Technology and Policy Drivers for Standardization: Consequences for the Optical Components Industry

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ABSTRACT

Optical communications promise the delivery of high bandwidth service to all types of customers. The potential for optical communications is enormous and has generated excitement and anticipation over the last decade. However, the emergence of a growing market has not materialized and the 1990s communications "bubble" has burst. One result of the bubble burst is that manufacturers of optical components have seen demand for their products plummet and are now struggling to survive. The future of the communications industry depends on its ability to provide better services and higher reliability. At some point, the upward curve of communications demand will require a strong optical components industry to support the industry. If the current stagnation continues, and the manufacturers fail, the economic pillar that is communications will suffer. The MIT Microphotonics Center has initiated a Communications Technology Roadmap study to better understand the technical, economic, and political factors that are inhibiting growth in the optical communications industry.

This thesis examines the current state of the optoelectronic manufacturing industry and the causes of the decline. The primary focus is the rampant proliferation of optical transceiver designs resulting from abnormal market conditions during the "boom years" of the 1990s. The transceiver provides send/receiver capabilities and is the major component of optical networks. Convergence, or standardization, could potentially allow the industry to reach its full potential.
System Dynamics is used to analyze transceiver standardization as a potential solution to the industry's lackluster growth. To support the findings of the System Dynamics model, historical examples are explored to better understand the behavior of the industry and the potential effects of standardization.

The industry currently offers literally hundreds of transceiver varieties. One major challenge to standardization is the development of a reasonable platform for the standard. This thesis will also examine the technical requirements of a transceiver platform and then provide a basic example of a transceiver platform before finishing with proposed policy measures that could guide the industry as it takes its first steps down the path to standardization.

Thesis Supervisor: Lionel C. Kimerling
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Acknowledgements

I think that my time here at MIT would be considered somewhat unique. I entered a two-year masters program, and now three and a half years later, bisected by a semester on leave, I finally graduate. Throughout the journey, I have been fortunate enough to have had the support and guidance of professors, colleagues, friends, and family. I cannot possibly thank everybody that has helped me to finish this thesis. The hardest part of writing this section is making sure I have not forgotten any of the key people from the last three and a half years.

First and foremost, I have to thank my advisor, Lionel Kimerling. In June of 2003, the communications industry was completely new to me and I had some reservations about diving into new subject matter a year and a half into the "two year" program. My gut told me that this would be a great professor to work for and the experience would be well worth any struggles in learning a new industry. I can say now that my gut did not let me down, and I would not have wanted to work with any other advisor. Professor Kimerling's extensive technical knowledge and his ability to put it in the context of broader issues have amazed me from day one, and he has redefined my definition of "guru."

I would also like to thank the efforts of my original research advisors, John Deutch, Ernest Moniz, and more directly, Richard Lester. My work with the Future of Nuclear Power study was short-lived, but extremely valuable. More important than the substance of the work was the patience, understanding, and guidance that these professors provided as I worked out my research and academic interests.

Jefferson Tester had perhaps the biggest impact on my decision to stray from the "normal" Masters program track. Aside from willingly offering sound advice, professor Tester provided an avenue for me to spend a semester at the National Renewable Energy Laboratory in Golden, Colorado. That experience solidified my desire to pursue dual masters and confirmed that Materials Science would be the perfect compliment to the Technology and Policy Program. In addition, living in Colorado for four months gave me access to some kick-ass skiing, mountain biking, hiking, etc.
While on the subject of Colorado, I have to thank Larry Kazmerski for providing the means for my visit to NREL, and to all the research scientists and the management group that patiently worked with me and did everything they could to make sure I got the most out of my time at the lab.

My experience at MIT was in not limited to classes, problem sets, and research. Without a doubt, the most important part of the learning in TPP is through interaction with fellow students. I have gained so much insight and perspective from the people that I have been fortunate enough to spend some time with. I don't have the space to thank all of them, but I cannot understate how much I appreciate the environment of open and thoughtful conversation that is cultivated at MIT. It is what I will miss the most.

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Chapter five of this thesis would simply not have been possible without the contribution of my classmates in course 3.46 *Optical and Optoelectronic Properties of Materials*. Emily, Kelvin, George and I were able to slosh through the complexities of optoelectronic materials and arrive at some semblance of an

understanding. It took too many Sunday afternoons and late night sessions, but if I had to work on waveguides and detectors on Sundays, I wouldn't want it to be with anybody else but those three.

The other parts of the thesis benefited form the enormous contributions from members of the MIT Communications Technology Roadmap. Elizabeth Bruce from MIT, Michael Schabel from Lucent Technologies, and Professor Kimerling served as the source of most of the base knowledge presented in this thesis. In additional, many CTR industry participants and other MIT faculty have offered insight and feedback, either individually or as part of the various meetings and conferences that have been held in the last two years. I can only hope that my efforts contribute in some way to the CTR and the greater goals of the communications industry.

In addition, I have to thank Professor James Hines from the Sloan School of Management for his guidance in the System Dynamics modeling that provides the basis for much of the analysis in this thesis. Jeroen Struben, a teaching assistance for course 15.875 *Applications of System Dynamics* was also a tremendous resource as I tried to learn the standard method and apply System Dynamics to the optical communications industry.

The most important people in my life are my family. I cannot thank my mom and dad enough for the love and support they have selflessly given to me throughout my academic career (not to mention the rest of my life). One of the greatest gifts I have ever received was the unconditional support they gave me that fateful day in Pittsburgh, when over the phone, I said, "I want to stay a couple years longer, and I might need some money to do it." Without so much as a flinch, they both gave me their blessings and I was staying another couple years to finish/extend my studies. Without that extra work that I was able to accomplish during that time, I am certain that my application to attend MIT would have been denied.

My brothers have also been an enormous support. Rudy is in Portland, OR, Derek in Raleigh, NC, and Curtis in Lexington, VA, but we remain as close as ever. I don't know if I can ever convey how important it is to me that we remain involved in each other's lives despite the distances. I hate that we can't all find what we need in the same place, but I couldn't be more proud that we have all found the courage to live life to the fullest and make our own paths. I am still holding out hope for an invention that can take us instantly to weekend barbeques, little league games and birthdays. Despite tremendous effort, I was unable to find an MIT laboratory working on the tele-porter. If I had found it, this thesis would have been slightly different.

I also want to thank the newer members of the family; Jen, Heather, Zach and Katie. As our family grows, I am reminded of what an important part of my life my family has been and will remain.

Finally, I have to thank Aimee for being my best friend and biggest supporter. I am so lucky to have been able to share this time with her as we have grown as individuals and as a couple. Her support and love brought me to MIT. Her companionship and strength motivated me to get the most possible from my time at MIT. More importantly, she has helped me to live life to the fullest and to be grateful for every moment. I am simply a better person with her in my life, and I cannot imagine a life without her.

Our courtship thus far has been defined by academic life, and I think it is appropriate that the last step of that academic life be the first step of the rest of our lives together. I can think of no better way to thank her for all that she has meant to me over the past six years than to offer her the rest of my life…

Aimee Lynn Crombie, I love you more than you can know, will you marry me? I know this proposal might solidify our places in the dorkdom that is MIT, and I wish I were a more elegant writer, but it will be special on our 50th anniversary when we return to MIT and look up my old thesis.

Thank you all for the memories, the experience, and the education.

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Prologue: An Overview

The Motivation

The United States becomes more dependent on communication technologies every year. From the internet to mobile phones, from storage databanks to home entertainment, a link to the world's information sources becomes more and more critical to our daily activities. As the use of the communication channels expands, so does the demand for higher bandwidth and higher reliability. The promise of massive growth in broadband demand led to an investment boom in the middle to late 1990s, commonly referred to as the "telecom bubble" (See Figure 1). During this boom, optical networks took shape as the next generation of communications technology because it promised the higher bandwidth and greater performance that was to allow communication capacity to meet the anticipated levels of demand.

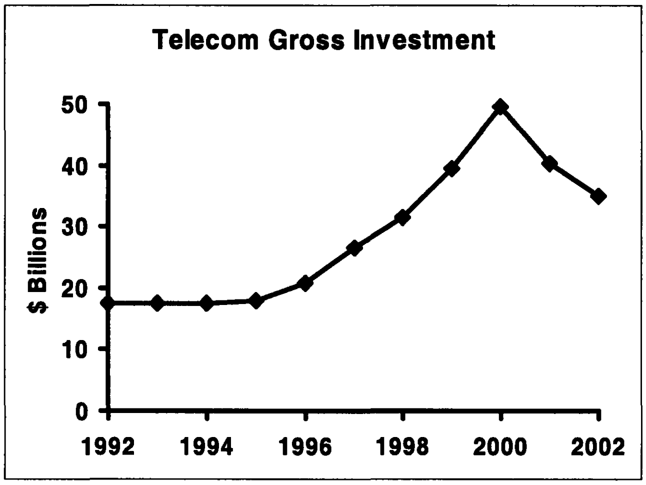

Figure 1: Telecom Investment.[1] Peak occurs at network saturation followed by period of decline that strips the optical industry of a valuable source of revenue

Figure 2 shows an advantage of optical connections as the reach, or distance, of a link increases. Electronic connections become more and more reach-limited as data rates get higher. Physical limitations (distortion from dispersion and interference) become more prevalent as the data rate gets higher. The result is the need for more frequent regeneration of the signal, which is expensive. For example, a 10 Gbps signal may only go a couple meters before the signal is so distorted that is can't be read. The figure shows the costs to reach curve for a generic data rate. The y-intercepts of the curves may increase with increasing data rate (higher fixed costs) and the steps in the electrical curve may be bigger with greater bit rate (more expensive equipment to regenerate the signal). In general, the curves and their intersection point will be different for every situation, but Figure 2 illustrates the basic idea of optical as an alternative to electrical communications links. Optical becomes more competitive as either the data rate increases, or the distance that a signal needs to be sent increases.

The influx of investment lead to rampant infrastructure installations and manufacturing capacity build. Unfortunately, the killer applications that were supposed to make optical the *only* choice for

[1] Source: Hassett, Kevin and Kotlikoff, Laurence. *The Role of Competition in Stimulating Telecom Investment.* October 2002.
http://216.239.57.104/search?q=cache:LuLiCjd0L_YJ:econ.bu.edu/kotlikoff/modelpap10-5-02.pdf+telecom+investment&hl=enCombined investment from CLECs (from William Lehr) and ILECs (from Banc of America Securities)

communications and data transfer have not yet materialized. Manufacturing capacity built in the strong years was much greater than what was actually needed and over capacity now threatens the viability of the OEM industry. As if that weren't bad enough, the corporations that were supposed to continue to support even the weakened telecommunications industry fell victim to scandal and collapse. The result was an optoelectronics manufacturing (OEM) industry that was left with too much to sell and nobody to buy. The condition continues to this day and threatens the OEM firms and the important industry that it supports. This thesis will assess strategies to achieve sustainable growth in the OEM industry and secure the lifeblood to the massive communications industry that is vital to the United States' economic strength.

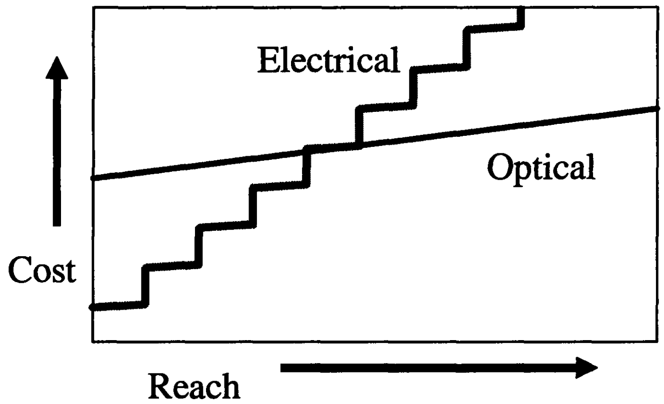

Figure 2: Generic cost to reach comparison for optical and electrical communications links. For any given data rate, electrical signals can only go so far regeneration is needed, which is expensive. At some point, wither at longer distances or at higher bit rates, optical becomes more attractive

In 2002, Tele-communications brought in $425 billion in total revenue while data-communications added another $87 billion[2]. Some experts estimate that nearly two-thirds of US economic growth is attributable to information technology innovation. The enormous impact of the communications industry on the US economy is clear, and the continued growth of the communications industry depends largely on the increased performance and broadband that only optics can provide. The performance and costs of optical components are critical to the transformation of the communications industry to the next generation of high speed technology. It is uncertain whether the current state of the OEM industry will allow adequate investments into research and development (R&D) that would produce adequate improvements. The challenge now before the industry is to create an environment in which it is advantageous for component manufacturers to develop lower cost devices, thereby enabling the deployment of optical functionality across many market segments.

The Means

While the motivation to address the complex problems associated with the optical communications industry is clear and present, it takes a concerted effort by an organization with the means, the resources, and the desire to tackle the issues with adequate resolve. To that end, the

[2] 2002 Economic Analysis. US Census Bureau. Table 1: Advanced Summary Statistics for the US, 2002 NAICS Basis. http://www.census.gov/econ/census02/advance/TABLE1.HTM

Microphotonics Center at the Massachusetts Institute of Technology has initiated the Communication Technology Roadmap (CTR). The purpose of the CTR is to develop technology targets for the long-term evolution of the optical communications industry based on careful market, policy and technology analysis. Meeting these targets will require collaboration among the manufacturers, network providers, and policy makers to develop regulatory and technical standards that will allow the industry to progress to the next generation of communications. Drawing from research efforts in the engineering departments and the Sloan School of Management, as well as knowledge and experience from members of the Microphotonics Industry Consortium, the CTR will provide valuable insights into the future of the industry

The CTR is made up of four Technology Working Groups (TWG), each consisting of approximately fifteen industry representatives. Each of these TWGs focuses on a specific challenge for the industry. The four groups are the Next Generation Transceiver TWG, the III-V Materials TWG, the High Performance Transceiver TWG, and the Silicon Materials TWG. This thesis is most closely associated with the Next Generation Transceiver (NGT) TWG and will provide a contribution to the on-going market, policy and technology analysis.

The Goals

Two of the four CTR TWGs focus specifically on the optical transceiver. The transceiver, which serves as the link between the traditional electronic signal and the optical signal, is the single most important component in the optical network. It is the optical-electronic-optical (OEO) conversion device that makes optical communications possible. The primary goal of this thesis is to propose a strategy for the next generation transceiver that will represent a solution that allows optical communications to prosper while at the same time provides a healthy and viable market environment for OEMs.

The bubble years created an isolationist culture within the OEM industry as individual firms saw little need to collaborate with other firms. Customers were aplenty, and there was no reason to alter component and network designs to fit a more universal concept. The result is enormous product variety in the transceiver market as firms have independently developed network technologies. This large variety has been identified as one of the most important issues that must be addressed. Product variety can be reduced by either waiting for market forces to eventually allow the superior design to win, or the industry can introduce a standard design. The standard would represent an industry judgment about the most likely winning solution for communications. A single standard would allow greater competition within the industry as manufacturers would no longer have exclusive access to networks served by their unique transceiver solution. In addition, all OEMs would be improving the same device, in a sense pooling resources to achieve a better product that could out-compete copper-based and wireless technologies.

These and other advantages of standardization make it a promising option, worthy of further study. This thesis is part of the effort to analyze standardization and other potential solutions leading to the formulation of a strategy for growth that will lead the communications industry into the next generation.

The thesis is separated into five chapters, each examining the role of the transceiver from a different perspective. The first chapter presents a basic description of the optical network that provides a starting point for the analysis. The second chapter discusses the current state of the industry and details the results of the boom of the 1990s that lead to the proliferation of transceiver designs and no coherent plan to direct the technical developments of individual manufacturers. The third chapter introduces a tool for demonstrating the potential impact of standardization. System Dynamics uses a rigorous model-building process as a framework for analyzing the industry and the dynamics that may be important as the industry works toward standardization. The message of chapter three is that standardization is a path that can potentially pull the OEM industry out of its recent recession. The fourth chapter gives a historical account of standardization in other growth industries that reinforces the assertion that standardization would be an important step toward OEM industry viability. In particular, the chapter will describe the experience of the railroad industry in the middle to late 19^{th} century, the Ethernet standard that evolved for Local Area Networks, and the IrDA standard that was implemented to spur the growth of the wireless infrared market. Each story lends lessons that can be taken by the optical communications industry as it explores its growth strategy for the next two decades. The fifth chapter uses the analysis of the previous chapters to formulate potential solutions to the issues that have been raised. This chapter not only proposes policy and regulatory solutions, but also includes a detailed discussion on the technical barriers to standardization and how those barriers might be overcome.

This thesis will examine standardization as a path to restoring the transceiver infrastructure that will support the communications industry. Certain aspects of the industry are more conducive to a single transceiver solution than others. The analysis in this document will explore the barriers and drivers to the single transceiver solutions, make the case that standardization is a sound solution, and then propose recommendations far a path to realize a standardized industry. The conclusions presented in this work are a starting point for further work, and it is hoped that the results in this thesis will serve as a meaningful and useful perspective into an industry that needs to create a more unified vision of its future.

Chapter One: A Starting Point for Analysis

The goal of this chapter is to introduce the basic concepts of the optical network and provide a general assessment of any barriers to a standardization solution.

1.1 The Market Segments

There are many ways to divide the complex and synergistic modern optical network. This thesis will focus on four major market segments: LAN, Broadband access, Storage, and Servers. These four segments represent a spectrum of important markets for optical communications and provide a broad base for a systems-level study. LAN and Broadband access can be considered part of the telecommunications industry and represent applications that are likely familiar to the reader. Any information exchange involving the telephone, the television, or the computer likely travels along a LAN network that transports the information throughout and between metro regions. Broadband access is the use of optical fiber to transport information into, or very close to, homes and buildings. Fiber already reaches many buildings that are part of university campuses and business complexes. The next generation of optical communications promises to include Fiber-to-the-Home (FTTH).

Storage Area Networks (SAN) consist entirely of servers and storage devices and are part of the data-communications network. The networks serve as off-site storage centers for all kinds of users. The Server market segment consists of data connections within a central communications office[3] and is perhaps the most demanding in terms of broadband demand. The Server bus requires that an enormous amount of data flows over a very short distance.

Currently, significant parts of the LAN market use optical communications, although wireless and traditional copper based connections are highly competitive. Optical is almost non-existent in the Broadband Access segment, although there are large installments of fiber-to-the-building (FTTB) and so-called fiber-to-the-Curb (FTTC). The Broadband Access market is comprised of all of these fiber-to-the-x (FTTx) applications. SANs are dominated by optical interconnections, and Server applications have not yet widely adopted the technology, but are ripe for conversion, as we will see.

The current status of optical deployment in each segment is largely a measure of the performance to costs ratio as compared to the performance to costs ratio of legacy copper based networks and wireless networks. LAN networks were developed in the 1980s as the personal computer was introduced into the market. Therefore, much of the existing infrastructure was installed as copper wires. The costs of replacing the copper with optical fiber is an obstacle and will continue to be a barrier until applications

[3] The central communications office (CO) are at the nodes of communications networks and include functions such as signal switching (sending signals down the correct fiber), amplification, data exchange, etc. Enormous data traffic passes through the CO and the transferred of data among different component in the CO require large bandwidth capacity and high reliability.

that require greater broadband than copper can provide are widespread. There are many barriers to optical deployment in FTTH, however, FTTC and FTTB are making the switch in many areas[4]. SANs were virtually non-existent before optical networks were available. In fact, SANs were enabled by the performance and reliability that optical could provide and copper lines could not. Server connections also developed in the copper age, and the costs of re-fitting the cost intensive server "boxes" and overcome other technical obstacles has thus far proved prohibitive. Today's transceivers have been developed to serve longer distance, lower bandwidth connections, and are not yet suitable for the dense information flow required for servers.

