Methods to Determine the Cost-Effectiveness of Local Area Networks

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(ABSTRACT)

Local area networks are a cost-effective scheme to provide communication between equipment such as computers, terminals and printers. The cost-effectiveness of a local area network is determined by the performance and cost of the network. In this report, necessary performance criteria and cost factors that should be considered for a network evaluation will be established and defined. Methods will be developed, using systems engineering techniques, to determine the performance and cost of an Ethernet network at both the component and network levels. Finally, an example Ethernet configuration will be examined to demonstrate the application of the methods developed in the report.

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1. Introduction

A computer network is used to interconnect equipment such as terminals, printers, and computers. The network allows various services, including print services, electronic mail, data storage, communication between computers, and file transfers.

A network is designed by considering different alternatives for each design area, for example topology, transmission media, communication controllers, servers, etc. These alternatives may result in different system performance and cost. The performance of a network design can be studied using analytical and/or simulation methods. The total system cost can be evaluated by considering software and hardware cost, maintenance cost, and other "hidden" costs like installation and labor costs. Lastly, the performance and cost-effectiveness of the network design can be compared to alternative designs.

The objective of this project is to develop methods, using systems engineering techniques, for the performance and cost analysis of Ethernet local area networks implemented in an office environment.

1.1 Overview of Project

A convenient and widely-used method of connecting computers and other equipment over short distances is the local area network (LAN). One very popular and cost-effective local area network for office automation purposes is Ethernet, which is a trademark of the Xerox Corporation.[1] Ethernet is a high-speed, local area network, suitable for office automation and other purposes. Ethernet networks provide rapid access to remote data and the high data rate, typically 10 megabits per second (Mbps), makes file transfer practical. Ethernet is named for the historical *luminiferous ether* through which electromagnetic radiation was once alleged to propagate. An Ethernet transmitter broadcasts completely-addressed bit sequences called packets onto the "ether" and hopes that they are heard by the intended receivers. The ether is a logically passive element for the propagation of digital signals and can be constructed using a number of media including "thinwire" or "thickwire" coaxial cables, twisted wire pairs, and optical fibers [1]. Building a complete Ethernet network requires a combination of hardware and software components that fit into the physical and data link layers of the International Organization for Standardization's (ISO) Open Systems Interconnect (OSI) model. The OSI model is a way of systematically describing and implementing communication functions by viewing the task in terms of layers, each of which contains protocols. The rest of the layers of the OSI model are taken care of by other protocols such as the Department of Defense's Internet Protocol (IP) and Transmission Control Protocol (TCP). This project considers only Ethernet, i.e. the physical and data link layers, since it has primary influence on the performance and cost of the system that can be affected by a network designer.

Some of the components and issues that will be discussed for the design of an Ethernet network are discussed below [2].

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1 The original Ethernet was an experimental network developed by Xerox in the early seventies. The Ethernet design has since been developed by Xerox, Intel, and Digital Equipment Corporation, and the Ethernet specification has evolved.

Transmission Media

There are four different types of cables that can be used in the design. These are thickwire coaxial, thinwire coaxial, twisted pair, and optical fiber. These media differ from each other in cost, capacity, range, and number of taps that can be used. Each can be selected for use in different parts of the network.

Interconnecting Devices

Ethernet segments can be connected to each other using either repeaters or bridges. Both of these devices have some advantages and drawbacks. Repeaters are less costly than bridges, but bridges are more versatile than repeaters. To select between repeaters and bridges, one has to analyze the trade-offs in using them for the intended purpose. These trade-offs can be in terms of performance and cost.

Ethernet Communication Controllers

Ethernet communication controllers implement the Ethernet or IEEE 802.3 data link layer functions and carrier sense multiple access with collision detection (CSMA/CD) protocol and make electrical connections between nodes. Ethernet communications controllers are interfaces that connect systems to an Ethernet local area network. Several companies, such as Digital Equipment, Excelan, Black Box, and Xerox, offer these devices. For example, DEC offers the following communication controllers: DECNA, DELUA, DEPCA, DEQNA, DESVA, and NIA20. The controllers offered by different companies can be studied and selected according to their cost and use in the network.

Servers

Ethernet servers are dedicated, special purpose sub-systems that allow resource sharing across many host systems within a local area network. There are a number of types of servers: terminal servers, disk servers, application servers, routers, and print servers. These servers can be studied and selected according to the needs of the system. A performance analysis can be done on these servers using analytical and/or simulation methods since the server is one of the most heavily used resources in the network. Since servers can support multiple users the cost of servers can be found on a cost per user basis.

The above components can be selected by comparing different alternatives offered by several companies since there is a trade-off between performance and cost offered by each alternative.

For a given selection of components, the performance and cost of the system can be evaluated. Costs such as hardware and software costs, installation cost, and maintenance cost will be considered to determine the cost of the system.

Performance metrics that will be considered are throughput and delay. The performance evaluation will be done analytically using queueing theory and considering the CSMA/CD protocol used by Ethernet. Once the methods for performance and cost evaluation are developed, the method for the evaluation of cost-effectiveness will be determined. An example network analysis demonstrating the usefulness of the techniques and results is reported.

1.2 Motivation for the Study

In the 1950's computers were large complex machines that could only be operated by specially trained personnel. There was no direct communication involved between the computer and a user. But in the 1960's advances in teletypewriter and data transmission technologies led to the development of the interactive terminal. This device allowed users to remotely access a computer directly via a low-speed data line that connected the terminal to the computer. Thus a very simple type of network was established. As the demand for adding more and more digital devices to the computer increased, it became uneconomical to have a separate long distance communication link from the computer to each device. Thus multiplexers, concentrators, and other resource sharing devices were developed [3].

The dramatic decrease in hardware cost due to the advances in very large scale integration (VLSI) circuits has led to widely available low-cost intelligent terminals and workstations. Thus, in recent years these types of devices have been installed in large numbers in localized areas such as offices and universities. However, other expensive devices such as printers, disk storage, and central files and databases are best utilized on a shared basis. To effectively manage these digital devices and resources in a geographically limited area is a function of a local area network.

To achieve a cost-effective system, one needs to select the different combination of hardware and software that will fulfill the requirements of the system, but at the lowest possible cost. Since so many different combinations are possible, designing a cost-effective LAN requires a detailed study of each factor influencing the design. Although this problem is challenging and the design of a cost-effective network is difficult, it is a very important area.

1.3 Overview of Report

The goal of this report is to develop methods to evaluate the performance and cost of an Ethernet local area network at the component and network levels and eventually find the cost-effectiveness of the network. Section 2 of this report provides a brief description of local area networks. It also provides an understanding of Ethernet, its components, and the design options available for Ethernet design.

Since performance evaluation is one of the key issues in this report, Section 3 defines the metrics used and states their importance in performance analysis of a LAN. The section provides methods for the evaluation of each metric at both the component and network levels. It gives a description of assumptions, analytical models, and shows how techniques for each performance metric are developed.

Another goal of this report is to develop methods for cost evaluation of an Ethernet network. Section 4 defines and states the importance of cost factors influencing the design of a LAN. Assumptions, cost models, and a description of evaluation techniques for each factor are presented.

Section 5 provides a general description of cost-effectiveness and its usefulness in comparative analysis of different network designs. Cost-effectiveness evaluation techniques are also presented.

A demonstration of performance and cost analysis of an Ethernet LAN using the techniques developed in this report is shown in Section 6. It includes the assumptions made, configuration of an Ethernet network and its segments, and the evaluation and results.

Section 7 summarizes this research and discusses possible future work in local area network design.

2. Technical Background

The purpose of this section is to provide an overview of local area networks. The nature of a local area network is determined primarily by three factors: transmission medium, topology, and medium access protocol. In this section, one very popular LAN, Ethernet, is discussed focusing on the design options that influence the performance and cost-effectiveness of the network.

2.1 Local Area Networks

A local area network (LAN) [3] is a privately owned data communication system that offers high-speed communication channels optimized for connecting information processing equipment. The geographic area is usually limited to a section of a building, an entire building, or a cluster of nearby buildings. Local area networks can be designed with a variety of technologies and can be arranged in different configurations. Consequently, they vary with respect to their transmission speeds, the distances they span, their operating and performance characteristics, and the capabilities and services they offer.

2.1.1 Motivation for Using a Local Area Network

The main reason for the use of a LAN is to connect computers and various other devices together such that they are able to exchange information. LAN technology has several advantages over a centralized computer system that uses one large computer to perform all system activities, such as file and data access and electronic mail. Some of the important reasons for the LAN being given preference over a centralized system are listed below [4].

Resource Sharing

A LAN makes all programs, data, and equipment available to anyone on the network without regard to the physical location of the resource and the user. Load sharing is another aspect of resource sharing. In a centralized system, load is mostly on the central computer which may adversely affect the performance of the system.

High Reliability

Since many machines are connected together, data and computation can be replicated on two or more machines, so if one of them fails, the other copies could be used. In a LAN, the failure of one machine usually does not affect other devices. Whereas in a centralized system, if the central machine fails then all the files are inaccessible and all activities must be abandoned.

Cost

Small computers typically have a better cost/performance ratio than large ones. Mainframes are roughly a factor of ten times faster than the fastest single chip microprocessors, but cost a thousand times more. Also, if load on the system increases gradually, a LAN allows small processors to be added gradually. In centralized system, however, at some point the central computer has to be replaced by a larger one, usually at much greater expense and disruption to the users.

Communication Medium

A computer network provides a powerful communication medium among widely separated people. Two or more people can hold conferences or work on collaborative projects using the network.

2.1.2 Required Capabilities of Local Area Networks

A computer network must have the following characteristics in order to be cost-effective and provide high performance [5].

Simplicity

Features that complicate the design without improving performance should be omitted.

Resource Sharing

The LAN must provide the ability to connect and share various resources.

Low Cost

To be suitable for connecting equipment whose cost continues to fall, the cost of the network should be kept low.

Fairness

All nodes should have equal access, or some other controllable priority, to the network.

Low Delay

For a given level of offered load, the network should introduce as little delay as possible.

High Throughput

The network should be able to provide a high throughput under heavy load.

Stability

The network should be stable under all load conditions in the sense that the delivered traffic should be a monotonically non-decreasing function of the offered load.

Maintainability

The network should allow for efficient maintenance, operation, and planning.

Reliability

The network should be reliable over long periods of time, in other words, the probability of network failure should be low.

2.1.3 Evaluation of a Network

A computer network can be evaluated by determining the cost-effectiveness of the network which is the measure of the performance per dollar for a network or its components. To determine the two components of cost-effectiveness, several metrics and factors should be considered. These metrics and factors can be evaluated at the component and network levels.

2.1.3.1 Performance Metrics

The metrics that are to be used for performance evaluation of the network are as follows [3].

Throughput (S) The throughput of the network is the total rate of data being transmitted between stations. Throughput is often normalized to be expressed as a fraction of network capacity.

Average delay (D)	The average delay that occurs between the time a packet or frame is ready for transmission from a station and the completion of successful transmission.
Utilization (U)	The fraction of total network capacity being used.

2.1.3.2 Cost Factors

The total cost for a LAN is determined through an analysis of the following factors [6].

