Cost and Performance Impacts of Optical Amplifier Technology on Fiber-Optic Communication Networks

By

Davidson Arthur Scott

Project Report submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Systems Engineering

APPROVED:

Dr. Anbo Wang, Chairman

Professor Ben Blanchard

Dr. Dinesh Verma

August 1995

Blacksburg, Virginia

Key Words: Optical Amplifier, Fiber-Optic, Broadband, Bandwidth, Repeater

c.2

Cost and Performance Impacts of Optical Amplifier Technology on Fiber-Optic Communication Networks

by

Davidson A. Scott

Committee Chairman: Anbo Wang

Electrical Engineering

(ABSTRACT)

The current telecommunication infrastructure cannot support the future bandwidth requirements of consumers. The application of optical amplifier technology in fiber-optic networks is demonstrated and analysis is performed on methods that can help meet the need for ever-increasing bandwidth in optical telecommunications while contributing to lower network operating costs in both the local and long-haul domains. Systems engineering methods are used to analyze the need for increased bandwidth and to delineate costs associated with operating a fiber-optic network using current technology involving the application of regenerative repeaters spaced periodically over a given communications link. This is contrasted with estimated recurring costs of operating a fiber-optic link applying fiber-optic amplifier technology. Possible architectures and problems associated with providing integrated broadband services to consumers is also analyzed.

Acknowledgements

I would like to thank my wife, Nancy, and our three children Sally, Russell, and Anne for their essential help and patience in completing this endeavor. I would also like to thank my committee chairman, Dr. Anbo Wang and members Professor Ben Blanchard and Dr. Dinesh Verma for their expert guidance.

Table Of Contents

Table Of Contents

Table Of Contents

List Of Figures

List Of Figures (continued)

1.0 Introduction

The current telecommunication infrastructure cannot support the future bandwidth requirements of consumers. This project demonstrates the application of systems engineering concepts to plan and design the upgrade of existing local and long-haul telecommunication networks to meet the future requirements. Today, citizens in the developed world depend increasingly on the acquisition, processing and storage of information. In the near future, the typical consumer telecommunication needs will be image based, requiring at least 100 times the bandwidth available today. This performance will have to be delivered at approximately today's level of cost while maintaining a typical (99.99 %) availability rate.

1.1 Definition of Need

Most telecommunication equipment for typical consumer or business use is limited to the 64kbps bandwidth of a digitized voice channel. This is insufficient for many current and most future modes of communication. Specifically, it may take several minutes to transmit a single high-resolution graphic or video image over current switched telecommunication networks. One image-based application that has become available widely to consumers in the past few years over the Internet is the World Wide Web (WWW). WWW applications perform reasonably well as long as sufficient bandwidth is available, which means by-passing the normal telephone network and directly connecting to a high-capacity network, typically at a rate of 1.5 Mbps or greater. Bandwidth demand from WWW applicactions is growing at 10% per month [Netgen 95] driven by consumer and business communication usage. By definition, multi-media applications require greater data rates than text-based applications. For example, a page of text is typically 4000 characters, a single high-resolution image 4 inches by 4 inches can take 1000 times this. This illustrates the growth in bandwidth required for image-based multimedia applications. Another application that is currently using fiber-optic communication infrastructure is cable television. Cable television providers today typically offer 50 analog channels of television using 1950's era communication standards and resolution. Standards are currently being developed for High Definition Television (HDTV) that will require an order of magnitude more bandwidth (100 MHz Vs 6 Mhz) [Reed 92, p. 154] to transmit a video signal, with additional growth in the number of channels of programming expected. Other services like video telephony, high-resolution facsimile, video-on-demand, electronic newspapers, and high-speed computer networking will soon touch the lives of all consumers, but only if the communication infrastructure is in place to support the services.

2.0 Systems Engineering Process

The systems engineering process is a continuous, iterative method used to find an optimal solution to a particular problem over its entire life-cycle. [Blanchard 90, p.16-31] The problem of telecommunication is particularly challenging because it is growing at a rapid rate and is continuously affected by technological changes, which are also evolving at a rapid rate. This project concentrates on the implementation of technology to increase bandwidth without increasing maintenance costs or decreasing reliability. This project is a product of this iterative process. The first iteration (or generation) of fiber-optic links was simply the replacement of copper infrastructure in point-to-point links. The second iteration, the current generation, is the aggregation of many voice circuits onto a single fiber link, a sort of high-capacity bit pipe. The third iteration, the topic of this project, seeks methods for cost effective increase in bit-rates. The process is illustrated in the following figure:

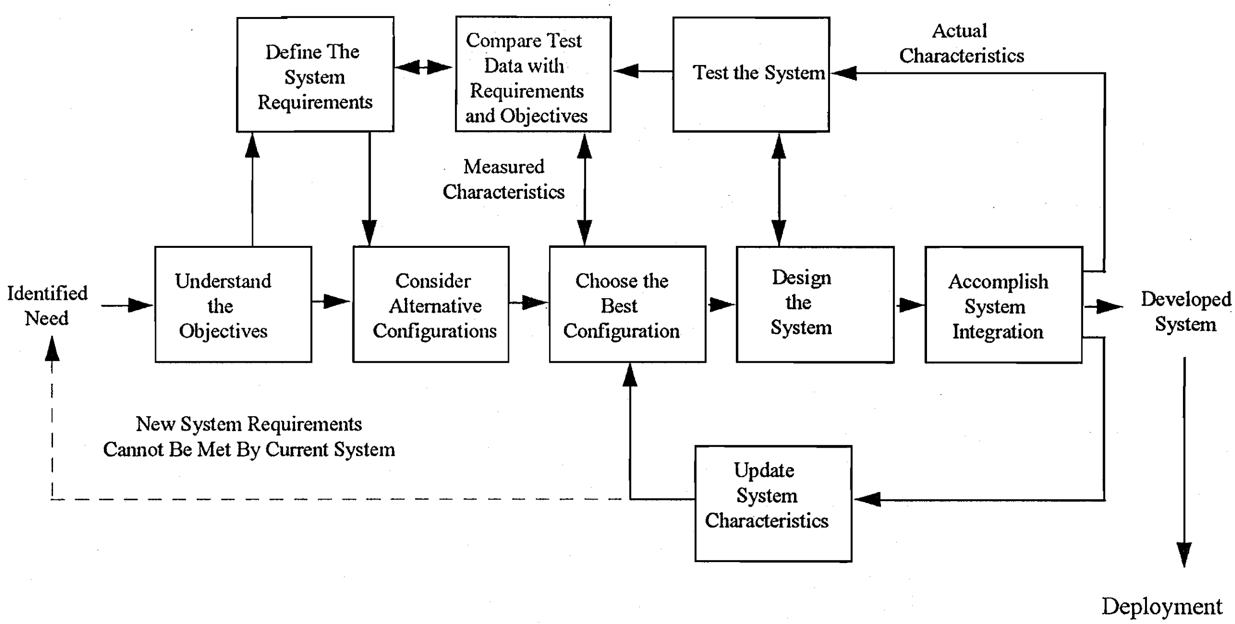


Figure 1. Feedback in the Systems Engineering Process

(Adapted From [Blanchard 90, p.24])

In this figure, when desired system requirements change and can no longer be met by the current system (bandwidth in this case) then the need for another "generation" of fiber-optic system is identified. The application of this evolutionary loop is illustrated by the dased line. The systems engineering process, properly applied over the entire system life-cycle, can reduce the frequency of application of the dashed loop, and therefore reduce the number of evolutionary generations required to continuously meet the need. In the case of fiber-optic communication links, a substantial capital investment can be required to upgrade to the next generation technology.

3.0 Historical Background

Since the invention of the telegraph in 1838 by Samuel Morse, electronic communication has held a permanent place in our culture and society. As our society has flourished, so has the demand for telecommunication to the point where our economic and cultural vitality depends on the continuing growth of telecommunication. Throughout the history of telecommunication the growth in traffic in terms of information conveyed has been tremendous. In fact the use of telephones alone has sustained a 6-8% annual growth rate since the late 1940's [O'Neill 82, p. 720]. While growth has soared, cost has gone down. Telecommunication has brought on what has been called the "Third Wave" or the Information Revolution that is driven by the generation, transmission and use of information. Fiber optic technology is the latest realization of the attempt to keep up with this revolution. Optical communication technology is undergoing somewhat of a revolution itself.

3.1 Early Fiber-Optics

Fiber Optic communication systems have an interesting history. Optical fiber communication has only been practical for some 25 years. Early efforts were geared toward producing silica glass fibers that had significantly lower losses than the 1000 dB/km values of the first fibers [Keiser 91, p. 1-14]. These early fibers were not useful for communication purposes at distances greater than a few meters because of extremely high attenuation. Once the process for manufacturing lower-loss fibers (10dB/km) was developed in the early 1970's optical communication became competitive with copper wire based infrastructure and began to be installed in communication systems as a substitute for copper wire. Incremental improvements have yielded attenuation levels (0.2dB/Km today) that have made long-haul communication systems practical.

3.2 Sources and Detectors

The development of optical sources and detectors is of equal importance to the success of optical communication systems. Typical sources in fiber optic communication include Light Emitting Diodes and Laser Diodes. Typical detectors include photodiodes and avalanche photodiodes. Spectral properties of silica glass give three distinct "windows" for its use in communication systems (see figure 2). Sources and detectors in the early 70's were designed to take advantage of the "first" optical window in silica glass at optical wavelengths of around 850nm. As fiber technology developed, longer wavelength sources and detectors were manufactured to use the 1300nm window. This window has the added benefit of being the silica glass minimum dispersion point, or the point where a given pulse "spreading" is at a minimum, affecting link bandwidth. The third window at 1550 nm is being exploited in more communication links because it is the point of minimum attenuation for silica glass material and because of the availability of optical amplifiers. [Keiser 91, p. 11]

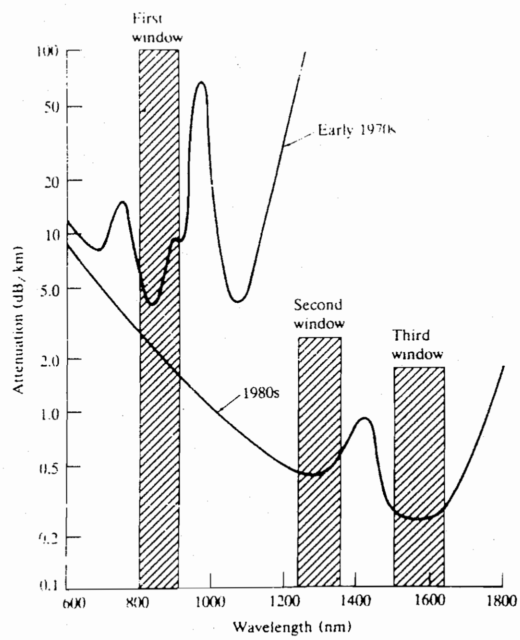


Figure 2. Silica Glass Communication Windows

From [Keiser 91, p.11]

4.0 Technical Background

4.1 Proliferation of Fiber-Optic Communication

Fiber Optic communication has proliferated since the 1970's because it offers distinct advantages over copper wire technology. Longer link distances, immunity to electromagnetic interference and higher bandwidths and lower cost are the chief advantages of this technology.

4.2 Basic Fiber Optic Laws

In order for a fiber optic cable to guide light and make communication possible, it must posses certain physical properties. That is, it must be constructed with a core region of glass with a higher index of refraction than the surrounding glass cladding area. This is achieved with silica glass fibers by using dopants such as germanium in the core region. Undoped Silica glass has an index of refraction of around 1.45 at communication wavelengths [Keiser 91, p102]. Depending on the dimensions of the core region, the index of refraction difference between the core and cladding regions of the fiber and the wavelength of the source signal, light will propagate (or not propagate) with certain characteristics known as modes. (see figure 3)

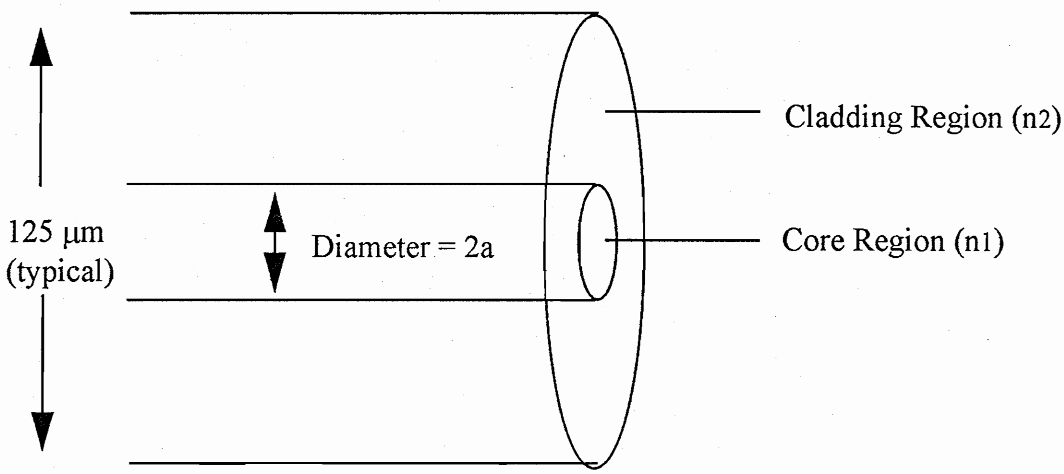


Figure 3. Fiber Optic Waveguide

The number of propagation modes in a fiber has direct bearing on its application and usefulness. Multimode fiber is characterized by a larger core region. Multimode fibers are selected for applications because inexpensive sources and detector components are available but is limited in bandwidth and distance due to modal interference and source characteristics. Most fiber optic Local Area Networks (LAN's) use multimode fibers. Communication links of any significant distance will typically use single-mode fiber. A single mode fiber is denoted by the relationship:

$$V := \frac{2 \cdot \pi \cdot a}{\lambda} \cdot \sqrt{n_1^{\,2} - n_2^{\,2}} \qquad < \qquad 2.40$$

Where V is a parameter (V-number) designation used in the design of fiber optic waveguides and λ is the wavelength of the communication light source. If the V-number exceeds 2.405 then a fiber is considered multimode [Keiser 91, p.44].

4.3 Fiber Optics in Communication Systems

Fiber optic based communication systems began to replace copper and terrestrial microwave links in the late 1970's. Fiber optic communication was chosen because it offered flexibility for future evolution of consumer expectations and requirements. The time has come for some of these technological developments to be considered to meet the fast growing need for data communication.

5.0 Feasibility Analysis

An inventory of today's requirements versus future requirements for individual users is the first step to improvement. This assessment will facilitate the design and development of relevant telecommunication systems to meet this increase in consumer demand and in quantifying the magnitude of necessary bandwidth improvement.

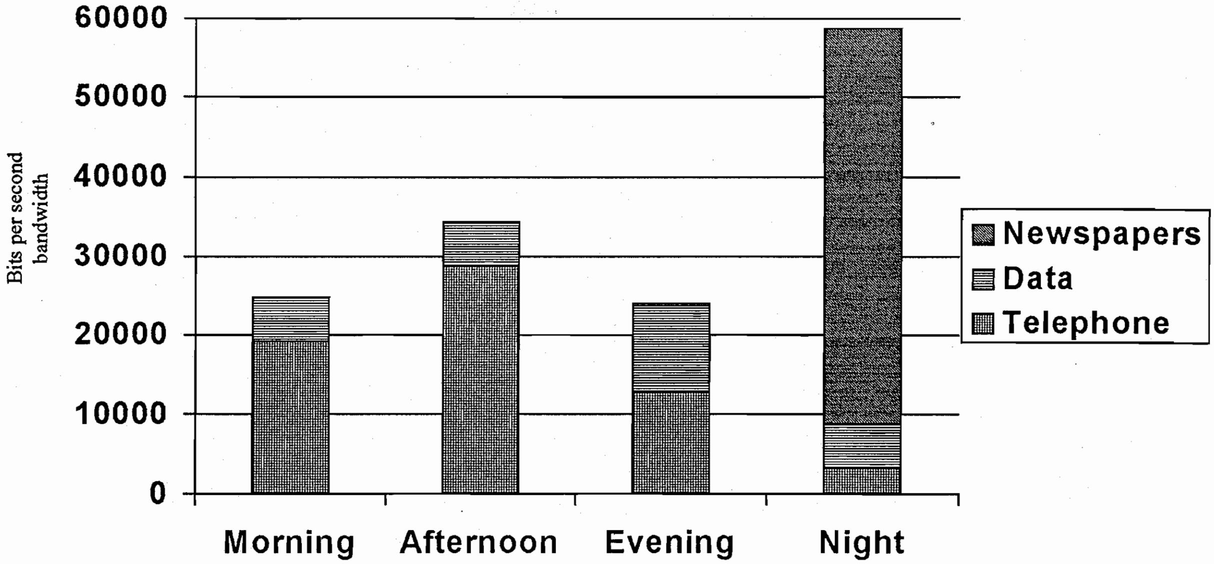


Figure 4. Usage Profile of Today's Requirements

5.1 Today's Requirements:

Device	*Morning*	*Afternoon*	*Evening*	*Night*	*Capacity bps*
Telephone	30%	45%	20%	5%	64000
Cable TV	25%	25%	25%	25%	300000000
Audio Services	25%	25%	25%	25%	20000000
Data	20%	20%	40%	20%	28000
Newspapers	0%	0%	0%	100%	50000

3.20E+08

Figure 5. Current Requirements Table

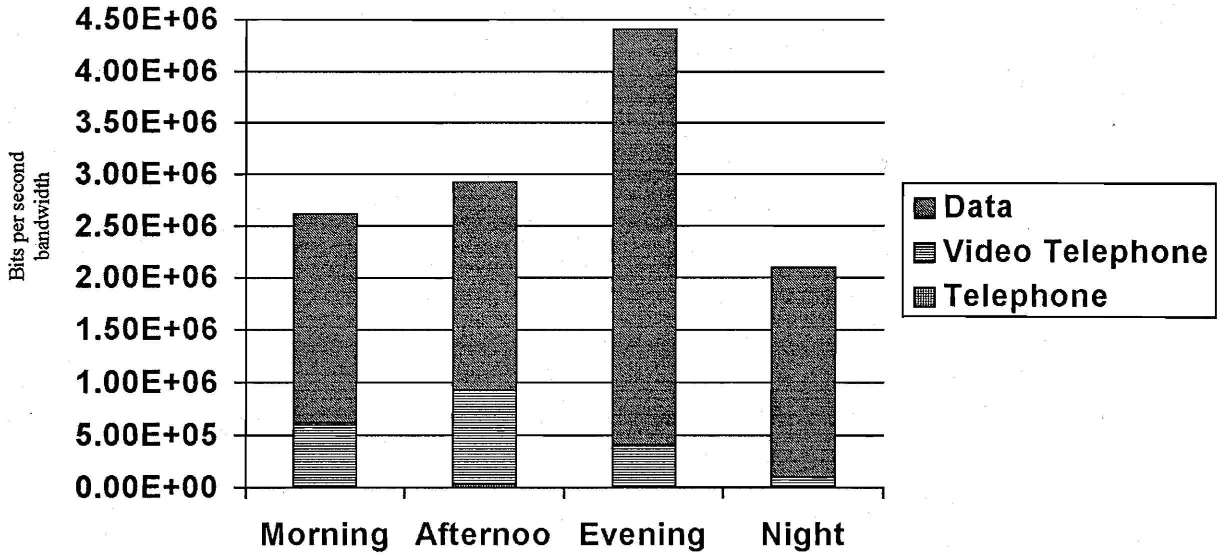


Figure 6. Usage Profile of Future Requirements

5.2 Future Requirements:

Future requirements represent nearly 100 times currently available bandwidth. There are three feasible alternatives to meet this need.