This thesis will use a systems level perspective accounting for all of the segments and consider how synergies between the segments can be exploited and how the differences can be restrictive to future growth. This thesis will explore the assertion that standardization of the transceiver design is the key to unlocking the promise of the optical communications industry[5].

1.2 The Basics of the Optical Communications Network

Before any progress can be made toward helping the optical communications industry achieve higher growth, it is necessary to first understand the basic technical structure of the networks in question. The basic building blocks of the optical network can be extremely complex. The purpose of this thesis is not to present an in-depth picture of the network structure, rather, this section will provide a fundamental understanding of the network on a very high level. It is convenient to think of the optical network in terms of the three important conceptual areas of the network; the hardware, data handling, and the network architecture. This section will present a very generic overview of each of these three conceptual areas as they relate to the four market segments listed above; Local Area Network (LAN), Broadband access, Storage, and Servers.

1.2.1 Network Hardware

The focal point of the discussion will be the optical transceiver. In its simplest form, the transceiver is an optoelectronic device that converts electronic data signals into light pulses, sending them down optical fiber by means of a laser while it also receives light from a fiber into a photo-detector and converts it to an electrical signal. Suffice it to say that as a central component in the physical

[4] Reference to Angie Kelic's work for a more complete discussion on the access markets

[5] This assertion is made based on input from members of the Next Generation Transceiver Technology Working Group (formerly the Low-Cost Transceiver TWG), a sub-unit of the MIT Microphotonics Center's Communications Technology Roadmap effort, at October 10, 2003 meeting.

infrastructure, the transceiver industry can have an enormous impact on what is a juggernaut of the US economy[6].

The network hardware refers to the physical components of the optical network. Aside from the optical fiber, the network consists of optical components such as amplifiers that regenerate the signal if it has weaken too much, Add-Drop Multiplexers (ADM) that add and drop different wavelengths of light at each network node, switches that receive the data signal and resend that signal in the appropriate direction (according to the data packet's network layer protocol's address), and the transceiver.

As indicated earlier, the main focus of this thesis is the transceiver, and in fact routers, switches and other optical devices contain transceivers as the OEO interfaces. While the basic components of the transceivers in LAN, FTTx, SAN, and Server networks are the same, the capabilities of each is dramatically different.

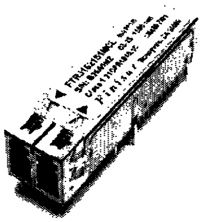

Figure 3: SFP Transceiver

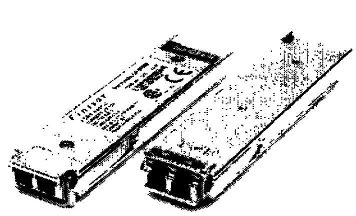

Figure 4: XFP Transceiver

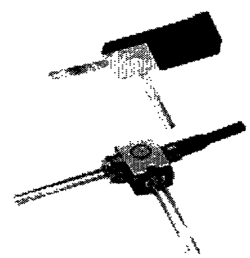

Figure 5: FTTH Discrete Transceiver

The LAN and the SAN transceivers are quite similar. In fact, many transceivers have been designed to be used in both networks with minimal adjustments. In what may be considered the first steps in the road to standardization and a sign that there some recognition of the need to standardize, there have been several cooperative efforts to settle on a single transceiver design for some applications. These efforts, or Multi-Source Agreements (MSA), are likely the result of firms jockeying to be the chosen standard when and if standardization occurs than they are concerted efforts to improve the industry, but they are certainly a step in the right direction. Two common MSAs are shown in Figure 3and Figure 4. The SFP is the most widespread MSA today, however, a more recent MSA that is generating acceptance is the XFP. Time will tell if any of these devices will serve as the basis for a truly utilitarian standard.

The transceivers for FTTx are simpler. Whereas the SFP and XFP package the laser, the detector and the accompanying electronics that drive the laser and perform other functions together, the FTTx

[6] Tivoli Systems, Inc., an IBM company. *SANity Check Preparing for a Storage Area Network.* 2000. ftp://ftp.software.ibm.com/software/tivoli/whitepapers/sanity_check_wp.pdf. This report states that in 2000 over 50% of the world's capital investment in the world was in IT.

transceiver, often referred to as biplexers or triplexers[7], consists only of the laser and the detector, each sealed in a TO-can and then incorporated into a metal box. Figure 5 shows a typical FTTH transceiver, and Figure 6 shows a generic schematic of a typical FTTx transceiver. The leads from the laser and detector subassemblies are connected to the appropriate electronics that drive the laser and manipulated the incoming data.

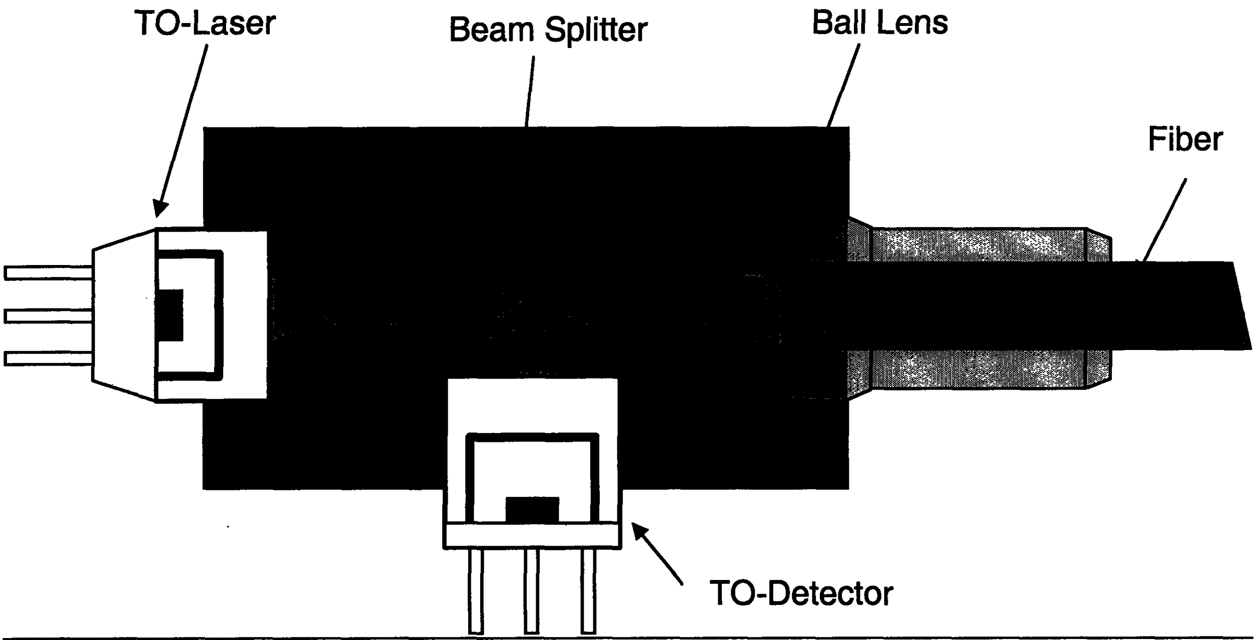

Figure 6: FTTx Discrete transceiver schematic. The laser and the detector are separately manufactured and hermetically sealed in a TO-can. The TO-cans are then integrated into a box along with a beam splitter to separate the incoming light and a lens used to focus the laser light into the fiber.

1.2.2 Data Management[8]

Data management refers to the way in which data is handled in the networks. Data is sent through an elaborate network of fiber and devices, but it cannot just be sent into the optical world without first being conditioned and encoded in a way that the switches, routers and transceivers know what to do with the data once they receive it. This system of languages and codes is referred to as the software of the network.

For the telecom segments (LAN and FTTx) and for the SANs, the language that networks use to talk to computer, routers, and servers is referred to as protocols. A protocol can be thought of as an envelope that encases the core data and delivers it to the appropriate destination. When an internet user

[7] The terms biplexer and triplexer are derived from the number of different wavelengths entering and exiting the transceiver. For FTTH applications, voice and data will enter at one wavelength, exit at another, while video signals are receive at yet another wavelength. This is discussed in more detail in later chapters.
[8] This section is adopted largely from the “Beginner's Guide” section on www.lightreading.com

moves the mouse pointed over a link and clicks, the action initiated a complex procedure of encoding the data inherent in the click, sending it out to the destination, and then decoding the data at the other end

There are a number of layers of protocol that serve to get data from one point to another. The most tangible way to visualize the protocol concept is to consider what occurs when an internet user goes to a particular website, for example www.mit.edu. The *application* protocol layer, usually part of the browser software, tells the computer to display the link. Once the user has clicked, the *presentation* layer protocol, also part of the browser software, translates that click into a data packet.

Table 1: The Basic Protocol Layer Structure for Webpage Data Transport:

Open System Interconnect (OSI)

Layer Number	Layer Name	Layer Description
7	Application	Presentation of link
6	Presentation	Translates click into data – "I want www.mit.edu"
5	Session	Initiates contact between PC and server
4	Transport	Controls quality of established link – Transport Control Protocol (TCP)
3	Network	Translates data (click) into a data bundle – Internet Protocol (IP). The bundle acts as an envelope with an address.
2	Data-link	Ticket to get out of the PC, the stamp for the envelope. Likely Ethernet.
1	Physical	The roads and trucks – optical fiber and, perhaps, the Synchronous Optical Network (SONET)

So, now there is a packet of data residing in the computer that is saying, "I want www.mit.edu." That request is of little use unless there is contact with the world outside of the computer. The *session* protocol layer initiates the contact with another machine, in this case the MIT web server, and maintains that connection for the length of the exchange. The *transport* layer serves as the quality control manager of the connection. This network protocol layer bundles the data packet into an envelope that will deliver the data to the MIT server. This envelope will contain an address that will tell the network routers what to do with the envelope once it is received.

Just as is the case with real mail, the envelope needs a stamp, and that comes as part of the *data-link* layer of protocols. The data-link allows the envelope to roam outside the PC into whatever network type is appropriate. For the www.mit.edu request, that network is usually the Ethernet. For SANs, it would be Fibre Channel. It is convenient to think of this protocol layer in terms of postal carriers. The stamp must be consistent with the carriers – a Federal Express label cannot be used to send a package through the US Postal Service. Finally, the *physical* layer is the roads and trucks of the Federal Express analogy. Optical data packets cannot be delivered without optical fiber and further framing of the data packet by the vehicle for network transport, perhaps the Synchronous Optical Network (SONET).

Table 1 summarizes this basic description of network protocol for webpages, known as the Open System Interconnect (OSI). All networks operate with a more complicated protocol layer than the simple seven layer OSI. In most applications, there are additional layers that account for functions such as error correction and network management. The OSI layer structure presents a straight forward model for the protocol systems and serves as a foundation for understanding data management in telecom and SAN applications.

The few smaller Server networks that have used optical connections also use a similar structure to encode the data as the Server interconnects are little more than an extension of the telecommunication or data-communication network that the Servers service. More advanced data management techniques have not been developed as larger capacity Servers do not employ optical connections.

The data itself, carefully packaged and ready to be sent, enters the world outside the PC and joins billions of other packets of data as they crisscross the network. One of the advantages of optical signal versus traditional electronic signals is that the data stream does not produce any type of field (electric or magnetic) and are not affected by any field. In contrast, in electrical communications, the system engineers must be careful keep each data packet isolated from other data packets so that they do not disrupt each other. There are a number of ways that optical communications takes advantage of this condition to supply much faster information transfer.

One method to dramatically increase transfer speed is with Wavelength Division Multiplexing (WDM). Lasers send light down a fiber in a series of flashes. For technical reason that will be considered in chapter five, there is a limit to how fast the laser can produce those flashes. To overcome the limitations of the single laser, it is possible to simply add more lasers. Since there is no field interaction among data packets, in theory it is possible to send as many signals as the sender cares to send, all at the same time. The catch is that if the sender sends every data stream at the same wavelength, the information will get mixed up and there will be no way to distinguish one data packet from another at the receiving end.

The solution is to send the data packets on different wavelength pulses, and this is in fact the basic concept behind WDM. There are two problems with this solution also. First, because of the optical properties of the fiber, certain wavelengths suffer higher degrees of dispersion forms of loss as it travels down the fiber. There is a narrow range of wavelengths that can be used in today's optical fiber, and all communications are conducted at or near 850 nm, 1310 nm and 1550 nm wavelength light. This restriction reduces the number of different wavelengths that can be used. The other problem is that in designing an optical network, it is important to reduce costs and complexity. WDM requires multiple lasers and adds to both costs and complexity.

There are two manifestations of WDM in optical networks today, DWDM and CWDM. DWDM, or Dense WDM, was developed to cram more wavelengths into a fiber and was originally developed as a method for increasing available bandwidth. CWDM, or Coarse Wavelength Division Multiplexing, utilizes on the order of 10 wavelengths, each separated by about 20 nm. CWDM is a recent application of WDM used in Access networks where the voice, data, and video streams are separated onto different wavelengths.

Another method for increasing the data transfer rate is Time Division Multiplexing (TDM). TDM uses precise timing of the laser signal to combine multiple sources of information. For example, if there are 100 PCs in an MIT laboratory, and each of them send a request to access www.nerdsunite.com, TDM will assign each request a time slot and send the request at the appropriate time. This serves to reduce any bottlenecking and prevents any one user from consuming all the bandwidth. The downside is that each user is only allowed to use a portion of the available bandwidth of the fiber. In our MIT laboratory example, if the fiber serving the lab is a 10 Gbps fiber, each researcher has access to only 10 Mbps.

The functionality of TDM embedded into the Silicon integrated circuit that controls the timing of each multiplexed signal. The functionality of the WDM is a simple filter that separates light waves. While integrated circuitry is more complex than optical filters, silicon ICs have advanced to the point where TDM is a fairly simply function to support.

Depending on the needs of the network and the protocol employed, data can be sent through fiber in two fundamental ways. Packet switched networks transfer complete data sets in components broken in packets. The information is separated into packets as dictated by the Transport and Network protocols (see Table 1) and reassembled at the destination. If the communications needs to be more continuous, the data can be sent through a direct line. In direct line communications, connections between two devices is opened and remains open until the transfer is complete. Packet switching is fine for most communications such as the internet and some data transfers. Other communications need direct line service, such as a telephone call. It would be inconvenient to have a conversation with someone when sentences are chopped and responses are delayed. Also, a direct line can provide a more reliable and secure mode of transmission for sensitive transfers[9].

The data management schemes presented in this section offer no resistance to the implementation of a standard solution. The packaging and sending of data is handled by electronics embedded in the integrated circuit that drives the laser and converts optical signals back to electronic signals. The manner in which this OEO conversion is done is more of a software concern outside of the core functioning of the transceiver. The accompanying electronics may be a point of controversy for the standard transceivers as experts debate whether or not the standard transceiver should include these electronics, or if the they should be keep separate, allow consumers to use whatever electronics bests suits their particular needs.

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[9] There is a growing interest in making all communications via IP packets. Data management technology is advancing that could allow all the advantages of direct line service via a packet switched network.

1.2.3 Network Architecture

The network of optical fiber and the components that control the flow of traffic on the fiber can be arrange in various ways to achieve an efficient and practical system. The topology of this system of physical medium constitutes the network architecture. The network architecture can have an impact on the reliability, performance and cost of a network. The number and type of transceiver depends on topology and therefore any standardized transceiver must account for the typical network configurations

.

LAN networks connect large geographical areas and are served with a number of different topologies. Four of the most common network topologies are shown here;

1) **Local Bus** – The bus topology is a linear system. The signal is sent from a network station and is sent the length of the medium, and is received by all other stations. The local bus topology is simple in it implementation, however, it is inefficient in its function. Signals are transmitted from the central station to every device, and every return signal from the devices must go to the central station before it goes to its final destination.

Figure 7: LAN Local Bus Topology. A simple linear connection between neighborhoods and campuses

2) **Ring Topology** – Ring topologies connect a series of devices via unidirectional links. Unlike the Local bus, where signals are sent back and forth along the backbone, in a ring network the signal always travels in one direction. Token ring uses a ring network[10]. The token system is more efficient than the local bus in terms of directness of the signal. It is, however, more difficult to implement in high data rate environments or when there are many users trying to use the network at the same time.

[10] Token ring is a LAN protocol in which a device will send out a "token" when it is ready to transmit. Once the token returns to the sending device, the network is clear, and the device sends.

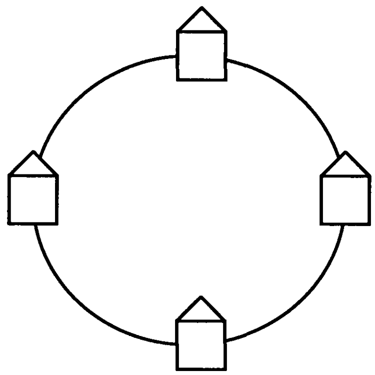

Figure 8: Ring Topology. Often use with the Token ring protocol, the design is problematic if there are too many users.

3) **Tree Topology** – The tree topology is essentially the same as the Local Bus, except that branches are formed to make a tree. This topology improves on the linear Local bus in that the signals do not have to go through all of the devices on the network, only those on the common branch. The star topologies of the FTTH as described below are similar to this tree topology.

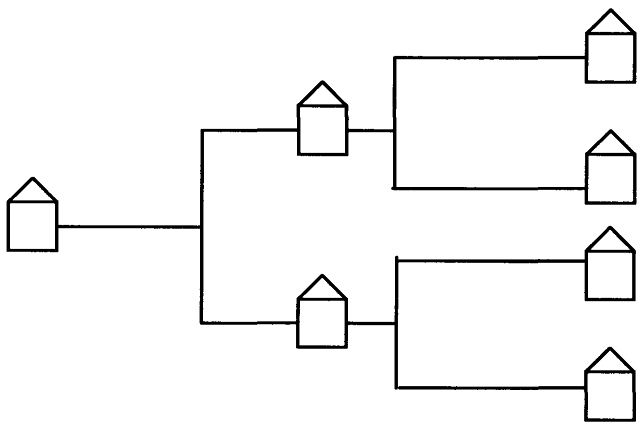

Figure 9: Tree Topology: Basically, a combination of multiple Local Bus connections.

The network architecture for FTTx is perhaps the most varied of any segment. The following is a catalog of those architecture varieties with a brief explanation of each;

1) **Active Star** – The active star is a practical and effective way to introduce optical networks to the home and the building. The technology involves active switches at remote nodes that read the data and send to the correct destination. The big advantage to this network architecture is that the data signals can run over existing copper lines. Therefore, if DSL or cable broadband is instituted before optical fiber has been installed, there is no need to change the technology to accommodate the switch. This allows for implementation of fiber on a case-by-case basis and is much more cost effective. The

disadvantage is that it requires active components, which means power is needed at the remote nodes and therefore the costs of operation is increased.