Cabling Cost	Total cost of coaxial cable, twisted pair cable, and optic fiber cable.
Software Cost	LAN software cost, which enables the user to exchange files, share resources, etc.
Hardware Cost	Cost of splitters, taps, transceivers, bridges, repeaters, controllers, servers, and other essential hardware devices.
Installation Cost	Labor cost for installing the entire network from laying cables to testing software.
Maintenance Cost	Cost of running diagnostics, locating, and correcting errors and replacing faulty devices. It also includes repair cost, and post-installation labor cost.

The cost evaluation for the network can be performed on a cost per user basis.

2.2 Ethernet Networks

Ethernet is a packet-switching network designed to interconnect computers and other devices within 2.5 kilometers of each other. Ethernet addresses the physical and the data link layers of the OSI model. A maximum of 1024 stations can be attached to the network.

Ethernet networks use a bus, for example coaxial cable, terminated at both ends for communication at data rates of 10 Mbps, and belong to the class of LANs known as CSMA/CD, or carrier sense multiple access with collision detection, systems.

Each segment is terminated at both ends by an impedance characteristic of the medium. Thus, although each segment is physically a bus topology, the overall Ethernet topology, which consists of one or more segments interconnected by means of bridges or repeaters, is that of a non-rooted tree. A message transmitted from any station on the network can be sent to any other station attached on the network.

Each station, which may be a computer, a user terminal or some other equipment, is connected to the network cable by means of a transceiver and a tap. The tap and transceiver make a physical and electrical connection to the cable conductor and the latter contains logic to transmit and receive serial data to and from the cable. Each station has a unique physical address on the network, usually implemented by means of a hardwired address plug or a row of switches [7,8].

The commercial Ethernet, sometimes called the DIX Ethernet [2], consists of two architectural layers: the data link layer and the physical layer. Ethernet itself implements only the first two layers of the ISO OSI model, referring to layers 3 through 7 as the client layer. Hardware and software products from manufacturers such as Xerox, Digital Equipment Corporation, and Intel Corporation can be used in the implementation of the upper five layers of the OSI model [4].

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2 This version was introduced in the specification document published jointly by Digital, Intel and Xerox in 1980.

2.2.1 Medium Access Protocol

Ethernet uses a passive, equitable, and efficient medium access method known as carrier-sense multiple access with collision detection (CSMA/CD) that enables stations on the network to share access to the coaxial cable transmission medium. Carrier-sense means that each station "listens" to the cable before transmitting a packet. If some other station is already transmitting, the first station senses the presence of the carrier and defers transmitting its own packet until the medium is idle. Multiple-access means that all stations tap into and share the same medium. Every transmitted packet is heard by all stations on the Ethernet. The intended stations detect incoming packets by recognizing their addresses embedded in the packets while other packets are ignored.

If two or more stations transmit packets at the same time, their signals will be garbled. This is known as a collision. By listening while transmitting and comparing what is heard on the cable with the data being transmitted, each station can detect a collision and back off by waiting a random time interval before attempting to retransmit the packet. The efficiency of the network remains high, even under conditions of heavy load, because the mean of the random backoff interval increases each time a collision occurs [9].

2.2.2 Components

The CSMA/CD access protocol can use any broadcast multi-access channel, including radio, twisted pair, coaxial cable, and fiber optics. There are four components of an Ethernet network [10].

Station

A station makes use of the communication system and is the basic addressable device connected to an Ethernet network. Examples are a computer, server, bridge, etc.

Controller

A controller for a station is the set of functions and algorithms needed to manage access to the channel. These include signalling conventions, encoding and decoding, buffering, basic CSMA/CD channel management, packetization, serial-to-parallel conversion, and address recognition.

Transmission System

The transmission system includes all components used to establish a communication path among the controllers. It includes a transmission medium, transmitting and receiving devices, or transceivers, and optionally repeaters or bridges to extend the range of the medium. Coaxial cable, which is the backbone of Ethernet, also uses terminators, connectors, and taps.

Controller-to-transmission-system interface

One of the major interfaces in an Ethernet system is the point at which the controller in a station connects to the transmission system. In most cases, the connection from the controller is made to a transceiver, and this interface is called the transceiver cable interface.

The nature of a local area network is determined primarily by two factors: topology and transmission media [9].

2.2.3 Topology

Ethernet uses a bus topology, characterized by the use of a multipoint medium. The bus is a special case of the tree in which there is only one trunk, with no branches. Because all devices share a common communication medium, only one pair of devices on a bus or tree can communicate at a time. A distributed medium access control protocol is used to determine which device transmits next. Twisted pair, coaxial cable, optical fiber, or a combination of these cables can be used as transmission media.

2.2.4 Ethernet Design Options

An Ethernet network can be designed using various transmission media or a combination of them depending on the requirements of the network. Interconnecting devices such as repeaters and bridges can be used to connect two or more Ethernet segments together or to simply extend the network connecting more cables to the backbone cable. These are the two main design options in an Ethernet network since they influence the performance and cost of the network. Other Ethernet design components such as controllers, topology, and media access protocol are the same in all Ethernet networks so designers have no other options for them.

2.2.4.1 Transmission Media Options in Ethernet

Twisted Pair

Twisted pair supports fewer stations at lower speed than a coaxial or optical fiber, but at far lower cost [3]. There are three types of simple components needed:

1. a twisted-pair bus,
2. terminators, and
3. controller interface units.

With this kind of network, the following parameters are reasonable.

1. Length: up to 1 km.
2. Data rate: up to 1 Mbps.

3. Number of devices: tens.

The latest technology provides an improved version of twisted pair and some of the specifications of this new twisted pair cable are listed below [2].

1. The distance from concentrator to concentrator or from concentrator to transceiver should not exceed 360 feet (109.7 meters).
2. Flexible twisted pair patch cables and twisted pair drop cables should not exceed 50 feet (15.2 meters) of the total 360 feet (109.7 meters) total cable segment length.
3. Data rate of 10 Mbps is achievable.

Twisted pair is a good medium for several reasons. First, it has lower cost than coaxial cable while providing equal noise immunity. Second, virtually anyone can install the network, which consists of laying the cable and connecting the controllers. Installation requires only a screwdriver and a pair of pliers, and is similar to installing hi-fi speakers.

Thickwire Baseband Coaxial Cable

The simplest baseband coaxial Ethernet consists of an unbranched length of cable with a terminator at each end to prevent reflections. A maximum length of 500 meters is recommended to guarantee signal quality. Stations attach to the cable by means of a tap, with the distance between any two taps being a multiple of 2.5 meters to ensure that reflections from adjacent taps do not add in phase. A maximum of 100 taps is recommended. Each tap includes a transceiver that contains the electronics for transmitting and receiving [11].

The specifications above are for a 10 Mbps data rate. To extend the length of the network, a repeater or bridge may be used. Thickwire is used in the bus/tree topology.

Thinwire Baseband Coaxial Cable

Thinwire coaxial cable offers an alternative baseband transmission media that provides full Ethernet capability for personal computers, workstations, and low-end systems in offices and other local work areas. Thinwire is a low-cost transmission media that can be used to connect up to 30 stations in one 185 meter segment.

Some of the Thinwire characteristics are listed below [2,3].

1. The maximum length of a coaxial cable segment is 607 feet (185 m).
2. The maximum length of coaxial cable between two stations is 3035 feet (925 m). This is three segments in series with two repeater links.
3. The minimum length of coaxial cable between two stations is 1.6 feet (0.5 m).
4. The maximum number of connections on a network is 30.
5. A maximum of eight Thinwire Ethernet segments may be connected to a repeater to form a network of up to 232 stations.

Optical Fiber

An optical fiber is a thin, 2 to 125 μm, flexible medium capable of conducting an optical ray. Various glasses and plastics can be used to make optical fibers. The following characteristics distinguish optical fiber from twisted pair and coaxial cable [3,12].

1. ***Greater Bandwidth.*** The potential bandwidth, hence data rate, of a medium increases with frequency. At the high frequencies of optical fiber, a data rate of about 100 Mbps is easily achieved over tens of kilometers. This is significantly higher than twisted pair or coaxial cable.

2. ***Smaller Size and Lighter Weight.*** Optical fibers are at least an order of magnitude smaller in diameter for a comparable data transmission capacity than coaxial cable or bundled twisted-pair cable. This quality is advantageous when many pieces of equipment are to be connected in a small room or building.

3. ***Lower Attenuation.*** Attenuation is significantly lower for optical fiber than for coaxial cable or twisted pair, and is constant over a wide range. This means repeaterless transmission for

fiber-optic is possible for distances over about 140 km; whereas for coaxial links maximum repeaterless transmission is limited to approximately 50 km.

4. ***Improved Electromagnetic Isolation.*** Optical fiber systems are not affected by external electromagnetic fields. Fibers do not radiate energy and are difficult to tap. This is a great advantage for security purposes since it can be made virtually impossible to tap by some extra measures. Although difficulty in tapping is good for security purposes, it is also difficult to attach a node on the bus and coupler losses are approximately equivalent to 1 km.

5. ***Greater Repeater Spacing.*** Fewer repeaters means lower cost and fewer sources of errors. Coaxial cables and twisted pair generally need a repeater or bridge every few hundred meters or every kilometer.

2.2.4.2 Interconnecting Device Options in Ethernet

Repeater

The repeater is a physical layer device that merely extends the length of the cable, since it just amplifies and retransmits all signals, including collisions. All traffic is routed automatically across repeaters and appears on all LAN segments. Thus, the system is regarded as a single network. Consequently, the collision detection mechanism applies and restricts the span of the network to about 2.5 km.

Bridge

A bridge interconnects two or more LANs, either similar or dissimilar, at the media-access level of the data-link layer, and hence is also called a media-access-control or MAC-level bridge. The bridge filters or forwards traffic between two electrically independent cable systems attached to it. The main advantages of incorporating bridges in a LAN are greater geographical coverage, improved performance, better fault isolation, reliability and security [13].

2.2.5 Design Evaluation Process

The methods devoloped in this report can be useful tools in the network design evaluation process. A network can be designed and evaluated for certain requirements and constraints such as cost, performance and feasibility as shown in Figure 1. A designer can select network components from various options, such as media and interconneting devices, to design the required network. Once the components are selected and the network is designed, the network design can be evaluated for its performance and cost using the methods developed in this report. If the design meets the requirements then designer may choose it as a satisfactory design solution. Otherwise, the designer may make some changes in the design by selecting different media options or interconnecting devices and evaluate the new network design. Then, the designer can compare the two design solutions and select the best design. Cost-effectiveness can be used as one of many measures for the network design comparison. This process may be repeated until the designer is satisfied with the design solution or an optimum solution is obtained.