Device	*Morning*	*Afternoon*	*Evening*	*Night*	*Capacity bps*
Telephone	30%	45%	20%	5%	6.40E+04
Video Telephone	30%	45%	20%	5%	2.00E+06
Cable TV	25%	25%	25%	25%	2.00E+10
Audio Services	25%	25%	25%	25%	2.00E+07
Data	20%	20%	40%	20%	1.00E+07

2.00E+10

Figure 7. Future Requirements Table

5.3 Feasible Alternatives

All feasible alternatives must take into account the following requirements:

1. Increased bandwidth for broadband services.
2. Cost effectiveness, leading to no more than double current service cost .
3. Reliability and maintainability leading to 99.99% availability.
4. Timeliness of implementation.
5. Use of existing infrastructure.
6. Upgradability.

Option 1

Duplicate Current Network to provide sufficient bandwidth

This option requires the overlaying of existing infrastructure with a functionally and technologically equivalent infrastructure to include optical sources, detectors, repeater hardware, electronic switches and fiber-optic cable.

Pros

This option provides for full use of existing infrastructure

Cons

This option is costly, requiring labor-intensive installation of large amounts of cabling and equipment. This option requires large amounts of cabling at the customer site to meet bandwidth needs.

Option 2

Replace Current Network with newer, higher capacity technology

This option discards current infrastructure and completely replaces it with newer, broadband technology.

Pros

This option provides for maximum compatibility and eliminates the support burden of older systems. Provides a standard foundation for upgradability.

Cons

This option requires a long transition period where the old and the new system will have to be supported. Do not get any benefit from already installed infrastructure.

Option 3

Update Current Network with new technology, implement new technology on new installations, including Fiber Optics to the Home (FOTH).

This option utilizes technical improvements to migrate toward high-bandwidth capability, replacing elements of the local, and long-haul as bandwidth demand warrants.

Pros

Allows for system evolution that matches actual demand for bandwidth. Allows for customers to keep current systems.

Cons

Requires support of many different systems.

6.0 Mode Selection

The options were consolidated and placed in the mode selection matrix below:

	Option 1		Option 2		Option 3	
	Local	Long-Haul	Local	Long-Haul	Local	Long-Haul
Cost	○	△	△	○	□	□
Bandwidth	△	□	□	□	□	□
Reliability	○	△	△	△	□	□
Timeliness	○	○	○	○	△	△
Infr. Re-use	□	□	○	○	□	□
Upgradability	○	○	□	□	□	□

Requirement Characteristic

○ Poor

△ Medium

□ Good

Figure 8. Mode Selection Matrix

All options are feasible because they all offer medium to good bandwidth performance characteristics.

6.1 Mode Selection Assessment

Option 1, Duplicate Current Network, is deficient because it has poor or medium cost, reliability, timeliness of implementation, and upgradability characteristics.

Option 2, Replace Current Network, is deficient because it has poor timeliness of implementation, infrastructure re-use characteristics and medium or poor cost and reliability characteristics.

Option 3, Update Current network with new technology, has best requirement characteristics based on the Mode Selection Matrix. Option 3 is the recommended mode.

7.0 Operational Requirements

Performance Profile:	The telecommunication network will operate 24 hours per day, 7 days per week.
Performance Parameters:	The communication network will provide interactive and non-interactive data communication including audio, video, voice and data services.
Capacity:	Provide 100 times current aggregate bandwidth to the consumer.
Environmental:	Network will operate in all weather environments including those to which the current network is subjected.
Use Requirements:	Consumer will be limited to 10Mbps outbound.

Life Cycle:	The system will operate for 20 years after which time it will be replaced and have no salvage value.
Effectiveness Factors:	The system will be available 99.99% of the time and cost will be no greater than 2 times the aggregate total of current services. Implementation of bandwidth improvements will be timely, new services will not be hindered by lack of bandwidth.

8.0 Technical Analysis

The technological improvements in option 3 fall into the following categories:

1. Upgrade of existing medium and long-haul networks
2. Interactive broadband to the Home (upgrade of local network)

8.1 Medium and Long-Haul networks:

Existing medium and long-haul terrestrial communication networks almost universally use fiber optic technology. The limiting factors in the capacity of these fiber optic links are the electronics involved in modulating and demodulating the signals. Current technology limits links to approximately 2.4 Gbps of bandwidth for this reason. This is consistent with OC-48 in the Synchronous Optical Network (SONET) heirarchy. These links also require significant infrastructure in the form of repeaters to demodulate and retransmit the signal every 30-40 km for high bandwidths. While the reliability of these repeaters is in the range of 45500 hours MTBF (See Laser Diode Reliability calculation in Appendix F), they represent a significant cost in the operation and maintenance of a fiber-optic communication link. Maintenance cost calculations for a sample 2-way communication link are included in Appendix J. With the growth of interactive and broadband services, greater bandwidth must be made available.

8.2 Repeater Failure Characteristics

A repeater unit consists of receiver optics, a receiver, processing circuitry, a transmitter, and transmitting optics, along with a power supply and monitor/control circuitry. The individual component parts of a repeater are highly integrated using Very Large Scale Integrated Circuit (VLSI) technology. [MIL-HDBK-217F] states that discrete semiconductor devices and silicon integrated circuits have extrapolated failure rates on the order of a million hours, given a stable power source and reasonable levels of environmental temperature control (0-50 degrees Celsius). The main contributors to the failure of repeaters are the Laser Diode (LD) sources, failures in the power supply, and failures in the environmental controls of the electronics housing.

8.3 Laser Diode Source Reliability

From [Schumate 88, p.746] and [MIL-HDBK-217F], Laser Diode sources have failure rates on the order of 22,000 FITs (Failures In Time = 10^9 hours) corresponding to an MTBF of 45,500 hours. LD source failures are particularly sensitive to high temperature extremes, with particular attention required for the proper housing and environmental control of LD sources.

8.4 Power Supply Reliability

Typically, a remote repeater station is powered by electric power cables layed along with the fiber-optic cable or by Nickel-Cadmium (Nicad) batteries charged by a fixed solar panel array. Nicad battery lifetime is measured in charge cycles, with a value of 1000 charge/discharge cycles being typical. The actual charge/discharge of a nicad battery system is dependent on factors such as latitude and weather that are not controllable by the designer, therefore a 1-day cycle may not always correspond to a charge/discharge cycle for the battery pack. Failures when they occur are gradual [Kusko 89, p.190] and can be accurately predicted before actual occurance. For this reason, replenishment/replacement/monitoring of elements of the power supply set the upper limit in the frequency of repeater station periodic maintenance.

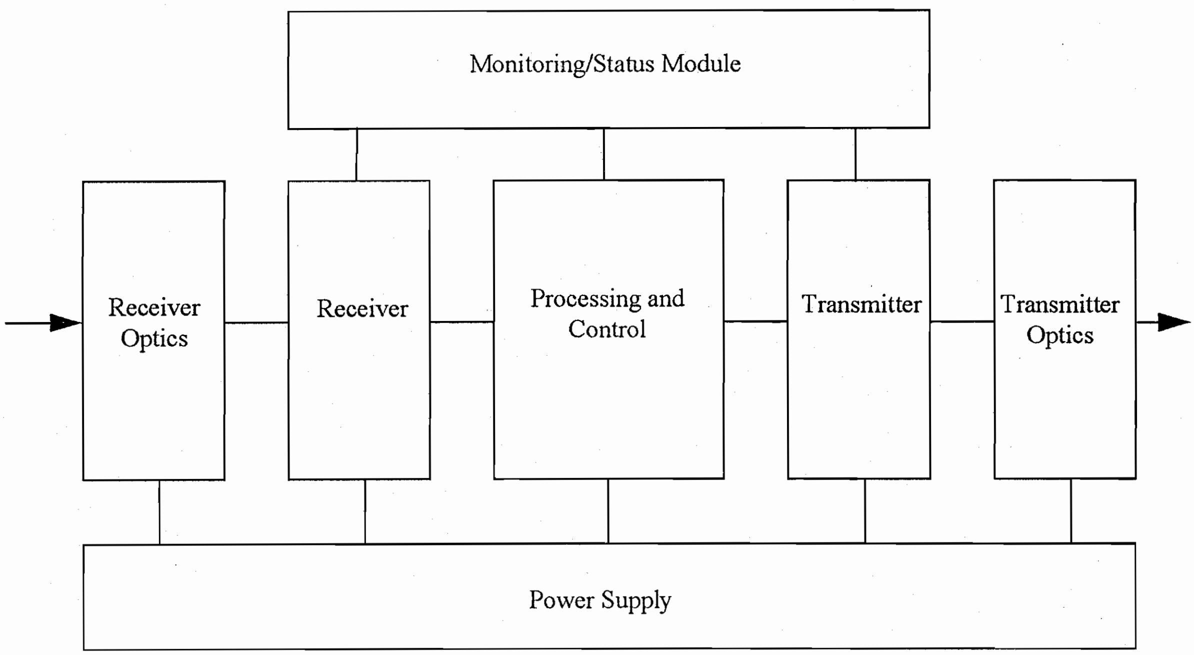


Figure 9. Repeater Block Diagram

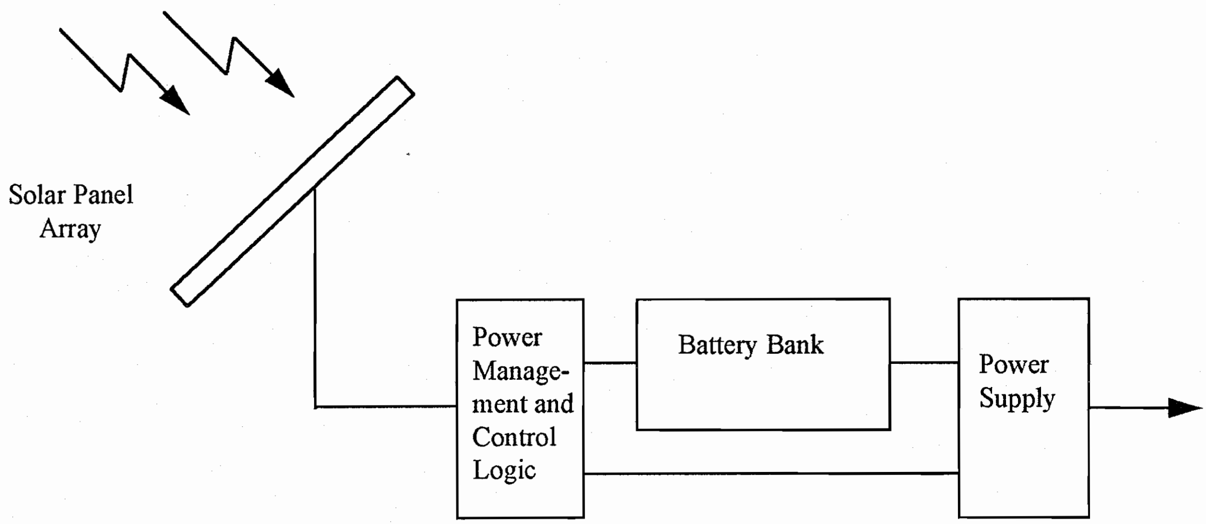


Figure 10. Power Supply Block Diagram

8.5 Reducing Repeater Requirements

Using current methods, a reduction in the number of repeaters would require a reduction in the bandwidth of the fiber-optic link. This is not a feasible option since more bandwidth is required to meet the demand of new services. The number of repeater stations may be significantly reduced without decreasing bandwidth through the use of technological advances using optical amplifiers. Optical amplifiers use physical properties of rare-earth elements doped into a section of fiber-optic cable to achieve broad band amplification. Utilizing a pump laser as a power source, optical amplifiers effectively increase the distance between repeater stations, or if other technical measures are taken like dispersion cancellation, completely eliminate the need for repeater stations [Shimada 94, p.87-95].

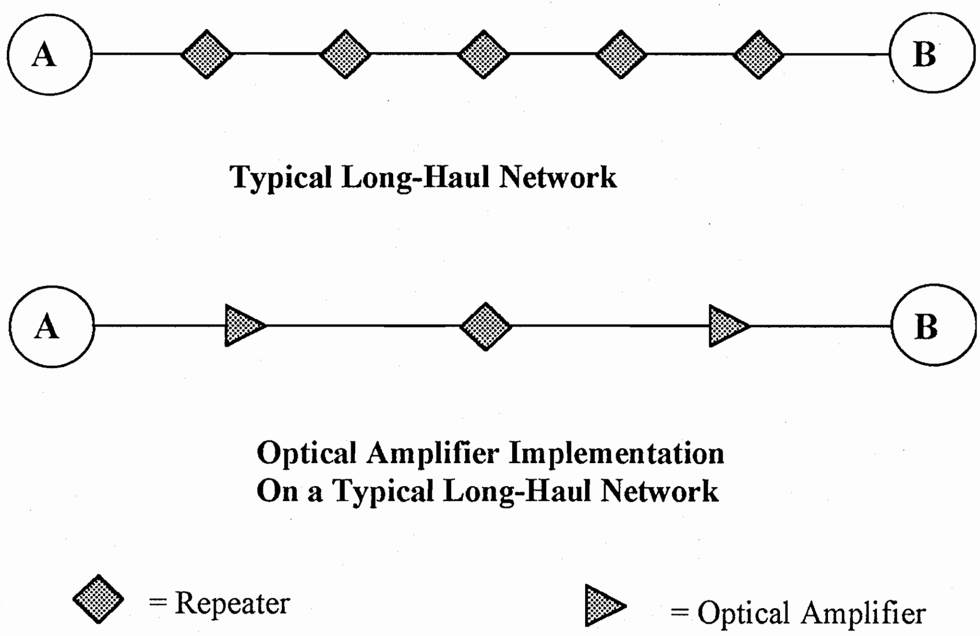


Figure 11. Typical Link Configurations

8.6 Increasing Available Bandwidth

Wave Division Multiplexing (WDM) is a useful method of achieving greater bandwidth. Using this method, multiple data streams are sent through the same existing fiber optic cable over different optical wavelengths. Each data stream behaves as if it has a dedicated fiber and is not affected by any of the other data streams. However, repeater stations must still be present at regular intervals, and there must be a dedicated repeater for each data stream. For communication links of any significant distance, the reliability and maintainability cost impacts due to the need for repeater stations is great. This point is illustrated in Appendix J.

9.0 Evaluation Criteria

9.1 Figures of Merit

Throughput Bandwidth per link and Life-Cycle Maintenance costs are the figures of merit used to compare the current and updated systems. Procurement and installation costs are equal in both systems and therefore not included in this analysis. Maintenance cost consists of the aggregate cost to maintain the transmitting equipment/facilities, the receiving equipment/facilities and all of the repeater equipment/facilities.

9.2 Design Variables

Bandwidth is the primary design variable for communication links. In practical design of fiber optic communication links Bandwidth-Distance product is the parameter used. This is generally a constant for a given transmitter source and fiber. The spacing of repeaters is dependent on the bandwidth of the signal so arbitrarily increasing bandwidth to satisfy demand is not an option unless repeaters are spaced more frequently. Maintenance costs are also a function of bandwidth. For a given link, maintenance and reliability penalties increase with the frequency of repeater stations. The design variable is Bandwidth, with design dependent parameters of Number of Repeaters and Recurring Maintenance Cost.

9.3 Bandwidth Distance Product

The bandwidth distance product is a fundamental concept used to design communication system through any medium. In radio frequency (e.g. satellite) links, if a signal can not propogate effectively across a fixed distance, then bandwidth must be adjusted until the signal is detectable above the noise threshold, yielding a fixed bandwidth-distance product for the link. This is also true of fiber optic links, hence the quantum limit for detection of light in a fiber at a given bandwidth is one of the parameters considered in link design. Optical fibers have additional properties that add additional limitations on the design of fiber optic communication links. There are three main components limiting the bandwidth-distance product in fiber optic links, Material Dispersion, Waveguide Dispersion, and attenuation.

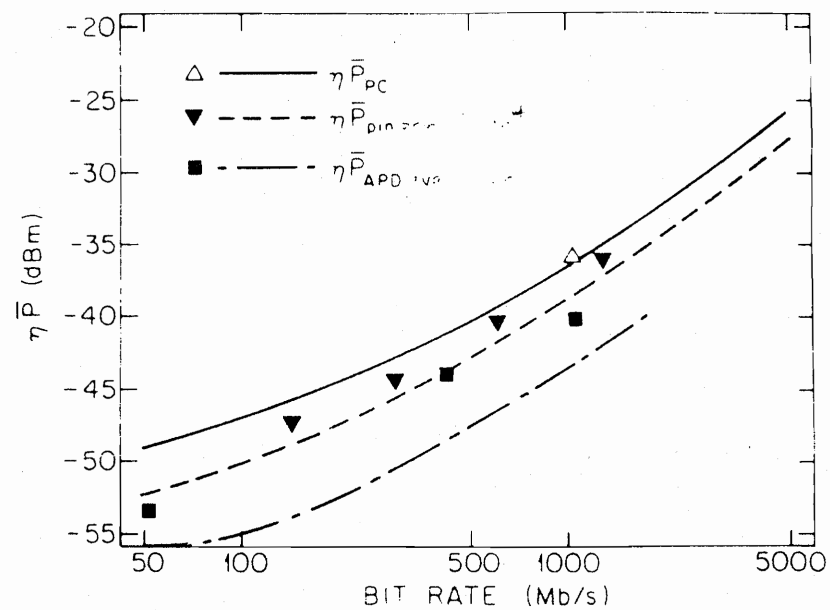


Figure 12. Detector-Bandwidth Graph

(From [Forrest 88, p589])

9.4 Material Dispersion

Material dispersion is generally a fixed value at a particular operating wavelength, and is caused by the dependence of core refractive index on transmitted wavelength. The value of material dispersion is usually positive for silica glass at most commonly used communication wavelengths, that is higher-frequency components of a transmitted light pulse travel slightly slower than the lower-frequency components. This limiting component of bandwidth-distance product is a function of the optical source spectral width. Laser Diodes (LD's) typically have very narrow spectral widths when compared with other optical sources like Light Emitting Diodes (LED's). A perfect LD would have an infinitely small spectral width. Real-world LD's are constructed with semiconductor materials that contain some levels of imperfection and are limited by the physical tolerances of the fabrication methods used in their manufacture. As a result they typically have a linewidth around 1 nm at communication wavelengths. For typical LD sources this can be significant contributing factor to limited bandwidth-distance product. Detailed Dispersion calculations are shown in Appendix B.