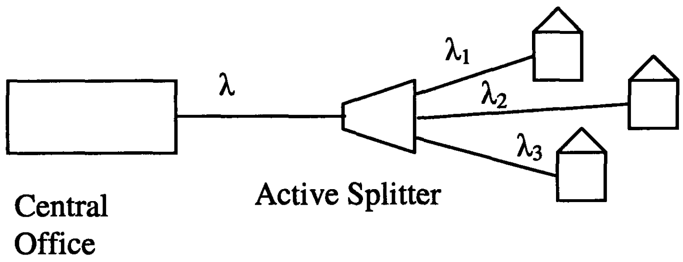

Figure 10: Active Star Network. The active splitter receiver a data stream and sends a unique signal to every user

2) **Home Run** – This architecture can also be described as point-to-point. Unlike the active star, there is no remote node, and each end user has a dedicated line from the central office. The advantage to this architecture is that there is no broadband sharing, meaning each end user gets the whole capacity of the line. Also, there is no power lost from splitting, so the signal can travel longer distances without the need of amplification. In addition, each user can use a different service, creating a more competitive marketplace. The big disadvantage is that fiber must be laid for the entire distance from the central office (could be 10s of kilometers) for each user. Such a network is costly and could make rapid deployment of FTTx difficult.

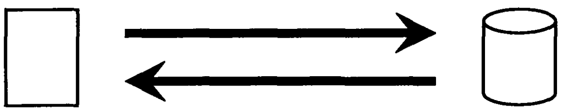

Figure 11: Home Run Network. Linear, direct connection

3) **Passive Star network** – Passive star is a common configuration in the Passive Optical Network (PON) family of architectures. The advantage of a passive star network is that there are no active components. The data signal is broadcast, through an optical splitter, to each home or building, where the appropriate data is selected out from the entire flow. There are a couple disadvantages to this design. First of all, there are potential problems with security as every user receives all the data for every other user on the star. In addition, the costs to upgrade the systems are large because each upgrade requires that every component at the central office, the splitter and the home/building requires an upgrade. Figure 12 shows a schematic of the passive star

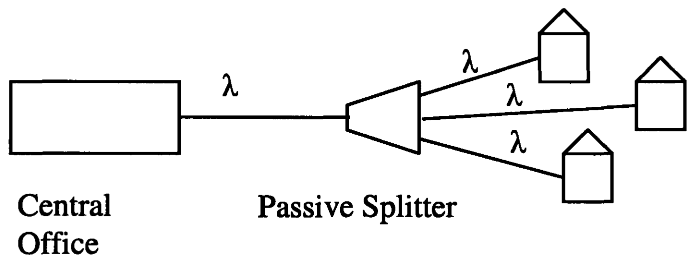

Figure 12: Passive Star Network. Similar to active star, except splitter uses no power, and all customers get the same signal. The appropriate signal is then stripped out by the end user's equipment

4) **WDM PON** – The other basic architecture for the PON family of networks, this architecture takes advantage of WDM technology by installing a wavelength dependent splitter. Each home or building's data is sent at a specific wavelength. The splitter separated the wavelength and sends only the appropriate data to each end user, solving the security problem of the Passive Star. Additionally, the technology can evolve independently in each home or port. Technological advances can be implemented at one wavelength and not there others, allow for a more time sensitive deployment

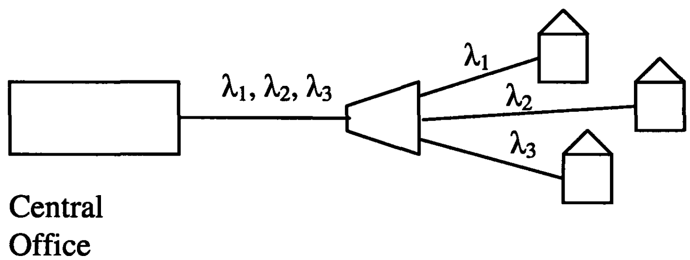

Figure 13: WDM Network. A multiplexed signal is split by the splitter, sending a particular wavelength to each end user. Depending on the data-link protocol, it can be Ethernet PON (EPON) or ATM PON (APON).

5) **Optical Fiber Aggregation Point** (OFAP)[11] – OFAP employs more complicated, but more efficient architecture to allow for a higher utilization of the ports. This network allows for greater flexibility in service rollout as neighboring homes and buildings can be served by different technology generations. Also, the cost of expansion is reduced. In Figure 14, the dotted line represents possible market reach that would need just a fiber roll, without the additional cost of the central office and the splitter node. OFAP can be deployed as either a passive star or a PON infrastructure or both.

[11] Adopted from Sirbu, Marvin A. *FTTH Technology.* FTTH Council, October 16, 2002. Carnegie Mellon University, Department of Engineering and Public Policy.

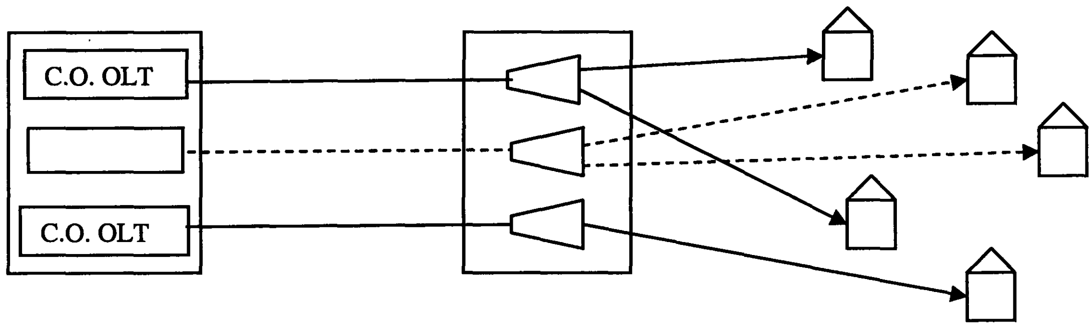

Figure 14: OFAP Network. More flexible and more scalable version of the PON or the active star network

The SAN network topology can also be somewhat varied and, again, will determine the transceiver flavors necessary. There are three basic topologies used in SAN; Point-to-Point, Arbitrated Loop, and Switched Fabric.

1) **Point-to-point** - This is a simple topography and is self explanatory. It is equivalent to the home run lines in FTTH.
2) **Arbitrated Loop** – Arbitrated Loop is capable of supporting up 127 ports (although in practice, much less). When a port is ready to transmit, it sends a signal that basically says "I am ready to send." Once that signal makes its way around the loop and arrives back at the point of origin, the port has control of the loop and transmits to desired destination. This architecture is essentially point-to-point with a middle man – the "channel" part of the structure

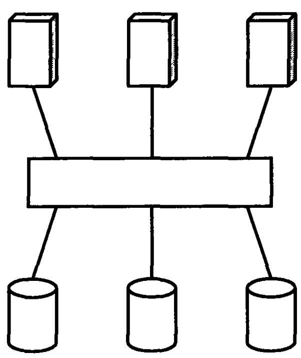

Figure 15: Arbitrated Loop. All connected Servers share bandwidth through the hub, or channel. The channel can be relatively inexpensive, but cannot support too many devices.

3) **Switched Fabric** – The arbitrated loop can get bogged down if there are too many devices on the loop. With many users, the switched fabric is a superior option, although it is more expensive. It this topology every device has an independent connection to every other device. It is an expensive option because there are redundant connections. Every device uses a transceiver at the

device and another at the fabric, as opposed to the arbitrated loop topology that requires just one transceiver at the device.

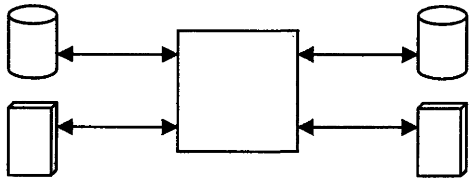

Figure 16: Switched Fabric. Each device has an independent connection with every other device, providing full duplex communications and high redundancy.

The fiber channel networks have been used in SANs because of their high speed and reliability, however, they can be complex to implement and manage. Technical standards do exist for Fiber Channel, but these standards have been interpreted differently, leading to the deployment of optical components (i.e. transceivers) that are not interoperable. There has been a move toward IP-based storage solutions. This type of convergence of operating protocols (IP is the protocol of choice for most internet based communications) is an important part of transceiver standardizing, as we will see later.

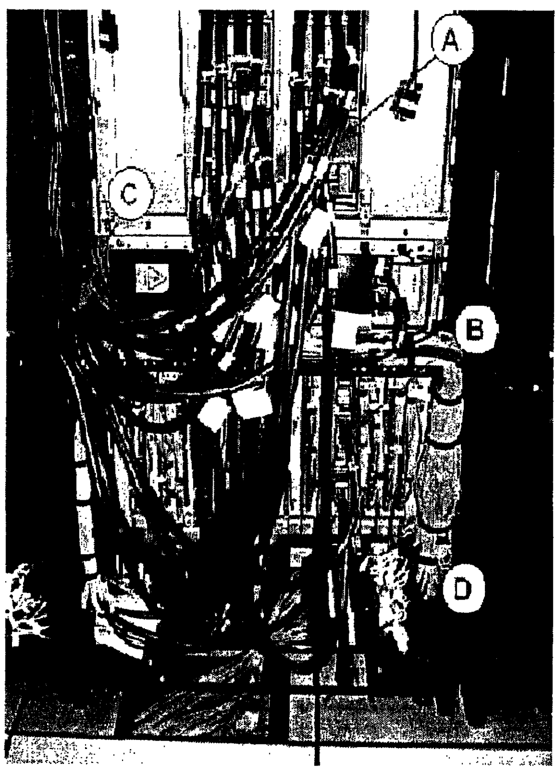

Figure 17: Server Box with cable interconnects

The Server segment of the optical communications industry refers to the interconnection between servers that reside in the same "box." There is no real network architecture to speak of beyond the simply point-to-point connection that spans a distance on the order of meters or less. Figure 17 shows an illustration of the limits of copper based server connections and gives some idea of the potential benefits of adopting an optical infrastructure.

Understanding a general description of the network is crucial to performing an analysis of the industry. Much more detailed understanding is ultimately required as the analysis becomes more evolved. This section provides the foundation for that evolution. The rest of the thesis will explore the current state of the optical components industry, study the potential impact of standardization as a solution to the industry's recent slump, and then offer policy and technology solutions for how to get to a standardized industry.

Chapter Two: The Current State of the Optical Components Industry

Network communications services have evolved from plain old telephony (POT), to broadband internet, to the promise of video-on-demand service as the next boon in home entertainment. There are also data networks that use optics to manage high data flows in Storage Area Networks (SAN), server buses, and optical cross-connects. The future of optics includes data transfer in automobiles (already being developed in high-end luxury models), personal electronics, and eventually chip to chip and on-chip interconnections on the micro scale. Deployment of more advanced services, along with the continued expansion of existing services, suggests enormous growth potential for the industry. The critical question, then, is why has this potential not materialized? This chapter offers one explanation: the unmanageable proliferation of transceiver varieties has rendered impossible any path to a low cost device that would allow optical networks to be cost competitive with other communications technologies. As is discussed in the next section, a major obstacle to achieving lower costs is the lack of volumes that would allow economies of scale and learning in manufacturing. The proliferation of transceiver designs means that each OEM is limited in the scope of their product reach. If each design can only serve a limited consumer base, there is a greatly reduced potential for high volumes. This idea that design variety can be a barrier to high volume is the basic theory for this thesis and the rest of the document will explore that theory.

The problem is double-sided in that the industry faces a chicken-and-egg dilemma. One the one hand, costs will drop once there is a sufficient volume of transceiver sales to activate economies of scale and manufacturing learning. On the other hand, volumes will not be realized until optical networks are cheap enough to install in place of other networks (wireless and copper-based networks). To add a third dimension, development of bandwidth intensive applications could supply the necessary demand for optical networks to drive volumes, however, developers will not sink money into developing those applications until the infrastructure is in place – i.e., until there is sufficient volume of optical interconnections.

This chapter gives a description of the current state of the industry. Beginning with a summary of the first meeting of the NGT TWG and working though the current available options for transceivers, the case is made that proliferation is indeed a problem and that many firms are beginning to recognize the need to change the trend of divergence that has dominated the industry for a decade or more.

2.1 Are High Transceiver Costs to Blame for Industry Ailments?

The original name of the Next Generation Transceiver TWG was the Low Cost Transceiver TWG. "Low Costs" turned out to be too loaded a term for transceiver manufacturers because of the difference of opinion of the definition of "low costs" as well as the role of "low costs" in a healthy industry. It is clear, however, that lower costs transceivers are of critical importance. Chapter four will further illustrate the basis for the focus on low costs.

A survey of the TWG members conducted prior to an October 10, 2003 meeting provides a snapshot of the industry thinking on achieving low costs. The survey asked participants to comment on the requirements for achieving a low cost solution and the barriers to that low cost solution[12]. The results of the survey provide a chronicle of the key issues for reducing transceiver costs. The key points were that 1) volume is the key issue. No cost reduction can be achieved without significantly higher volumes of transceivers sold. 2) Packaging constitutes a large portion of the costs for each transceiver and is the main barrier for reducing costs[13]. These two points suggests the central question that is addressed by this thesis; Does one package applied across all applications solve the problem by providing volumes necessary that can ultimately reducing packaging costs by economies of scale and manufacturing improvements through enhanced learning?

Appendix I-B gives a summary of the survey responses. The survey divides responses into three representative market segments; Core/Metro, Enterprise, and Access/FTTx[14]. The responses were further divided into three broad categories of the industry; design of the transceiver itself, manufacturing of the transceiver, and factors related to the transceiver market. The tables in the appendix give a more detailed account of the survey responses and will provide a guide to the solutions offered in later chapters.

The survey responses highlight a number of issues for developing a Next Generation Transceiver. First of all, some common themes for design issues include implementing electronic dispersion compensation[15], the use of long wavelength VCSEL[16]s, and some kind of dramatic design change, be it the switch from TO-can[17]-based devices to PIC[18] devices or other changes. Of course, not all thoughts on the requirements for a more cost-effective design are the same. In particular, there is a difference of opinion as to whether the electronic and optics should become more integrated or more separated. One school of thought is to allow the electronics advance on their own as the electronics industry has

[12] A reproduction of the survey of included in Appendix I-A
[13] Comment by Art Wilson (JDSU) at the October 10, 2003 Low Cost Transceiver Technology Working Group Meeting.
[14] Some sort of definition of these segments
[15] Electronic dispersion is the spread of a light pulse as it travels down fiber. If the spread is too great, adjacent signals become mixed and unreadable.
[16] VCSEL – Vertical Cavity Side Emission Laser. A favored laser design due to low costs and relatively easy manufacturability.
[17] TO-can refers to a hermetically sealed device that contains either the laser of the photon-detector and is coupled to electronics to receive and delivery information, and to optical fiber to send and receive optical signals.
[18] PIC – Photonic Integrated Circuit refers to the monolithic integration of two or more integrated optical circuits on a single substrate. It is the optical equivalent of microelectronic chips.

developed its own expertise and has been extremely successful. As the electronic functions such as electronic dispersion compensation and TDM improve, the transceiver can be upgraded accordingly, providing an additional avenue for competition. The other side argues that the electronics must be integrated into the transceiver design to provide a more pluggable device that can be used in any applications. This question of partitioning[19] will be important for the development of a standard transceiver, as we will see in chapter five.

Most respondents agreed that transceiver costs could be reduced by developing manufacturing solution such as automated processes[20] and active alignment techniques[21]. As mentioned above, decreasing the packaging cost is one of the most important areas in need of improvement.

Market-based solutions are also very important. Again, volume is sited most often as the key to achieving low costs. In addition, many of the survey responses indicate a need to converge the vast number of current technical standards that exist for many market segments. The convergence of standards should not only allow inter-operability within each market segment, but also across segments. This convergence would allow manufacturing to leverage their volumes and increase the ability to decrease costs.

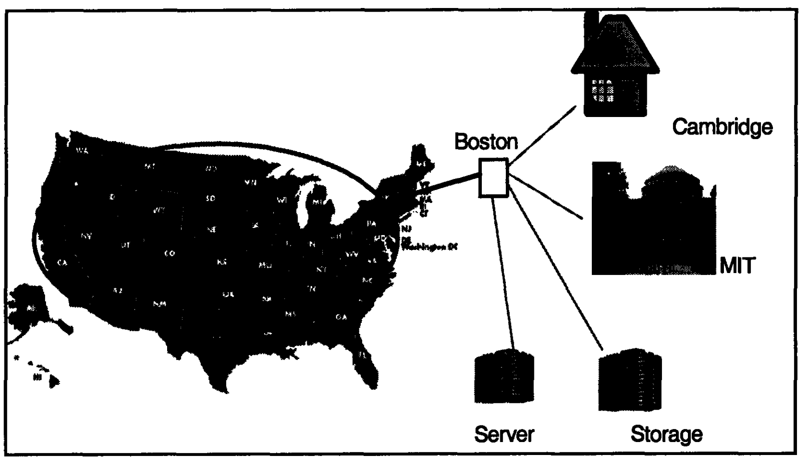

Figure 18: Abstraction of the communications network. The country is connected by a series of large loops. Metro areas and larger concentrations of users connect to the cross-country loop and then connect to smaller networks through a variety of network configurations (see section 1.2.3). The network connects all individual homes, buildings, storage units, Servers, etc to each other

The results of the survey are extremely insightful and provide a direction for the research in this thesis. The evolution of the Low Cost Transceiver TWG to the Next Generation Transceiver TWG has shifted the emphasis of the TWG away from low cost, although the some sort of cost reduction remains a core issue. The lessons remain relevant even if the emphasis on low costs does not.

[19]A transceiver consists of transmit functions, receiver functions, multiplexing functions, electronic functions, etc. Partitioning refers to the separation of those functions within the transceiver or external to the transceiver.

[20] Most manufacturing today is done overseas and uses hand assembly. Cheap labor and lack of demand have allowed this manufacturing trend to persist.

[21] Much of the alignment of the laser and photo-detector with the optical fiber is currently done with active processes that require to device to be activated and connected to a sensor that allows the worker to gauge the quality of the alignment. Passive technique would not require that the devices be powered.

2.2 *A Snapshot of the Problem*

A logical starting point to begin a discussion on the issue of proliferation of transceiver designs is to paint the picture of the optical communications world. Optical signals travel around the country in a loop of fiber with various drop points that serve LAN sub-regional markets along the way. Figure 18 shows a representation of this system. There exist a number of transceivers (depending on the bandwidth needed and the network architecture) at every link on the network. Each of these links utilizes a different transceiver with different technical parameters. For example, the link from LA to Boston uses 1550 nm wavelength light to travel the long distance to reduce the effects of dispersion and scattering that result in a weakening of the signal[22]. The link between MIT and some central office in Western Massachusetts (part of the LAN) may use 1310 nm light at a lower laser power because the signal does not need to travel as far and the network designers are less concerned with loss mechanisms[23]. Each of the different links shown in Figure 18 operates at a different bit rate, and uses different protocols to encode the data, and probably uses a different package to house all of the required functionality. Add to that diversity the different types of transceivers that are produced by the numerous firms competing within each market segment, and the number of transceiver varieties can quickly expand. For example, firm A serves MIT by

> **The Network Effect**
>
> As a classic example of network effects, it is easy to consider the telephone industry. When Alexander Graham Bell invented the telephone in 1875, it was a world-altering accomplishment of modern science. But, the full benefits of the telephone would not materialize immediately. The telephone's functionality is predicated on the condition that someone else has a telephone, and that the telephones are connected by a wire that carries the signal. Without such architecture, a telephone is essentially useless. It is easy to see that as more people acquired a telephone and were connected to the network, the more valuable the telephone became.
>
> In the environment after the 2001 crash of the telecommunications bubble, the lack of this network advantage became evident. Optoelectronic manufacturers that supplied one market could not communicate or interact with another similar network nearby. In other words, the advantages of network effects were minimized because the extensive array of optical networks could not be integrated into one network. While this lack if interoperability did not greatly impact the end user, the network providers suffered because their services could not be offered to more potential customers. In addition to the telephone and communications, similar network effects are at work in the railroad and electric power distribution industries, as well as any industry that relies on interconnectivity.