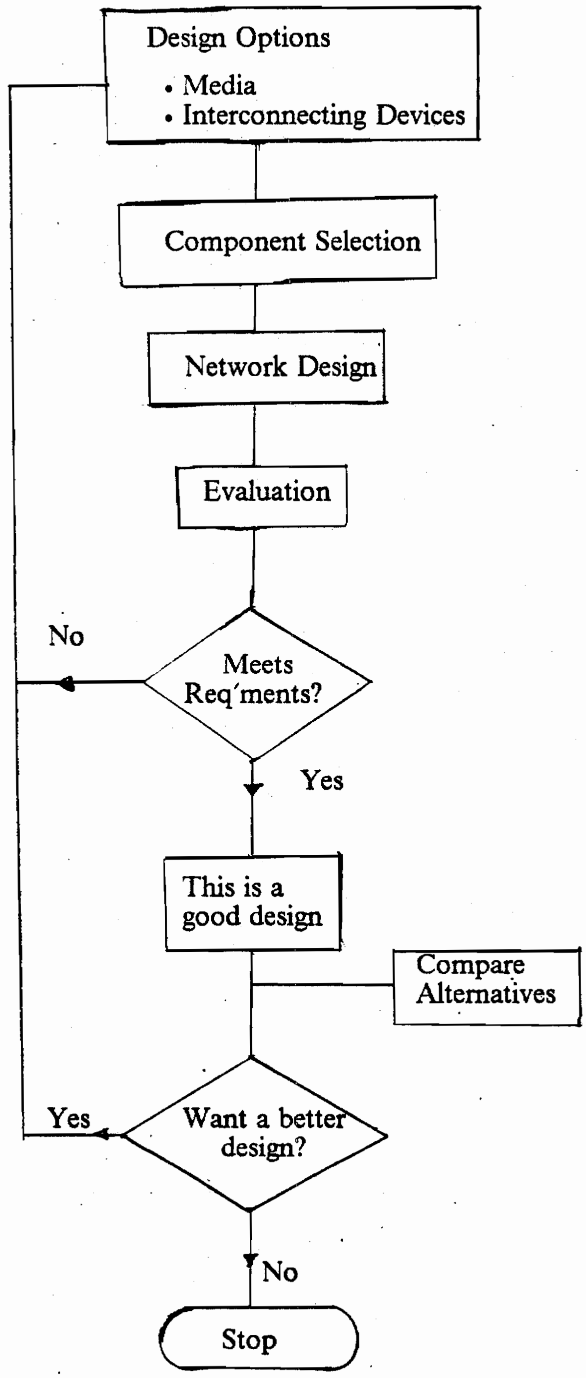

Figure 1. Design evaluation process.

3. Performance Evaluation

Local area networks can be implemented at a reasonable cost with a physical channel that has a high data rate and a low error rate. For this reason, most local area networks are constrained in performance by protocol operation, e.g. CSMA/CD, and by competition among the equipment connected to the network for resources, such as transmission media, memory, and CPU time.

Network performance evaluation techniques will be developed in this section focusing on both the component and the overall network performance. In Section 3.1, the metrics to evaluate a network and its components will be established. The techniques to evaluate the performance of transmission media and stations such as servers and bridges will be developed in Sections 3.2 and 3.3. The results found in Sections 3.2 and 3.3 will be used to develop a method to evaluate the overall network performance. The techniques that will be developed can be used to evaluate the performance of an Ethernet network at the component and network levels.

3.1 Metrics

To carry out an analytical study of Ethernet performance, which is one objective of this project, appropriate criteria must be defined. Two criteria, throughput and average delay at the component and network levels are used as performance metrics. These two metrics are defined and discussed in this section. See [7,14] for more detail.

3.1.1 Definitions

The two performance metrics, throughput and average delay, are defined below.

3.1.1.1 Throughput

Throughput is the average number of bits per second either entering or leaving a section of a network. Frequently, throughput is normalized by dividing by the channel capacity, in bits per second, to obtain a number that is between 0 and 1. Normalized throughput, or simply throughput, is denoted by the symbol S. Throughput can apply to a complete network as well as to a single connecting link. When applied to a complete network, unnormalized throughput is the total number of bits per second entering or leaving the network.

Once the throughput of the component and network are evaluated, their utilization which is the fraction of total capacity of any component or network being used, can be determined as follows.

$$\text{Channel utilization} = \frac{\textit{Unnormalized Throughput}}{\textit{Maximum Data Rate}}$$

Thus channel utilization can also be interpreted as S, the normalized throughput.

3.1.1.2 Average Delay

Delay is defined as the time from the departure of the last bit of a packet from one station until the last bit of this packet is delivered through the network to its destination station and is usually denoted by the symbol D.

There are two components of delay in the network:

- the time the packet must wait in an interface buffer before being transmitted, and

- the time required to transmit the packet through the network, including propagation time.

The first delay component accounts for delay in network servers, stations, and bridges or routers. The second component accounts for delays in transmission media.

3.1.2 Importance

For performance measurements of a complete network or any of its components such as servers and transmission media, the two metrics, throughput and delay are very important. The reason is that these two metrics are influenced directly by several network design parameters that are listed below [3].

1. ***Capacity or bandwidth:*** the rate at which data can be transmitted over a given communication path, or channel, under given conditions.

2. ***Propagation delay:*** the time it takes information to propagate from one node to the next. For example, this may be the time to propagate one bit.

3. ***Average number of bits per packet:*** the average number of bits in a packet. This number differs for different protocol standards and applications.

4. ***Medium access protocol:*** for broadcast networks, the method of determining which device has access to the transmission medium at any time.

5. ***Offered load:*** the total rate of data presented to the network for transmission.

6. ***Number of stations:*** total number of the stations or other equipment sharing the medium.

7. ***Error rate:*** the ratio of the number of packets in error to the total number of packets. An error in packet transmission necessitates a retransmission. Error rates are typically very low for Ethernet LANs and it is assumed to be negligible in the performance estimations of this report.

The overall network performance can be estimated by determining the throughput and average delay for the network analytically using queuing theory. Once the general equations for these two metrics are found, the performance of the Ethernet LAN can be determined for known network parameters such as number of stations, message generation rate of network stations, and component performance specifications. The overall performance is influenced by the performance of the network components, traffic, and the access method used by the network. Since an Ethernet always uses CSMA/CD slotted 1-persistent protocol for medium access, this performance factor can be ignored in the evaluation of network design.

At the component level, throughput and delay are very important criteria for performance since they indicate how efficient the components are and help in selecting components with better performance. The two performance metrics, throughput and delay, can be evaluated using queueing theory and other analytical methods. Several queueing models are available for the evaluation of throughput and delays for different types of servers and these models will be used later in this section. Later, the equations that give performance estimates can be used in comparing different servers and other network components such as bridges and routers and transmission media.

3.2 *Performance Evaluation of Transmission Media*

The techniques to determine the performance of the transmission media between any two stations are developed in this section using a reciever-sender model. This approach is based on a derivation in [10].

3.2.1 Assumptions

The data packets are assumed to be of equal and fixed length. The propagation velocity, v, for a guided medium, such as cables, is $2 \times 10^8 \frac{m}{\text{sec}}$, which is two-thirds of the speed of light. There are time delays in putting the whole message on the medium by a sending station and in collection of that message by the receiving station. These delays are assumed to be equal. Define the following parameters.

B = Data rate, rate at which data can be data can be sent on the medium.

L = Packet length, number of bits in a data packet.

T_p = Propagation time, time taken by any data to travel from one station to another.

T_t = Transmission time, time taken by a station to put whole message on the medium.

3.2.2 Analytical Model

In this model, two stations are connected to each other by a transmission system that includes cable segments, connectors, and transceivers. Messages can be sent and received by both stations through the transmission system. This scenario is shown in Figure 2.

3.2.2 Analytical Model

In this model, two stations are connected to each other by a transmission system that includes cable segments, connectors, and transceivers. Messages can be sent and received by both stations through the transmission system. This scenario is shown in Figure 2.

3.2.3 Evaluation

In local area networks, the product of data rate or bandwidth (*B*) and the length of the media (*d*) are the most important parameters for performance evaluation of the transmission media. Other things being equal, a network's performance will be the same for equal values of $B \bullet d$, for example, for both a 50 Mbps, 1 km bus and a 10 Mbps, 5 km bus.

A good way to visualize the meaning of $B \bullet d$ is to divide it by the propagation velocity, v, of the medium which is nearly constant for all media of interest. So, $\frac{Bd}{v}$ = length of transmission medium in bits.

This is the maximum number of bits of data that may be in transit between two stations at any one time. For example, a 500 m Ethernet system (10 Mbps) has a bit length of 25 bits. Local networks generally have a bit length shorter than that of a packet up to about same the order of magnitude. Local area network protocols, e.g. CSMA/CD, generally allow one packet to be in transit at a time. The length of the medium, expressed in bits divided by the length of a data packet in bits is usually denoted by *a*:

$$a = \frac{\text{length of data path in bits}}{\text{length of packet}} = \frac{\frac{Bd}{v}}{L} = \frac{Bd}{vL},$$

where L equals the packet length.

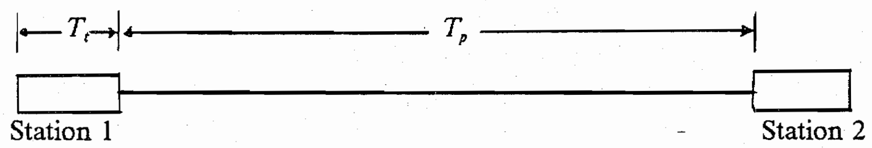

Figure 2. Model of delay between Station 1 and Station 2.

But $\frac{d}{v}$ is the worst case propagation time on the medium, and $\frac{L}{B}$ is the time it takes a transmitter to get an entire packet out onto the medium [14]. Then

$$a = \frac{T_p}{T_t}$$

By definition, throughput is the rate of data transmission between two stations and the rate of data is simply the packet length divided by the total time taken to reach from one station to other. Therefore,

$$Throughput = \frac{L}{T_p + T_t} = \frac{L}{(\frac{d}{v}) + (\frac{L}{B})} \quad (bps) \tag{1}$$

Now once the throughput has been found the utilization can also be found as follows.

$$Utilization = \frac{throughput}{B} = \frac{\frac{L}{(\frac{d}{v} + \frac{L}{B})}}{B} = \frac{1}{1+a} \tag{2}$$

The delay is simply the sum of the time required for transmission and propagation of a packet. The delay determined here is the average transfer delay.

$$Delay = T_t + T_p = \frac{L}{B} + \frac{d}{v} \quad (seconds\ per\ packet) \tag{3}$$

These results can be useful in determining the performance of different media options used in an Ethernet LAN design.

3.3 Performance Evaluation for Stations

The performance metrics established earlier in this section can be evaluated analytically using queueing models, such as the M/M/1/K model [11,14], since stations such as servers and interconnecting devices can be viewed as a system with a servicing node and a queue (buffer) of storage capacity of K messages. This view of a server or interconnecting device can be used to determine their performance as demonstrated below.

3.3.1 Assumptions

The following assumptions are made for the performance evaluation of stations such as servers, computers, and interconnecting devices.

1. All network stations are assumed to be single server single queue systems with a storage capacity of K messages including the one being serviced.
2. All messages arriving at a station are in the form of packets that are equal in length, i.e. contain the same number of bits. The messages are equal in length and consist of X packets of length L bits each.
3. Messages are serviced on a first come first serve basis.
4. The message arrival rate at any station follows Poisson statistics and the service times are exponentially distributed.
5. Message arrival and service rates at any station are stationary. For arrival rates,

$$\lambda_n = \lambda \quad for\ n = 0,1,2,\dots,K-1$$

$$= 0 \quad for\ n \geq K$$

where λ_n is the arrival rate of a message that has n messages ahead of it in the queue. A message that has n messages ahead of it upon arrival is said to be in state n . Since the arrival rate is assumed to be the same for all the incoming messages at a station, it is simply denoted by λ.

