathematic analysis and discrete-event simulation.

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