[22] The cross continental links are part of the Core or Long Haul market segment. The Core is not treated directly in this thesis because the technology is very closely related to LAN. At present, Long Haul communications are dominated by optical connections.

[23] Since 1550 nm laser are more expensive than 1310 nm laser, the network engineer will use the cheapest device capable of meeting the demands for the application. 850 nm light is more susceptible to loss, however, the laser is much cheaper and therefore in the shorter distance applications, 850 nm light is common as the light does not travel far enough for scattering to be a major performance issue.

building its network from the Boston central office to MIT. That network is optimized for the specific application of supplying broadband to MIT and the transceivers used in that network are uniquely design for that optimization. Firm B serves parts of Boston's financial district in a similar way. Both firms service the same market segment, but they do so with different data management, network hardware, and network architecture, requiring a different transceiver design[24]. Each combination of bit rate, wavelength, package, etc that is developed to accommodate the specific specifications of each network installment constitutes a "flavor" of transceiver. It is plain to see that, left unchecked, the potential variety could result in a rapid proliferation of transceiver "flavors."

During the middle to late 1990s, the telecommunications industry was booming (see Figure 1). Investment dollars to build new networks and infrastructure was in no short supply. This meant that suppliers had plenty of business and there was very little competition. Each firm developed and marketed its own brand of network with the corresponding optical equipment feeling that cooperation with their competition was not needed to be successful. The end result was an industry fragmented and disorganized. Each of the links shown in Figure 18 would be equipped with optical components from different vendors. Essentially, the potential variety of transceivers described above was indeed left unchecked.

In addition to proliferation of transceiver designs, the development of new manufacturing technologies was stifled as firms scrambled to collect any and all manufacturing capacity they could get. The result was that old manufacturing technology was valuable, and new technology was not developed.

When the market crashed at the end of the 20^{th} century, the traditional industry model proved problematic. Consolidation of networks was very difficult because each network functioned with different software and hardware. One firm's transceivers and network could not be readily incorporated into another firm's. Mergers could not result in the cost-saving consolidation of manufacturing processes as the discrete network components still needed unique manufacturing parameters. In other words, firm A and firm B from the example above could not effectively combine operations. Aside from the inability to consolidate manufacturing costs, the industry also suffered from deficiencies in network benefits (see box previous page). The industry is now faced with a choice; it can either continue on the current path waiting for Darwinian forces to eventually settle on the one best solution – and hope that the solution does not arrive too late, or the industry can seize the opportunity to formulate a strategic plan for further development based on multi-company cooperation and analysis[25].

[24] This is a hypothetical narrative to illustrate a point. The story is not an accurate description of any specific firm or the actual division of services.
[25] Michael Schabel, Lucent Technologies, chair of the NGT TWG. Remarks from the TWG meeting October 10, 2003

2.3 Evidence of the Proliferation Phenomenon

The results of the period of non-cooperation that coincided with the boom years of the 1990s are plain to see. To illustrate the extent of the proliferation that has occurred in the transceiver market, a database of current product offers has been produced. The data is constructed from the commercial offerings of six major OEM players in the transceiver supply market; Finisar, JDSU, Infineon, Excelight, Agilent and Intel. While the sample pool is by no means comprehensive, the result is representative of the current market.

The first step in the analysis of the collected data is to define the parameters that will constitute differing transceiver flavors. For the purposes of this exercise, the major parameters include application, bit rate, wavelength, reach and form factor. Table 2 gives definitions for each technical category that is used in this analysis. These are overly simplistic designations, but they provide a meaningful way to think about the devices. These technical categories and their specifications allow a more detailed analysis of the results of this exercise.

Table 2: Definition of Technical Definition of Transceiver Flavors

Technical Category	Specification
Application[A]	SAN, LAN, WAN/MAN
Bit Rate (Gb/s)[B]	0.155, 0.622, 1.0, 2.5, 10
Wavelength (nm)	850, 1310, 1550
Reach[C]	SR, IR-1, IR-2, LR
Form Factor	SFF, SFP, GBIC, XFP, MSA[D], Other[E]

A: For simplification purposes, all Fiber Channel enabled devices are included in the Storage Area Network (SAN), all Ethernet devices are included in Local Area Network (LAN) applications, and Metro Area Network (MAN)/Wide Area Networks (WAN) are populated with SONET/SDH transceivers.
B: Many of the devices, particularly in the 0.622 Gbps level, are multirate and therefore there is some overlap in the data gathered in this survey. The data indicates the highest data rate available each device.
C: Short Reach (SR) is specification less than 2 km. Intermediate-1 (IR-1) includes ranges from 2 km to 20 km, Intermediate-2 (IR-2) is anything above 20 km to 40 km, and Long Reach (LR) includes all devices that reach beyond 40 km. Some devices specifications included both multimode and singlemode reach specifications. In those cases, the singlemode number is given.
D: MSA includes packages that meet all Multi-Source Agreement specification and footprint parameters, except that they do not follow the 2x5 or 2x10 pin configuration for SFF electrical contacts.
E: Other packages do not fit easily into any category as they as configured to fit a particular network application.

2.3.1 Worst Case Scenario

The starting point of this analysis is to demonstrate the number of products available if all of the combinations of devices were possible and offered by the industry. Table 3 represents the worst case scenario for transceiver proliferation. Given the five technical categories and the corresponding specifications, there are over 1,000 possible transceiver "flavors." A particular transceiver flavor is defined as a hypothetical transceiver with a uniquely defined set of five specifications, one for each technical category. It is worthwhile to note that while there may be different ways to represent the important technical categories and their respective specifications, the point is likely the same – the potential for proliferation is enormous.

2.3.2 Current Case

The survey of six major transceiver suppliers was important in that it gives an indication of the current state of the industry and the level of proliferation. Each bin in Table 4 represents a class of transceivers that is defined by two independent (not in the same technical category) specifications. The specifications for the remaining three technical categories can be considered variable. Therefore, each bin actually represents a class of transceiver flavors defined by the specifications corresponding to the row and column of the bin. The diagonal numbers indicate the total number for each parameter. For example, there are 105 total SAN devices and there are 91 total SR devices. It is important to note that there is some overlap (some transceivers serve both SAN and LAN networks, for instance) and therefore a simple arithmetic sum of the diagonals does not result in the total number of transceivers in the survey. In reality, there were approximately 340 total types of transceivers included in the survey, with more than 600 product numbers. Many product numbers refer to products with different latch designs, temperature tolerances and other features that were not considered to be major technical categories[26]. Some aggregation reduced and simplified the data set.

Beyond the simplification of the data set, some combinations of technical categories do not mix. For example, there are no devices that offer 850 nm light at long reach. Some of these combinations are simply not offered by any of the six suppliers in the survey, and some are not feasible for technical reasons. The combinations that are not available are indicated with a zero

[26] While latch design and temperature tolerance are not considered major technical categories, it should be pointed out that proliferation is considered problematic because it increases the required number of production lines and inhibits the potential for volume per line that can help reduce costs. Adjusting production for different latches and adding shielding for temperature resistance certainly requires some variable production processes.

in Table 4. Each of these non-available combinations represents the elimination of the entire class of transceivers for that bin. Some assumptions are made to make the analysis more reasonable. For instances, some of the 1.0 Gbps GBIC transceiver are multi-rate and therefore there actually are 0.622 and 0.155 Gbps GBIC devices available.

Table 3: Mathematic Potential of Proliferation

Technical Category	Specification	Number of Specifications
Application	SAN, LAN, WAN/MAN	3
Bit Rate	0.155, 0.622, 1.0, 2.5, 10	5
Wavelength	850, 1310, 1550	3
Reach	SR, IR-1, IR-2, LR	4
Form Factor	SFF, SFP, GBIC, XFP, MSA, Other	6
	Multiplicative Total	**1080**
	Approximate Number of Logical Exclusions	**~500**
	Effective Total	**580**

If all the excluded flavors are totaled, taking care not to double count, the total non-available flavors would be about 500. This means that there are still almost 600 flavors left in the current market and proliferation potential remains enormous (see Table 3). This is an imperfect analysis of the market, but the message is clear – the variation in transceiver design and the corresponding manufacturing differences creates a concern for interoperability and long term price reduction and profitability for the optical components industry.

2.4 The Standardization Option

OEMs have experienced a sharp downturn in revenues as transceiver sales have dried up. This state of the industry has motivated the manufacturers and the firms that rely on those manufacturers for low cost, high performance network installations to participate in the CTR. The initial meetings of the NGT TWG have demonstrated that lack of volume is at the core of the industry's sluggishness. It is largely believed that lowering costs is the way to drive volumes. Volume will allow manufacturers to produce cheaper transceivers that will in turn make optical connections more attractive to network providers.

The previous chapters have hinted that standardization is proposed as a solution to the problems of lack volume and overall industry health that have plagued the optoelectronics industry in recent years. Standards have many recognized benefits that could help the OEM industry to survive[27]. First of all, since the OEMs will all be making the same transceiver platform that can theoretically be plugged into any network, customers (network providers) will have more suppliers to choose from. On the surface, this is bad for the OEMs, and very good for the providers. OEMs will no lose niche markets and will be exposed to severe competition as providers will be able to shop around for the cheapest supplier even for network upgrades and expansions. The long term affect, however, will be a product more attractive to the providers, and a larger piece of pie for suppliers to fight for. Margins will be squeezed by price pressures, but the theory is that volumes will increase more than enough to offset.

There are other benefits of standardization that will help the industry in general. Foremost among the benefits is the reduced production costs that result from economies of scale and enhanced learning effects in manufacturing. Inventory costs will decline as the cyclical ordering trends of particular OEM customers will not dominate that OEMs production, and more steady demand will be felt by the manufacturer. Investment risks will also decrease as the competition to win network builds will evaporate. Suppliers will be able to sell to new or existing networks of all kinds. In the non-standard world, if a deal falls through, or a network is scrapped, the supplier would likely see big chunks of its business disappear. The risk involved in such a hit or miss environment are much greater than is the cliental is more balanced and suppliers are able to hedge against such collapses.

Of course, there are disadvantages to standardization. Primary among the disadvantages are the restrictions to innovation. If the standard specifies a particular platform that must be used in all networks, the ability to develop a superior solution is greatly hindered. As discussed in the following chapters, the standard should consider these restrictions and be as flexible as possible to technological advances. Optical performance will continue to improve, and it is difficult to standardize a "moving target." Every effort should be made to avoid technological lock-in.

The next chapter makes the case for standardization by applying the System Dynamics modeling method to better understand the industry and the underlying dynamics. The fourth chapter then seeks to defend standardization as tried and true path toward growth by comparing the experiences of other industries throughout the last century and a half.

[27] For a discussion of the advantages and disadvantages of standardization, see Sirbu, Marvin and Farrell, Joseph, *Industry Structure and Standardization.* MIT Communications Forum, Seminar Notes. May 1, 1986

Table 4: Results of Industry Transceiver Survey

		Application			Bit Rate (Mbps)					Wavelength			Reach				Form Factor					
		SAN	LAN	MAN/ WAN	.155	.622	1.0	2.5	10	850	1310	1550	SR	IR-1	IR-2	LR	SFF	SFP	GBIC	XFP	MSA	Other
App	SAN	105			1	1	45	43	9	51	36	12	54	21	9	6	30	28	14	5	8	1
	LAN		134		15	4	56	35	22	38	61	30	45	32	28	14	48	39	16	5	13	4
	MAN/ WAN			179	52	39	7	65	16	6	126	45	15	48	76	29	83	51	2	1	32	7
Bit Rate (Mbps)	0.155				70					(0)	62	5	1	18	46	4	39	12	(0)	(0)	18	1
	0.622					41				1	34	6	3	10	24	4	20	10	(0)	(0)	11	(0)
	1.0						83			40	29	14	49	19	5	2	24	28	16	(0)	15	2
	2.5							99		23	50	26	28	25	20	20	40	44	4	(0)	3	10
	10								34	4	17	13	5	16	7	5	18	(0)	(0)	4	(0)	3
Wave length (nm)	850									71			70	(0)	(0)	(0)	22	23	7	2	8	5
	1310										195		16	83	87	2	92	42	8	3	38	5
	1550											65	2	5	12	33	24	30	1	(0)	1	6
Reach (km)	SR												91				29	24	9	2	14	7
	IR-1													88			43	17	5	2	14	2
	IR-2														104		57	28	1	(0)	16	1
	LR															35	13	14	1	(0)	(0)	6
Form Factor	SFF																143					
	SFP																	96				
	GBIC																		20			
	XFP																			5		
	MSA																				50	
	Other																					17

Table 4: Each bin contains the number of transceivers offered commercially by Finisar, JDSU, Infineon, Excelight, Agilent and Intel. The bins represent all transceivers that contain the specific specification given by the axis, combined with any combination of specifications from the remaining categories. A zero denotes that the pair, as well as all the combinations represented by that bin, are not available or not technically possible. The diagonal represents all transceivers for each particular specification (some devices are double counted as they meet the requirements of multiple specifications within the same category).

Chapter Three: Standardization Through System Dynamics Simulation

The optoelectronics industry is the engine that will drive the communications industry into the next phase of growth. After the bubble of the late 1990s burst, OEMs come under intense stress as demand shrunk, leaving the industry in a state of overcapacity. No manufacturer could secure the volumes that would allow economies of scale and manufacturing learning to set in. Without that volume, R&D is unjustified, further restricting the development of low cost manufacturing techniques. Industry decision makers are now faced with a choice; maintain the business environment and hope that market forces will eventually solve the problem, or adopt standardization as a way to erode the vast transceiver variety and allow inter and cross-segment volume leverage that could make components manufacturing a more viable business.

That decision between continuing on the current path and going to standardization is based on the mental models of the decision makers. Mental models are abstractions of reality that decision makers use to manage the complex and dynamics business environment. These models have been formulated over the years through experience and are used to shape strategy and structure decision rules. System Dynamics is a method of improving that formulation by introducing a more systematic way of assimilating the inherent complexity of the system.

The evidence in chapter two is a snapshot of the optical communications industry as it stands currently and reflects the mental models that have been used by decision makers in the past. The detail of the products offered to the public shows that the variety of transceivers has proliferated to a point that should, and does, raise concerns for many industry participants. The current state of proliferation can be traced to a mental model that compelled firms to seek differentiation as a means to gain market share as demand plummeted. This chapter will use System Dynamics methods to test the wisdom of that mental model and to test alternative policies to remedy the current situation, specifically a standardization policy. In other words, System Dynamics will be used to ask whether the current mental models are sufficient, or if standardization is a better solution for the transceiver industry.

System Dynamics is a method proven to be useful in analyzing various market environments that was developed by faculty at the MIT Sloan School of Management. System Dynamics has been a part of numerous decision making processes in companies such as GM, the Department of Energy, the Department of Defense, foreign governments, and others. This chapter outlines the application of Systems Dynamics to the problems faced by the optical communications industry. This exercise is the key to developing a path to solving the problems that ail the OE industry.

3.1 Introduction to System Dynamics[28]

System Dynamics is used as a tool to help clients manage better. As will be shown later in this chapter, the process of developing the model is valuable as a learning exercise even without building a working model. System Dynamics has helped managers in other industries better manage everything from overtime policy, to pricing a firm's products, to a deciding when and where to build new capacity. And, as this thesis will attempt, it can help industries map out a plan for future technology and policy developments. The deliverable of this technique is an increased understanding of the dynamics involved in the system. This enhanced understanding leads to better and more informed decision making. One difficulty in using System Dynamics is that this wholly intangible deliverable is difficult to quantify. There is no real data production that results from this process, and it is hard to convince a client or an industry that the results are real and powerful.

System Dynamics can be used to produce more tangible results for point prediction[29]. Using the word "model" naturally draws most people to think in terms of the point prediction. To this extent, System Dynamics has been used to help firms in litigation cases where retrodiction data is calculated. The technique has also been used to predict commodity markets, with variable success. And, System Dynamics has been used to help make accurate contract bids. Using System Dynamics for these purposes is extremely difficult and requires a complex and thorough model that can take years to complete. Additionally, unlike the management-based use of System Dynamics that is used in this thesis, the benefit comes only at the end. This reliance on the end result increases the risk of wasted investment in the case that the model does not work properly.

The procedural differences between formulating a predictive model and a management model are not significant, only the time necessary to bring a project to completion can be different. Both approaches to System Dynamics require a "policy" model that involves understanding the dynamics of an issue and creating and testing policies. The predictive model goes on to precisely calibrate the model while the management model develops understanding and policy testing more fully. The predictive model may seem more useful because it delivers the best of both worlds. Unfortunately, it suffers it that few project sponsors can supply the resources to adequately develop the dynamics understanding as well as predictive results. What generally happens is that time is short and the model analysis is marginalized and the modelers concentrate on getting a model that fits the data. There are numerous modeling techniques that can fit data and produce some quantitative predictions (that are always wrong). The power of System

[28] Much of the background information given in this section is adopted from notes from MIT course 15.875 "Applications of System Dynamics", professor Jim Hines, 2004

[29] A point prediction refers to a specific quantity that can be used in the modeled world. For example, tomorrow's stock predictions, next week's price predictions, or next year's demand predictions are considered point predictions.

Dynamics is in the analysis of the model dynamics and the data that it produces. The technique can be used as a tool to assess multiple interaction phenomena and develop a deeper intuition about the industry and the forces that work to drive the industry. Therefore focusing a strict fit to the data can erode the marginal return on investing in the technique, in many cases.

3.1.1 A Conceptual Picture

Professor Jim Hines of the Sloan School of Management has presented a picture of the System Dynamics method that effectively illustrates both the benefits and the difficulty of using System Dynamics to analyze an issue. Figure 19 shows a sort of before-and-after picture of an issue being studied with System Dynamics. If the red dots represent the bits of information that are known, the first thing to realize is that System Dynamics may not produce addition pieces of information. Instead, the technique allows managers to see how those data fit together. System Dynamics challenges the traditional mental models business or industry dynamics and proposes new ways to think about an issue. Dynamics of a system are infinitely complex. System Dynamics offers a way to better understand that complexity. As shown in the figure, not only does System Dynamics rearrange the connection between the dots of information, it also exposes longer, or more complex, connections.

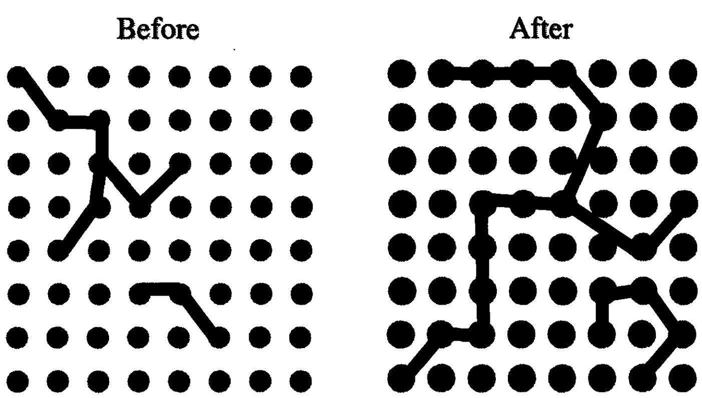

Figure 19: Systems Dynamics, Before and After. The known pieces of information do not change, rather, understanding of the connections among those pieces of information is enhanced and broadened.