For service rates,

$$\mu_n = \mu \quad for\ n = 0,1,2, \ldots , K$$

$$= 0 \quad for\ n > K$$

where μ_n is the service rate for a message that is in state n. Since service rates are assumed to be the same for all messages in a station buffer, they are denoted simply by μ.

3.3.2 Analytical Model

The behavior of a network depends on the interaction of the system workload and the system resources such as servers, computers, and bridges. An Ethernet station can be viewed as a queueing model with one service node and one buffer with storage capacity of one or more messages as shown in Figure 3.

In this model, messages are generated by some message source and arrive at a station according to a Poisson process. This model, called the M/M/1/K model, is a single server single queue system with a storage capacity of K messages including the one in the server. Messages can join the system only if there is enough buffer space available in the system, otherwise it will not be allowed to enter the queue. One message is serviced during each service time in this model. Since the messages are serviced on a first come first serve basis, the messages stored in the system can be viewed to be organized in a queue as shown in Figure 3. A more detailed description of this model can be found in [11].

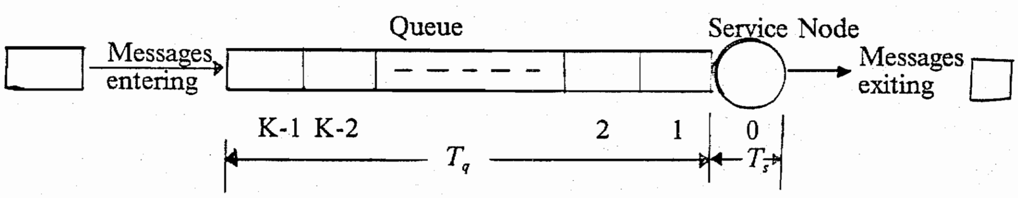

Figure 3. Queueing model for a station.

3.3.3 Evaluation

Once a model for a station has been developed, the techniques for the evaluation of performance metrics can determined based on the derivations for the M/M/1/K queueing model in [11,13].

Let the time taken to service a message at any station be denoted by T. This includes the time spent in waiting in queue, T_q, and the time required by the station to service that message, T_s. Therefore, the total time spent by any message in the system is T = $T_q + T_s$.

Poisson statistics are based on a discrete distribution of events. Under the assumption that a system has a large number of independent messages, Poisson statistics state that the probability $P_n(t)$ of exactly n messages arriving during a time interval of length t is given by

$$P_n(t) = \frac{(\lambda t)^n \bullet e^{-\lambda t}}{n!}$$

where λ is the mean arrival rate and $n = 0,1,2, \ldots$

The following random variables are defined.

$N(t)$ = the number of messages in the system at time t.

$N_q(t)$ = the number of messages in the queue at time t.

$N_s(t)$ = the number of messages being processed at time t.

Therefore, at any time t, the total number of messages in the system, which is either a server or a bridge, can be determined as

$$N(t) = N_q(t) + N_s(t)$$

For a steady state condition, it can simply be written as

$$N = N_q + N_s$$

Traffic intensity is the ratio of the message arrival rate and the service rate, $\rho = \frac{\lambda}{\mu}$. The parameter ρ is of importance since it determines the minimum number of servers required to keep up with the arrival of messages.

The probability $p_n(t)$ that n messages are present in the system at time t is denoted by p_n for the steady state. In this model, the steady state probabilities are given by

$$p_n = p_0 \prod_{i=0}^{n-1} \frac{\lambda}{\mu} = \rho^n p_0 \quad for\ 0 \le n \le K \tag{4}$$

and

$p_n = 0$ otherwise

To solve for p_0, we note that the probabilities of the finite set of states must sum to one. Thus, we have

$$\sum_{n=0}^{K} p_n = 1 = p_0 \sum_{n=0}^{K} \rho^n = p_0 \frac{1-\rho^{K+1}}{1-\rho} \tag{5}$$

or,

$$p_0 = \frac{1-\rho}{1-\rho^{K+1}} \tag{6}$$

Substituting Equation 6 into Equation 4 then yields

$$p_n = \frac{(1-\rho)\rho^n}{1-\rho^{K+1}} \quad for\ 0 \le n \le K \tag{7}$$

and

$p_n = 0$ otherwise

The probability that the buffer is full and messages are turned away or blocked from entering the system is simply the probability that there are K messages in the buffer. Using Equation 7 this is given by

$$p_K = \frac{(1-\rho)\rho^K}{1-\rho^{K+1}} \tag{8}$$

Using Little's formula [11], we can find the parameters N, T, N_q, and T_q. If $\lambda < \mu$ then the expected number of messages N in the system is

$$N = E[\tilde{N}] = \sum_{n=0}^{K} n p_n$$

where $\tilde{N}$ is the value of N when the system is in steady state. Substituting Equation 4 in the above equation gives the following.

$$N = p_0 \rho \sum_{n=0}^{K} n \rho^{n-1}$$

$$= p_0 \rho \sum_{n=1}^{K} \frac{d}{d\rho} (\rho^n)$$

$$= p_0 \rho \frac{d}{d\rho} \sum_{n=1}^{K} (\rho^n)$$

$$= p_0 \rho \frac{d}{d\rho} (1 + \rho^2 + \rho^3 + \cdots + \rho^K)$$

Since $1 + \rho^2 + \rho^3 + \cdots + \rho^K$ is a geometric series whose sum is given by $\frac{1-\rho^{K+1}}{1-\rho}$, therefore

$$N = p_0\rho \frac{d}{d\rho}\left(\frac{1-\rho^{K+1}}{1-\rho}\right)$$

$$= p_0\rho \frac{1-(K+1)\rho^K + K\rho^{K+1}}{1-\rho^2}$$

Substituting Equation 6 for P_0 gives the following.

$$N = \frac{\rho[1-(K+1)\rho^K + K\rho^{K+1}]}{(1-\rho^{K+1})(1-\rho)}$$

This equation can be simplified to get following equation for the average number of messages in the system.

$$N = \frac{\rho}{1-\rho} - \frac{(K+1)\rho K + 1}{1-\rho K + 1} \tag{9}$$

Therefore, the average number of messages N_q waiting in the queue is given by

$$N_q = N - N_s \tag{10}$$

where $N_s = E[\tilde{N}_s] = 1 - p_0$. The average number of messages being serviced is simply the probability that the system is not empty, or $1 - p_0$ times 1, the average number of messages that are serviced under this condition.

Once the M/M/1/K system is full, no further messages will be allowed to enter the system until some queued message is serviced and sent on. The probability of the system being full upon the arrival of a message is p_K, so the probability that a message can enter the system is given by $1 - p_K$, and the average rate λ_a of messages entering the system is given by

$$\lambda_a = \lambda(1 - p_K) \tag{11}$$

where λ is the message arrival rate.

Substituting Equation 8 into Equation 11 gives

$$\lambda_a = \lambda[1 - \frac{(1-\rho)\rho^K}{1-\rho^{K+1}}] \tag{12}$$

Little's formula, $N = \lambda T$, which states that the average number of messages in the queueing system is equal to the average arrival rate times the average time spent in the system by messages, can now be used. The average time a message spends in the system is $T = \frac{N}{\lambda_a}$ and the average time a message spends in the queue is $T_q = \frac{N_q}{\lambda_a}$. These derivations can be found in detail in [8].

Since the average delay, D, is the time spent in the system,

$$D = \frac{N}{\lambda_a} = \frac{[\frac{\rho}{1-\rho}] - [\frac{(K+1)\rho^{K+1}}{1-\rho^{K+1}}]}{\lambda[1 - \frac{(1-\rho)\rho^K}{1-\rho^{K+1}}]} \tag{13}$$

If there is no buffer space in the station, then K = 1, and average delay reduces to $\frac{\rho}{\lambda} = \frac{1}{\mu}$ and the mean throughput of server becomes μ, the service rate.

If the buffer size is very large that it can be assumed to be infinite then by taking the limit of Equation 13 with K going to infinity, the average delay reduces to the following.

$$D = \frac{1}{\mu - \lambda} \tag{14}$$

Therefore, the mean throughput of the station becomes $\mu - \lambda$.

3.4 Performance Evaluation of Overall Network

As mentioned previously, the main focus of this report is on the design and the performance of the network as a whole. Since the network may be regarded as being embedded in a user-to-user system, user-level performance measures are more dependent on specific types of equipment. A user can be defined as an individual that has access to the network through an attached device such as a computer, a terminal, or a workstation. The performance of a transmission system or server depends on their individual characteristics and can be determined using techniques discussed earlier.

At the network level, throughput, which is the number of bits per second that can be processed through the network, and average transfer delay of messages in going from one station to another can be determined. In this section, techniques for evaluating the two performance metrics will be developed.

3.4.1 Assumptions

An Ethernet network consists of two or more stations that generate messages with constant rates and are equally likely to gain the control of the transmission medium when it becomes available.

3.4.2 Model

An Ethernet configuration consisting of several network segments that are interconnected by a multi-port bridge is shown in Figure 4. Each of the segments has several stations, such as servers, computers, and bridges, attached to it. A station that generates messages with a rate of λ packets per second is attached to the network (top left in Figure 4). Messages generated by the user can be destined to any station in the configuration and can be routed to any of the other network segments by the bridge.

As shown in Figure 4, a fraction β_0 of the messages generated by a station are destined for a station on the same network segment and the remaining fraction, $\alpha_0 = 1 - \beta_0$, are destined for a station on a different segment. The delays suffered by messages may be different depending on the delays they suffer due to transmission time, propagation time, delay at the bridge, and waiting and

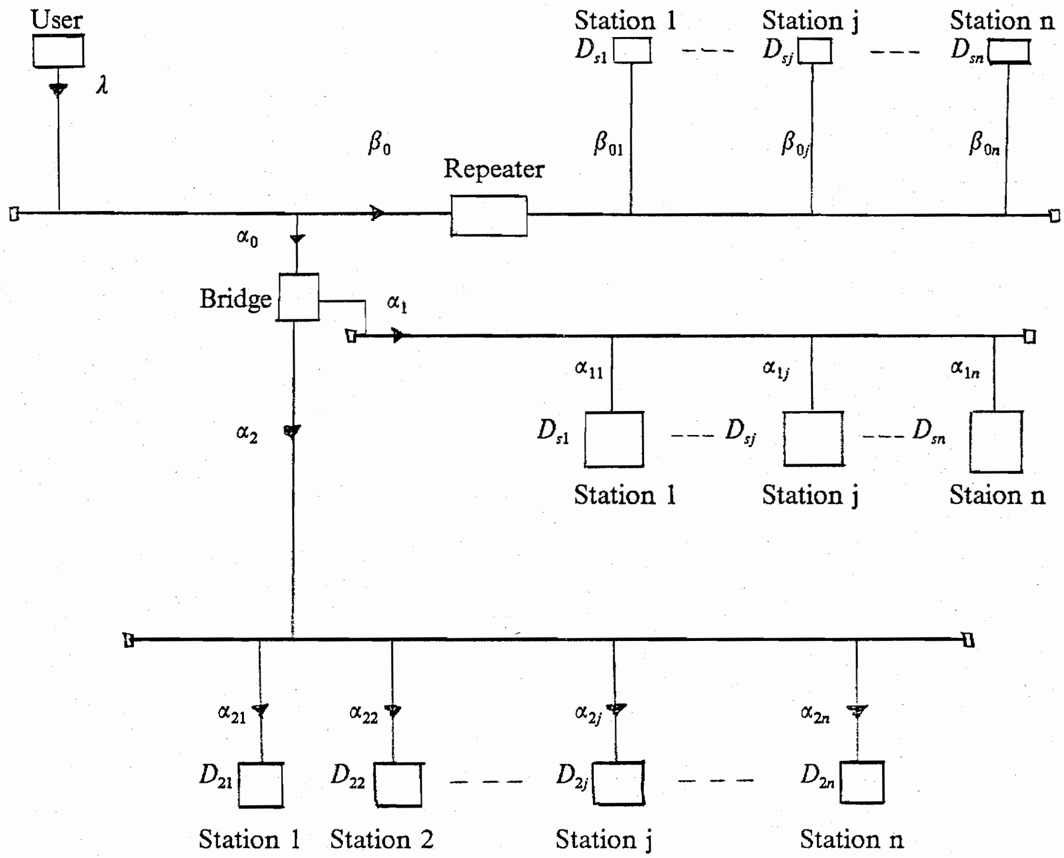

Figure 4. Ethernet network segments interconnected by a bridge.

service time at the destination station. These delays can be determined by the techniques developed earlier in this report.