9.5 Waveguide Dispersion

Waveguide dispersion is dependent on the waveguide refractive index parameters and core dimensions. Waveguide dispersion is typically a negative value, that is, higher-frequency components of a light pulse travel slightly faster than lower-frequency components Waveguide dispersion can be modified with the particular design of the fiber. The combination of waveguide and material dispersion can offset each other. Around 1300nm, typical fiber-optic waveguides dispersion is near zero [Keiser 91 p.100].

Careful selection of fiber dimensions and index differences can shift the minimum dispersion point of optical waveguides, yielding dispersion shifted fibers that can be used to optimize the dispersion characteristics of a communication link [Keiser 91, p.114-125]. Example calculations are included in Appendix C.

9.6 Attenuation

Attenuation is dominated by absorption and scattering. Absorption is usually caused by the presence of water ions in the material. These ions have strong absorption peaks at several frequencies. Water ion absorption is responsible for the classification of communication "windows". At communication wavelengths less than 1000nm, attenuation is dominated by Rayleigh scattering [Keiser 91, p.91]. As such, the trend in optical communication has been toward longer wavelengths. Silica glass exhibits increasing attenuation in wavelengths greater than 1550 nm due to infrared absorption.

9.7 Example Application

To illustrate the application of these concepts, consider the following example communication link between New York and Los Angeles:

Path Length:	4000 km
Data Rate:	1000 voice channels (64000 bps x 1000 = 64 Mbps)
Fiber Type:	Single-Mode, 1300nm
Aggregate AttenuationLoss:	0.55 dB/km
Bandwidth-Distance Prod:	10 GHz-km
Modulation Scheme:	Digital Return-to-Zero, FSK

Detailed calculations are shown in Appendix A. The maximum repeater spacing for this scenario is 78 kilometers. Therefore to traverse the total path length, 52 repeater stations are required. Assuming an MTBF of 45,500 hours yields a failure every 875 hours, or one every five weeks. Since this calculation is only for a one-way path, including an outbound and an inbound path would yield a failure rate of half the one-way rate or 438 hours. Repeater redundancy must be incorporated to meet 0.9999 availability requirements, as detailed in Appendix J under "Repeater Maintenance Calculations", therefore the population of repeaters must be doubled again, yielding one repeater failure in the system every 219 hours. This figure is for one two-way communication link carrying the equivalent of 1000 voice channels only. When the number of data links is multiplied by the number of long-haul fiber optic communication links in operation today, The failure statistics alone require a great maintenance effort to be mounted. When the bandwidth requirements of current and future high-bandwidth services are considered it is clear that more long-haul optical links need to be established to meet the needs of these new services.

10.0 Maintenance Concept

10.1 Level of Maintenance

Maintenance tasks required for the system are performed to assure system availability is not compromised below the 99.99% level. Preventive maintenance tasks are performed to assure the integrity of the cable right-of-way in areas that may face encroaching development. Repeater facilities must be inspected and tested to assure proper environmental conditions are maintained and power supply degradations are discovered before any failures occur. Corrective maintenance tasks reflect the modular nature of repeater electronic components. New modules are removed and replaced when failures occur. At least one cable break is assumed over the 20 year lifetime of the system. The following levels of maintenance are required for the communication link. Repeater maintenance calculations are detailed in Appendix J :

Preventive Maintenance:

Action	Frequency	Time to accomplish
Inspect cable right-of-way	Annually	1 week
Remote Repeater Facility	Quarterly	2 hours

Corrective Maintenance:

Action	Frequency	Time to accomplish
Remove/Replace electronics module	219 hours	250 hours (maximum includes travel and waiting time)
Splice cable	80,000 hours	6 hours

10.2 Repair Policy

Corrective and Preventive maintenance of repeater stations will consist of removal and replacement of individual system modular components. Components that are removed will be discarded. No intermediate or depot level maintenance will be required.

11.0 Fiber Amplifiers

11.1 Description

Fiber optic amplifiers are sections of fiber-optic waveguide that have been doped with special elements, usually a rare-earth element like erbium, neodymium, or yttrbium. These sections of fiber-optic waveguide can be spliced into an existing communication fiber or incorporated into new fiber installations. When a fiber amplifier is excited by a pump-laser, it effectively amplifies signals passing through it that are within its flourescence spectrum.

11.2 Application

Currently, attention has been focused on erbium-doped fiber amplifiers because they are capable of amplifing signals at 1550 nm, the third window of silica glass fibers. The third window corresponds to the point of minimum attenuation for silica glass material, therefore it is of great interest in fiber-optic communication. [Digonnet 93, p.1]

New fiber installations can utilize dispersion-shifted fiber to yield a repeaterless system that has both minimum dispersion and minimum attenuation at the third window. A link incorporating this design could greatly increase its data carrying capacity because fiber attenuation is effectively eliminated from the capacity equation. A repeaterless fiber-optic link is of particular interest where very high-reliability is an important link characteristic, as in undersea cables, where repair of the cable is very difficult and expensive [Runge 88, p.881]. Existing installations can utilize WDM and dispersion cancellation devices to increase the data density on the fiber.

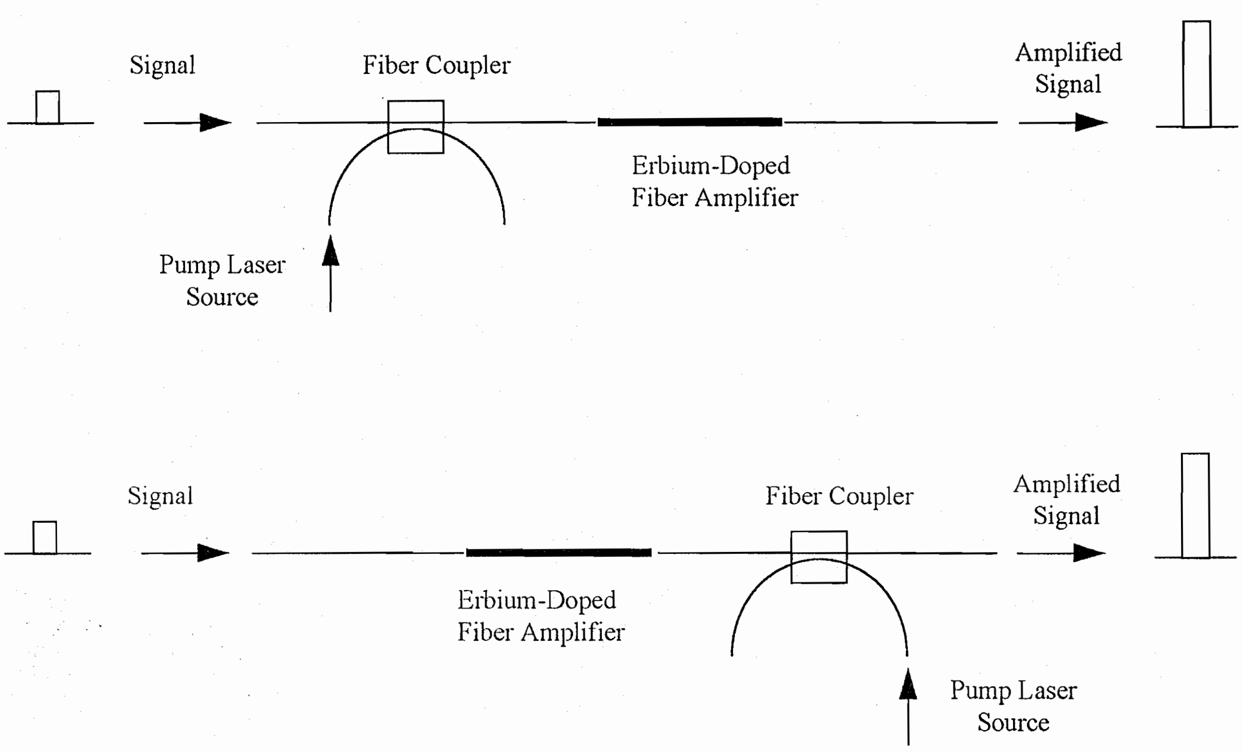


Figure 13. Fiber Amplifier Example Configurations

The previous illustrations show an interesting characteristic of fiber amplifiers. The location of the pump laser can be either on the source or the destination side of the link. Fiber amplifiers are bidirectional devices so the link designer has flexibility in placing the pump source.

11.3 Fiber Amplifiers and WDM

Fiber amplifiers inherently make the application of Wave Division Multiplexing (WDM) on a single fiber much easier to implement. Implementing WDM on current generation fiber optic communication links requires that a repeater be located periodically for each individual communication wavelength [Shimada 94, p.264]. For instance, if a 10 frequency WDM scheme were implemented on the example link between New York and Los Angeles, it would have capacity for 10,000 simultaneous voice channels without having to lay new fiber. However, the 208 repeater units required for this bandwidth and 0.9999 availability would blossom to 2080 repeater units. The failure rates would also increase by a factor of 10 and costs would equally rise.

Using fiber amplifier technology, a single fiber amplifier can be configured to simultaneously amplify all 10 individual wavelengths. This allows WDM to be used across links using cascaded fiber optic amplifiers without the addition of any hardware and therefore without increasing the failure rate of the system.

11.4 Design Considerations of Fiber Amplifiers

With the replacement of regenerative repeaters with amplifiers in cascade in long-haul links, noise becomes a more significant consideration. Noise causes bit-errors in digital systems whereby a 1 is recognized as a 0 and vice-versa. Fiber amplifiers generally have excellent noise characteristics. Signal-to-noise ratio (SNR) levels of 13 dB will generally give good bit-error rates (BER) in the vicinity of 1 error per billion bits transmitted. SNR can be given by the following equation from [Henry 88, p.821]

$$SNR := \frac{P_t \cdot 10^{-\frac{A \cdot L}{10}}}{\left(\frac{L_{tot}}{L}\right) \cdot K \cdot h \cdot v \cdot B}$$

Where the critical parameters are A - attenuation, L - Length between cascaded amplifiers, L_{tot} - total link length, B - data stream bandwidth, Pt - power coupled into the fiber. Calculations for expected SNR are shown in Appendix I. Using parameters of the hypothetical New York-Los Angeles link at 10 times the original bandwidth, SNR is excellent, leading to an acceptable BER.

For the upgrade of an existing optical fiber communication link, the components required to replace a repeater station are the fiber amplifier, pump laser source, a coupler, and a dispersion compensation module. The components could be configured as illustrated in figure 14.

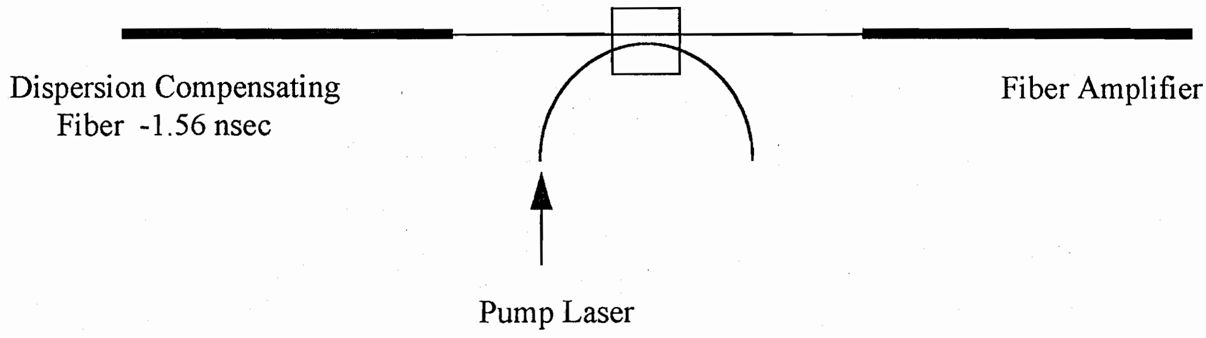


Figure 14. Fiber Amplifier Example Application

11.5 Reliability Considerations

All components with the exception of the pump laser are fiber devices that have high inherent reliability, resulting in MTBF characteristics in the hundreds of thousands of hours or greater of system operation. The pump lasers are different in application than communication lasers. They are continuous wave (CW) lasers that are available with high power output and efficiency with greater reliability than communication lasers. Additionally, redundancy can be employed with pump lasers to further increase overall reliability. Expected reliability of these pump lasers is on the order of 100,000 hours MTBF [Shimada 1994, p.215]. MIL-STD-217F calculations are detailed in Appendix G.

11.6 Additional Characteristics

Fiber amplifiers offer distinct advantages of cost and reliability for new and existing communication links as previously detailed. They also offer distinct advantages for upgradability. Current fiber optic links are locked into a particular protocol, data rate, and throughput once they are designed and installed, unless all terminal equipment and repeaters are replaced to reflect any changes in desired network characteristics. In the case of undersea links, There is no way to upgrade the link, even though technological developments may warrant it because the link is inaccessible once installed. In the case of links implementing fiber-optic amplifiers, the upgrade of the communication link characteristics is simply a matter of replacing the terminal equipment provided broad parameters of the the amplifier are not exceeded [Senior 92, p.514]. This characteristic from a cost perspective is difficult to quantify, but assuming that over the 20-year lifetime of the example link, an update in the character of the link behavior is warranted every five years, the cost of the update will necessitate the purchase and installation of equipment for each node. Cost calculations for updates are shown in Appendix J.

11.7 Fiber Amplifier Prototype Links

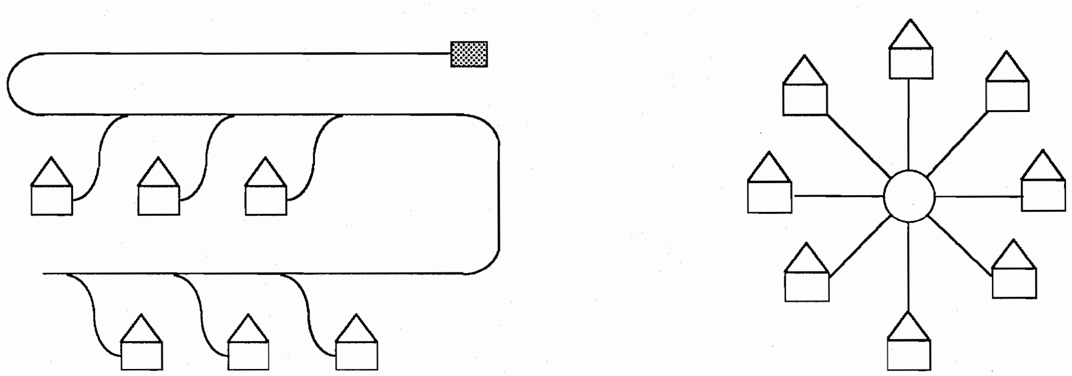
The feasibility of fiber amplifiers has been demonstrated with prototype links. One such experiment [Chraplyvy 94] demonstrated the use of 16 WDM channels, each operating at 2.5 Gb/s over a 1420 km fiber link with erbium-doped fiber amplifiers. This achievement represented a combined throughput of 40 Gbps over the link distance. Recreating this throughput with current technology would require the installation of 568 repeater units. Another demonstration by [Park 95] demonstrated the use of erbium-doped fiber amplifiers in the 1550 nm window over 1300nm optimized fiber. This experiment utilized 2 WDM channels and Dispersion Compensating Fiber (DCF) modules to achieve a 20 Gbps transmission link over 360 km. This field experiment demonstrated the feasibility of the configuration proposed in this report.

12.0 Local Loop

While the long-haul networks are important to achieving overall network bandwidth, providing bandwidth increases to the consumer is the key to the success of the high bandwidth services. To date there is no infrastructure in place on a wide scale to provide these services. This is mostly due to regulatory uncertainties. At this time cable television companies cannot provide phone service and telephone companies cannot provide cable television services to the consumer. Regulatory reform of telecommunication is required before any significant progress will be made providing the conduit for high-bandwidth services, fiber-optics to the home.

12.1 Local Networks:

Most communication services provided to consumers alway traverse a fiber-optic communication link at some point before delivery. Extension of telephone and cable fiber-optic feeders into a fiber-optic distribution network is therefore a logical step to providing broadband services to the consumer. Cable television and telephone companies are the most likely entities that will provide the consumer with broadband services in the future [Reed 92, p.20]. Currently, they serve the consumer using two different communication network topologies, the bus and the star respectively.



Bus Network Topology

(Cable Television)

Star Network Topology

(Telephone Network)

Figure 15. Example Network Topologies

The topology used is dependent on the type of service being provided, the cost constraints and the protocol used to provide communication.

12.2 Bus Networks

The bus topology is particularly suited to providing broadband broadcast services to consumers inexpensively. Today, cable television companies provide services to many customers using this topology for distribution of broadcast programming to the consumer. Unfortunately, it can be a relatively poor performer interactively, because many users must share the bandwidth to provide the cost advantages over other topologies.

12.3 Star Networks

The star topology is particularly suited to providing fixed, switched bandwidth to multiple points. The telephone company needs to provide fixed bandwidth to many locations and needs to interconnect the locations at the whim of the customer. The star network is well suited to this requirement but is dependent on a complex and expensive switch at the hub of the star.

12.4 Fiber-Optics to the Home (FTTH)

When fiber-optics reaches the consumer directly, it will likely be in the form of a bus network, a star network or some hybrid of the two. Most of the bandwidth will be used for video services. The extent to which these video services will be interactive is a subject of industry debate. If video services are provided in the future that will be similar in nature to today's video services, then a bus topology is favored. However, if video-on-demand and other interactive services are provided, then the network will favor the switched star topology. Industry seems to favor the switched interactive services whereby the consumer can be charged for each service transaction, while inertia favors the current broadcast medium scenario [Reed 92 p.23-50].