The difficulty is also shown in the figure. It is a challenge to convey what could be fairly subtle differences in the understanding of the dynamics. If there are no new pieces of information, it is tough to show the new learning. The rest of this chapter will demonstrate the System Dynamics process as it was applied to the optical communications industry.

3.1.2 The Client

One of the most important components of System Dynamics analysis is the participation of the client. Much of the learning and the value of the exercise stems directly from the involvement of the principle stakeholders. Identifying a client is not always straight forward, as it is not necessarily the party funding the study. For the optical communications project, it is difficult to identify a client due to the nature of the problem. There are many stakeholders that are affected by the health and direction of the transceiver industry, and working with a single client could introduce bias and could prevent full treatment of the issues. To this end, the client for this project became a team of three diversely qualified individuals. Michael Schabel of Lucent Technologies was able to offer a balanced perspective. Lucent deals primarily with providing network telecommunications services to its clients, and Mr. Schabel was able to lend his expertise on that sector of the industry. In addition, his association with Bell Laboratories and his engineering background allowed him to consider the technical aspects of the industry further upstream from the Lucent position. Most importantly, as the chairman of the NGT TWG, he has committed his time to understanding the transceiver in the context of the larger goals of the CTR.

The other contributor was Professor Lionel Kimerling, Director of the Microphotonics Center and professor of Materials Science and Engineering. Prior to entering the academy, Professor Kimerling spent 20 years at AT&T's Bell Laboratories developing the technologies that are the foundation for today's optical communications networks. His long association with the optical industry as well as his vast knowledge of the industry and the technology make him a valuable contributor to the System Dynamics process.

Finally, Elizabeth Bruce provided input on the market related issues and the overall functioning of the communications industry. She has spent time in the industry and has become an expert in the issues relating to the optics industry.

The three-person client "team," as well as other industry stakeholders that have contributed whenever possible, has been consulted throughout this effort and has provided information contributing to the formulation of the model. The efforts have been guided by the System Dynamics standard method that provides a sort of guide through the process. This chapter will walk through the steps of the standard method and present the learning that has provided useful insights into the dynamics of the optical industry.

3.2 The Standard Method

System Dynamics is used explore the effectiveness of standardization in delivering volume to the components industry and bringing the industry back from the brink of extinction. The standard method has been developed by System Dynamics experts at the Sloan School and has been utilized in academic and professional work. Most practitioners use something similar to the standard method used here, although some modification is natural. The five steps of the standard method include problem definition, momentum policies, dynamic hypotheses, model development, and model analysis. While each project is unique and requires specialized work at every step, the standard method nonetheless serves as a template for the analysis.

3.3 System Definition

The first step in the standard method is to define the concerns of the client. Simply stating the problem can be misleading and flawed in that it may not identify the underlying issues. Therefore, the problem definition includes three important components; list of variable, reference modes, and then the problem statement.

3.3.1 List of Variables

An effective way to get a quick synopsis of the problem is to sit with the clients and brainstorm, collecting a list of all the variables that may influence the industry or the issues at hand. Elizabeth Bruce's diverse experience in the industry and her efforts over the years to understand the industry through interaction with industry stakeholders put her in a unique position in that she has a constantly evolving understanding of the stakeholder concerns. The list reproduced in appendix II is comprehensive and is a great snapshot of the industry and the variables that drive it. Simply having this list of variables is an incredible way to get industry members involved in the conversation and to begin to understand the problem at hand. The brainstorming provides a sort of rapid communication that engages all the stakeholders in the discussion.

3.3.2 Reference Modes

The list of variables is long and needs to be reduced in some way to allow for a more focused discussion. There are a number ways of narrowing the list, but usually it is possible to get the clients to agree on five or six that represent the main concerns. The three-client team for this research was able to narrow it down to 1) optoelectronics industry revenue, 2) average cost per bit per transceiver, 3) product variation (or, level of standardization), 4) manufacturing capacity, and 5) manufacturing capacity utilization. It is important to note that just because these six variables were selected does not mean that the other variables are unimportant, and many of them will find their back into the model as it develops.

Reference modes were then created for the six variables selected as the most important. Reference modes should be pictures of the client's concerns showing a time evolution of the variables. The behavior in these graphs does not require exact data or extensive research. The point is to capture an image of the concerns that the clients have expressed. The reference modes created for this project are shown in Figure 20.

The first reference mode shows industry revenues from the sale of transceivers. Revenue from transceivers has experienced a recent dip after the bubble years of the 1990s. The dip coincides with the bursting of the bubble and the resulting cut backs in infrastructure investments. The industry is worried that the dip will remain a permanent low and transceiver revenue does not rebound. What the industry would like to see is a return to a higher, more stable high level of revenue.

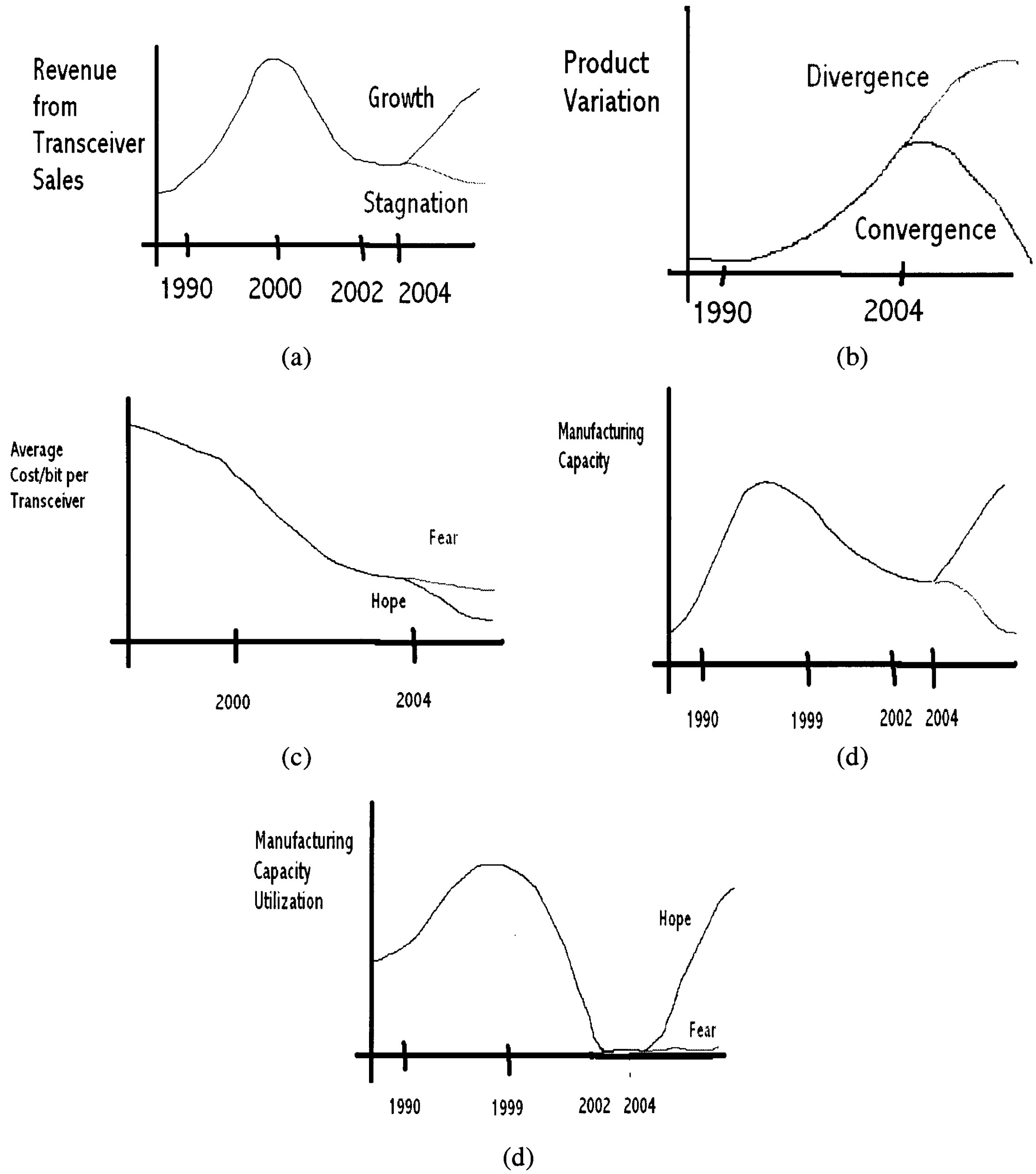

Figure 20: Reference Modes for System Dynamics. (a) Revenue peaked around 2000, and then quickly crashed. (b) Product variation grew during the "boom" years, and continues to grow despite the market crash. (c) Cost/bit per transceiver has decreased more quickly since the crash. (d) Manufacturing capacity increased rapidly during the boom, and remains high now, resulting in a very low (e) capacity utilization.

Average cost per bit per transceiver is hard to quantify as there are hundreds of different transceivers, operating at different bit rates. The conventional wisdom says that the costs of producing transceivers have fallen due to a combination of the natural learning processes and in response to market conditions. The crash was devastating to the industry, but there was some reaction. Manufacturers redoubled efforts to further reduce costs once they realized that demand was falling sharply. With the prospect of rapidly falling demand, the only way to make up the revenue in the short run would be increase margins by lower costs. Medium term and long term solutions are offered in this thesis. Despite the best efforts of manufacturers, the fear is that the prices will not drop low enough to allow more serious competition with the copper-based and wireless communications systems and thus create greater volumes.

The point has been made in previous chapters that product variation is a major obstacle to achieving volume demand for the transceiver industry. The industry has witnessed high rates of proliferation, and fears that it will continue for some time without taking some measures to reign in the divergence. It is important to note that the reference mode for product variation is increasing through the bubble and the crash. This indicates that there are multiple and independent forces driving proliferation, and is a point that will be addressed in more detail as the process progresses.

Manufacturing capacity and manufacturing capacity utilization are closely linking. Manufacturing capacity speaks to the concern that there will not be enough capacity to handle the glut of orders once/if the promise of fiber materializes. There was an enormous investment in capacity during the boom years to keep up with the massive demand for infrastructure. After the crash, much of the capacity remains, but some has been dismantled or reassigned. Capacity utilization is important in that it is costly for empty capacity to sit around. Low utilization leads to unrest in the industry as firms try to find ways to use that capacity. As will be shown later, this dynamic will be used as a key driving force for policy formulation.

The reference modes are not independent of each other. The industry would like to see production capacity increase, as shown in the figure, however it makes no sense for capacity to increase without a corresponding increase in broadband demand. The fact that there was no reference mode developed for broadband demand demonstrates the importance of all the variables identified in the first step. Just because a variable has no reference mode does not mean it is unimportant.

3.3.3 Problem Statement

With the list of variables and of the reference modes, a problem statement can be articulated. Stating the problem is important to provide an initial direction. The problem statement evolves over time and is not critical to the process. Usually, the problem statement is straight forward and needs no further discussion, however, to illustrate the inherent difficulty in studying the optical industry and to show the progressive nature of the problem statement, it is helpful to document the evolution of the problem statement for this project.

It seemed easy enough to simply ask, "What motivated the members of NGT TWG to attend these meetings?" A brief discussion with the client along these lines produced an initial problem definition;

- How can the member of the TWG reach a plan that will improve the health of the industry? This served as a working problem until it became clear that it was too broad and abstract to talk about the "health" of an industry. A concise definition of "health" was needed to focus the efforts. It became clear that health really referred to sufficient capacity and revenues, and the problem became two-fold:
- The demand for bandwidth continues to grow. Will the optoelectronics industry be able to expand and serve that demand?

And,

- Optoelectronics firms have seen flat profits for a number of years. What needs to happen to buck that trend?

One the hand, there is a concern that there has not been enough investment in manufacturing and processes that would enable a high capacity production line. Today, most of the world's transceivers are produced by hand in parts of the world where labor is cheap. This model works fine when hand-production can meet demand, but fails when demand ramps up. The other problem concerns revenue and the sluggish performance of manufacturing companies in the last 5 years. It seems only natural that industry members are not concerned about the state of the industry until they see profits dipping.

This two part problem definition served to guide the development of the model, as is shown in the coming sections. Near the end of the modeling, the problem definition morphed one more time, and became more related to the transceiver manufacturer's importance to the optical communications industry, and in fact the communications industry in general;

- Optoelectronics components manufacturers support an industry with enormous economic importance. The industry is on the verge of collapse and its demise could have untold affect on the US economy in general. How can the industry evolve in a way that allows the manufacturers to provide cheaper products to the optical communications providers, resulting in a more competitive product while at the same time supporting a viable transceiver industry?

The succession of problem statements is detailed here to show one measure of the effectiveness of the standard method. The fact that the problem changed is indicative of progressive learning throughout the process and in fact, the changing problem statement is a sign of accomplishment and should be expected.

3.3.4 Summary of Insights from Problem Definition

List of Variables:

- The list of variables sharpens the picture of the varied and (sometimes) competing interest in this issue. Listing the variables by sector provides a great resource for quickly checking the motivation and concerns of each of these sectors. In addition, having a written record of the level of complexity is extremely helpful to emphasize the systems level approach necessary for this project

Reference Modes:

- Product variation has continued to increase, unmolested by neither the bubble conditions of the late 1990s nor the subsequent crash. This behavior hints that there are multiple forces driving divergence.
- During the bubble, manufacturing grew enormously because of the high demand forecast and the surge of new network installments. In the period after the crash, demand fell sharply, resulting in a drastic drop in capacity utilization. This extra capacity is problematic in two ways, 1) the absolute number of production lines sitting idle is extremely costly to manufacturers, and 2) There are many more firms than the industry can support, resulting in a glut of human and administrative capacity.
- Many manufacturers have anticipated the loss of revenues as demand plummeted. The result is that there have been ingoing efforts to decrease the costs of transceiver manufacturing in an effort to improve margins to make up lost revenues due to the loss in volume. This effect may have significance as we examine the impact of volume production on cost reduction.

Problem Statement:

- Stating the problem is only important as a starting point for the research, but the evolution of the working problem throughout the process indicates that new perspectives are being created and mental models are adjusting.

3.4 Momentum Policies

Momentum policies are those actions that the industry is taking currently, or would take immediately if forced into action, in response to depressed revenues and low volumes. The point of listing these current policies is to better understand the current thinking in the industry and to serve as a starting point when looking back to measure the value of the System Dynamics exercise. The efforts do far have been disorganized and incoherent;

- As evidence of the awareness to the ill-effects of proliferation, various corporations have joined together to create Multi-Source Agreements (MSA). These MSAs are attempts to agree on a common transceiver design that can be plugged into any participating network. These efforts have achieved some level of success, but do not drive at the cross-segment standardization that might be needed, and there is much more that needs to be done.

- The federal regulators, particularly the IEEE, have codified technical parameters as standards for the industry. Many of these standards address the Access segments, and none of them suggest a specific physical structure for the transceiver. The specification standards are extremely varied and have evolved in response to pressures different from those to create a more unified industry[30].
- Despite other efforts to create some sense of continuity in the industry, the dominate policy enacted by firms has been to combat the fall in demand by redoubling efforts to gain market share. Most firms have had little choice but follow this policy as there is no framework by which they could move toward standardization, even if they wanted to. Market share is best won by offering a superior product and therefore the number of unique transceiver solutions has continued to proliferate.
- Finally, as mentioned previously, many firms recognize the dangers of proliferation and support efforts such as the MIT CTR as a means to find a path toward greater health. The decision to support this effort both intellectually and financially is a clear policy decision.

3.4.1 Summary of Insights from Momentum Policies

- Most standardization efforts thus far fall short of the need for cross-segment convergence. The IEEE standards do not address the physical standardization that is necessary to leverage manufacturing processes over greater volumes.
- The dominant policy of firm's continues to be differentiation to gain market share.

3.5 Dynamics Hypotheses

The reference modes developed as part of the problem definition become the basis for the dynamics hypotheses that will eventually evolve into the model itself. Dynamic hypotheses are explanations for the behavior of the reference modes. They are theories of the structures and processes that could produce the observed behaviors. There is not a distinct statement of the hypothesis, rather it is a story about the reference mode that the eventual model will test.

Developing the dynamics hypotheses is extremely useful in furthering the understanding of the industry. If done carefully and thoroughly, it can be just as useful to policy formulation as the actual working model that is the end point of this exercise. One of the reasons for the usefulness of this step in the standard process is that it enables consideration of more variables and more dynamics structures than traditional mental models may include. Building the model is quite time consuming and therefore it is not

[30] Reference Angie Kelic's work – Most of the standards have been instituted in response to a particular firm's, or group of firm's, own network. The idea is to get a particular network configuration "standardized" to make the network more attractive to customers.

unusual that many of the structures included in the dynamic hypotheses are omitted from the model, making the dynamic hypothesis a more complete consideration of the issues.

While the dynamics of each of the four market segments treated in this thesis can be significantly different, the basic casual connections are similar enough that the following work has been developed for just the telecommunications industry. Some of the more specific difference between the segments will be uncovered in the model development and analysis sections.

3.5.1 The Causal Loop Diagram

The dynamics hypothesis introduces the concept of causal loop diagrams. The causal loop diagram is a series of casual connections between variables that ultimately form a loop. This is distinct from the traditional approach to analyzing problems that tends to focus on the cause-effect nature of events[31]. In a cause-effect perspective, every behavior is the effect of some cause, which is in turn the effect some other cause. This reasoning regresses indefinitely until you arrive at some ultimate cause. System dynamics uses a structure-oriented approach that seeks to identify the casual structure, rather than the causal chain, that produces behavior.

Of course, the example above is simplistic and actual casual loop diagrams can get quite complicated. Discussions with the client group for this research led to the development of casual loop diagrams that propose to explain the reference modes and provide insight into the industry.

It is worthwhile to point out that it would be foolhardy to claim that any of the causal loops presented in this thesis are flawless. The goal is not to create a perfect model of the world, but rather to have a tool that captures some of the important driving forces. The behaviors and lessons from these less-than-perfect loops and models can be used to make more informed judgments regarding the factors that are not explicitly included.

3.5.2 Dynamics Hypothesis #1 – Revenue

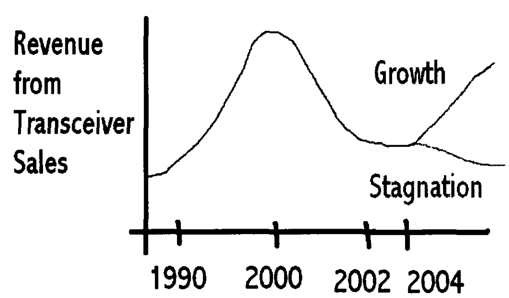

Figure 21: Transceiver Revenue Reference Mode

What drove the increase in revenues during the bubble years? What drove the severe dip in sales that coincided with the bursting of the bubble? Figure 22 shows the basic revenue loop used for this project. Following the causal link, the logic says that optoelectronics firms increase

[31] Business Dynamics, John Sternman

revenue as orders for transceivers (or, demand) increases. The increased revenue is then used to invest in additional R&D that aims to improve the transceiver. The Transceiver Figure of Merit, as it is called here, is a ratio of performance (bit rate x distance) to costs. Network providers then evaluate the transceiver figure of merit and the other available options (copper-based networks, wireless, etc.) and the overall broadband demand that they would like to service, and they make a decision on how many, if any, optical links to install. The assumption here is that as the figure of merit for transceivers improves, it will be more attractive for communications networks and thus orders will increase, thereby completing the loop to firm revenue.