3.4.3 Evaluation

The performance of an Ethernet, such as shown in Figure 4, can be determined by examining the station-to-station performance. First, consider the case where messages are generated by a user for a station on the same network segment. In this case messages are transmitted through the medium and reach the destination station for service. The average delay includes the transmission and propagation times on the media and the waiting and service times in the destination station. Therefore, the total delay equals the delay on the media plus the delay in the station. Taking the weighted average of delays for messages going to all stations on the same network segment gives

$$D_{SN} = D_m + D_s = \frac{\beta_{01}(D_{m1} + D_{s1}) + \beta_{02}(D_{m2} + D_{s2}) \dots + \beta_{0n}(D_{sn} + D_{sn})}{\beta_{01} + \beta_{02} + \dots + \beta_{0n}}$$

$$= \frac{1}{\beta_0} \sum_{j=1}^{n} \beta_{0j}(D_{mj} + D_{sj}) \tag{15}$$

β_{0j} is the percentage of generated messages going to station j on the same network segment, D_{mj} is the delay on the media for messages going to station j, and D_{sj} is the delay at destination station j, which can be a server, a computer or some other device.

Now assume fraction α_0 of the generated messages are destined for a station on a different network segment. Messages will pass through an interconnecting device such as a multi-port bridge that can support more than two network segments. The technique for determining the average delay for messages routed to a different network segment is developed below.

Let the number of interconnected network segments be $m + 1$, then for each network segment there are m different network segments where messages can be routed. For Figure 4, $m = 2$, since the total number of network segments is 3.

Assume the percentage of messages going to each of the m different network segments is $\alpha_1, \alpha_2, \ldots, \alpha_m$. These fractions add up to α_0, the overall fraction of generated messages destined for different network segments. The average delay suffered by a message on another network segment after it has passed through the bridge will be

$$D_{AD} = \frac{\alpha_1(\textit{delay on network } 1) + \alpha_2(\textit{delay on network } 2) + \cdots + \alpha_m(\textit{delay on network } m)}{\alpha_1 + \alpha_2 + \cdots + \alpha_m}$$

$$= \frac{1}{\alpha_0} \sum_{j=1}^{m} \alpha_j D_j \tag{16}$$

D_j is the average delay suffered by the messages on network segment j once they have passed the bridge. The delay D_j can be determined by viewing the bridge as a message generating station such as the user in Figure 4. Then the delays for messages passing through the bridge can be determined in same way. If the messages reach the destination network segment after passing the bridge then Equation 15 can be used to determine the average delay on the destination network segment since the bridge is on the same network segment. These delays may be different for each network segment depending on the design options such as media, server, and interconnection scheme. If messages have to pass over several network segments that are interconnected by bridges before reaching the destination station then the delays due to interconnecting devices and media on each network segment it passes through must be considered. For simplicity, only two-level networking is considered in this report as shown in Figure 4.

Now, the average transfer delay suffered by packets destined for different network segments can be determined.

$$D_{DN} = D_m + D_b + D_{AD} \tag{17}$$

where D_m is the delay due to media before the packet reaches the bridge, D_b is the delay due to bridge service, and D_{AD} is the average delay after the packet has been passed by the bridge to the destination network segment, as determined using Equation 16.

Now the average transfer delay suffered by a packet once it has been generated by a station i and until it has been serviced by a station can be determined as follows.

$$D_i = \beta_0 D_{SN} + \alpha_0 D_{DN} \tag{18}$$

D_{SN} can be determined using Equation 15 and D_{DN} can be determined using Equation 17.

The average transfer delay using Equation 18 is the delay for one user station that is generating messages with a constant rate of λ packets/second. But a computer network such as Ethernet allows several user stations to share the network resources at the same time. These user stations may generate messages at different message rates say λ_i, where $i = 1,2, \dots, N$ for N user stations and these messages may suffer different delays D_i. The average transfer delay for any message in the network, $D_{network}$, can now be determined by taking the weighted average of transfer delays for all users in the network.

$$D_{network} = \frac{\sum_{i=1}^{N} \lambda_i D_i}{\sum_{i=1}^{N} \lambda_i} \tag{19}$$

Since the throughput for the messages sent by each station is the reciprocal of the average delay, the average throughput for the overall network can be determined as follows.

$$S_{network} = \frac{\sum_{i=1}^{N} \lambda_i / D_i}{\sum_{i=1}^{N} \lambda_i} \tag{20}$$

Until now, the focus has been on the performance of interconnected network segments as a system. But Ethernet's medium access protocol, CSMA/CD, plays an important role in the performance of the Ethernet network. A station may waste a significant amount of time due to either message collisions or waiting to gain control of the medium. This wasted time, often called contention time, w, must be taken into consideration and included in the performance evaluation metrics.

Consider time on the medium to be organized into slots whose length is twice the end-to-end average transfer delay, excluding the delay in destination station, i.e. considering only the delay due to the media. This is a convenient way to view the activity on the medium; the slot time is the maximum time, from the start of transmission, required to detect a collision. Note that the time slots are of length $2T_p$.

Clearly, if each of the N stations always has a packet to transmit, and does so, there will be only collisions. So it is assumed that each station refrains from transmitting during an available slot with probability P.

Time on the medium consist of two types of time periods. One is the average transfer delay on the medium and second is the contention time. In the Ethernet network protocol, A, the probability that exactly one station attempts a transmission at a time slot and therefore acquires the medium, is binomially distributed and can be determined [3,4] to be

$$A = \binom{N}{1} P^1 (1-P)^{N-1} = NP(1-P)^{N-1}$$

A has a maximum value of $(1-\frac{1}{N})^{N-1}$ at $P = \frac{1}{N}$.

Now the mean contention time w in slots can be estimated as follows.

$$E[w] = \sum_{i=1}^{\infty} iP_r[i \textit{ slots in a row before another transmission}]$$

$$= \sum_{i=1}^{\infty} i(1-A)^i A$$

The summation converges to $E[w] = \frac{1-A}{A}$ slots. Then, denoting E[w] as w, $w = \frac{1-A}{A}$. Since this is the time in slots, the wasted time due to contention in seconds can be denoted as D_w, and can be estimated as follows.

$$D_w = (\frac{1-A}{A})2T_p$$

Notice that D_w is a function of N, the number of stations ready to transmit.

This is the wasted time due to contention. To determine the total time delay between the transmission of two packets from a station, The delay due to the medium is added to the contention delay. The time delay after a packet has reached a server should be ignored since once a packet is off the medium, the medium can be granted to any of the N stations. Therefore,

$$Average\ delay = D_m + D_w \qquad (21)$$

$$Mean\ throughput = \frac{1}{D_m + D_w} \qquad (22)$$

where D_m is the delay due to transmission medium.

Since the channel utilization is simply the fraction of time medium is busy, it can be determined as follows.

$$Channel\ utilization = \frac{D_m}{D_m + w}$$

The methods developed in this section for the performance evaluation of an Ethernet network and its components can be used as a decision making tool in the design process of an Ethernet LAN. An example of the application of the methods will be given in Section 6.

4. Cost Evaluation

The term "cost" generally refers to the outlay of funds for goods or services. Two major categories of the cost of operating a network system are fixed costs and variable costs. The sum of these two types of costs is the total cost [15]. Evaluation of network cost requires a complete knowledge of all costs required to build and operate the network. The costs of cabling, software, interfaces, communication servers and controllers, installation, and maintenance all add to the total life-cycle cost of a network system.

Selecting and buying a local area network and its components is a very difficult task today due to the number of available technologies, their claims of superiority and different prices for each type of component. These crucial buying decisions can be made according to the needs of the network, such as geographical situation, number of stations, data rate, and user-justifiable costs.

The total cost per user for any network can be determined through an analysis of cost factors involved in the overall network.

4.1 Cost Factors

To analyze the cost of a local area network, all costs involved in building, bringing to an operational form, and maintaining the network must be considered. These cost factors are discussed in detail below.

4.1.1 Definitions

Cabling Cost

Cabling cost is the cost of buying transmission media or cable for the network. Some of these cables are thin and thick coaxial cable twisted-pair, and fiber optic cable. It also includes the cost of buying taps, terminators, and connectors.

Installation Cost

Installation cost is the cost of setting up the network, including the labor cost from laying cables to testing software and the cost of either buying or renting the tools and materials used in installation.

Hardware Cost

Hardware cost is the cost of buying interface hardware for devices such as terminals, file servers, and computers. It also includes the cost of buying communication controllers and interconnecting devices such as bridges and repeaters.

LAN Software Cost

LAN software cost is the cost of software that enables users to exchange files, share resources, and perform other activities.

Maintenance and Management Cost

Maintenance and management cost is the cost of maintaining and managing the network during its life cycle. It includes monitoring network activity, troubleshooting problems, debugging protocols and application software, and fine-tuning network performance. It also includes replacement and repair costs for faulty components.

4.1.2 Importance

Cabling cost is often understated while evaluating the total cost of a network and making a buying decision for cable. This cost increases significantly if the cable has to be routed between floors and hallways in a building which requires the installation of conduits or wiring troughs at a much higher cost than the cable itself. Therefore, selecting and buying a cable is a very important task in network design.

Usually installation cost is ignored while evaluating the total cost of the network, but the labor cost, which includes the cost of hiring engineers, technicians, and laborers, is very high today and increases with the complexity of the network.

LAN software is the most important part of any network, since without it a network cannot perform its activities. This cost varies depending on the technology, functions, and software vendor. It is a fixed cost for a system which increases the total cost of network eventually affecting the cost-effectiveness of the system.

Maintenance and management costs are very important factors in the cost evaluation of a network since these costs may be significant depending on the reliability of the system. If a system such as a LAN has low reliability, then the number of maintenance and management activities during a network's life cycle may increase, thereby increasing the maintenance and management cost to a large value. Therefore the present worth of all the maintenance and management costs should be included in the overall cost evaluation.