12.5 Cost Considerations

Reliability of today services is generally good, owing to the superior operating characteristics of electronic devices. These electronic devices, as in long-haul fiber optic links, are the primary bandwidth limiter and maintenance cost item. Fiber Amplifiers again offer promise of eliminating the requirement for electronic hardware. In the bus topology, each tap on the bus reduces the amount of signal by some fraction that after cumulative effects of many taps and attenuation, requires amplification. The fiber-optic bus network with optical amplifiers offers cost advantages that current cable TV providers are faced with using RF technology distribution systems [Reed 92 p.28]. An analysis of current bus vs. star networks is located in Appendix P.

12.6 A Likely Scenario

Until regulatory confusion is resolved for telecommunication industry players, broadband services will not reach the consumer widely. This is because the cost of installing and maintaining a fiber network to the home justifies the providing of services to the consumer over an integrated broadband network. [Reed 92, p.116] estimates that the costs of providing broadband services to the home are from $920 - $2948 per subscriber in 1992, depending on architecture and approach. At these cost levels, it is unlikely that competing providers like cable TV and the telephone company would be able to profitably install separate, competing fiber-optic networks directly to the home. Clearly, some regulatory compromise that allows for the integration of broadband services onto a single fiber to the home would greatly aid the development of broadband services. These technical developments for increasing bandwidth will likely be implemented (and have already been implemented, in some cases) on long-haul and undersea links first where they will replace and/or update current infrastructure, and the regulatory environment is considerably clearer.

13.0 Conclusion

It has been shown that it is possible to implement technical measures that allow an increase in bandwidth on existing and new long-haul fiber-optic communication links with positive cost impact. Using the sample link cost assumptions, a $3.7 million maintenance/upgrade cost savings is shown (Appendix K) by implementing optical amplifiers instead of using the current system. System reliability is increased to 0.999999 from 0.999975 by using optical amplifier technology. Actual implementation of this technology depends upon several factors: (1) the regulatory environment, (2) the actual demand for broadband services, and (3) the cost of the services and the network. At some point, a portion of or all of the broadband services described in this research project report will be offered to the consumer. The success of these services depends directly on the ability of the telecommunication infrastructure to expand in terms of bandwidth to meet the expanding need as well as the cost of providing these services. Developments in the area of optical amplifiers will certainly be part of expanding the infrastructure bandwidth, and will likely be implemented in many long-haul links because of the positive impact they have on the complexity and cost of fiber-optic communication links.

14.0 Future Considerations

There are other technologies which may be applied to varying degrees to influence the impact of increasing bandwidth requirements. Compression technology uses detected data redundancy to send amounts of data that otherwise exceed the bandwidth capacity of a communication link. Video, for instance, usually contains a large amount of redundancy and can generally utilize compression with great success in most cases, yielding a 10 to 1 compression ratio or greater by using specialized hardware and algorithms. ATM, or Asynchronous Transfer Mode, is a protocol that facilitates the aggregation of data onto high-capacity fiber-optic links, as well as the routing of data from source to destination in a logical fashion. ATM is already being implemented on a large scale within organizations and telecommunication providers. ATM will certainly have an impact in terms of providing broadband services to consumers, once the broadband pathways are made available at the consumer level. The consideration of these and other technical developments are essential to increasing the useful life of current and future generation fiber-optic communication links. The approach used here can have general application to the upgrade of systems involving legacy infrastructure.

15.0 References

[Blanchard 90] Benjamin S. Blanchard, Wolter J. Fabrycky, "Systems Engineering and Analysis", 2nd ed. Prentice Hall, 1990.

[Chraplyvy 94] Chraplyvy et al., "1420km Transmission of Sixteen 2.5-Gb/s Channels Using Silica-Fiber-Based EDFA Repeaters", IEEE Photonics Technology Letters, Vol 6, No. 11, November 1994.

[Digonnet 93] Michel Digonnet, "Rare-Earth Doped Fiber Lasers and Amplifiers", Marcel Dekker, Inc, 1993.

[Forrest 88] S.R. Forrest, "Optical Detectors for Lightwave Communication - Optical Fiber Telecommunications II", Bell Communications Research, 1988.

[Henry 88] P.S. Henry, R.A. Linke and A.H. Gnauck, "Introduction to Lightwave Systems, Optical Telecommunications II", Bell Communications Research,1988.

[Netgen 95] World Wide Web Site: "http://www.netgen.com/info/growth.html"

[Kusko 89] A. Kusko, "Emergency/Standby Power Systems", McGraw-Hill, 1989.

[Keiser 91] Gerd Keiser, "Optical Fiber Communications", 2nd ed. McGraw-Hill, 1991

[MIL-HDBK-217F] Military Handbook 217F "Reliability Prediction of Electronic Equipment", Department of Defense 2 December 1991.

[O'Neill 82] E.F.O'Neill (ed.) "Engineering and Science of the Bell System", ATT Bell Labs, 1982.

[Park 95] Park, et al. "A Field Demonstration of 20-Gb/s Capacity Transmission over 360 km of Installed Standard (Non-DSF) Fiber", IEEE Photonics Technology Letters, Vol 7. No. 7, July 1995.

[Reed 92] David P. Reed, "Residential Fiber-Optic Networks", Artech House, 1992.

[Runge 88] P.K.Runge and N.S. Bergano, "Undersea Cable Transmission Systems - Optical FiberTelecommunications II", Bell Communications Research, 1988.

[Senior 92] John M. Senior, "Optical Fiber Communications - Principles and Practice", 2nd ed. Prentice-Hall, 1992.

[Schumate 88] P.W. Schumate, "Lightwave Transmitters - Optical Fiber Telecommunications II", Bell Communications Research, 1988.

[Shimada 94] S. Shimada and H. Ishio, "Optical Amplifiers and their Applications", John Wiley & Sons, 1994]

Appendix A

Typical Fiber-Optic Communications Link Calculations

Given the following Parameters:

Path Length:	4000 km
Data Rate:	1000 voice channels (64000 bps x 1000 = 64 Mbps)
Fiber Type:	Single-Mode, 1300nm
Aggregate Loss:	0.55 dB/km
Bandwidth-Distance Prod:	10 GHz-km
Modulation Scheme:	RZ FSK

$\mathrm{Path} := 4000 \cdot \mathrm{km}$

$\mathrm{DataRate} := 64 \cdot \mathrm{MHz} \cdot 2$ Using RZ coding doubles the required bandwidth

$\mathrm{Loss} := 0.55 \cdot \frac{\mathrm{dB}}{\mathrm{km}}$ Including Fiber loss, Splices, and coupler losses

$\mathrm{BW}_{\mathrm{prod}} := 10 \cdot \mathrm{GHz} \cdot \mathrm{km}$ Typical Long-haul BW-Distance Product [Senior, 92] page 184 Result of Source Spectral Width and Fiber Parameters

$P_o := 10 \cdot 10^{-3} \cdot \mathrm{watt}$ Laser Diode Power Output

$P_r := 5 \cdot 10^{-7} \cdot \mathrm{watt}$ Receiver Intensity Requirement for PIN (Typical at 128Mbps) [S.R.Forrest, Optical Detectors for Lightwave Communication *Optical Fiber Telecommunications II,* p 589]

$L := \frac{10 \cdot \mathrm{dB}}{\mathrm{Loss}} \cdot \log\left(\frac{P_o}{P_r}\right)$ $L = 78.201 \cdot \mathrm{km}$ Detector Quantum Maximum

$\frac{\mathrm{BW}_{\mathrm{prod}}}{\mathrm{DataRate}} = 78.125 \cdot \mathrm{km}$ Bandwidth-Length Product Limited Spacing

Therefore for 1300nm Links, Attenuation is the main limiting factor in repeater spacing

Typical Fiber-Optic Communications Link Calculations (Cont'd)

Using the typical Bandwidth-Distance Product and the detector quantum limits, the repeater spacing is the lower of the bandwidth product-data rate ratio and the quantum maximum.

$$\text{Repeater\_Spacing} := \text{if}\left(\frac{BW_{prod}}{\text{DataRate}} < L, \frac{BW_{prod}}{\text{DataRate}}, L\right) \qquad dB \equiv 1$$

$$\text{Repeater\_Spacing} = 78.125 \cdot km$$

The one-way number of required repeaters is:

$$\frac{\text{Path}}{\text{Repeater\_Spacing}} = 51.2$$ Rounding up required

Appendix B

Example Dispersion Calculations

From [D. Gloge, "Weakly Guiding Fibers", *Applied Optics*, vol 10, pp 2252-2258, Oct. 1971] , the following relationships are defined

The parameter b, or normalized propogation constant is defined for the fundamental mode, LP01:

β	- Propogation Constant	λ	- Wavelength
n_1	- Core Index of Refraction	n_2	- Cladding Index of Refraction
V	- V-parameter	Δ	- Index Delta

$$b_{LP01}(\beta,\lambda,n_1,n_2) := \frac{\dfrac{\beta}{\left(\dfrac{2\cdot\pi}{\lambda}\right)} - n_2}{n_1 - n_2}$$

$$u_{LP01}(V) := \frac{\left(1+\sqrt{2}\right)\cdot V}{1+\left(4+V^4\right)^{\frac{1}{4}}}$$

Mode Propogation constant, β, of the fundamental mode is defined as:

$$\beta_{LP01}(V,\Delta,n_2,\lambda) := n_2\cdot\frac{2\cdot\pi}{\lambda}\cdot\left[1+\Delta-\Delta\cdot\left[\frac{\left(u_{LP01}(V)\right)^2}{V^2}\right]\right]$$

$c := 3\cdot 10^{8}\cdot\dfrac{m}{sec}$

$ps \equiv 10^{-12}\cdot sec$

$nm \equiv 10^{-9}\cdot m$

$\mu m \equiv 10^{-6}\cdot m$

Example Dispersion Calculations (Cont'd)

The following parameters are given, n2 is set by the intrinsic index of refraction of silica fiber at the given wavelength. The wavelength is selected to be compatible with existing fiber optic amplifiers, and the minimum attenuation point of silica optical fibers. V-number is selected to yield a single-mode fiber (V < 2.405)

Given the following parameters, design a circular core, step index weakly guiding fiber to obtain zero dispersion (i.e. 20 ps/nm/km waveguide dispersion)

$V := 2.2 \qquad \lambda := 1550 \cdot nm \qquad n_2 := 1.45 \qquad D_{want} := 20 \cdot \frac{ps}{nm \cdot km}$

Lookup on plot below: $\quad dVb2 := .188$

Waveguide dispersion is given by: $\quad D_{wg} := \frac{-n_2 \cdot \Delta}{c \cdot \lambda} \cdot V \cdot dVb2$

$$n_1 := \frac{n_2^{\,2} \cdot V \cdot dVb2}{-D_{want} \cdot c \cdot \lambda + n_2 \cdot V \cdot dVb2} \qquad n_1 = 1.473$$

$$\Delta := -\frac{n_2}{n_1} + 1 \qquad \Delta = 0.016$$

Solving for core radius, a: $\quad a := \frac{V \cdot \lambda}{2 \cdot \pi \cdot \left(\sqrt{n_1^{\,2} - n_2^{\,2}} \right)} \qquad a = 2.101 \cdot \mu m$

Verifying V-number: $\quad V := \frac{2 \cdot \pi \cdot a}{\lambda} \cdot \sqrt{n_1^{\,2} - n_2^{\,2}} \qquad V = 2.2$

Verifying waveguide Dispersion: $\quad D_{wg} := \frac{-n_2 \cdot \Delta}{c \cdot \lambda} \cdot V \cdot dVb2 \qquad D_{wg} = -20 \cdot \frac{ps}{nm \cdot km}$

Example Dispersion Calculations (Cont'd)

Summary of the fiber parameters for 20 ps/(nm-km) waveguide Dispersion:

$\lambda = 1550 \cdot \text{nm}$ $\quad n_1 = 1.473$ $\quad n_2 = 1.45$ $\quad \Delta = 0.01551$

$V = 2.2$ $\quad a = 2.10052 \cdot \mu\text{m}$

low := .01 step := .05

V := low, low + step .. 3

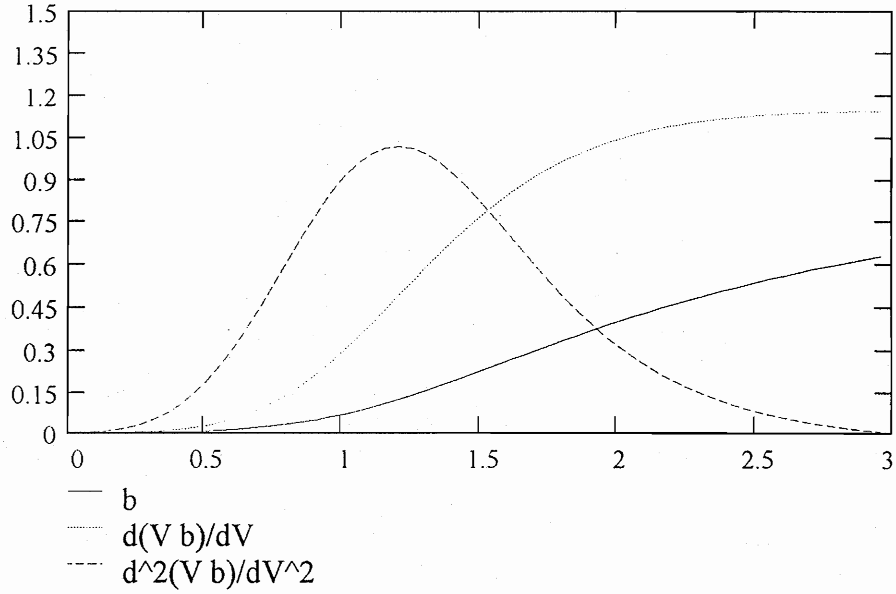


Figure A1. Normalized Propogation plots

$V := 2.2$

$b_{LP01}\left(\beta_{LP01}\left(V, \Delta, n_2, \lambda\right), \lambda, n_1, n_2\right) = 0.454$

$b_{LP01}\left(\beta_{LP01}\left(V, \Delta, n_2, \lambda\right), \lambda, n_1, n_2\right) \cdot V = 0.999$

$\frac{d}{dV}\left(V \cdot b_{LP01}\left(\beta_{LP01}\left(V, \Delta, n_2, \lambda\right), \lambda, n_1, n_2\right)\right) = 1.085$

$\frac{d^2}{dV^2}\left(V \cdot b_{LP01}\left(\beta_{LP01}\left(V, \Delta, n_2, \lambda\right), \lambda, n_1, n_2\right)\right) = 0.188$

Appendix C

Dispersion Shifted Fiber

Previous calculations yielded a Dispersion Shifted Fiber with the following parameters:

$a = 2.101 \cdot \mu m$ $\quad n_1 = 1.473$ $\quad n_2 = 1.45$ $\quad \Delta = 0.016$

$V = 2.2$

$$V_1(\lambda) := \frac{2\cdot\pi\cdot a}{\lambda}\cdot\sqrt{n_1^{\,2} - n_2^{\,2}}$$

$$D_{wg}(\lambda) := \frac{-n_2\cdot\Delta}{c\cdot\lambda}\cdot\left[\frac{d}{dV}\left(V\cdot b_{LP01}\left(\beta_{LP01}\left(V_1(\lambda),\Delta,n_2,\lambda\right),\lambda,n_1,n_2\right)\right)\right]$$

$\lambda := 800, 850 .. 2000$

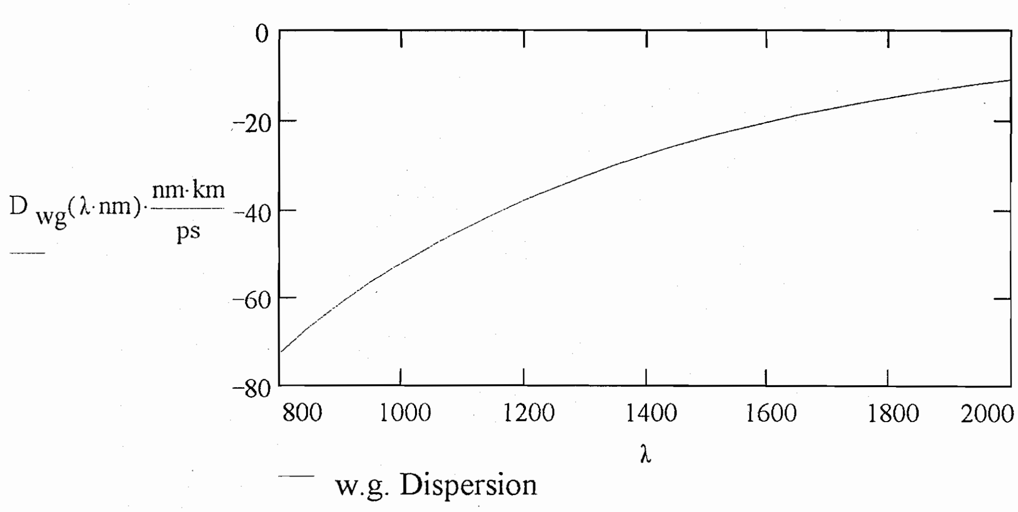


Figure A2. Waveguide Dispersion Vs Wavelength

Appendix D

Wavelength Dependence of Silica Glasses

This model for index of refraction is based on [S. Geckler 87, "Optical Fiber Transmission Systems, p. 67]

Sellmeier parameters of Germanium-Doped Silica Fiber:

$$a := \begin{pmatrix} .7136824 \\ .4254807 \\ .8964226 \end{pmatrix} \qquad b := \begin{pmatrix} .003808952 \\ .01614969 \\ 97.93401 \end{pmatrix} \qquad \mu m := 10^{-6} \cdot m$$

$$n_{1f}(\lambda) := \sqrt{1 + \sum_{i=0}^{2} \frac{a_i \cdot \lambda^2}{\lambda^2 - b_i \cdot \mu m^2}}$$

$\lambda := 200..4000$

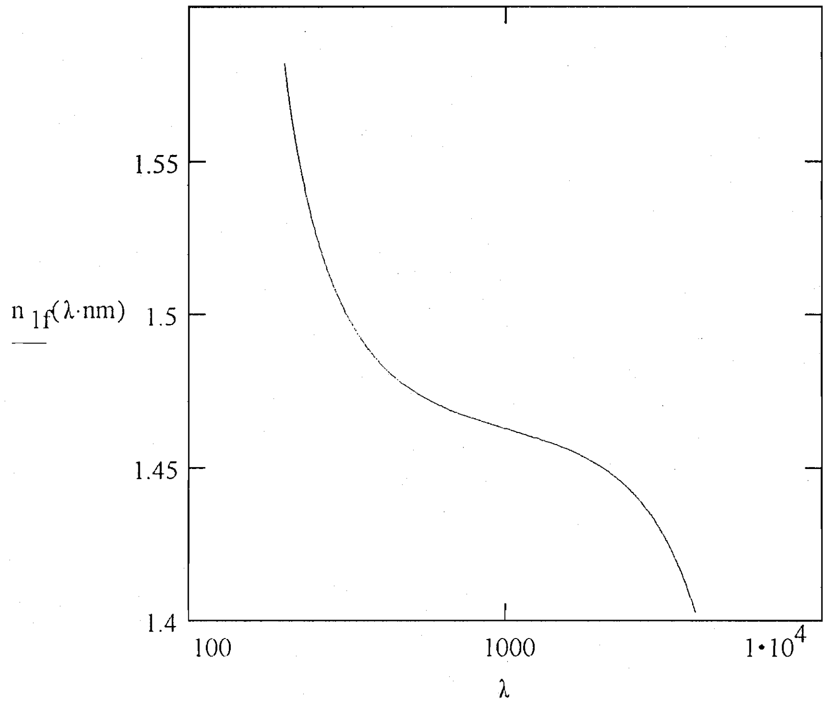


Figure A3. Index of Refraction as a function of Wavelength

Appendix E

Fiber Optic Link
Group Delay Model

These calculations are based on a typical Laser Diode source linewidth of 1 nm for a 1300 nm communications link, which is typical for Fabry-Perot (FP) or Distributed Feedback (DFB) Lasers in use in many fiber optic links. [Bowers, 1988, Semiconductor Lasers for Telecommunications , *Optical Fiber Telecommunications II* p 539. These equations are from [Keiser, 1991, Optical Fiber Communications p 100.

$$nm \equiv 10^{-9} \cdot m$$

$$ps \equiv 10^{-12} \cdot sec$$

$\Delta\lambda := 1 \cdot nm$ — Spectral Line Width (typical)

$\lambda := 1550 \cdot nm$ — Center Wavelength

$n_1(\lambda) := 1.45 - \frac{.005 \cdot (\lambda - 1000 \cdot nm)}{500 \cdot nm}$ — Core Index of Refraction Modeled after Figure 3-12 in [Keiser,91] pg 102.