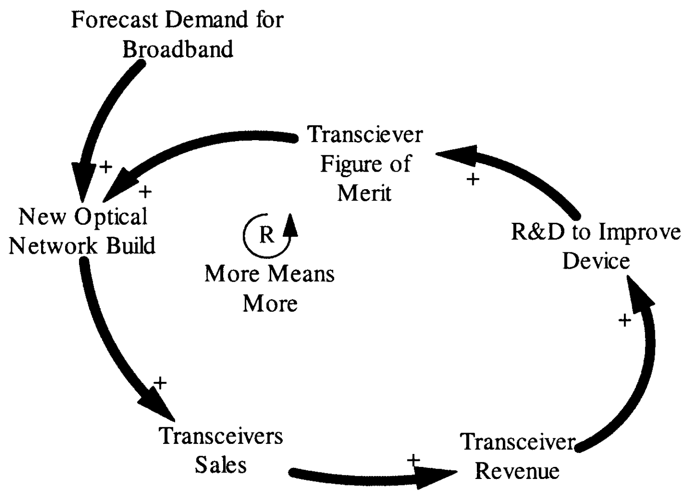

Figure 22: Base Causal Loop Diagram for Revenue. "More Means More" reinforcing loop says the more transceivers sold, the more revenue for R&D, the better the product, the more transceiver sales.

This loop is termed a "reinforcing loop" because the effects of increasing revenue are that revenue increases further. The loop can explain a continuing increase once the market moves in the positive direction. It can also predict a continual erosion of revenues once the forces are reversed. What is missing from this diagram is some force that turned the industry from the boom of the mid 1990s to the crash of the late 1990s, and then another driving force (or the same one) that can return the industry to greater prosperity. Figure 23 is a more complete diagram with three additional structures.

The reversal in the behavior of revenue growth can be seen by realizing that the bubble was driven by unsubstantiated expectations for further growth. By adding "Actual Demand" as a key input for the "Forecast Demand for Broadband" it is clear that at some point, forecasters realigned expectations to match the actual demand. Once that reality hit, the forecast demand dropped, and no new optical networks were built. This short circuited the "More Means More" loop and lead to the crash.

Actually, the steep decline in revenues was caused by a combination of the overstated demand forecasts and the demise of Enron, Williams and other large companies that invested heavily into the optical communications industry. The double-whammy that hit OEMs was devastating and the industry is struggling to survive. The investment-based business model that supported the industry in the bubble years is not applicable to the future of the industry, and so is not included in the modeling.

Figure 23 also adds two additional loops that would strengthen the "More Means More" loop. The "Lower Costs Increases Revenue" loop shows the feedback introduced by economies of scale and learning. These economic affects lower the costs of manufacturing and increases revenues, assuming that the reduced costs are not completely passed to the customer in the form of price reduction. In some segments of optical communications, manufacturers are strongly dependent on a few major clients. This can result in sever supply chain pressures as the producers are hostage to the ordering cycles of those few clients as represented by the "Sporadic Ordering" loop. Increasing total sales can help smooth those cycles and allow more efficient plant management.

The bottom two reinforcing loops strengthen the argument that volumes are vital to the success of this industry. One of the lessons from this loop is that had there been sufficient volumes, perhaps the "Lower Costs" and "Sporadic Ordering" loops could have strengthened the "More Means More" loop to the point that the drop in forecast demand could have been avoided or lessened significantly.

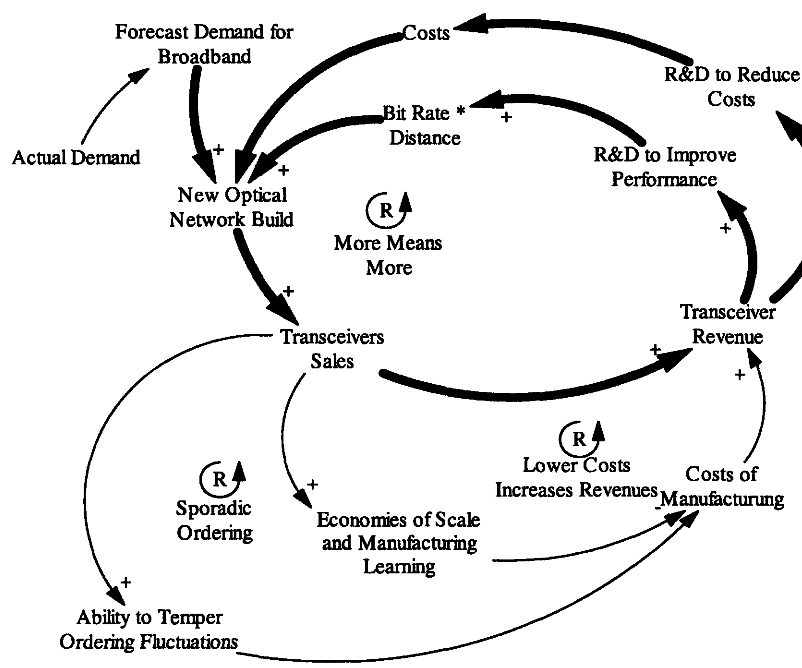

Figure 23: More Complete Causal Loop Diagram for Revenue. The Figure of Merit is split into performance (BRxD) and costs. Additional structures include "Lower Costs Increases Revenues" that shows the effects of economies of scale, and "Sporadic Ordering" captures the smoothing effect of volume on fluctuation in ordering.

Finally, the "R&D to Improve Device" to "Figure of Merit" link has been expanded to explicitly show the two components of the figure of merit, costs and the bit rate * distance product. This added detail states explicitly the two major components of the figure of merit. It is easy to see that an increase or decrease in either one of those components can impact the industry.

The dynamics hypothesis is formed by using the loop in Figure 23 to explain the behavior in the reference mode. It is a hypothesis in the sense that it is a theory of the forces that could produce the observed and desired behavior. Model development later in the standard process provides a means by which to test the hypothesis. The hypothesis is expressed as a series of statements describing the behavior of the reference mode;

- As exaggerated "Forecast Demand" was driving the bubble, perceived industry prospects gave a false sense of potential, leading to large growth.

- The lack of "Actual Demand" (and the disappearance of major investors such as Enron and Williams) caused the "Forecast Demand" to drop quickly and drastically. The resulting erosion of demand led to the drop in industry revenues.
- The hope is that "Actual Demand" can be boosted and the reinforcing loop that increases revenues can be rejuvenated. Actual demand can be increase by either opening up new markets to the OEMs or by the development of new bandwidth intensive applications and services. Alternatively, acceleration of the improvement in the performance and costs of the transceivers may introduce obsolescence into the market, making it more desirable to upgrade network components more frequently.
- The fear is that new demand will not materialize and the market will remain stagnant.

3.5.3 Dynamic Hypothesis #2 – Product Proliferation

Despite the sever boom and bust of the last decade, the product variation has continued to increase, and the fears are that this trend will continue. The causal loop diagram in Figure 25 is the result of extensive discussion on how to formulate the dynamics of proliferation in this industry. The forces of proliferation are complex and many. There are many ways to represent these dynamics and the client group feels confident that the final causal loop diagram presented here is an adequate representation.

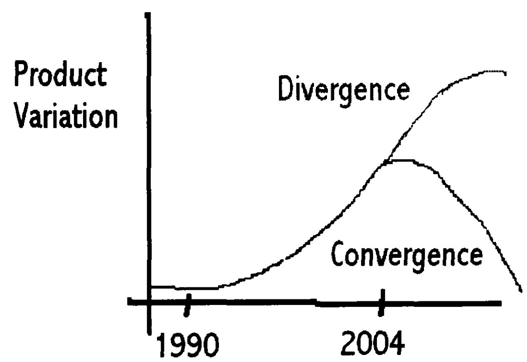

Figure 24: Product Variation Reference Mode

Figure 25 shows the causal loop diagram for this reference mode[32]. The important feature in this loop is the ability for divergence to dominate during both good times and bad, as the reference modes suggests happened in practice. The root of any drive to improve the industry comes from capacity utilization. Again, other factors can provide motivation for action, but generally speaking, if capacity utilization is high, there is less impetus on the manufacturers than if utilization is low. "New Optical Network Build" from the Revenue Loop has been replaced by "Communications and Interconnects" to account for the different market segments that can be generalized to this loop, not all of them optical networks.

The loop contends that when capacity utilization is high, there is a little perceived need to do something. In this case, corresponding to the bubble years, there is a low drive to differentiate to secure

[32] The links in bold indicate overlap with the central revenue loop, which serves as the heart of the analysis

market share, thereby weakening the "Fight For Market Share" loop. However, there is no driving force to increase the total market through standardization. The "Standardization" loop is short-circuited during periods of high capacity utilization. The differentiation loop wins by default. Essentially, it costs more to organize the industry and plan a path to standardization than it does to simply continue to trying to produce a superior product, particularly when there is little cause to out-compete when there is plenty of business to go around.

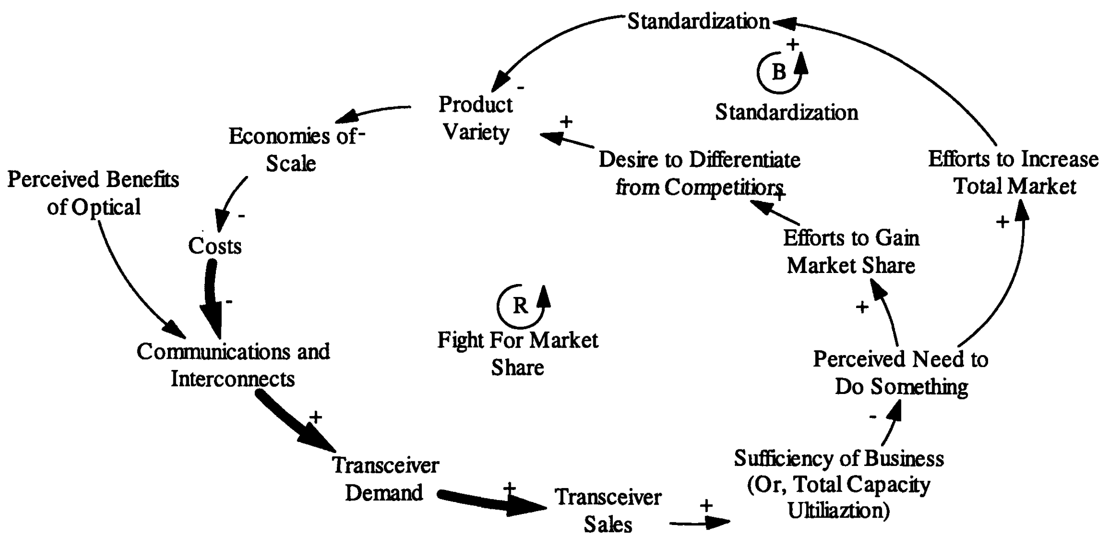

Figure 25: Casual Loop Diagram for Standardization. This loop shows a decision between the balancing loop "Standardization" and the reinforcing loop "Fight For Market Share." The bold arrows indicate that the link map to the Revenue Loop in the last section.

The crash resulted in a drop in capacity utilization, and the "Standardization" loop is now more active, as evidenced by the MSAs and the formation of efforts such as the MIT CTR. However, thus far the "Fight For Market Share Loop" has dominated and differentiation continues. The dynamics hypothesis for this loop describes the behavior in the following way;

- In the bubble years, each firm was content with the demand for its own services and there was no incentive to cooperate with competitors to improve the industry. Capacity utilization was high (in fact there was the sense that capacity could not be added quickly enough) and the "Perceived Need to Do Something" was low.
- During this time, the "Standardization" loop was essentially short circuited as firms only saw a need to differentiate their products from their competitors to maintain exclusive network solutions.
- As the bubble burst and capacity utilization plummeted, the "Need" became much greater. As there was no structure in place that would allow the OEM industry to follow the "Standardization" path, the naturally continued to fight for market share and further differentiate. The negatively reinforcing

"Fight For Market Share" loop resulted in a sort of downward spiral and did more harm to the industry.

- The hope is firms will recognize the follies of differentiation on the industry scale and reverse the trend.
- The fear is that it will be impossible to convince the industry of the benefits of standardization and differentiation will continue as firms are reluctant to give up market share. Eventually, natural market forces will begin to erode the number of transceiver designs, but it may be too late to save the industry.

As indicated at the beginning of this section, the process of modeling is much more time intensive than the formulation of dynamics hypotheses. The first two hypotheses are more developed than the rest, as the modeling will center on these two loops. The other loops are still important to the problem, and further work on the CTR could include the development of the other loops.

3.5.4 Dynamic Hypothesis #3 – Transceiver Costs

The cost of transceivers has been identified in previous chapters as an important factor in the success of the optical communications industry. The dynamic hypothesis provides insight into the variables that affects the costs.

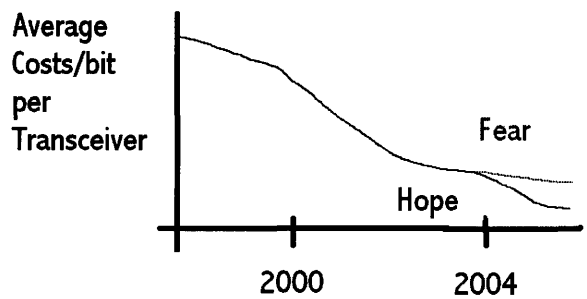

Figure 26: Costs/Bit/Transceiver Reference Mode

Figure 27 has many components of the of the revenue loops (indicated with bold lines). The added feature is the consideration of margins that provides a different driving force for investment in cost reducing advances. As the market crashed, OEMs recognized that the drop-off in volumes would mean a corresponding drop-off in revenues. The reaction was to stretch margins by pushing down costs. When incorporated into the revenue loop, the balancing impact of reducing costs to maintain improve margins will counteract the downward spiral of transceiver sales, but price pressure resulting from increased competition will pinch margins. The dynamic hypothesis for transceiver costs can be stated with the following points;

- Before the crash and during the bubble years, the reinforcing loop entitled "The Cheaper They Are, The More You Sell" drove R&D investment and resulted in lower costs.

- After the crash, the "The Cheaper They Are, The More You Sell" loop worked in reverse and may have caused an increase in costs if not for the "Keep Margins Up" balancing loop proved stronger than the reinforcing loop, resulting in an acceleration of the costs reductions.
- Competitive price pressure then eroded the margins, forcing costs down more and more.
- The fear is that real costs savings cannot be achieved without a fundamental shift in manufacturing processing including automation and active alignment. The investment needed for such an overhaul is unlikely to come with such poor prospects for significant volumes that would provide returns on the investment. The existing production techniques can only be improved so much.
- The hope is that volumes will materialize, prompting investment and costs will fall further.

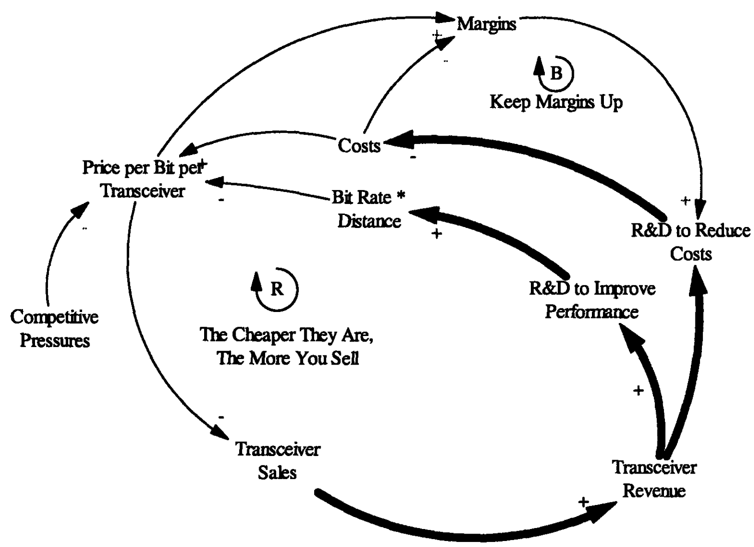

Figure 27: Causal Loop Diagram for Transceiver Costs. The loop emphases the impact of costs on prices and margins. In the reverse "Cheaper They Are The More You Sell" loop, Transceiver Sales fall and revenues fall. To combat the fall in revenues, "Keep Margins Up" puts further down pressure on Costs.

3.5.5 <u>Dynamics Hypothesis #4 – Manufacturing Capacity and Capacity Utilization</u>

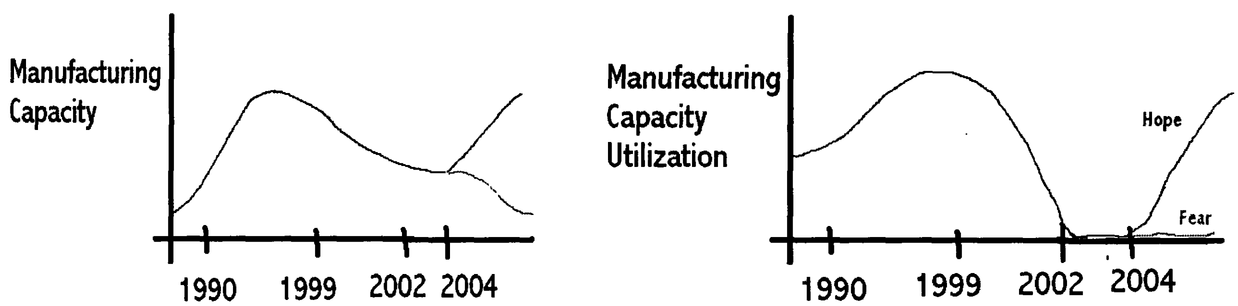

Figure 28: Manufacturing Capacity and Capacity Utilization Reference Modes

Manufacturing capacity and capacity utilization go hand-in-hand and are combined in one dynamic hypothesis. Figure 29 shows the causal loop diagram for this hypothesis. Again, many of the variables appear in the other loops. The overlap suggests that even without modeling these variables, the results of other models will give significant insight into the behavior of these variables.

The loop causal loop diagram in Figure 29 shows the dynamics for manufacturing capacity and utilization. The "Efficiency" loop captures the effect of growing transceiver demand. As demand increases, capacity utilization increases resulting in a reduction in operating and maintenance (O&M) costs. The "Don't Grow Too Fast" loop balances the "Efficiency" loop in that new capacity is build as demand grows. If capacity additions outpace demand growth, the result could be a *reduction* in the capacity utilization. The "Right The Ship" loop represents the decision process for building new capacity. The idea is that OEMs look at the needed capacity versus the actual capacity and decide how much new capacity is needed.