The IEEE 802.3 CSMA/CD LAN is probably the most mature of today's available IEEE 802 network technologies. The offerings of products using large-scale integration (LSI) and very large-scale integration (VLSI) components from several manufacturers, such as DEC, Excelan and Black Box Corporation, to name a few, for Ethernet LANs is rapidly reducing hardware cost.

These costs are very important to the design of a cost-effective LAN. As stated earlier, this project is concerned with the development of techniques useful in designing and evaluating a local area network.

Performance evaluation techniques for an Ethernet-type LAN have already been discussed. Cost evaluation techniques will be developed and discussed in this section on the same basis. Since the 802.3 class of LANs, such as Ethernet, offer a true media-sharing and networking capability, network resources such as servers, software, bridge, and media can be shared by several users, the cost-evaluation can be made on per user basis.

4.2 Transmission Media Cost

In this section four different transmission media options for Ethernet are considered. These options are thinwire coaxial, thickwire coaxial, twisted pair, and fiber optic cable.

In general, fiber optic cable is more expensive than coaxial cable which is itself two or three times more expensive than twisted pair. There are both material costs and installation costs to be considered. The cost of terminating the cable at each station must be included since it contributes significantly and varies widely according to the method and type of cable selected.

4.2.1 Assumptions

Since costs are to be evaluated on a per user basis, it is assumed that there are N users attached to the media. It is also assumed that three costs, namely material cost, installation cost, and termination cost, are the only significant contributors to the total cost of setting up a physical medium. The labor costs of installing all types of cables are assumed to be the same.

4.2.2 Cost Model

In this model, an Ethernet configuration, such as the one in Figure 3, consists of j cable types. The length of a cable of type i, where $i = 1,2, \dots ,j$ is X_i meters. The material cost of a cable of type i includes a fixed cost, F_i , and a variable cost, V_i, depending on the cable length. The cost for terminating a cable segment of type i is T_i dollars. The installation cost includes the cost of buying tools used in installation, I_t, and labor cost, I_l per meter. I_t is a fixed cost, while I_l is variable cost depending on the complexity of the network and the number of man-hours needed to install the transmission media.

A network segment can be extended or connected to another network segment using an interconnecting device such as a repeater, a bridge, or a router. The acquisition and interfacing costs of such devices contribute to the overall transmission media cost. Let B_i be the cost of buying and interfacing an interconnecting device i.

4.2.3 Evaluation

The cost involved in setting up any cable segment shared by N users can now be calculated [16].

C_{media} = material cost + installation cost + termination cost + interconnection cost

$$= \sum_{i=1}^{j} (F_i + V_i \times X_i + I_t + I_l \times X_i + T_i) + \sum_{i=1}^{k} B_i \quad (23)$$

where j is the number of cable types in the network and k is the total number of interconnecting devices in the configuration.

Cost per user for media, CPU_{media}, can be calculated by simply dividing the total cost of installing the transmission media by the number of users using it.

$$CPU_{media} = \frac{C_{media}}{N} = \frac{\sum_{i=1}^{j} (F_i + V_i \times X_i + I_t + I_l \times X_i + T_i) + \sum_{i=1}^{k} B_i}{N} \quad (24)$$

Thus, the cost per user of a transmission system can now be determined using Equation 24 if the value of each component cost and the number of users sharing the system are known.

4.3 Station Interfacing Cost

In this section, techniques for evaluating the costs involved in interfacing stations such as servers, computers, and terminals to the network are developed. Servers and computers, such as PCs, workstations, and mainframes, can be attached to the network using communications controllers and transceivers. Terminals can be attached to the network using a terminal server.

4.3.1 Assumptions

Servers are impartial to their users, that is users supported by a server can use it with equal probability. Therefore, the cost of interfacing a server to the network is assumed to be divided equally among all users. The labor cost of interfacing a device to the network is assumed to be included in the equipment cost.

4.3.2 Cost Model

A network often includes servers, such as file servers, terminal servers, and print servers, that support multiple users. There can be more than one of these servers on the network. Assume that file servers, terminal servers, disk servers, and print servers can each support N_f, N_t, N_d and N_p users, respectively, and mainframe or minicomputers can be shared by all N users on the network. The cost of attaching a device that can support only one user, such as a PC, is simply added to the total cost per user. The cost of interfacing terminals to the network includes the acquisition and interfacing cost of a terminal server that can support multiple terminals.

4.3.3 Evaluation

The cost model described above can be evaluated to determine the cost per user. Let the cost of buying interfacing hardware such as Ethernet cards, transceivers and other necessary equipment for file servers, terminal servers, print servers, disk servers, mainframe computers and PCs be C_f, C_t, C_p, C_d, C_{mf} and C_{PC}, respectively.

The cost per user for interfacing servers and computers is just the cost of each component divided by the number of users sharing it.

$$CPU_{interface} = \frac{C_f}{N_f} + \frac{C_t}{N_t} + \frac{C_p}{N_p} + \frac{C_d}{N_d} + \frac{C_{mf}}{N} + C_{PC} \tag{25}$$

A more general equation can be used to evaluate the cost contributed by stations such as servers and computers and can be written as

$$CPU_{interface} = \sum_{i=1}^{k} \frac{C_i}{N_i} \tag{26}$$

where C_i is the interfacing cost of station i, N_i is the number of users that station i can support, and k is the total number of stations.

4.4 Software Cost

4.4.1 Assumption

The labor cost of installing and testing software on the network is assumed to be included in the software cost.

4.4.2 Cost Model

LAN software consists of one or more software units that can be shared among multiple users depending on software's capabilities and functions. These software units can perform functions such as electronic mail, file transfer, and virtual terminal connection.

4.4.3 Evaluation

The cost of LAN software can be determined on a per user basis since it is simply the sum of each software unit cost divided by the number of users supported by the software as shown below.

$$CPU_{software} = \sum_{s=1}^{k} \frac{C_s}{N_s} \tag{27}$$

where k is the number of different software units and C_s is the cost of a software unit s that can be shared by N_s users.

4.5 Maintenance and Management Cost

4.5.1 Assumptions

The cost involved in network maintenance and management is the cost of detecting and correcting the network faults. There is no cost involved in network maintenance to prevent any failures; that is preventive maintenance costs are assumed to be zero.

4.5.2 Cost Model

The maintenance and management cost consists of the following two components.

1. ***Fixed Cost:*** Initial investment in buying maintenance and management tools that are used in detecting and correcting network faults during the life cycle. This cost is shared equally among all network users.

2. ***Variable Cost:*** Cost of detecting and correcting network faults during the network's life cycle. This includes the cost of repairing and replacing faulty components and renting or buying tools needed in the maintenance activity. Each of these maintenance costs are shared equally among all network users.

4.5.3 Evaluation

Maintenance and management costs can be determined on a per user basis depending on the network configuration and geographical layout, and derived on a case-by-case basis. This makes it very difficult to estimate the maintenance and management cost. Therefore, cost evaluation is often based on an estimation considering the cost of buying tools and equipment that are used in maintaining and managing a network and the labor cost for repairing and replacing faulty components. Although network maintenance and management costs actually occur continually or at discrete points throughout each year of the life cycle, they are usually treated at the beginning or at the end of the applicable time period. The objective is to relate these maintenance and management costs in "today's" value. The cost determined in "today's" value is called the present worth cost. The present worth costs of all maintenance and management activities during the life cycle of the network are summed to obtain the total maintenance cost of the network. Therefore, maintenance and management cost per user for a network with life T years can be determined as follows.

$$CPU_{mtce} = \textit{fixed costs per user} + \textit{variable costs per user}$$

$$CPU_{mtce} = \frac{C_0}{N} + \frac{C_1}{N} + \frac{C_2}{N} + \cdots + \frac{C_T}{N} \qquad (28)$$

C_0 is the fixed cost or initial investment that is shared among N users. This is the cost of buying equipment, such as a LANalyzer, used for network management and maintenance throughout the network's life cycle. C_1, C_2, ... , C_T are the present worth of costs occurred during each year of the life cycle and are shared among all N users.

Equation 28 can also be written as follows.

$$CPU_{mtce} = \sum_{t=0}^{T} \frac{C_t}{N} \tag{28}$$

where C_t is the present worth of total maintenance and management cost during year t.

The cost of maintaining and managing the network may be different for each year depending on the number of network component failures and the cost of correcting each fault. These network failures occur at discrete points during each year. The cost of managing the network is also included in each year's cost, and this may be either continuous, discrete or both since a network is managed continuously and maintained at discrete points of time throughout network's life cycle. The sum of all the continuous and discrete costs for year t is the total maintenance and management cost, F_t. It may be either referred to the beginning or to the end of year t.

The present worth of costs, C_t, can be determined using the following equation.

$$C_t = F_t\left[\frac{1}{(1+i)^t}\right]$$

where i is the interest rate. If the maintenance and management cost is a constant value during each year of the network's life cycle and is shared shared among all N network users, then in Equation 28, $C_1 = C_2 = \cdots = C_T = A$, where A is the annual maintenance and management cost. The total present worth of annual maintenance and management cost can be determined using the following equation.

$$PWC = A\left[\frac{(1+i)^T - 1}{i(1+i)^T}\right]$$

Equation 28 can now be written as follows.

$$CPU_{mtce} = \frac{C_0}{N} + \frac{A}{N}\left[\frac{(1+i)^T - 1}{i(1+i)^T}\right]$$

The techniques discussed here can be used to estimate the overall network maintenance and management cost throughout the life cycle.

4.6 Overall Network Cost

Once the costs of the transmission media, servers, and network interface have been determined, the overall network cost per user can be determined. This section develops a technique to evaluate the cost per user of a local area network.

4.6.1 Assumptions

There are only four cost factors contributing to cost: transmission media, station interface, software, and network maintenance and management. The cost of phasing out the network is assumed to be negligible. The labor cost is assumed to be included in the equipment or hardware costs.

4.6.2 Cost Model

The overall network cost includes the cost of setting up the transmission system, the cost of interfacing stations such as servers, computers, and terminals to the media, the cost of buying LAN software, and the cost of maintaining and managing the network over its life cycle. The sum of these cost factors gives the overall cost of an Ethernet network.

4.6.3 Evaluation

The sum of transmission media cost, server and computer interfacing cost, LAN software cost, and network maintenance and management cost gives the overall network cost.

$$CPU_{network} = CPU_{media} + CPU_{interface} + CPU_{software} + CPU_{mtce} \quad (29)$$

This equation can be used to determine the overall network cost on a per user basis. The values of each of the four cost components in the equation can be determined using the techniques developed earlier in this section.

5. Cost-Effectiveness

In previous two sections, methods for performance and cost evaluation of an Ethernet network were developed. This section develops a method to evaluate cost-effectiveness, a useful metric for design decision-making.

5.1 Definition

Cost-effectiveness is a measure of level of performance for a certain cost. The performance of a system can be measured by metrics such as throughput or delay.

5.2 Evaluation

Cost-effectiveness for the overall network and individual components can be determined by using the results obtained for cost and performance in previous sections. Thus by definition

$$Cost - effectiveness = \frac{Performance}{Cost/User} = \frac{Performance}{CPU} \tag{30}$$

where performance is one of the metrics, such as throughput or delay, for the network.