$c := 3 \cdot 10^8 \cdot \frac{m}{sec}$ — Speed of Light

$L := 78 \cdot km$ — Typical Link Length

$\beta(diff, \lambda) := \frac{2 \cdot \pi}{\lambda} \cdot n_{1f}(\lambda)$ — Delta beta for a 1-nm wavelenth difference

$\tau_g(\lambda) := -\left(\frac{\lambda^2}{2 \cdot \pi \cdot c} \cdot \frac{d}{d\lambda} \beta(\Delta\lambda, \lambda) \cdot km\right)$ — Group delay

$$\tau_g(\lambda) = 4.916 \cdot 10^{-6} \cdot sec$$

Fiber Optic Link
Group Delay Model
(Cont'd)

$$\delta\tau := \left(\frac{d}{d\lambda}\tau_g(\lambda)\right)\cdot\Delta\lambda\cdot\frac{1}{\mathrm{km}} \qquad \delta\tau = 20.077\cdot\frac{\mathrm{ps}}{\mathrm{km}}$$

Assuming that 1/5 pulse overlap will cause excessive Bit Error Rate, then the implied bandwidith-distance product limitation would be:

$$\frac{1}{5}\cdot\frac{1}{\delta\tau} = 9.961\cdot\mathrm{GHz}\cdot\mathrm{km}$$

For the Link length, L, the upper limit on bandwidth would be:

$$\frac{1}{L}\cdot\left(\frac{1}{5}\cdot\frac{1}{\delta\tau}\right) = 0.128\cdot\mathrm{GHz}$$

Dispersion is designated:

$$D := \left(\frac{d}{d\lambda}\tau_g(\lambda)\right)\cdot\frac{1}{\mathrm{km}} \qquad D = 20.077\cdot\frac{\mathrm{ps}}{\mathrm{nm}\cdot\mathrm{km}}$$

$\lambda := 900 \cdot nm, 950 \cdot nm .. 1700 \cdot nm$

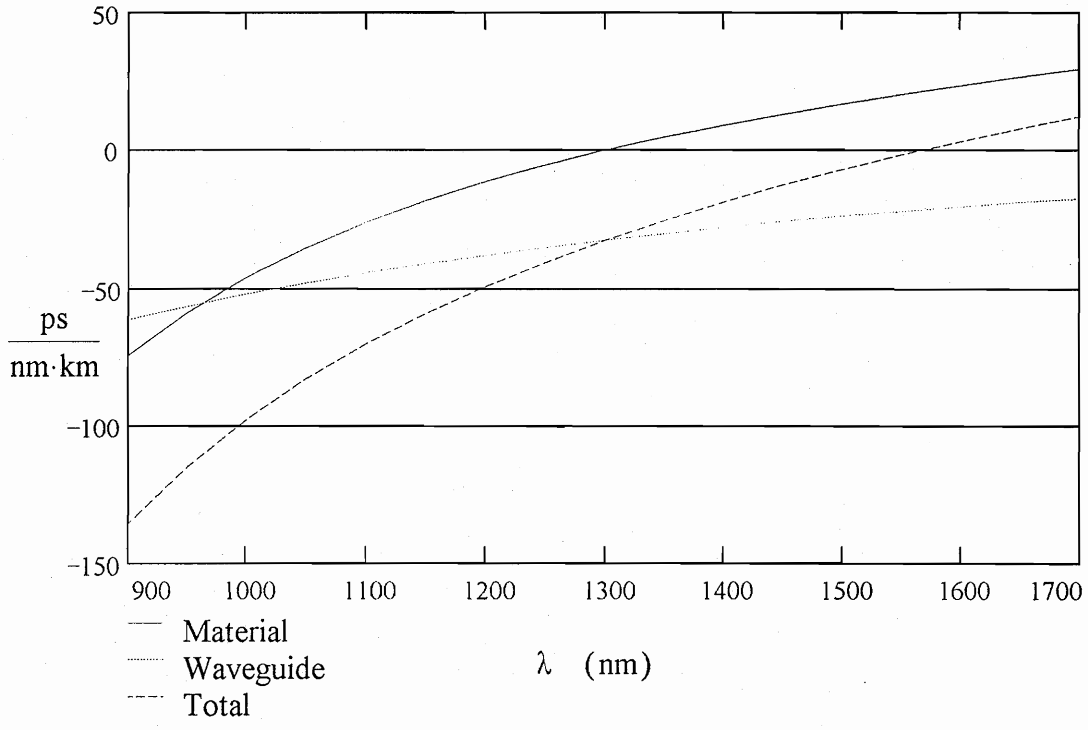


Figure A4. Material, Waveguide, and Total Dispersion Plot Using Dispersion Shifted Fiber

Appendix F

The Effect of Source Spectral-Width on Bandwidth-Distance Product

$\lambda := 1310 \cdot \mathrm{nm}$

$$\mathrm{SRC}(\Delta\lambda, \lambda) := \left| \frac{1}{\mathrm{km}} \cdot \frac{1}{5} \cdot \frac{1}{\left(\frac{d}{d\lambda}\tau_g(\lambda)\right) \cdot \Delta\lambda \cdot \frac{1}{\mathrm{km}}} \right| \cdot \frac{1}{\mathrm{GHz}}$$

$\lambda := 1275, 1276 .. 1325$

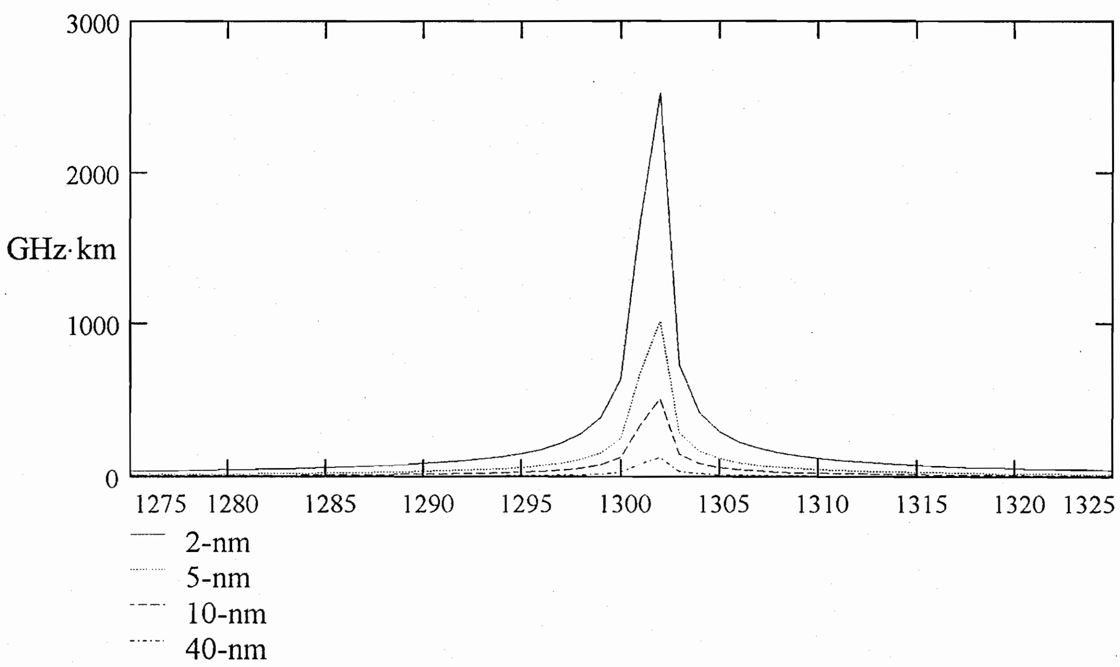


Figure A5. Effect of Source Width on Distance-Bandwidth Product
(centered at 1300nm)

Appendix G

Laser Diode Reliability
from MIL-HDBK-217F
Pump Laser Calculations

The following calculations follow the procedure of MIL-HDBK-217F for optoelectronic components found on page 6-21, values selected are typical.

Laser Diode Type:

InGaAsP (1.0-1.7μm) [Senior 92, p. 315]

$\lambda_b := 5.65$ Failures per Million hours (base)

Temperature Factor

$\pi_T := 1.0$ @ 25 C Junction temperature

Quality Factor

$\pi_Q := 1.0$ Hermetic Package

Forward Current Factor $I := .5$

$\pi_I := I^{.68}$ $\pi_I = 0.624$

Application Factor

$\pi_A := 4.4$ CW

Power Degradation Factor

$\pi_P := .71$ Required / Rated ratio of 0.3

Environment Factor

$\pi_E := 1.0$ GB, 35 C case temperature

Laser Diode Reliability
from MIL-HDBK-217F
Pump Laser Calculations
(Con'd)

$$\lambda_p := \lambda_b \cdot \pi_T \cdot \pi_Q \cdot \pi_I \cdot \pi_A \cdot \pi_P \cdot \pi_E$$

$\lambda_p = 11.017$ Failures per Million hours

$$\frac{10^6 \cdot hrs}{\lambda_p} = 90769.71 \cdot hrs$$

For Laser Diodes with Optical Flux Densities < 3MW/cm^2, and forward Current < 25 amps
Note: For the pump laser, Optical fluxes exceed the limits of this model.

$r := 2.5 \cdot \mu m$ Radius of Single Mode Fiber core

$P_{out} := 1000 \cdot mw$ $Area := \pi \cdot r^2$

$Flux := \dfrac{P_{out}}{Area}$ $Flux = 5.093 \cdot \dfrac{Mw}{cm^2}$

$Mw \equiv 10^6 \cdot watt$

$\mu m \equiv 10^{-6} \cdot m$

$cm \equiv 10^{-2} \cdot m$

$mw \equiv 10^{-3} \cdot watt$

$hrs \equiv 3600 \cdot sec$

Appendix H

Laser Diode Reliability
from MIL-HDBK-217F
Source Calculations

The following calculations follow the procedure of MIL-HDBK-217F for optoelectronic components found on page 6-21, values selected are typical.

Laser Diode Type:

InGaAsP (1.0-1.7μm) [Senior 92, p. 315]

$\lambda_b := 5.65$ Failures per Million hours (base)

Temperature Factor

$\pi_T := 6.3$ @ 65 C Junction temperature

Quality Factor

$\pi_Q := 1.0$ Hermetic Package

Forward Current Factor $I := .5$

$\pi_I := I^{.68}$ $\pi_I = 0.624$

Application Factor

$\pi_A := 1.0$ Pulsed Application, 100% duty cycle

Power Degradation Factor

$\pi_P := 1.0$ Required / Rated ratio of 0.5 giving 3-dB margin

Environment Factor

$\pi_E := 1.0$ GB, 35 C case temperature

Laser Diode Reliability
from MIL-HDBK-217F
(Con't)

$\lambda_p := \lambda_b \cdot \pi_T \cdot \pi_Q \cdot \pi_I \cdot \pi_A \cdot \pi_P \cdot \pi_E$ $\lambda_p = 22.217$ Failures per Million hours

$$\frac{10^6 \cdot hrs}{\lambda_p} = 45010.25 \cdot hrs$$

For Laser Diodes with Optical Flux Densities < 3MW/cm^2, and forward Current < 25 amps

$r := 2.5 \cdot \mu m$ Radius of Single Mode Fiber core

$P_{out} := 5 \cdot mw$ $Area := \pi \cdot r^2$

$$Flux := \frac{P_{out}}{Area} \qquad Flux = 0.025 \cdot \frac{Mw}{cm^2}$$

$Mw \equiv 10^6 \cdot watt$

$\mu m \equiv 10^{-6} \cdot m$

$cm \equiv 10^{-2} \cdot m$

$mw \equiv 10^{-3} \cdot watt$

$hrs \equiv 3600 \cdot sec$

Appendix I

Signal To Noise Ratio (SNR) Calculations

From [Henry, et al 1988, Introduction to Lightwave Systems, *Optical Telecommunications II*, 1991 p.821]

The theoretical noise limits of cascaded optical amplifiers can be given by using the following relation:

$A := .25\cdot\frac{dB}{km}$	Typical aggregate attenuation at 1550nm
$L := 78\cdot km$	Spacing between amplifiers
$L_{tot} := 4000\cdot km$	Total link distance
$h := 6.625\cdot 10^{-34}\cdot joule\cdot sec$	Planck's Constant
$\nu := \frac{c}{1550\cdot nm}$	Frequency of light signal
$P_t := 5\cdot mw$	Power coupled into the fiber
$B := 128\cdot MHz\cdot 10$	Bandwidth (1000 voice channels RZ coded)
$K := 2$	Additive noise figure as given in source, K = 2 yields 3 dB noise figure.

$$SNR := \frac{P_t\cdot 10^{-\frac{A\cdot L}{10}}}{\left(\frac{L_{tot}}{L}\right)\cdot K\cdot h\cdot \nu\cdot B} \qquad 10\cdot\log(SNR) = 35.228\cdot dB$$

SNR of 35 dB leads to bit error rates much better than desired 1 per billion bits.

SNR is not a critical factor for this link even at 10 times compared bandwidth , as bandwidths increase, SNR will be more of a limiting factor.

$dB \equiv 1$

$mw \equiv 10^{-3} \cdot watt$

$nm \equiv 10^{-9} \cdot m$

$c \equiv 3 \cdot 10^{8} \cdot \frac{m}{sec}$

Appendix J

Repeater Maintenance Calculations

These calculations are included for a sample fiber-optic communications link carrying 1000 2-way voice channels across a 4000km link.

Given the Repeater MTBF, The number of repeaters (52 per link, one link each way), and the time to repair each failure as 3 hours (including travel time to remote locations):

$$\text{Repeater}_{\text{MTBF}} := 45500 \qquad \text{TTR} := 3$$

$$\text{Qty}_{\text{repeater}} := 104$$

$$\text{Availability} := 1 - \left(\frac{\text{TTR}}{\text{Repeater}_{\text{MTBF}}}\right) \qquad \text{Availability} = 0.999934$$

System Availability is the Availability per repeater raised to the power of the quantity of repeaters.

$$\text{System\_Availability} := \text{Availability}^{\text{Qty}_{\text{repeater}}}$$

$$\text{System\_Availability} = 0.993166$$

The System availability is clearly not acceptable. A0 desired is 0.9999 Therefore each repeater unit will incorporate redundancy.

$$\lambda := \frac{1}{\text{Repeater}_{\text{MTBF}}} \qquad \lambda = 2.197802 \cdot 10^{-5}$$

Given redundant repeaters with identical characteristics, the probability that both repeaters will fail simultaneously is:

$$\lambda^2 = 4.830335 \cdot 10^{-10}$$

Yielding a redundant system failure rate of

$$\frac{1}{\lambda^2} = 2.07025 \cdot 10^{9}$$

Repeater Maintenance Calculations (Cont'd)

$$\text{Repeater}_{\text{MTBF}} := \frac{1}{\lambda^2} \qquad \text{TTR} := 250$$

$$\text{Qty}_{\text{repeater}} := 104 \cdot 2$$

$$\text{Availability} := 1 - \left(\frac{\text{TTR}}{\text{Repeater}_{\text{MTBF}}}\right) \qquad \text{Availability} = 0.9999998792$$

per redundant repeater cluster

System Availability is the Availability per repeater raised to the power of the quantity of repeaters.

$$\text{System\_Availability} := \text{Availability}^{\text{Qty}_{\text{repeater}}}$$

$$\text{System\_Availability} = 0.999975$$

System Availability requirements are achieved with repeater redundancy, but the population doubles. Each individual failure will still need to be repaired, but since redundancy is incorporated, the Time to Repair can be drastically increased from 3 hours to 250 hours (this includes travel and waiting time). The number of failures can be calculated for the entire system using the repeater MTBF and the total system population.

$$\text{Repeater}_{\text{MTBF}} := 45500$$

$$\text{Qty}_{\text{repeater}} := 104 \cdot 2$$

The Mean Time Between Failure over the entire population of repeaters is:

$$\frac{\text{Repeater}_{\text{MTBF}}}{\text{Qty}_{\text{repeater}}} = 218.75 \quad \text{hours}$$

Repeater Maintenance Calculations (Cont'd)

Conclusions: The Desired Availability of 0.9999 is not achievable for the MTBF limits of the repeater units, therefore, redundancy must be incorporated. Using redundant repeaters brings the Availability up to acceptable levels, while allowing the Time To Repair to increase to compensate.

An increased Time to Repair decreases the inventory requirements, if suppliers can deliver replacement units and repairs can be made within 250 hour, then availability is not compromised.