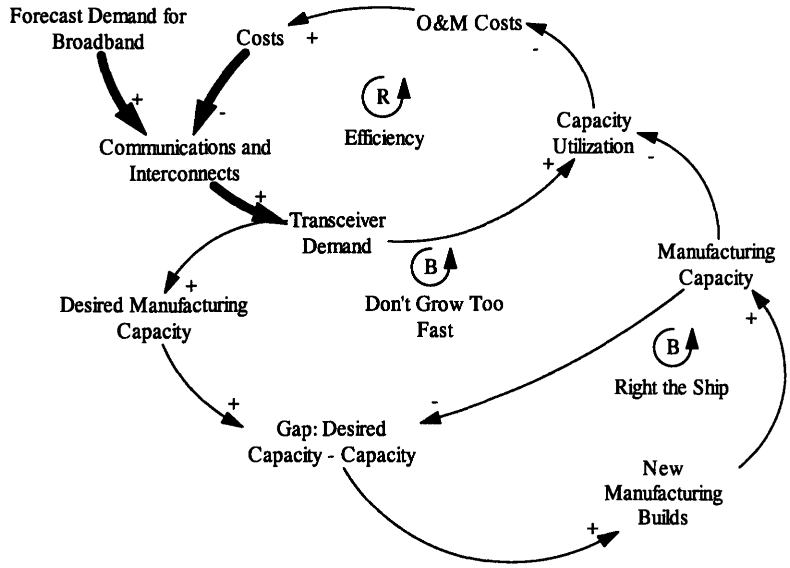

Figure 29: Casual Loop Diagram for Manufacturing. "Efficiency" says higher Capacity Utilization results in lower O&M Costs. As the market grows, capacity build can outpace Transceiver Demand, resulting in lower Capacity Utilization ("Don't Grow Too Fast"). Managing the Gap can "Right The Ship" and keep Capacity Utilization at manageable levels.

Referring to the loop in Figure 29 and the reference mode for manufacturing capacity and capacity utilization, the dynamic hypothesis consists of the following explanations;

- The bubble market drove demand for transceivers and the "Gap' remained large for much of the bubble period. The exaggerated "Forecast Demand" drove enormous build of new manufacturing capacity. Since building of that capacity could not keep up with demand, capacity utilization also rose.
- The crash snuffed out demand and the gap quickly went negative. The industry did in fact "Grow Too Quickly." The depressed capacity utilization reinforced the negative "Efficiency" loop resulting in lower "Transceiver Demand."
- After the crash, some of the capacity has been lost, however, the glut was so big that capacity utilization remains near zero.
- The hope is that demand will rebound and utilization will rise.

- The fear is that demand will not rebound, capacity utilization will remain near zero, and a capacity build-down will ensure as OEMs shed the weight of empty capacity.

3.5.6 Summary of Insights From Dynamic Hypotheses

Dynamic Hypothesis #1 – Revenue:

- The transceiver figure of merit is composed of performance and costs. R&D investment is made to both increase performance and decrease costs as the optical industry tries to make a product that out-competes other technologies on a cost per performance basis. Costs are only an issue for this study as long as the costs of network builds are dominated by the transceiver costs. At some point, costs will decrease to the point that further reductions in costs are insignificant. What, then, is another way to boost revenue? From the loop, broadband demand is the other way to boost sales and revenue. Traditionally, components manufacturers have been content to let others develop the uses for their products. Perhaps the components industry needs to take a closer look at what they can do to increase demand[33].
- While the reinforcing loop fueled the strong years of the industry, it is important to recognize that the same forces, acting in reverse, act to now keep the market down. Some other driving force will need to be identified and exploited in order to turn the industry around.
- The optics industry is essentially a series of causal loop diagrams similar to that presented in Figure 23, each representing a different market segment. Perhaps more important than the development of bandwidth intensive applications and services to increasing demand is the convergence these segments. This is one argument for standardization as a potential solution to improve the strength of the components industry.

Dynamic Hypothesis #2 – Product Variety:

- In times of high capacity utilization, standardization is nearly impossible to promote as the costs to organize greatly outweigh any benefits as firms are already maxed out.
- When firms are struggling and capacity utilization is low, standardization becomes an option as decision makers realize the negative impact of high product variety, however, before a path to standardization can be formulated and implemented, the fight for market share via differentiation will dominate.

[33] Similar to the example of Corning and optical fiber. Optical communications did not take off for years after Corning developed optical fiber. The take-off was enabled by Corning when they produced the end components that could take advantage of the fiber.

- There is very little difference in the technical performance of transceivers across industry segments. Everybody can make a 2 Gbps transceiver to fit a LAN, so it is not productive for a firm to try to out-compete a competitor on a performance level. The difference is in the design of that device and the design of the network. Competition, therefore, moves away from performance toward reliability, service, and costs that are all provided with unique solutions. The end result is a proliferation of product variety as network providers demand components optimized for each individual network.
- If foresight could have prevailed in the boom years, more standardization could have been accomplished. The weak link between perceived need to do something and efforts to improve financial performance also works in reverse in that there would have been less resistance to standardization.
- Standardization is more difficult when market share is precious as firms do not want to lose that share, as is likely to happen in a standardized market. Any move toward standardization has to be lead by the most powerful companies. The biggest companies stand to lose the most due to standardization.
- The difficulty is in overcoming "lost market share" barrier. If revenue is dictated by the simple equation,

  Market Share * Size of the Market = Revenue

  At what point does the increased pie overcome the decrease in market share, and how can firms be confident that that point will be reached?
- If the Revenue Loop suggested that manufacturers could turn their attention to creating applications as a way to increase demand, the Standardization Loop suggests that cross-segment standardization could also increase demand.
- The mechanism for lowering costs may not be economies of scale and learning as has been suggested to this point. Developing a new platform is extremely costly, and one of the advantages of standardization would be the elimination of the need to create new platforms for some applications as the standard would dictate the platform for all manufacturers.
- Perhaps the most important lesson from the dynamic hypothesis is that the "Fight For Market Share" loop is a reinforcing loop. That is to say that as sales decrease and firms fight for market share to offset the loss in market size, sales are decreased further because economies of scale and learning opportunities are lost, slowing the reduction is costs and rendering optical networks *less* attractive.
- Policies must be put in place that will allow the "Standardization" balancing loop to become stronger and combat the "Market Share" loop.

Dynamic Hypothesis #3 – Transceiver Costs:

- The market crash resulted in increased efforts to reduce costs as manufacturers tried to offset the falling sales volumes by increasing margins.
- The fear is that the efforts can only go so far without instituting automated manufacturing techniques (not likely with no volume to justify expenditures), reducing product variety, or make less costly (inferior) devices (which would result in lower market share).
- Revenue can be dedicated to two goals, increasing manufacturing processes or improving the device. When volumes are up, revenues go toward manufacturing technologies to increase capacity to meet increasing demand and gain volumes. When volumes are down, revenue goes to improve the device to make it less costly to gain margins.

Dynamic Hypothesis #4 – Manufacturing Capacity and Capacity Utilization:

- The over-stated demand forecast provided the motivation for build beyond what was necessary. This overbuild is one of the main problems in the industry to this day.
- The balancing loop that drives capacity build was feed by the inflated forecast, while the actual transceiver demand was lower than expected. The result was that balancing loop "Don't Grow Too Fast" was growing while the "Back to Even" reinforcing loop was actually working reverse, providing a double-whammy for the capacity utilization.
- The ideal situation for this structure is to keep the capacity utilization flat and closer to 100%. In this case, the capacity increases along with transceiver demand increase.
- It is feared that continued lack of volumes will continue to erode manufacturing capacity, and the need for multiple production lines will make further expansion too costly.
- Outsourcing could help alleviate the impact of multiple production lines as one company could handle various different varieties for different companies. The key would be that the transceiver varieties needed for each firm are similar enough that the outsourcer could handle all orders on one line. However, the volumes are still likely not great enough.
- Although it is not shown in the loop, any significant increase in manufacturing capacity is difficult and costly when there are numerous transceiver varieties that require different production lines.

The analysis in the last sections illustrated the power of the System Dynamics method. The lessons taken from the formulation of the dynamics hypothesis are powerful in their own right. The next chapter will use the lessons presented here, as well as those yet to come from the modeling to formulate solutions help the components industry return to health.

3.6 Model Development

Modeling of the dynamic hypotheses is a method by which policies can be tested and unexpected behavior can be analyzed. The modeling process is time intensive, and only a couple dynamic hypotheses were modeled for the purposes of this thesis. The criterion for selecting the dynamics hypotheses are that it is, 1) Easy to model (relative to others), 2) Central to the problem, and 3) Perceived as valuable to the client. The revenue loop is modeled because it is central to the problems of the industry. Sagging revenues has brought components manufacturers to the verge of collapse. The strength of the optical communications industry and of the continued growth of the communications industry in general, depends on the health of its supply chain, making the revenue loop very interesting to the clients. The revenue is also relatively easy as the drivers to creating revenue are readily understood.

Standardization has been touted as a possible solution to the underperformance of the optoelectronics industry, making it perhaps the most important hypothesis of the group. It is not necessarily any easier than other loops, but it is central in that other loops feed off of various parts of this loop. Therefore, the product variation loop is also modeled to enable simulation of the industry under standardization.

Extensive calibration to fit data is not undertaken for this thesis. The results presented here are qualitative and relative. Further System Dynamics work might be done to arrive at a reliable, quantitatively calibrated model, but that would require years of work and greater experience in the optical communications industry to include the level of detail needed for such a project. That being said, a less calibrated model is still quite valuable as it offers a further challenge standing mental models. There is no doubt that the marginal benefit in modeling at the level presented in this section is much higher than a calibrated model. The calibrated version of this model would take years longer to produce and, given the desire for more policy-oriented solution to the current case, the results would be only slightly more useful. The model in this thesis is extremely powerful as it stands now. It may be worth also modeling the other dynamics hypotheses (non-calibrated), but a full calibrated model would be a waste of valuable resources.

3.6.1 Modeling the Revenue Loop

The model process begins by identifying the variables in the model that can be expressed in terms of physical levels. The physical levels, or stocks[34], are then connected in the most obvious ways. Each link contains a mathematical relationship between the connecting variables. Figure 30 shows the model

[34] In System Dynamics, Stocks represent quantities that can be represented as physical levels, i.e. they can be increased and decreased pursuant to flows into and out of the stock. Stock can be visualized as water in a bath tub. The level of the water is increased when the faucet is turned on, and decreased when the drain is opened. System Dynamics calculates stocks as the time integral of the flow of material into and out of the stock.

for the portion of revenue causal loop diagram in section 3.5.2 (Figure 22) from revenues to the costs and performance of the transceivers.

Costs and the bit rate x distance product (BRxD) are represented as stocks. The "Costs to BRxD Multiplier" parameter is a measure of the amount of costs increase that accompanies any improvement in transceiver performance. The Multiplier is based in a "rule of thumb" for new product introduction that stipulates that for every four fold increase in performance, there must be just a 2.5x increase in costs[35]. Part of the R&D budget is dedicated to the improvement of BRxD performance. Another part of the budget works to decrease the "Costs to BRxD Multiplier," thereby changing the rule of thumb. The level of revenue that can be applied to the R&D effort is restricted by the number of transceiver platforms for each segment. The industry revenue must be divided among those platforms as each of them needs to keep pace with the market (both the other optical components and the other technologies). The productivity of both the BRxD and the costs R&D is limited by theoretical limits. Many experts believe that at some point the market simply won't support any more bandwidth increases. The limit can only be guessed, and it is different for each segment, but this model asserts that there is in fact a limit.

The ultimate measure of the benefits of optical is represented in the "Optical Attractiveness" variable. This variable is a simple ratio of BRxD stock to the costs stock in Figure 30 above[36]. As a point of comparison, BRxD and costs equivalents for "other" technologies[37] are also built into the model. These values are given a constant rate of growth and are not modeled explicitly.

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[35] This rule of thumb is offered by Michael Schabel (Lucent Technologies), and is only valid for the telecom industry. For the purposes of this model, the rule of thumb is applied across all segments, as the important result is the behavior, and not so much the exact market trends.

[36] Cost per performance is a more standard metric used in the industry to compare the quality of technology, however, the construct of the model lends itself more easily to the performance per costs metric.

[37] "Other" technology here refers to technologies most directly in competition with optical communications and includes electronically based communications and wireless.

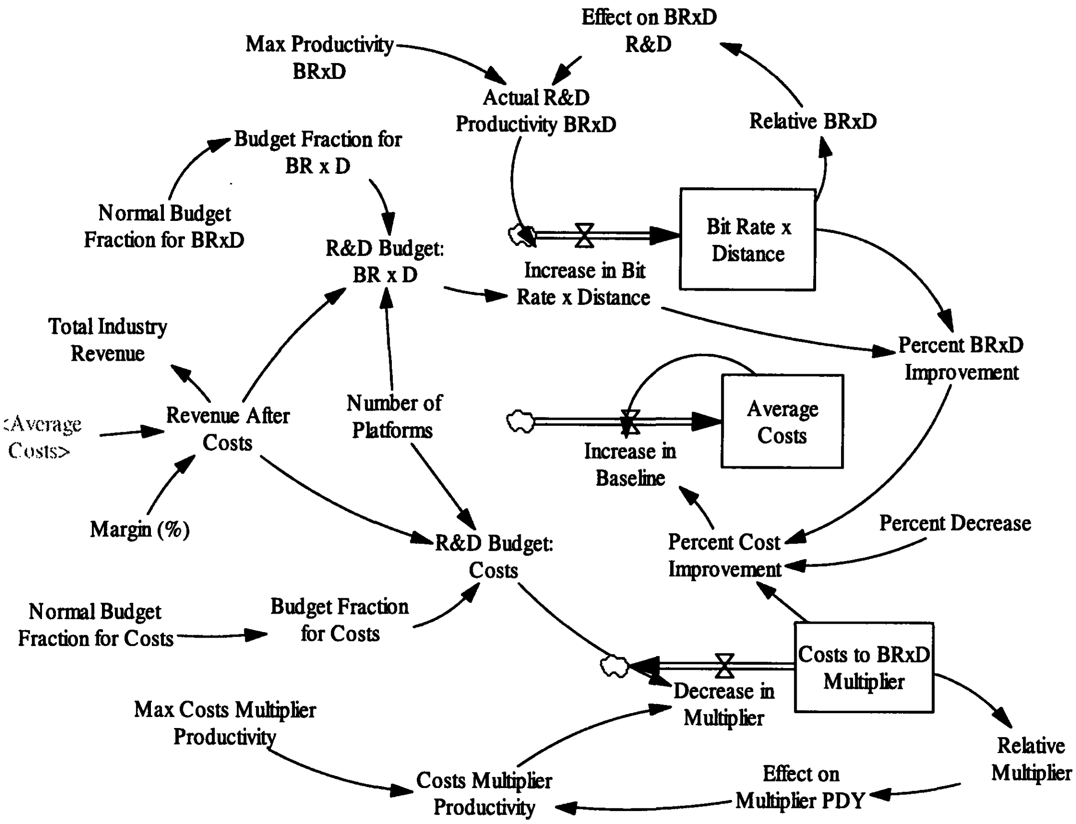

Figure 30: Model Rendering of the Revenue Causal Loop (Figure 23). This is the section from Revenues to Transceiver Costs and Performance

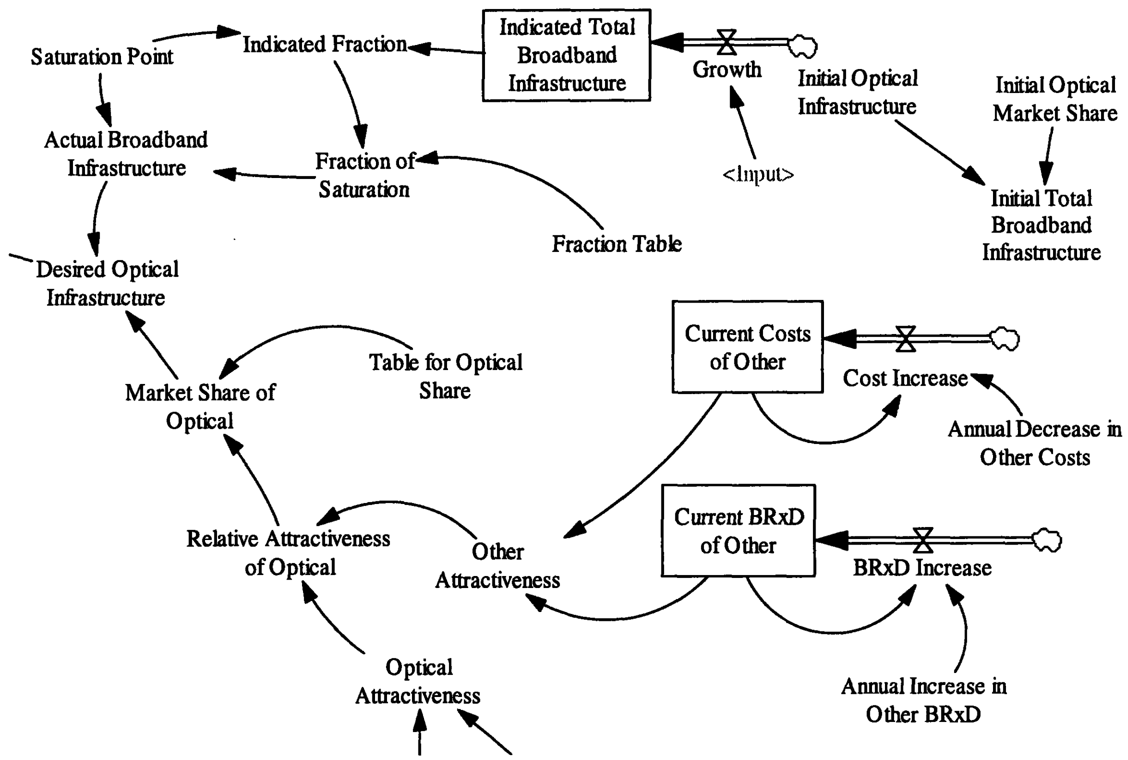

Figure 31: Model Rendering of the Revenue Causal Loop (Figure 23). This is the section from Optical/Other Comparison (the decision to build Optical or Other) to New Build

The decision process of network providers when deciding on the connection technology for new builds is represented in Figure 31. The "Optical Attractiveness" is compared to "Other Attractiveness" by a simple ratio. The basis of this construct is a simple assumption that optical market share will remain relatively low until the "Optical Attractiveness" is greater than "Other Attractiveness." At that point the desired market penetration will rapidly increase, with a slow down in conversion to optical as the market share approaches 100%. The market penetration of optical is then applied to the total broadband market, giving a level of "Desired Infrastructure," that is, the infrastructure needed to meet optical demand.