The performance and cost factors can be determined at component and network levels using the techniques developed in previous sections. The performance of the network can be determined using Equations 19 or 20 and the per user network cost can be determined using Equation 29. Using throughput from Equation 20 as the performance metrics,

$$Cost - effectiveness = \frac{\dfrac{\sum_{i=1}^{N} \lambda_i / D_i}{\sum_{i=1}^{N} \lambda_i}}{CPU_{media} + CPU_{interface} + CPU_{software} + CPU_{mtce}} \tag{31}$$

Equations 21 and 22 can be used to determine the performance and thus the cost-effectiveness of the network from user's view point.

6. Analysis Example

This section demonstrates how the methods to evaluate the cost-effectiveness of local area networks, such as Ethernet, can be used. The configuration considers several design options for media and servers that are available from vendors such as Digital Equipment Corporation [17], Black Box Corporation [18], and Excelan Corporation [19].

6.1 Network Configuration

A configuration of two interconnected Ethernet network segments is shown in Figure 5. This configuration consists of three different types of media, three repeaters, one bridge, a terminal server, a file server, a mainframe computer, and two PCs. The media types used in this example configuration are thickwire coaxial cable, thinwire coaxial cable, and fiber optic cable. A bridge is used to connect the two network segments using two sets of transeivers and transceiver cables. Stations are interfaced to the network using transceivers and transceiver cables as shown in Figure 5. The total number of users in this configuration are ten; there are two PC users and eight terminal users since the terminal server used in this configuration can support eight terminals.

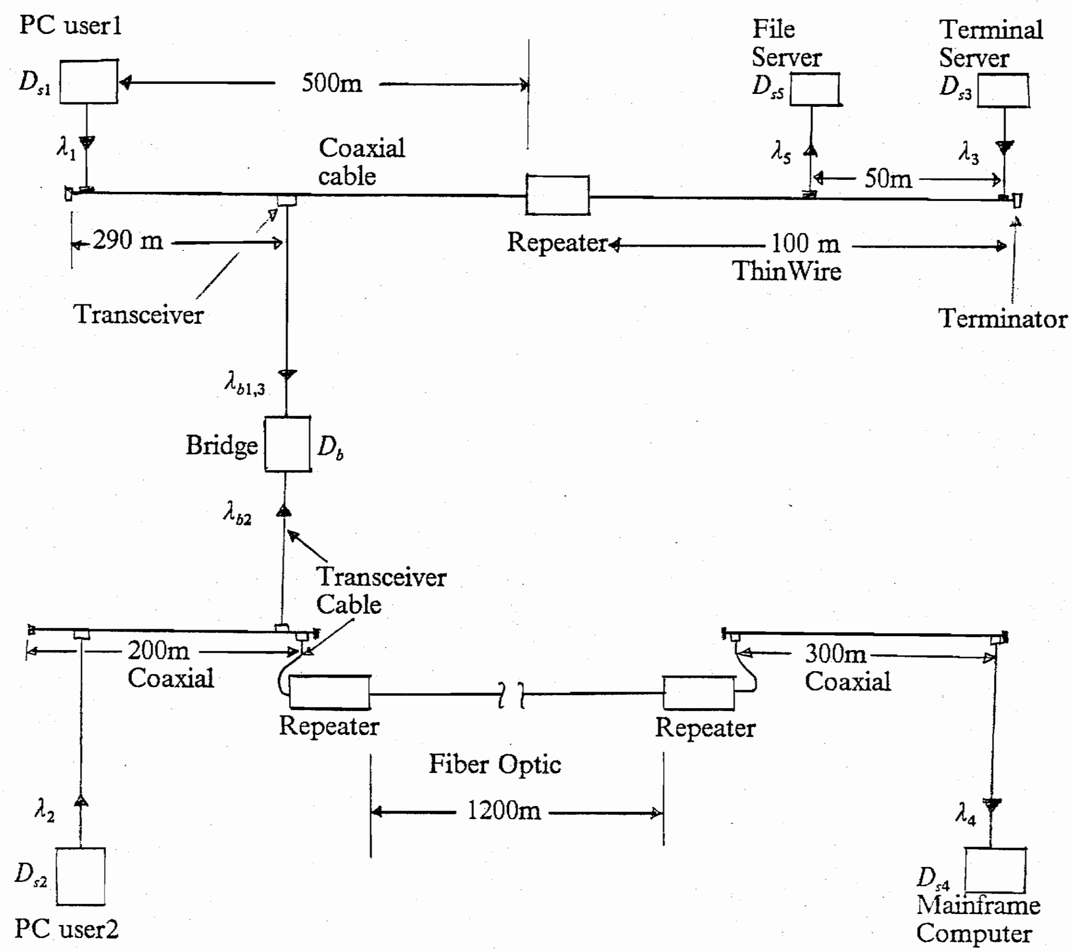

Figure 5. Example network configuration.

6.2 Cost Evaluation

The overall cost of the network can be evaluated using Equation 29 determined in Section 4. First, the values of the equation's variables must be determined using the network parameters and the costs of each component given by the vendors [17,18,19].

6.2.1 Transmission Media

The transmission system of the overall network consists of three different types of cables, coaxial, thinwire, and fiber optic cable, so j = 3. It is assumed that all the cables, repeaters, interfacing hardware, terminators and installation tools are Black Box Corporation products [18] and the LAN Bridge (DEBET) is a Digital Equipment Corporation product [2,17].

1. Standard coaxial cable
   a. Length X_1 = 500 m + 300 m + 200 m = 1000 m since there are three segments of length 500 m, 300 m, and 200 m.
   b. Material cost, F_1 = \$32.00, V_1 = \$3.50/m, where \$32.00 is the fixed cost and \$3.50/m is the variable cost.
   c. Terminator cost T_1 = 6(\$10.00) = \$60.00, since two terminators are needed to terminate each of the three segments. Terminators cost \$10.00 each.
2. Thinwire cable
   a. Length X_2 = 100 m.
   b. Material cost, F_2 = \$15.00, V_2 = \$1.00/m, where \$15.00 is the fixed cost and \$1.00/m is the variable cost.
   c. Terminator cost, T_2 = 2(\$10.00) = \$20.00, since two terminators are needed for a single thinwire cable segment and their cost is \$10.00 each.

3. Fiber optic cable

   a. Length X_3 = 1200 m.

   b. Material cost, F_3 = \$110.00, V_3 = \$3.93/m, where \$110.00 is the fixed cost and \$3.93/m is the variable cost.

   c. Terminator cost T_3 = \$0.00, since no terminator is needed for the fiber optic cable.

4. Installation cost (I)

   a. Labor cost I_l = \$2.00/m. This is a variable cost depending on the cable length and is assumed to be the same for all cable types.

   b. The cost of an Ethernet crimp tool is \$60.00 and the cost of accessories for installing transceivers is \$114.90, so the tool cost is I_t = \$60.00 + \$114.90 = \$174.90. This is a fixed installation cost.

5. Interconnection cost (B)

   a. Cost of connecting coaxial cable and thinwire cable B_1 = cost of a local repeater (NG - LN420B) + cost of one transceiver for thickwire + cost of 3 m transceiver cable = \$1460.00 + \$260.00 + \$52.50 = \$1772.50.

   b. Cost of interconnecting two networks using a bridge B_2 = cost of LAN Bridge (DEBET) + cost of two transceivers + cost of two 3m long transceiver cables = \$9000.00 + 2(\$260.00 + \$52.50) = \$9625.00.

   c. Cost of connecting two coaxial cables by a fiber optic cable B_3 = cost of two fiber optic repeaters + cost of two transceivers + cost of two 3m long transceiver cables = 2(\$2180.00 + \$260.00 + \$52.50) = \$4985.00.

Therefore, using Equation 24, the media cost per user can be determined as follows.

$$CPU_{media} = \frac{\sum_{i=1}^{3}(F_i + V_i \times X_i + I_t + I_l \times X_i + T_i) + \sum_{i=1}^{3} B_i}{10} = \$2965.79.$$

6.2.2 Interfacing Stations

1. Personal computer, C_{PC} = cost of the interface board (5010 Ethernet card w/ transceiver) + cost of a 3m long transceiver cable = \$495.00 + \$52.50 = \$547.50.
2. Terminal server (DECserver), C_t = cost of terminal server + cost of BNC Transceiver-2 + cost of a 15.2m long transceiver cable = \$3800.00 + \$285.00 + \$84.50 = \$4169.50. Since this device supports eight terminals, $N_t = 8$.
3. Mainframe interfacing (DEQNA), C_{mf} = cost of interface board (DEQNA) + cost of a Ethernet transceiver-2 + cost of 15.2m long transceiver cable = \$2600.00 + \$260.00 + \$84.50 = \$2944.50. Assume that mainframe is accessible only by users at the two PCs and eight terminals, therefore $N_{mf} = 10$.
4. File server cost, C_f = Cost of NP600 Ethernet card + cost of a BNC Transceiver for thinwire connection + cost of a 15.2m long transceiver cable = \$895.00 + \$285.00 + \$84.50 = \$1264.50. Assume that file server is only accessible by the two PCs and eight terminals, therefore $N_f = 10$.

Therefore, using Equation 25, the cost of interfacing stations on per user basis can be determined.

$$CPU_{interface} = \frac{\$1264.50}{10} + \frac{\$4169.50}{8} + \frac{\$2944.50}{10} + 2(\frac{\$547.50}{1}) = \$2037.09$$

6.2.3 LAN Software

Assume that all the software units are Excelan Corporation product.

1. PC software, C_1. Assume that both PCs use EXOS 8051-01 which includes a TCP/IP software

with file transfer (FTP) and virtual terminal connection with terminal emulation (TELENET). Therefore, $C_1 = \$295.00$ and this unit is shared by one PC user so $N_1 = 1$.

2. Mainframe software, C_{mf}. Assume the mainframe uses EXOS 8043-01 that is an Excelan software product for VMS systems. This software unit includes FTP, TELENET and a Queue Input/Output (QIO) programming interface. This software unit can be shared equally by all network users. Therefore, $C_2 = \$5000.00$ and $N_2 = 10$.
3. File server, C_3. Assume that the file server uses Advanced Netware (Ver. 2.11). This software unit can be shared equally by all network users. Therefore, $C_3 = \$2195.00$ and $N_3 = 10$.

Assume that these are the only software units in the network. The total software cost can be determined using Equation 27 as follows.

$$CPU_{software} = \sum_{s=1}^{3} \frac{C_s}{N_s} = 2(\frac{\$295.00}{1}) + \frac{\$5000.00}{10} + \frac{\$2195.00}{10} = \$1309.50$$

6.2.4 Maintenance and Management

1. An Excelan LANalyzer EX 5000E Kit, costing \$9500.00, is bought for network maintenance and management. It is assumed that there are no other tools needed for the maintenance and management of the network. The LANalyzer needs an Ethernet transceiver-2 and a 3 m long transceiver cable (\$52.50) for interfacing it to the network. The sum of these three cost components is the investment cost or fixed cost for maintaining and managing the network and is shared equally among the ten network users. So, $C_0 = \$9500.00 + \$260.00 + \$52.50 = \$9812.50$ and $N = 10$.