An increased Time to Repair also decreases the number of technicians and the number of maintenance base stations required:

$$\text{Repair\_Time} := 0.5 \cdot \text{hr}$$

$$\text{Average\_Travel\_Time} := 2.5 \cdot \text{hr}$$

$$\text{TTR} := \text{Average\_Travel\_Time} + \text{Repair\_Time}$$

$$\text{Length} := 4000 \cdot \text{km}$$

Assuming a technician responds by ground transportation averaging 50km/hr to the repair site, the response radius would be:

$$\text{Avg\_Speed} := 50 \cdot \frac{\text{km}}{\text{hr}}$$

$$\text{Response\_Radius} := \text{Average\_Travel\_Time} \cdot \text{Avg\_Speed} \cdot 2$$

$$\text{Response\_Radius} = 250 \cdot \text{km}$$

Note: Response radius is not simply Average Travel Time multiplied by Average Speed, this figure would give one half the response radius, the correct figure concludes half of the reponses will be more and half will be less than the Travel Time-Speed product.

The number of Maintenance bases is:

$$\frac{\text{Length}}{2 \cdot \text{Response\_Radius}} = 8$$

Each base needs at least one technician on call continuously.

Repeater Maintenance Calculations (Cont'd)

The effect of increasing TTR to 250 hours is shown below:

$$\text{Repair\_Time} := 0.5 \cdot \text{hr}$$

$$\text{Average\_Travel\_Time} := 249.5 \cdot \text{hr}$$

$$\text{TTR} := \text{Average\_Travel\_Time} + \text{Repair\_Time}$$

$$\text{Response\_Radius} := \text{Average\_Travel\_Time} \cdot \text{Avg\_Speed} \cdot 2$$

$$\text{Response\_Radius} = 24950 \cdot \text{km}$$

The number of Maintenance bases is:

$$\frac{\text{Length}}{2 \cdot \text{Response\_Radius}} = 0.08016$$

Round up to 1 maintenance base.

Repeater redundancy reduces the number of on-call maintenance technicians from 8 to 1

Repeater Maintenance Calculations (Cont'd)

Comparing the two options from a Present Cost perspective:

$$P_A(A,i,n) \equiv \left[A\cdot\frac{(1+i)^n - 1}{i\cdot(1+i)^n} \right]$$

Cost Assumptions (amounts in dollars):

$Repeater\_Cost := 5000$	each
$Technician\_Cost := 50000$	per year
$Travel\_Cost := 0.20$	per kilometer
$Capital\_Cost := 0.10$	per year
$Lifetime := 20$	years

<u>Option 1</u> 8 technicians, non-redundant repeaters, A0 = 0.9932

$Population := 104$

$$MTBF := \frac{45500}{Population}$$

$Avg\_Travel\_Cost := 2.5\cdot 50\cdot Travel\_Cost\cdot 2$ $\qquad$ $Avg\_Travel\_Cost = 50$

$Failures\_Per\_Year := \dfrac{24\cdot 365}{MTBF}$ $\qquad$ $Failures\_Per\_Year = 20.02$

$Recurring\_Cost := Failures\_Per\_Year\cdot(Repeater\_Cost + Avg\_Travel\_Cost) + Technician\_Cost\cdot 8$

$Fixed\_Cost := Population\cdot Repeater\_Cost$

$Present\_Equivalent\_1 := Fixed\_Cost + P_A(Recurring\_Cost, Capital\_Cost, Lifetime)$

$Present\_Equivalent\_1 = 4786278.13$ $\quad$ (\$)

Repeater Maintenance Calculations (Cont'd)

Option 2 assumes the maintenance base is located in the middle of the link and repair radius will be no more than 2000 km, and a return to base after each repair. Option 2 will include the same assumptions except for increased travel costs since lodging will have to be included:

$$Travel\_Cost := 0.40$$ per kilometer

<u>Option 2</u> 1 Technician, redundant repeaters, A0 = 0.9999

$$Population := 104 \cdot 2$$

$$MTBF := \frac{45500}{Population}$$

$$Avg\_Travel\_Cost := 1000 \cdot Travel\_Cost \cdot 2 \qquad Avg\_Travel\_Cost = 800$$

$$Failures\_Per\_Year := \frac{24 \cdot 365}{MTBF} \qquad Failures\_Per\_Year = 40.05$$

$$Recurring\_Cost := Failures\_Per\_Year \cdot (Repeater\_Cost + Avg\_Travel\_Cost) + Technician\_Cost$$

$$Fixed\_Cost := Population \cdot Repeater\_Cost$$

$$Present\_Equivalent\_2 := Fixed\_Cost + P_A(Recurring\_Cost, Capital\_Cost, Lifetime)$$

$$Present\_Equivalent\_2 = 3443082.28 \quad (\$)$$

<u>Cost Summary</u>

$$Present\_Equivalent\_1 = 4786278.13 \quad (\$) \qquad Present\_Equivalent\_2 = 3443082.28 \quad (\$)$$

Option 2 is preferable because it offers the desired availability (0.9999) and it is less costly from a life-cycle perspective.

Option 2 is favored by $Present\_Equivalent\_1 - Present\_Equivalent\_2 = 1343195.85$ (\$)

Appendix K

Cost of Updating the Network Every 5 years

$\text{Population} = 208$

$\text{Repeater\_Cost} = 5000$

$\text{Upgrade\_Cost} := \text{Population} \cdot \text{Repeater\_Cost}$

$$P_F(F,i,n) \equiv \left[F \cdot \frac{1}{n \cdot (1+i)} \right]$$

$\text{Upgrade\_Cost} = 1040000$

$$\frac{\text{Lifetime}}{5} - 1 = 3$$

$$\text{Upgrade\_PE} := \sum_{\text{update}=1}^{\frac{\text{Lifetime}}{5}-1} P_F(\text{Upgrade\_Cost}, \text{Capital\_Cost}, \text{update} \cdot 5)$$

$\text{Upgrade\_PE} = 346666.67$

Total Present Cost of the System Due to Repeater Corrective Maintenance/upgrade costs:

$\text{Total\_Cost} := \text{Upgrade\_PE} + \text{Present\_Equivalent\_2}$

$\text{Total\_Cost} = 3789748.95$

Appendix L

Cost of System with Fiber Amplifiers

Given the Pump-Laser MTBF, The number of Amplifiers (52 per link, two-way), and the time to repair each failure as 3 hours (including travel time to remote locations):

$$\text{Pump\_Laser}_{\text{MTBF}} := 100000 \qquad \text{TTR} := 3$$

$$\text{Qty}_{\text{repeater}} := 52$$

$$\text{Availability} := 1 - \left(\frac{\text{TTR}}{\text{Pump\_Laser}_{\text{MTBF}}}\right) \qquad \text{Availability} = 0.99997$$

System Availability is the Availability per amplifier raised to the power of the quantity of repeaters.

$$\text{System\_Availability} := \text{Availability}^{\text{Qty}_{\text{repeater}}}$$

$$\text{System\_Availability} = 0.998441$$

The System availability is clearly not acceptable. A0 desired is 0.9999 Therefore each amplifier pump-laser unit will incorporate redundancy.

$$\lambda := \frac{1}{\text{Pump\_Laser}_{\text{MTBF}}} \qquad \lambda = 1 \cdot 10^{-5}$$

Given redundant pump-lasers with identical characteristics, the probability that both lasers will fail simultaneously is:

$$\lambda^2 = 1 \cdot 10^{-10}$$

Yielding a redundant system failure rate of

$$\frac{1}{\lambda^2} = 1 \cdot 10^{10}$$

Fiber Amplifier Maintenance Calculations (Cont'd)

$$\text{Pump\_Laser}_{\text{MTBF}} := \frac{1}{\lambda^2} \qquad \text{TTR} := 1000$$

$$\text{Qty}_{\text{repeater}} := 52 \cdot 2$$

$$\text{Availability} := 1 - \left(\frac{\text{TTR}}{\text{Pump\_Laser}_{\text{MTBF}}}\right) \qquad \text{Availability} = 0.9999999$$

per redundant Pump Laser cluster

System Availability is the Availability per pump-laser cluster raised to the power of the quantity of pump-lasers.

$$\text{System\_Availability} := \text{Availability}^{\text{Qty}_{\text{repeater}}}$$

$$\text{System\_Availability} = 0.99999$$

With the Reliability Characteristics of the Optical Amplifier/Pump Laser in a redundant configuration, the Time To Repair effect on the availability is such that corrective maintenance can be eliminated, and any failures of Pump Lasers can be made during periodic maintenance checks. An assumption is made that preventive maintenance is the same with repeatered and optically amplified systems, there for the cost advantage of Optical Amplifier vs Repeatered operation is the total cost for Corrective Maintenance and upgrade costs or:

Cost Advantage Using Fiber Amplifiers:

$$\text{Total\_Cost} = 3789748.95 \quad (\$)$$

Top Level

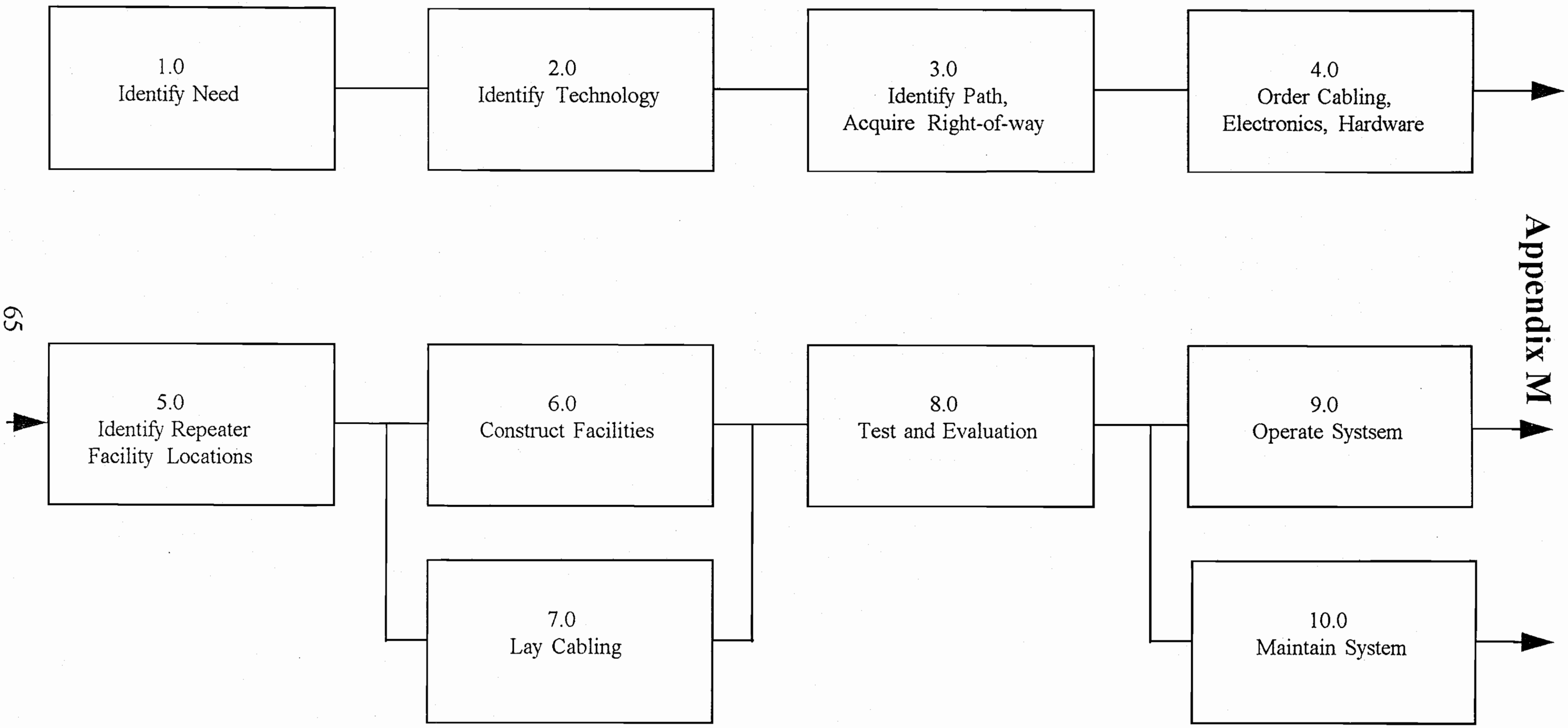


Figure A6. Fiber-Optic Communications System Functional Analysis (Top Level)

Second Level

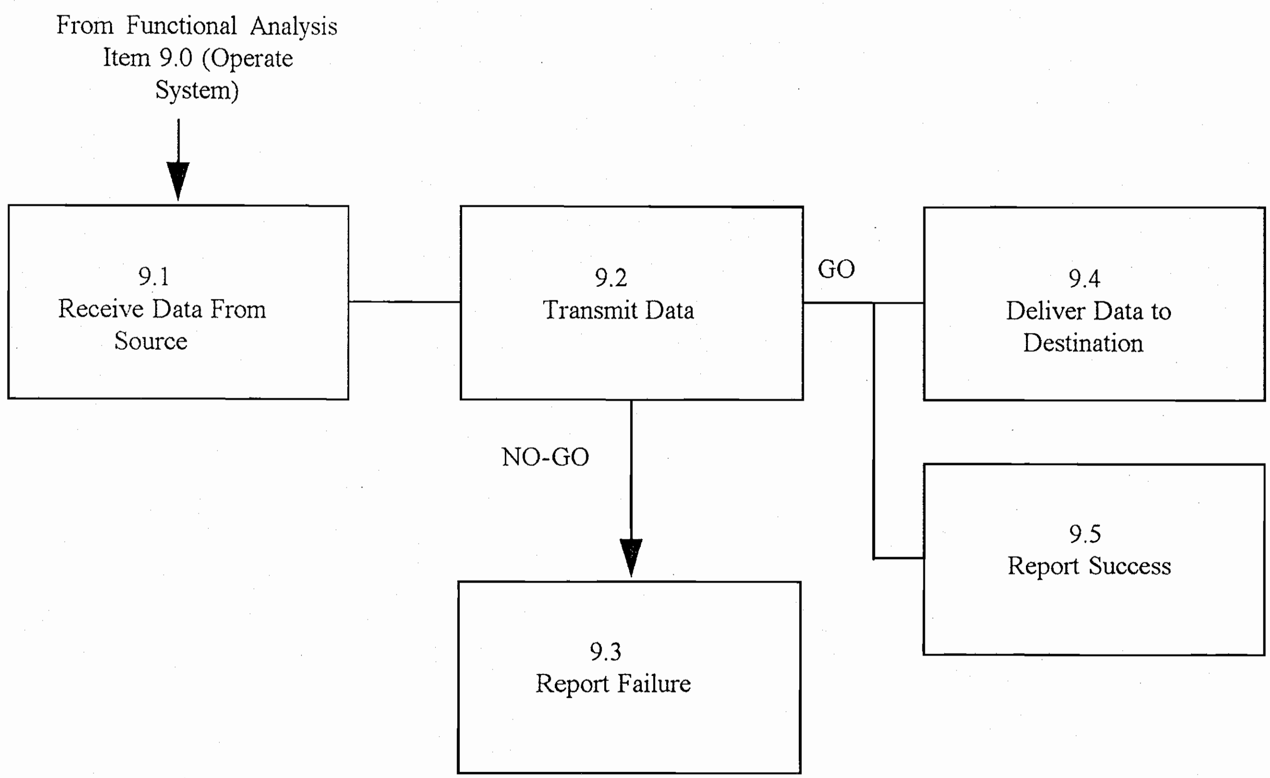


Figure A7. Fiber-Optic Communications System Functional Analysis (Second Level)

Third Level

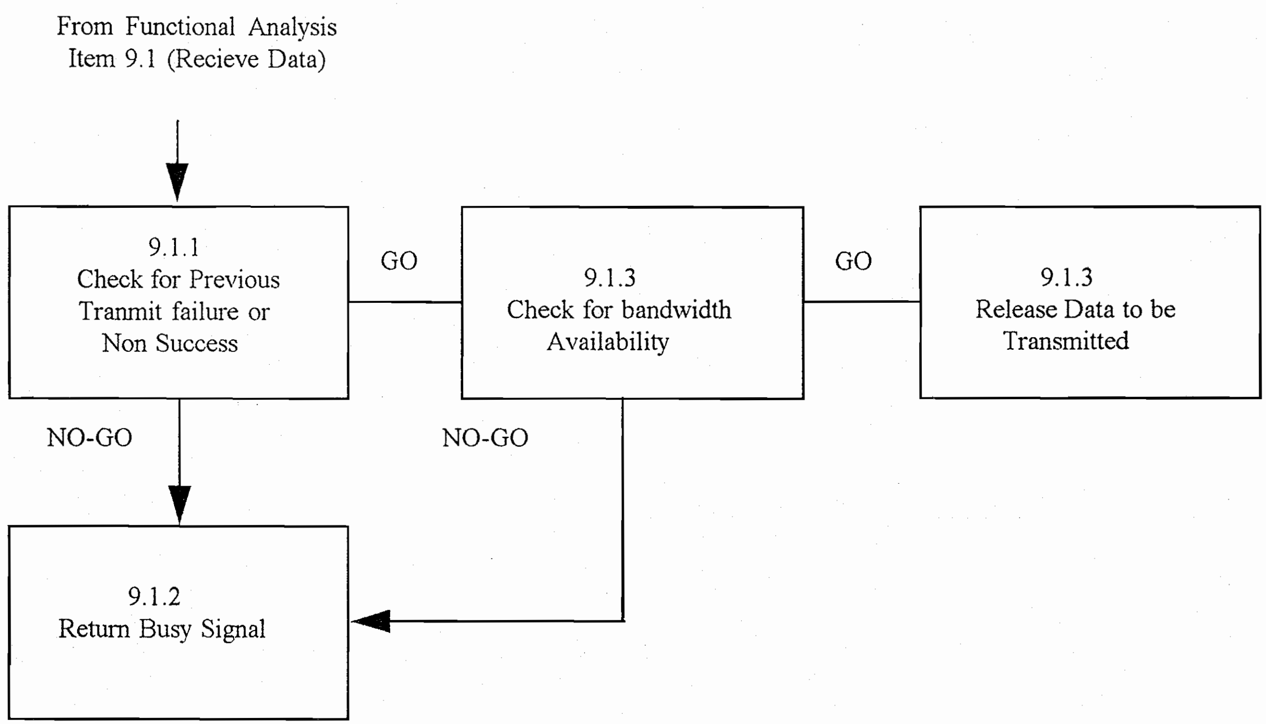


Figure A8. Fiber-Optic Communications System Functional Analysis (Third Level)