2. Assume that the total maintenance cost for each year is \$500.00, that it is equally shared among the ten network users, and the network life is 10 years. So, A = \$500.00, N = 10, and t = 10 years. Assume annual interest rate i = 10%.

Then, using the the techniques of Section 4.5 and Equation 29, the total maintenance and management cost can be determined as follows.

$$CPU_{mtce} = \frac{\$9812.50}{10} + \frac{\$500.00}{10}\left[\frac{(1+0.10)^{10}-1}{0.10(1+0.10)^{10}}\right] = \$1288.48$$

6.2.5 Overall Network Cost

Now the overall network cost per user can be determined using Equation 29 as follows.

$$CPU_{network} = CPU_{media} + CPU_{interface} + CPU_{software} + CPU_{mtce}$$

$$= \$2965.79 + \$2037.09 + \$1309.50 + \$1288.48 = \$7600.86$$

6.3 Performance Evaluation

The network performance can be evaluated using the methods and equations developed in Section 3 of this report. First, the performance of transmission system and network servers will be evaluated. The results obtained will then be used to determine the overall performance of the network considering the traffic on different segments. Assumptions about the network traffic are as follows.

PC1 generates messages at a rate of $\lambda_1 = 100\, packets/s$, of which $\frac{3\lambda_1}{4}$ of the traffic is destined for the mainframe and $\frac{\lambda_1}{4}$ of the traffic is destined for the file server. PC2 generates messages at a rate of $\lambda_2 = 60\, packets/s$, of which $\frac{2\lambda_2}{3}$ goes to the mainframe, and $\frac{\lambda_2}{3}$ goes to the file server. The total message rate of all terminals is $\lambda_3 = 100\, packets/s$, of which $\frac{\lambda_3}{2}$ goes to the mainframe and $\frac{\lambda_3}{2}$ goes to the file server. Assume that the same amount of traffic is sent back by the mainframe and file server to their respective origins.

The traffic distribution in the network can be represented in matrix form, T, as follows.

$$T = \begin{bmatrix} 0 & 0 & 0 & 75 & 25 \\ 0 & 0 & 0 & 40 & 20 \\ 0 & 0 & 0 & 50 & 50 \\ 75 & 40 & 50 & 0 & 0 \\ 25 & 20 & 50 & 0 & 0 \end{bmatrix}$$

where entry T_{ij} is the amount of traffic in packets per second going from station i to j. PC1, PC2, the terminal server, the mainframe and the file server are assumed to be stations 1, 2, 3, 4 and 5, respectively. So, for example, there are $T_{13} = 75$ packets per second from PC1 (station 1) to the mainframe (station 3).

The performance of the Ethernet network can be determined for these assumptions using the methods developed in Section 3.

6.3.1 Transmission Media

The performance of the transmission media connecting PCs and terminals to the computer and file server are determined using the equations of Section 3.1. Using Equation 3, the delay due to the transmission media can be determined as follows.

1. Delay from PC1 to file server $= \frac{L}{B} + \frac{d}{v}$

$$= \frac{512\ bytes}{10\ Mbps} + \frac{290\ m + 210\ m + 50\ m}{2 \times 10^8\ m/s} = 409.6\ \mu s + 2.75\ \mu s = 412.35\ \mu s$$

2. Delay from PC1 to mainframe $= 409.6\ \mu s + \frac{290\ m + 1200\ m + 300\ m}{2 \times 10^8\ m/s} = 418.55\ \mu s$

3. Delay from PC2 to file server $= 409.6\ \mu s + \frac{200\ m + 260\ m}{2 \times 10^8\ m/s} = 411.9\ \mu s$

4. Delay from PC2 to mainframe $= 409.6\ \mu s + \frac{200\ m + 300\ m + 1200\ m}{2 \times 10^8\ m/s} = 418.1\ \mu s$

5. Delay from terminal server to file server $= 409.6\ \mu s + \frac{50\ m}{2 \times 10^8\ m/s} = 409.85\ \mu s$

6. Delay from terminal server to computer $= 409.6\ \mu s + \frac{310\ m + 300\ m + 1200\ m}{2 \times 10^8\ m/s} = 418.65\ \mu s$

6.3.2 Stations

The performance of the stations, such as computers and servers, and of the bridge can be evaluated using the equations of Section 3.3. The assumption is made that the file server uses the File Transfer Protocol (FTP) and the mainframe uses the transaction protocol Remote Operations Service Element (ROSE) for servicing messages. The performance of these protocols are studied in detail in [20].

1. Delay at PC1 (D_{s1})

   Assume that the message service delay at the PC1 is negligible, therefore $D_{s1} = 0$.

2. Delay at PC2 (D_{s2})

   Assume that the message service delay at the PC2 is negligible, therefore $D_{s2} = 0$.

3. Delay at Terminal Server (D_{s3})

The terminal server is a DECserver 200 that has a maximum throughput of 273 packets/s for a packet size of 512 bytes. Assuming an infinite buffer size and service rate of 273 packets/s, Equation 14 can be used to find delay D_{s3} as follows.

$$D_{s3} = \frac{1}{\mu - \lambda}$$

where λ is the total traffic generated by terminal users in packets per second and μ is the service rate in packets per second. Since the total incoming message rate at the terminal server is the sum of the messages generated and received by all eight terminals, which is twice the amount of traffic generated by the terminals, $\lambda = 2\lambda_3 = 200\, packets/s$. Then

$$D_{s3} = \frac{1}{273 - 200} = 13.70\, ms$$

4. Delay at Mainframe Computer (D_{s4})

   An estimate of delay at the mainframe computer can be determined for the ROSE service from [20]. With a packet size of 512 bytes, the average delay D_{s3} will be about 29.3 ms since the throughput is 17.5 kbytes/s for this packet size. So $D_{s4} = 29.3\, ms$.

5. Delay at File Server (D_{s5})

   If the file server uses FTP, the average delay can be estimated from the results of [20] as 2.93 ms/packet for a 512 byte packet size since the throughput is about 175 kbyte/s. So $D_{s5} = 2.93\, ms$.

6. Delay at Bridge (D_b)

   The bridge in the example network is a LANBridge 100, whose service rate is 1675 packets/s for packet sizes of 512 bytes. Assuming an infinite buffer at the bridge, the delay can be determined using Equation 14 as follows.

$$D_b = \frac{1}{\mu - \lambda}$$

where λ is the total traffic passing through the bridge and μ is the service rate of the bridge. The total traffic passing through the bridge is

$$2(\lambda_{b1,3} + \lambda_{b2}) = 2[\frac{3}{4}(100) + \frac{1}{2}(100) + \frac{1}{3}(60)] = 290\, packets/s$$

where $\lambda_{b1,3} = T_{14} + T_{34}$ and $\lambda_{b2} = T_{25}$. So, $D_b = \frac{1}{1675 - 290} = 722.02\, \mu s$

6.3.3 Overall Network Performance

Once the component performance has been determined, the overall network performance can be determined using the techniques developed in Section 3.4. The network performance evaluation can be done by substituting Equation 17 in Equation 18 and then Equation 15 into this equation to get

$$D_i = \beta_0(D_m + D_s) + \alpha_0(D_m + D_b + D_s)$$

This equation can be used for determining the average delay for the messages of each of the N user stations.

1. Average delay for PC1 messages, D_1

$$D_1 = \frac{1}{4}(412.35\, \mu s + 2.93\, ms) + \frac{3}{4}(418.55\, \mu s + 722.02\, \mu s + 29.3\, ms) = 23.55\, ms$$

2. Average delay for PC2 messages, D_2

$$D_2 = \frac{1}{3}(412.10\, \mu s + 2.93\, ms) + \frac{2}{3}(418.1\, \mu s + 722.02\, \mu s + 29.3\, ms) = 21.30\, ms$$

3. Average delay for terminal messages, D_3

$$D_3 = 13.70\ ms + \frac{1}{2}(409.85\ \mu s + 2.93\ ms) + \frac{1}{2}(418.65\ \mu s + 722.02\ \mu s + 29.3\ ms) = 47.40\ ms$$

where 13.70 ms is the delay due to terminal server.

4. Average delay for mainframe messages, D_4

   Total messages generated by mainframe = $T_{41} + T_{42} + T_{43}$ = 75 + 40 + 50 = 165 packets/s. So,

$$D_4 = \frac{75(418.55\ \mu s + 722.02\ \mu s + 0) + 40(418.1\ \mu s + 0) + 50(418.65\ \mu s + 722.02\ \mu s + 13.70\ ms)}{165}$$

$$= 5.12\ ms$$

5. Average delay for file server messages, (D_5)

   Total traffic generated by the file server = $T_{51} + T_{52} + T_{53} = 25 + 20 + 50 = 95\ packets/s$. So,

$$D_5 = \frac{1}{95}[25(412.35\ \mu s + 0 + 0) + 20(411.9\ \mu s + 722.02\ \mu s + 0) + 50(409.85\ \mu s + 0 + 13.70\ ms)]$$

$$= 7.71\ ms$$

The overall network delay can now be determined using Equation 19 as follows.

$$D_{network} = \frac{100(23.55) + 60(21.30) + 100(47.40) + 165(5.12) + 95(7.71)}{100 + 60 + 100 + 165 + 95} = 19.14\ ms$$

Network throughput can be determined using Equation 20 as follows.

$$S_{network} = \frac{(\frac{100}{23.55}) + (\frac{60}{21.30}) + (\frac{100}{47.40}) + (\frac{165}{5.12}) + (\frac{95}{7.71})}{520} = 423{,}157\ bps$$

6.4 Cost-effectiveness

The cost-effectiveness of the network, based on average delay can now be determined using Equation 30 as follows.

$$Cost - effectiveness = \frac{423{,}157\ bps}{\$7600.86} = 55.68\ bps\ per\ dollar$$

7. Summary

One of the most challenging issues in the area of local area network design is how to determine the cost-effectiveness of a network. This report presents a methodology to estimate the cost-effectiveness of an Ethernet network. Several methods were developed for determining Ethernet LAN performance at both the component and system levels using queueing models and other analytical techniques. Methods were also developed to determine the overall network cost on a dollar per user basis considering important cost factors such as material cost, installation cost, software cost, interconnection cost, station interfacing cost, and maintenance cost. An example Ethernet configuration was presented to demonstrate the application of these techniques.

The methods presented in this report form a basis to evaluate a local area network. Although the techniques developed in this report are mostly applicable to Ethernet networks, the concept can be extended to develop methods to evaluate other type of networks.

Although the methods developed in this report are useful in determining the cost-effectiveness of a network for the purposes of design decision-making, they lack accuracy. The major factors reducing performance were found to be delays at stations such as servers and computers. This is due to application layer activities such as file transfers, remote procedure calls, and computations. Delays in other layers, such as the network layer, transport layer, session layer, and presentation layer, should also be taken into account to achieve accuracy. Better methods need to be developed using analytical techniques to estimate these delays for more accurately determining the network performance. Since it is very difficult to determine the network maintenance cost accurately, the overall network cost is an estimated value. The labor cost is highly variable depending on the complexity of the installation, number of staff-hours needed, and the cost of labor. These variables are extremely difficult to estimate. Techniques should be developed to estimate these factors more accurately. Techniques should also be developed to estimate network reliability since it will help in estimating the network maintenance cost during the life-cycle, thus allowing a more accurate estimate of the network cost.

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