Fiber-Optic Communications System Functional Analysis

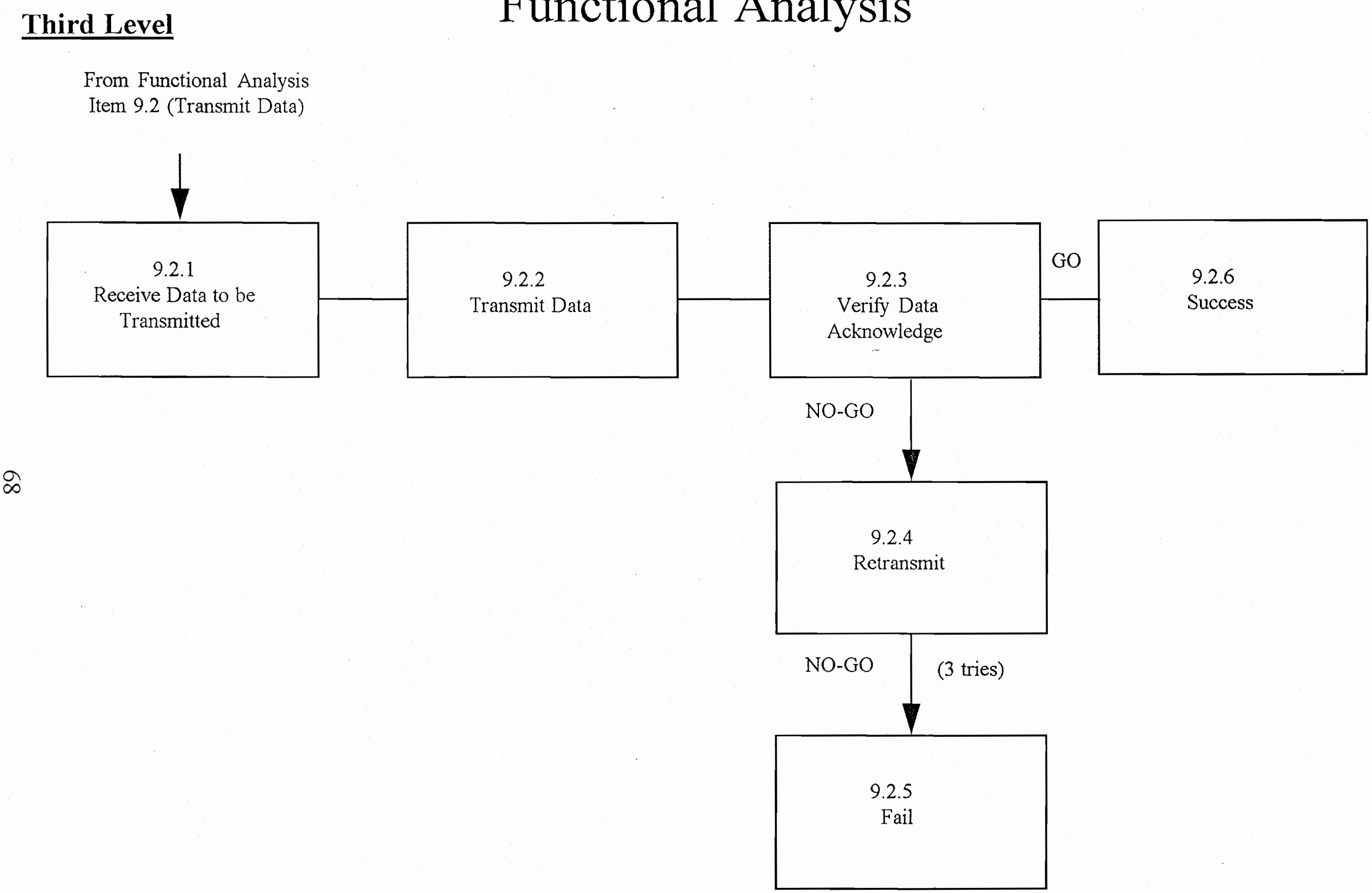


Figure A9. Fiber-Optic Communications System Functional Analysis (Third Level, cont'd)

Second Level

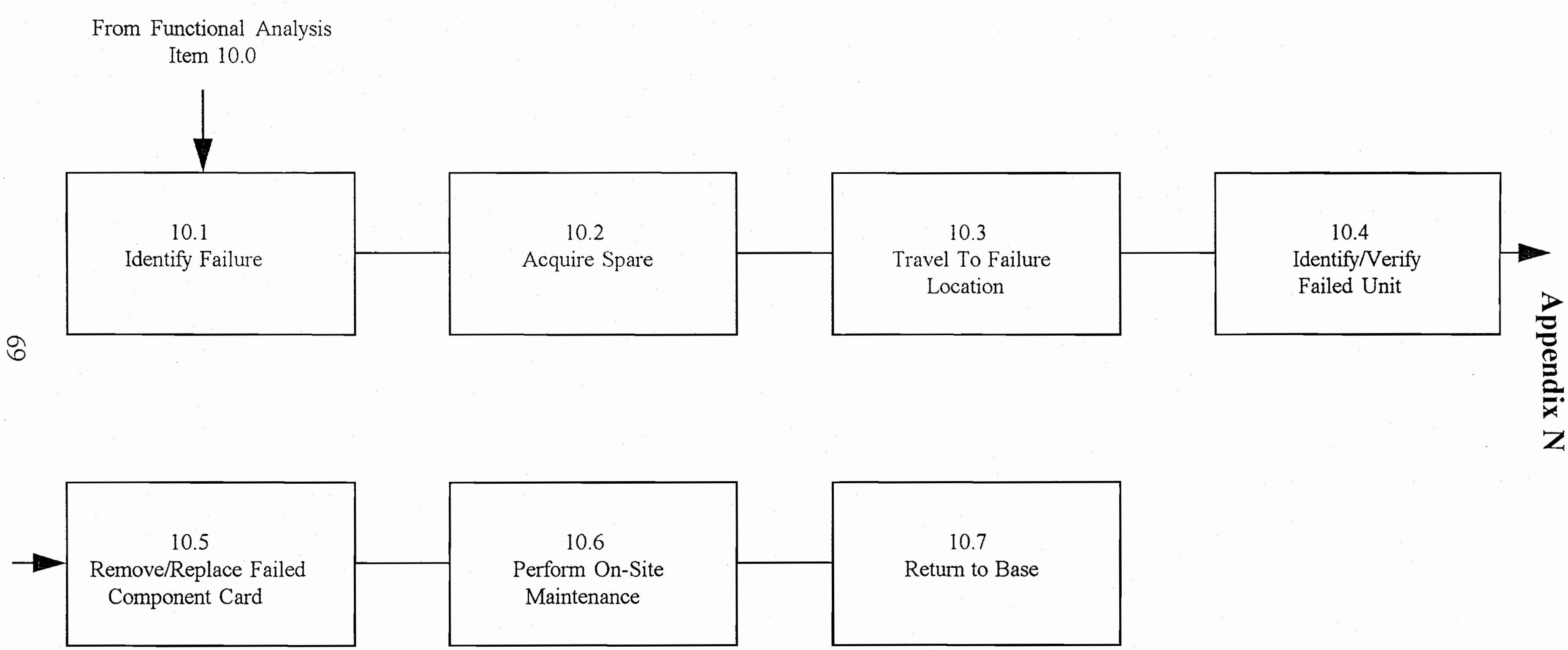


Figure A10. Fiber-Optic Communications System Corrective Maintenance Flow

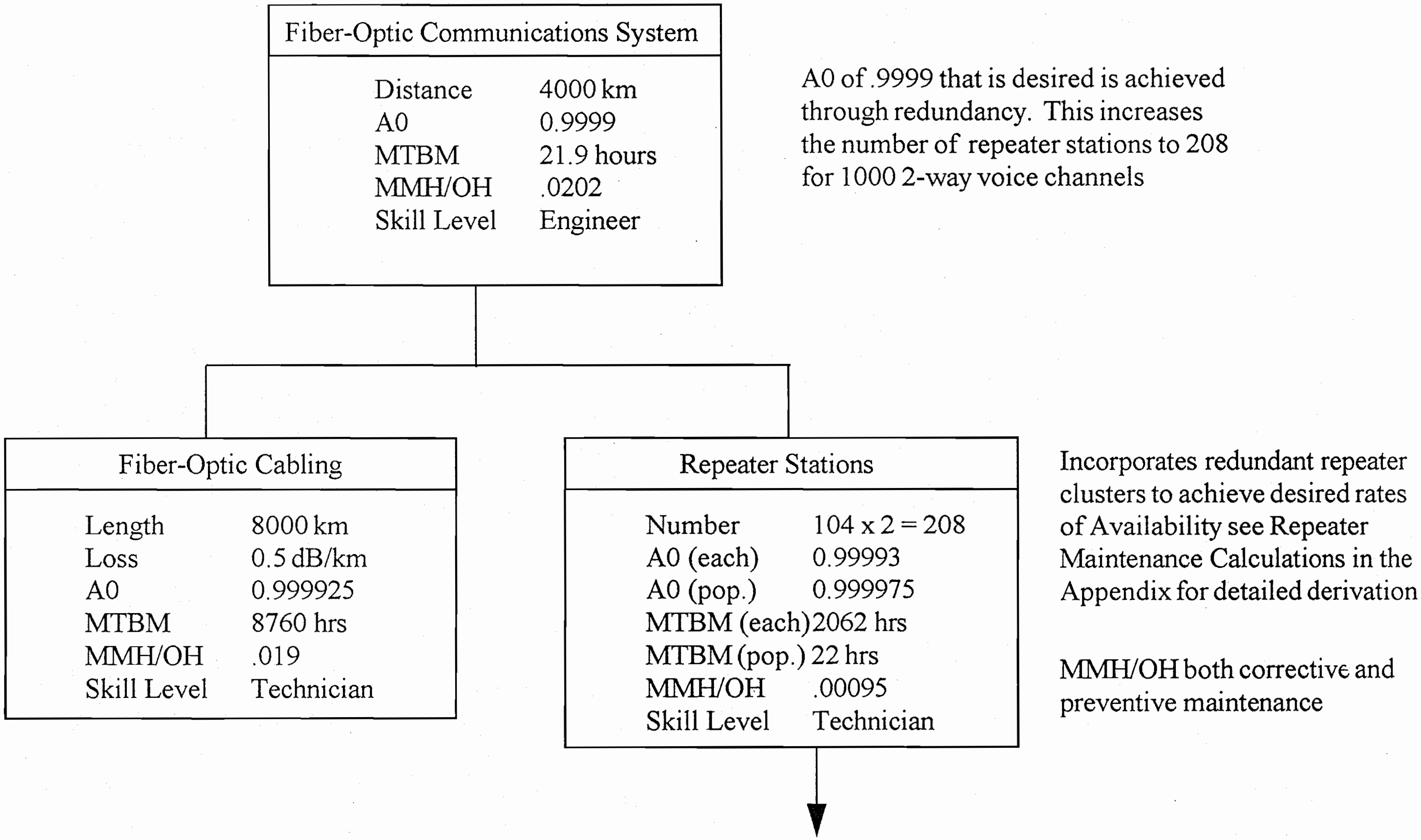


Figure A11. 2-Way Fiber-Optic Communications System Functional Allocation

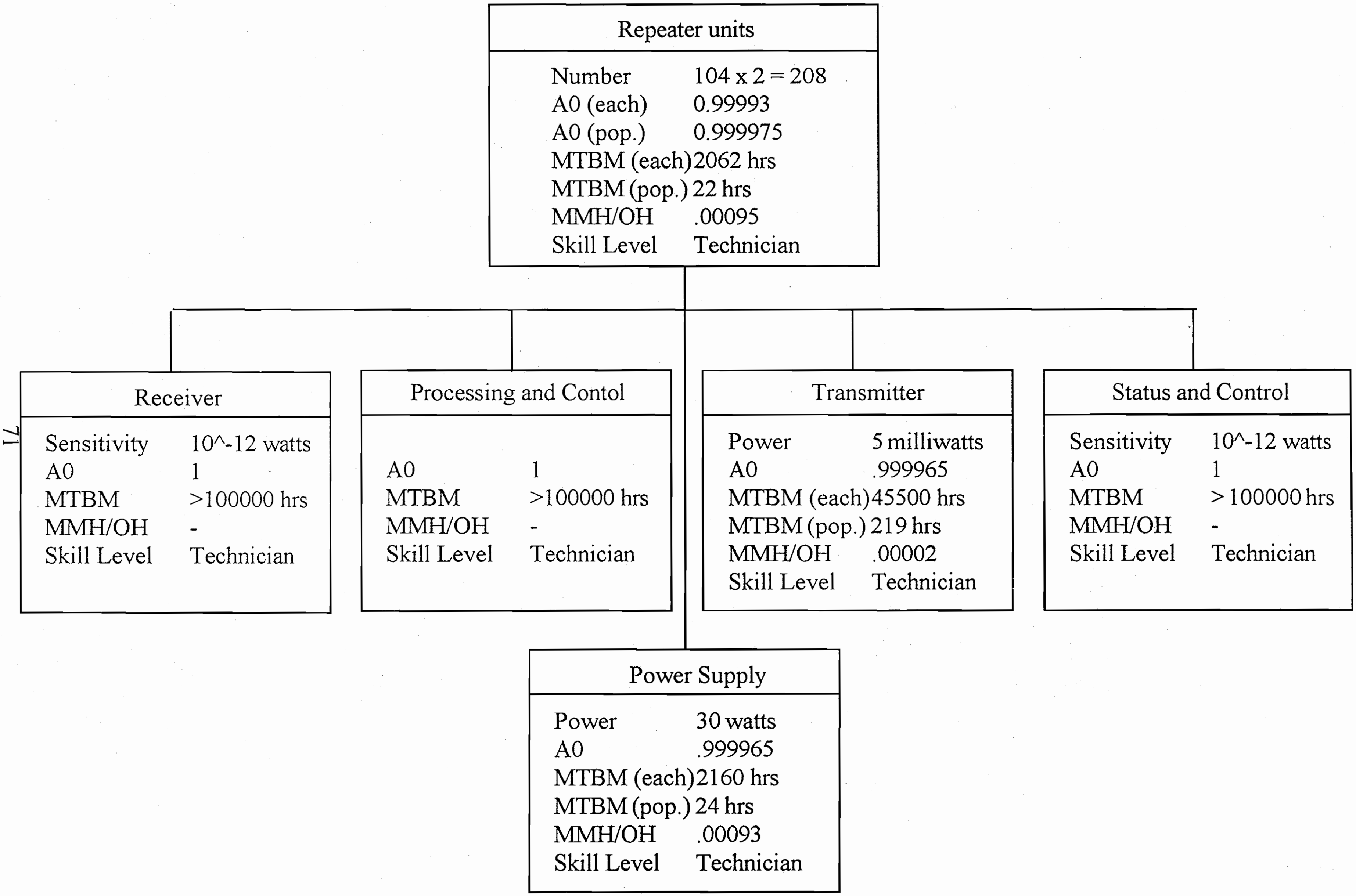


Figure A12. 2-Way Fiber-Optic Communications System Functional Allocation

Appendix P

Bus Network Topology Cost Analysis

Current Network, Blacksburg Cable Television, 50 Channels, 300MHz bandwidth non-interactive.

$Nodes := 10000$	Number of customer hookups
$Length := 400 \cdot km$	Total Span of the network
$Amp\_spacing := 600 \cdot m$	Required Amplifier Spacing for given Bandwidth
$Amplifiers := \frac{Length}{600 \cdot m}$	Number of Amplifiers
$Amp_{MTBF} := 60000 \cdot hr$	Individual Amplifier MTBF
$Amplifiers = 666.667$	Population of Amplifiers
$Amp_{Cost} := 1000$ ($)	Cost per Amplifier Repair
$Fail_{freq} := \frac{Amp_{MTBF}}{Amplifiers}$ $Fail_{freq} = 90 \cdot hr$	Failure frequency within entire population
$MTTR := 1 \cdot hr$	Time to repair amplifier failure
$A0 := 1 - \frac{MTTR}{Fail_{freq}}$ $A0 = 0.989$	Total System Availability

$$YearlyCost := \frac{365 \cdot 24 \cdot hr}{Fail_{freq}} \cdot Amp_{Cost} \qquad YearlyCost = 97333.33 \text{ (\$)}$$

$$FailuresPerYr := \frac{365 \cdot 24 \cdot hr}{Fail_{freq}} \qquad FailuresPerYr = 97.333$$

Note availability figure is for the entire system. Individual Customers will have Availability figures higher than A0 because an individual failure does not fail the entire system, only some portion of the system.

Appendix Q

Star Network Topology Cost Analysis

For Comparison purposes, a star network analysis is performed with the same number of customers:

$Nodes := 10000$	Number of customer hookups
$Length := 3 \cdot km$	Total Span of each connection
$Amp\_spacing := 5 \cdot km$	Required Amplifier Spacing for given Bandwidth
$Amplifiers := \dfrac{Length}{Amp\_spacing}$	Number of Amplifiers
$Switch_{MTBF} := 40000 \cdot hr$	Switch per node MTBF (with redundancy)
$SwitchRepair_{Cost} := 25$ (\$)	Cost per Switch Repair (Module Replacement)

$Fail_{freq} := \dfrac{Switch_{MTBF}}{Nodes}$ $\quad Fail_{freq} = 4 \cdot hr$ $\quad$ Failure frequency within entire population

$MTTR := .1 \cdot hr$ $\quad$ Time to repair failure, Switch co-located with repair facility - automated redundancy

$SystemFail_{freq} := \dfrac{Switch_{MTBF}^{2}}{Nodes} \cdot \dfrac{1}{sec}$ $\quad SystemFail_{freq} = 5.76 \cdot 10^{8} \cdot hr$

$A0 := 1 - \dfrac{MTTR}{SystemFail_{freq}}$ $\quad A0 = 0.999999999826389$ $\quad$ Total System Availability with redundancy

$YearlyCost := \dfrac{365 \cdot 24 \cdot hr}{Fail_{freq}} \cdot SwitchRepair_{Cost}$ $\quad YearlyCost = 54750$ (\$)

$FailuresPerYr := \dfrac{365 \cdot 24 \cdot hr}{Fail_{freq}}$ $\quad FailuresPerYr = 2190$

Note: Redundancy yields high availability, though a high number of failures occur.

Aggregate Bandwidth: $\quad Nodes \cdot 64000 \cdot Hz = 640 \cdot MHz$

Appendix R

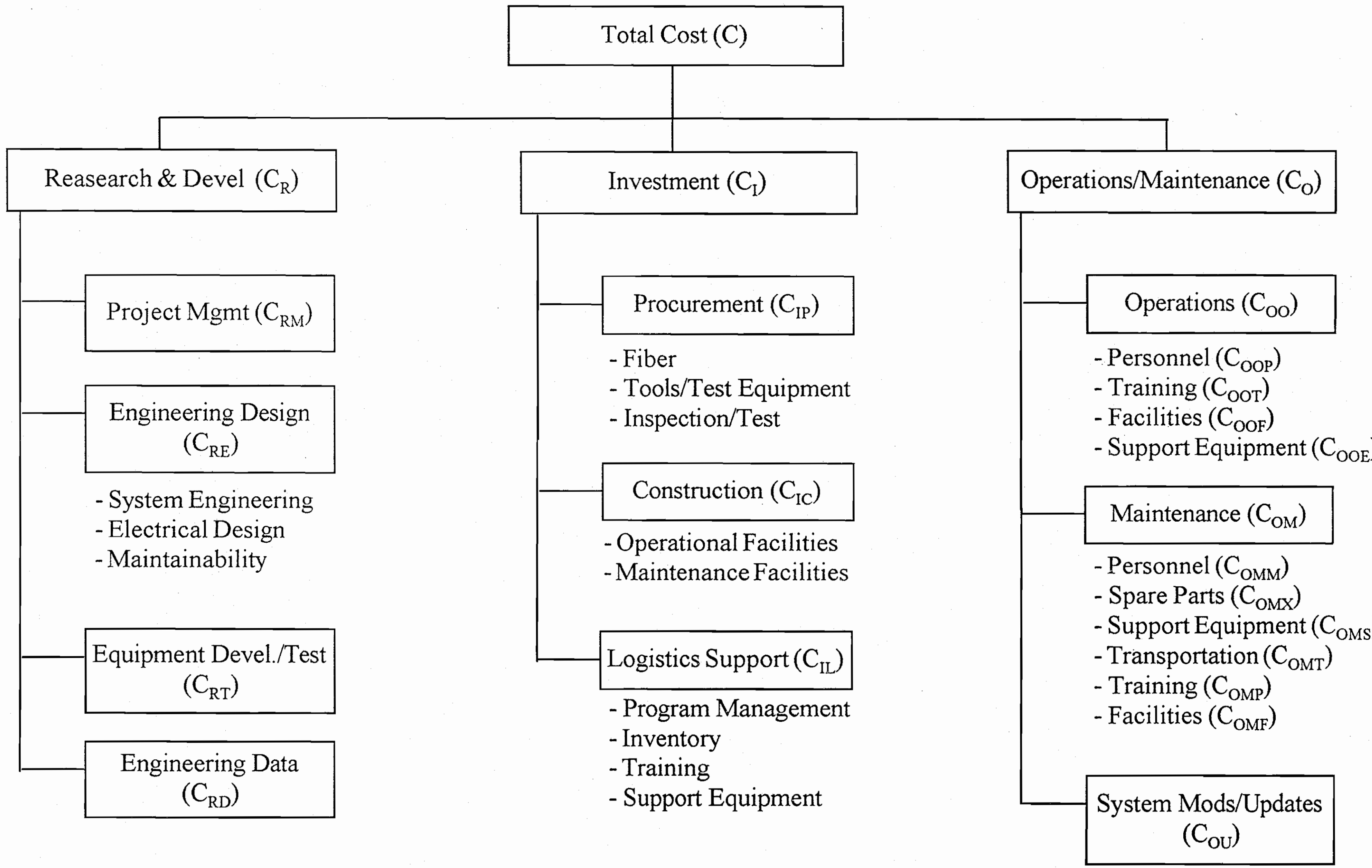


Figure A13. Cost Breakdown Structure Fiber-Optic Communications System

Cost Category	Current Generation PV Cost	% of Total	Next Generation PV Cost	% of Total
1. Research and Development (C_R)	$ 195,000	0.38%	$ 195,000	0.43%
(a) Program management (C_{RM})	$ 50,000	0.10%	$ 50,000	0.11%
(b) Engineering Design (C_{RE})	$ 25,000	0.05%	$ 25,000	0.06%
(c) Equipment Dev/Test (C_{RT})	$ 100,000	0.19%	$ 100,000	0.22%
(d) Engineering Data (C_{RD})	$ 20,000	0.04%	$ 20,000	0.04%
2. Investment (C_I)	$ 44,340,000	85.51%	$ 42,292,000	93.84%
(a) Procurement (C_{IP})	$ 2,440,000	4.71%	$ 1,852,000	4.11%
(b) Construction (C_{IC})	$ 41,700,000	80.42%	$ 40,400,000	89.65%
(c) Logistics Support (C_{IL})	$ 200,000	0.39%	$ 40,000	0.09%
3. Operations/Maintenance (C_O)	$ 7,317,759	14.11%	$ 2,578,986	5.72%
(a) Operations (C_{OO})	$ 2,128,391	4.10%	$ 2,128,391	4.72%
(b) Maintenance (C_{OM})	$ 3,868,760	7.46%	$ 425,678	0.94%
(c) System Mods/Updates (C_{OU})	$ 1,320,608	2.55%	$ 24,917	0.06%
TOTAL COST:	$ 51,852,759		$ 45,065,986	

Figure A14. CBS Summary Breakdown

Appendix R (Con't)

Cost Breakdown Structure Analysis

T_C Total Cost

C_R Research and Development

C_{RM} Project Management

C_{RE} Engineering Design

C_{RT} Equipment Development/Test

C_{RD} Engineering Data

C_I Investment

C_{IP} Procurement

C_{IC} Construction

C_{IL} Logistics Support

C_O Operations and Maintenance

C_{OO} Operations

C_{OM} Maintenance

C_{OU} System Mods/Updates

$$P_F(F,i,n) \equiv F \cdot \left[\frac{1}{(1+i)^n} \right]$$

$$P_A(A,i,n) \equiv \left[A \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \right]$$

$\text{dollars} := 1$

Common Cost Assumptions (Dollars, $)

Research and Development:

$$C_{RM} := 50000 \cdot dollars$$

$$C_{RE} := 25000 \cdot dollars$$

$$C_{RT} := 100000 \cdot dollars$$

$$C_{RD} := 20000 \cdot dollars$$

Research and Development Total Cost:

$$C_R := C_{RM} + C_{RE} + C_{RT} + C_{RD} \qquad C_R = 195000 \cdot dollars$$

Operations and Maintenance:

Operations

$$C_{OO} := P_A(250000, 10 \cdot \%, 20) \qquad C_{OO} = 2128390.93 \cdot dollars$$

Current Generation Cost Breakdown

Investment:

Procurement

C_{IPE} Cost of Terminal Equipment

C_{IPF} Cost of Fiber

C_{IPR} Cost of Repeaters

$$C_{IPE} := 100000 \cdot 2 \qquad C_{IPE} = 200000 \cdot \text{dollars}$$

$$C_{IPF} := .15 \cdot \frac{\text{dollars}}{\text{m}} \cdot 4000 \cdot \text{km} \cdot 2 \qquad C_{IPF} = 1200000 \cdot \text{dollars}$$

$$C_{IPR} := 5000 \cdot \text{dollars} \cdot 208 \qquad C_{IPR} = 1040000 \cdot \text{dollars}$$

$$C_{IP} := C_{IPE} + C_{IPF} + C_{IPR} \qquad C_{IP} = 2440000 \cdot \text{dollars}$$

Construction

C_{ICT} Terminal Facilities

C_{ICR} Repeater Facilities

C_{ICE} Excavation/Trenching

$$C_{ICT} := 200000 \cdot \text{dollars} \cdot 2$$

$$C_{ICR} := 25000 \cdot \text{dollars} \cdot 52$$

$$C_{ICE} := 10000 \cdot \frac{\text{dollars}}{\text{km}} \cdot 4000 \cdot \text{km}$$

$$C_{IC} := C_{ICT} + C_{ICR} + C_{ICE} \qquad C_{IC} = 41700000 \cdot \text{dollars}$$

Current Generation Cost Breakdown Structure (Cont'd)

Investment (Cont'd):

Logistics Support

$C_{IL} := 200000$ $\qquad$ $C_{IL} = 200000 \cdot \text{dollars}$

Investment Total Cost:

$C_{I} := C_{IP} + C_{IC} + C_{IL}$ $\qquad$ $C_{I} = 44340000 \cdot \text{dollars}$

Operations and Maintenance:

Operations

(Under Common Cost Assumption) $\qquad$ $C_{OO} = 2128390.93 \cdot \text{dollars}$

Maintenance

C_{OMP} Periodic Maintenance

C_{OMC} Corrective Maintenace

$C_{OMP} := P_{A}(50000, 10 \cdot \%, 20)$

$C_{OMC} := 3443082 \cdot \text{dollars}$

$C_{OM} := C_{OMP} + C_{OMC}$ $\qquad$ $C_{OM} = 3868760.19 \cdot \text{dollars}$

Current Generation Cost Breakdown Structure (Cont'd)

Operations and Maintenance (Cont'd):

System Modification/Update

C_{OUT}	Terminal Equipment
C_{OUR}	Repeater Equipment

$Population := 208$

$Repeater\_Cost := 5000$

$Upgrade\_Cost := Population \cdot Repeater\_Cost$

$Lifetime := 20$

$Capital\_Cost := 10 \cdot \%$

$Upgrade\_Cost = 1040000$

$$C_{OUR} := \sum_{update = 1}^{\frac{Lifetime}{5} - 1} P_F(Upgrade\_Cost, Capital\_Cost, update \cdot 5)$$

Current Generation Cost Breakdown Structure (Cont'd)

Operations and Maintenance (Cont'd):

System Modification/Update (Con't)

$\text{Population} := 2$

$\text{Terminal\_Cost} := 10000$

$\text{Upgrade\_Cost} := \text{Population} \cdot \text{Terminal\_Cost}$

$\text{Lifetime} := 20$

$\text{Capital\_Cost} := 10 \cdot \%$

$\text{Upgrade\_Cost} = 20000$

Upgrade/Modification every 5 years over the 20 year lifespan

$$C_{OUT} := \sum_{update = 1}^{\frac{Lifetime}{5} - 1} P_F(\text{Upgrade\_Cost}, \text{Capital\_Cost}, \text{update} \cdot 5)$$

$C_{OU} := C_{OUT} + C_{OUR}$ $\qquad$ $C_{OU} = 1320608.06 \cdot \text{dollars}$

Operations and Maintenance Total Cost:

$C_O := C_{OO} + C_{OM} + C_{OU}$ $\qquad$ $C_O = 7317759.18 \cdot \text{dollars}$

Total Cost by CBS Category (Current Generation)

$C_R = 195000$ Research and Development

$C_I = 44340000$ Investment

$C_O = 7317759.18$ Operations

$T_{Cold} := C_R + C_I + C_O \qquad T_{Cold} = 51852759.18 \cdot dollars$

Research and Development

$C_R = 195000 \cdot dollars$

$C_{RM} = 50000 \cdot dollars$

$C_{RE} = 25000 \cdot dollars$

$C_{RT} = 100000 \cdot dollars$

$C_{RD} = 20000 \cdot dollars$

Investment

$C_I = 44340000 \cdot dollars$

$C_{IP} = 2440000 \cdot dollars$

$C_{IC} = 41700000 \cdot dollars$

$C_{IL} = 200000 \cdot dollars$

Operations and Maintenance

$C_O = 7317759.18 \cdot dollars$

$C_{OO} = 2128390.93 \cdot dollars$

$C_{OM} = 3868760.19 \cdot dollars$

$C_{OU} = 1320608.06 \cdot dollars$

Next Generation Cost Breakdown Structure

Investment:

Procurement

C_{IPE}	Cost of Terminal Equipment
C_{IPF}	Cost of Fiber
C_{IPR}	Cost of Amplifiers

$$C_{IPE} := 100000 \cdot 2$$

$$C_{IPF} := .20 \cdot \frac{\text{dollars}}{\text{m}} \cdot 4000 \cdot \text{km} \cdot 2$$

$$C_{IPR} := 1000 \cdot \text{dollars} \cdot 52$$

$$C_{IP} := C_{IPE} + C_{IPF} + C_{IPR} \qquad C_{IP} = 1852000 \cdot \text{dollars}$$

Construction

C_{ICT}	Terminal Facilities
C_{ICR}	Repeater Facilities
C_{ICE}	Excavation/Trenching

$$C_{ICT} := 200000 \cdot \text{dollars} \cdot 2$$

$$C_{ICR} := 0$$

$$C_{ICE} := 10000 \cdot \frac{\text{dollars}}{\text{km}} \cdot 4000 \cdot \text{km}$$

$$C_{IC} := C_{ICT} + C_{ICR} + C_{ICE}$$

Next Generation Cost Breakdown Structure (Cont'd)

Investment (Cont'd):

Logistics Support

$$C_{IL} := 40000$$

Investment Total Cost:

$$C_I := C_{IP} + C_{IC} + C_{IL} \qquad C_I = 42292000 \cdot \text{dollars}$$

Operations and Maintenance:

Operations

(Under Common Cost Assumption) $C_{OO} = 2128390.93 \cdot \text{dollars}$

Maintenance

C_{OMP} Periodic Maintenance

C_{OMC} Corrective Maintenace

$$C_{OMP} := P_A(50000 \cdot \text{dollars}, 10 \cdot \%, 20)$$

$$C_{OMC} := 0 \cdot \text{dollars}$$

$$C_{OM} := C_{OMP} + C_{OMC}$$

Next Generation Cost Breakdown Structure (Cont'd)

Operations and Maintenance (Cont'd):

System Mods/Updates

C_{OUT} Terminal Equipment

C_{OUR} Repeater Equipment

$C_{OUR} := 0$

$\text{Population} := 2$

$\text{Terminal\_Cost} := 10000$

$\text{Upgrade\_Cost} := \text{Population} \cdot \text{Terminal\_Cost}$

$\text{Lifetime} := 20$

$\text{Capital\_Cost} := 10 \cdot \%$

$\text{Upgrade\_Cost} = 20000$

$$C_{OUT} := \sum_{\text{update}=1}^{\frac{\text{Lifetime}}{5}-1} P_F(\text{Upgrade\_Cost}, \text{Capital\_Cost}, \text{update} \cdot 5)$$

$C_{OU} := C_{OUT} + C_{OUR}$ $C_{OU} = 24917.13 \cdot \text{dollars}$

Operations and Maintenance Total Cost:

$C_O := C_{OO} + C_{OM} + C_{OU}$ $C_O = 2578986.25 \cdot \text{dollars}$

Total Cost by CBS Category (Next Generation)

$C_R = 195000$	Research and Development
$C_I = 42292000$	Investment
$C_O = 2578986.25$	Operations

$$T_{Cnew} := C_R + C_I + C_O \qquad T_{Cnew} = 45065986.25 \cdot \text{dollars}$$

Research and Development

$$C_R = 195000 \cdot \text{dollars}$$

$$C_{RM} = 50000 \cdot \text{dollars}$$

$$C_{RE} = 25000 \cdot \text{dollars}$$

$$C_{RT} = 100000 \cdot \text{dollars}$$

$$C_{RD} = 20000 \cdot \text{dollars}$$

Investment

$$C_I = 42292000 \cdot \text{dollars}$$

$$C_{IP} = 1852000 \cdot \text{dollars}$$

$$C_{IC} = 40400000 \cdot \text{dollars}$$

$$C_{IL} = 40000 \cdot \text{dollars}$$

Operations and Maintenance

$$C_O = 2578986.25 \cdot \text{dollars}$$

$$C_{OO} = 2128390.93 \cdot \text{dollars}$$

$$C_{OM} = 425678.19 \cdot \text{dollars}$$

$$C_{OU} = 24917.13 \cdot \text{dollars}$$

Cost Comparison of Current Generation Versus Next Generation

$T_{Cold} = 51852759.18$ $\qquad$ $T_{Cnew} = 45065986.25$

The new generation, incorporating fiber amplifiers offers a cost savings of:

$$T_{Cold} - T_{Cnew} = 6786772.93 \cdot \text{dollars}$$

This figure is for equivalent bandwidths, new generation fiber optic links can incorporate Wave Division Multiplexing (WDM) with an investment in Terminal Equipment only. Therefore, for 10 times current bandwidth, the link costs are

Cost of 10 times current bandwidth (current generation)

$$T_{Cold} \cdot 10 = 518527591.77 \cdot \text{dollars}$$

Cost of 10 times current bandwidth (next generation)

$$T_{Cnew} + 9 \cdot C_{IPE} = 46865986.25 \cdot \text{dollars}$$

Cost Comparison of Current Generation Versus Next Generation

$$Gen_{old}(N) := T_{Cold} \cdot N$$

$$Gen_{new}(N) := T_{Cnew} + (N - 1) \cdot C_{IPE}$$

$$N := 1 .. 10$$

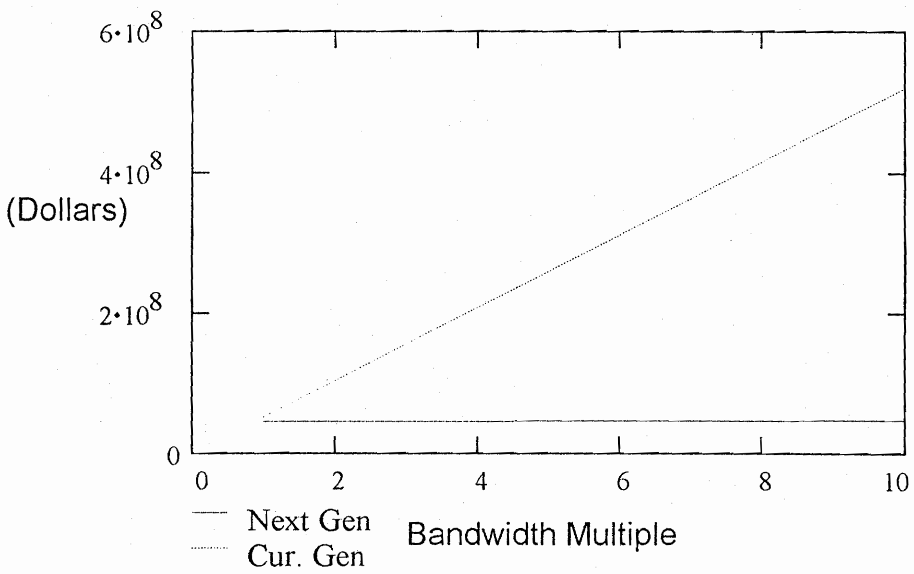


Figure A15. Cost Graph for Bandwidth Multiple