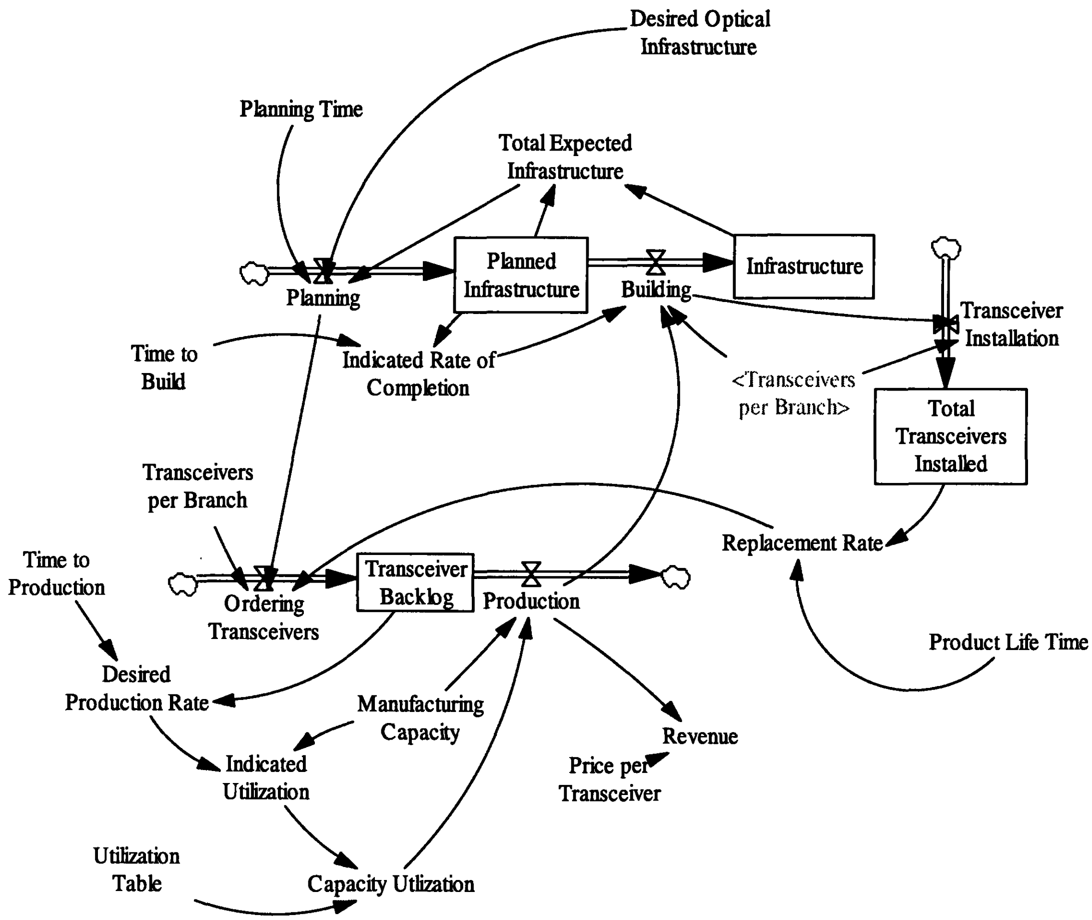

Figure 32: Model Rendering For Build Delay Chain

Now, the model has calculated the "Desired Infrastructure" for optical connections, the infrastructure is then put into planning and built, resulting in a demand for transceivers. Figure 32 is a delay chain that represents the delay between realizing that infrastructure is needed and building the infrastructure, complete with transceivers and other optical components. Once the infrastructure is planned, financed, and built, the revenue for the installed transceivers is registered. This section also accounts for the replacement of transceivers due to either wear and tear, or product obsolescence. We will see shortly that this is an important structure. As a prelude to the structure for standardization, and as an example of the modeling process adding new dynamics as new links are discovered as learning proceeds, the "Production" rate for transceivers is limited by the manufacturing capacity and is also modeled.

The preceding sections of the loop constitute the entire revenue loop as given in Figure 33. For space considerations and for added simplicity, Figure 33 omits structures that act to bind the stocks and flows. For example, the costs of the transceivers cannot go below zero. The full model, along with documentation of the Base Case parameters, is given in appendix III.

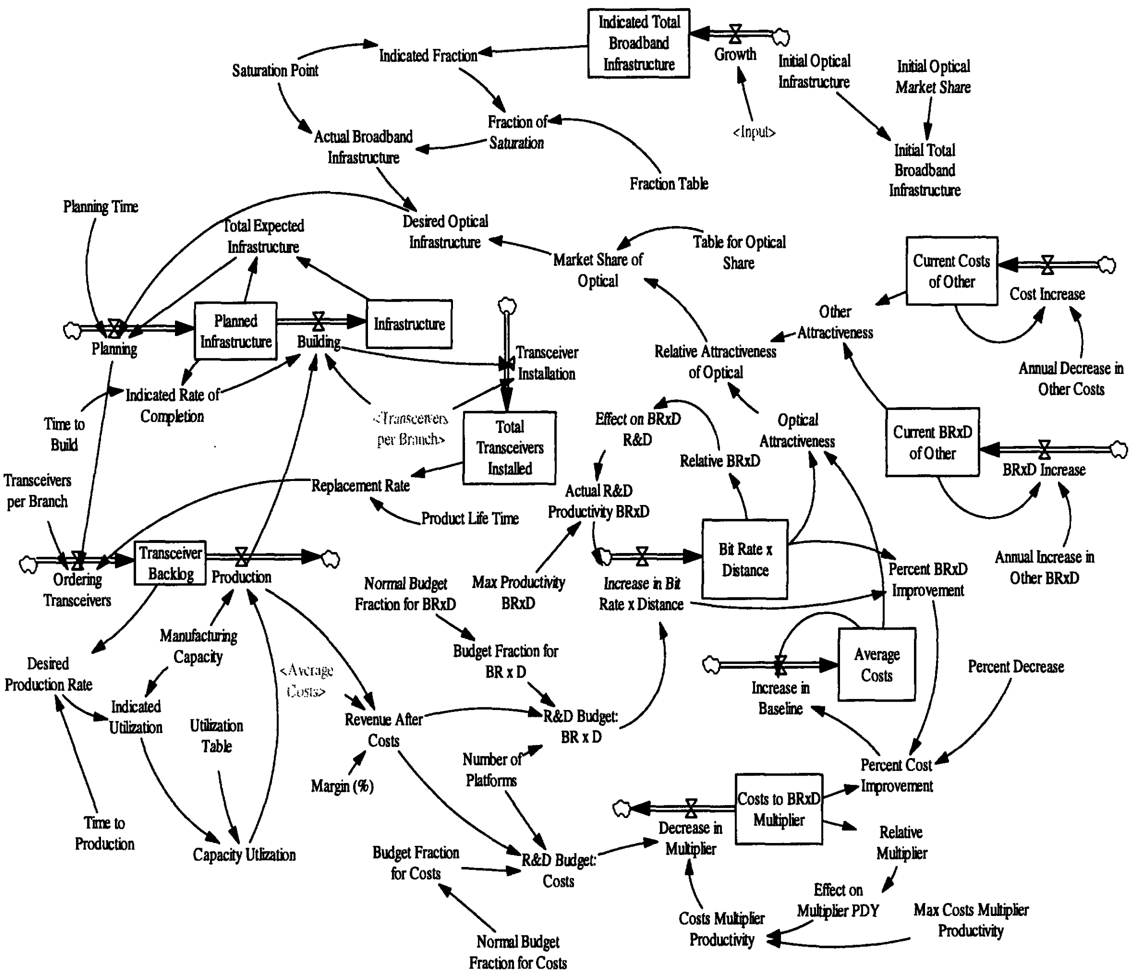

Figure 33: Entire Model for Revenue

3.6.2 Modeling the Standardization Loop

The Standardization loop is merely an extension of the Revenue Loop. Figure 25 (causal loop diagram) from section 3.5.3 shows the abstraction of the additional structures. The driver to take action in the industry is the capacity utilization. In this model, the response of the need to do something is left as a policy decision and is lever for analysis. If the policy is to standardize, as "Capacity Utilization" decreases and "Need" increases in response, the "Number of Platforms" will decrease. Conversely, if there is no standardization policy and divergence continues, the "Number of Platforms" will increase with increasing "Need," potentially resulting in the bubble behavior seen in the 1990s. Just as in real life, the policy path can be a combination of standardization and continued differentiation.

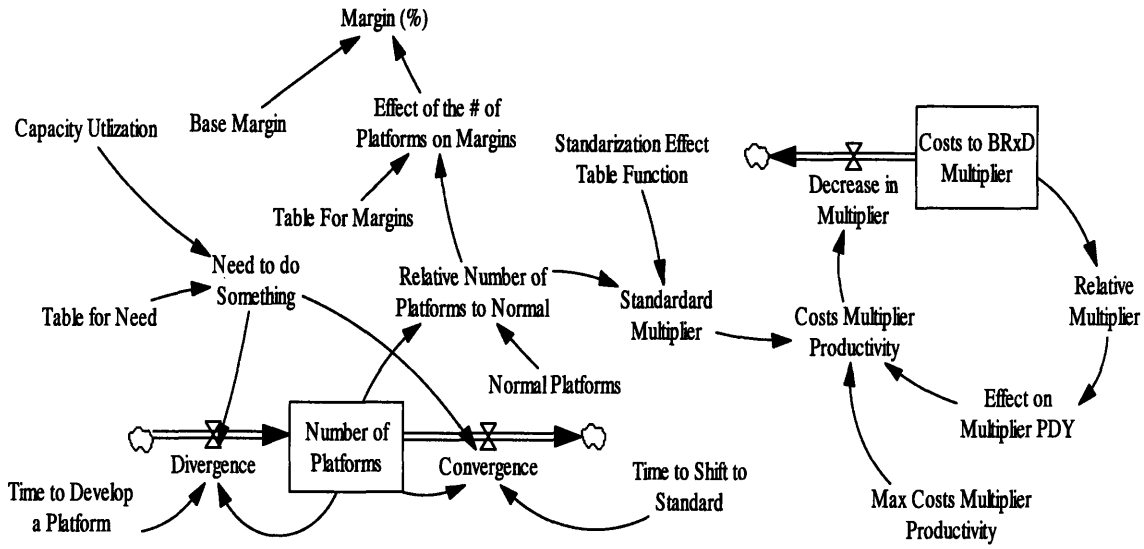

Figure 34: Model Rendering for Standardization

Depending on the policy, the "Number of Platforms" will increase or decrease. The result of standardization is rendered as an increase in the R&D productivity for lowering costs, on a percent improvement basis. The idea is that reduction in the number of platforms not only eliminates the costs to develop new platforms, but also the industry can work more efficiently as cost cutting measures are (eventually) shared throughout the industry and the companies can pool resources for R&D advances. The structure in Figure 34 attaches to the body of the Revenue model. The full model with documentation is given appendix III.

3.6.3 Summary of Insight From Model Development

When modeling a problem or an industry, the benefits are derived from the type of thinking that becomes necessary for the developer and the client. Links and feedbacks that may not have been given much attention in the past become prominent. In formulating the structures in the model as presented above, much of the logical base for the structures was realized only after a prior version of the model was run and assessed.

Modeling the Revenue Loop:

- Many of the added features of the model developed from the realization that there are limits to some of the dynamics. One such dynamic is that it may be easier to improve performance and limit the associated costs increases at the beginning of the period, when levels are relatively low. As performance increases and costs decrease, it will take more and more investment to maintain the same improvement rate.

- Also, the competitive nature of business dictates that industries may invest more intensely when the technology lags far behind that of the competitors, while investment becomes less important when the technology is superior.
- One of the more important additions to the model came in the formulation of the transceiver production flow. The production rate is restricted by the manufacturing capacity. When demand is not close to capacity (low capacity utilization), the industry builds as many transceivers as are needed. In period of high capacity utilization, the production of transceivers, and therefore the collection of revenue, is delayed.
- Another addition to the model regards a more logical representation of revenue. Originally, the revenue parameter that feed into the R&D was formulated as the total production * the price of the transceiver, with price set according to a set margin relative to the costs. To make the model more logical, the revenue was changed to "Revenue After Costs." That is, the revenue available for R&D is whatever money the sale of transceivers brings in less the costs of producing those transceivers. Since the model is not calibrated and we are only interested in the relative movement of the markets, this additional structure does not affect the results, it only contributes to a more realistic model.
- The original version of the model omitted the replacement of existing transceivers. The folly in this omission is clear once one realizes that in some cases the replacement is the only source of revenue for an industry. The importance of product obsolescence is not captured and a valuable piece of the analysis could be missed. This additional dynamic feature contributes significantly to the analysis.
- Some of the scenarios that the model attempts to address regard the increase in the overall broadband market. A new structure was added to account for the recognition that there are saturation limits to new broadband demand. For example, there are only 100 million households in the United States so the demand for FTTH cannot much exceed 100 million links.

Modeling the Standardization Loop:

- The Standardization loop essentially begins with the revenue loop, and extends it.
- While the decline in margins with standardization has long been a concern, the model did not include such a reduction of margins with increased standardization until the effect was deemed too important to not include.

3.7 Model Analysis

The models developed above resulted in behavioral patterns that result from the interaction of all of the variables included in the structure. The results are generated in graphic form and show the effects of delays and competing loops. Some of the behavior are expected, some are not. The analysis examines those behaviors and extracts any new learning that can be applied to the industry.

In the modeling stage, there is a more sophisticated account of different market segments than in the dynamic hypotheses. The model runs four segments simultaneously, the LAN, FTTH, SAN, and Servers. The sum of the segments can be combined to give a whole industry perspective.

The revenue model is just a simple representation of the industry, but it has some interesting results. To reiterate, the model is not calibrated to any real data, and the results are analyzed strictly for trends, sensitivities, and relative behavior. No absolute numbers or time frames should be pulled from the data. The starting points for the key parameters are in appendix III along with the model documentation.

3.7.1 Revenue Model Analysis

Without standardization, the four segments treated in this model act independently, and there is no real cross-segment synergy. The benefits of standardization and the resultant overlap of the four segments are explored in the next section. There are a number of conclusions from the initial runs that do not consider standardization policy as an option.

3.7.1.1 The Base Case For The Revenue Model

First, the base case of the model is run with the parameters as given in the appendix. The main feature of the base case is that total broadband demand remains constant. While this is unrealistic, it provides insight into the basic dynamics within the industry segments and between optics and other communication technologies.

The model stipulates that a portion of revenue goes to R&D to improve performance and decrease costs. No new demand means that replacements of existing optical transceivers due to wear or to obsolescence is the only source of revenue, and thus the only driving force for improvement in the performance per costs parameter. If revenue generated from the replacements can improve device performance and costs enough that optical begins to win market share, another driver to revenue will emerge in the form of additional volumes. The dynamics of such a driver is treated below.

The other way to increase revenue in this case is through further market penetration. The revenues generated from replacements would have to provide enough R&D to improve the devices to the point that they out-compete other technologies. The mechanism for gaining market share in this model is enhanced competitive position in the sense that bit rate x distance per dollar is superior to other network options[38]. If the productivity of R&D is too low due to either the lack of the possibility of cooperation

[38] The figure of merit for this model is BRxD/costs as opposed to the more familiar costs/BRxD. This reverse convention allows for more straight-forward model structures.

and resource sharing throughout the industry, or due to the low of investment based on poor volume prospects, the industry will never reverse recent sluggishness.

Figure 35 shows the generic trends for "Optical Attractiveness[39]" for the four market segments. All four trend up similar to the Server market shown, as is expected. However, in the Base Case, optical improvement lags the improvement of competing technologies ("Other Attractiveness" Figure 36), as is clear from the steady decline in the "Relative Attractiveness" (Figure 37). "Market Share" (Figure 38 and) and "Desired Infrastructure" (Figure 40) decline accordingly. In this model, infrastructure cannot be taken out once it is installed, and hence the "Production Rate" (Figure 41 and Figure 42) remains equal to the "Replacement Rate," resulting in the constant source of revenues based on replacements of existing infrastructure.

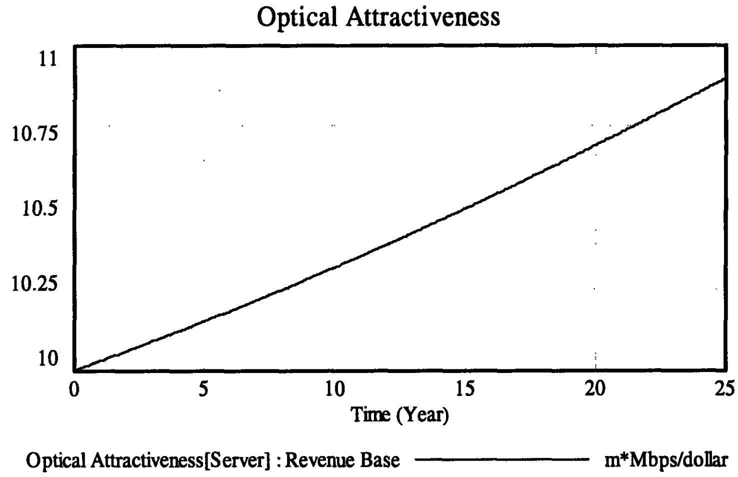

Figure 35: Base Case Optical Attractiveness for Server markets. As one would expect, Optical Attractiveness grows due to R&D fueled by revenue gained from replacement transceiver sales.

[39] "Optical Attractiveness" is simply a term used for the BRxD/cost figure of merit used in the model

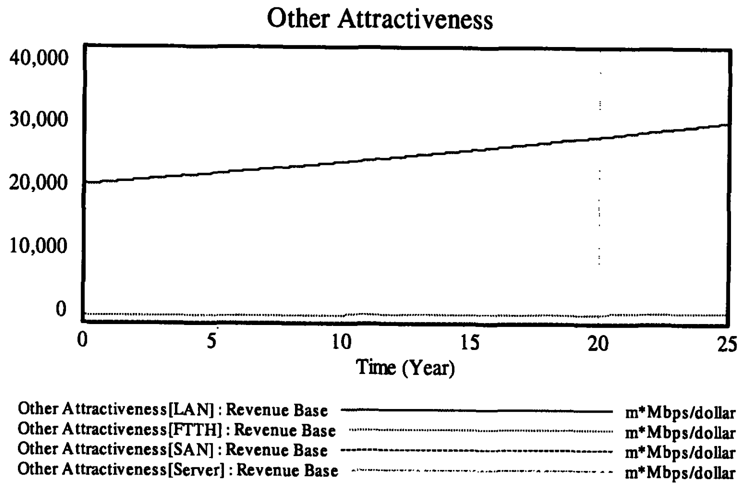

Figure 36: Base Case Other Attractiveness for all markets. Again, a steady increase is observed.

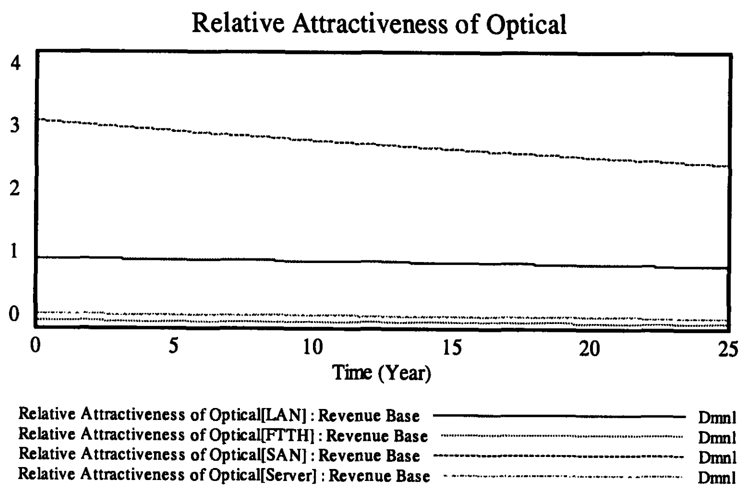

Figure 37: Base Case Relative Attractiveness[40] of Optical. While both Optical and Other Attractiveness grow, Relative Attractiveness declines, indicating a more rapid improvement for Other technologies.

[40] Relative Attractiveness is a ratio of "Optical Attractiveness" to "Other Attractiveness"

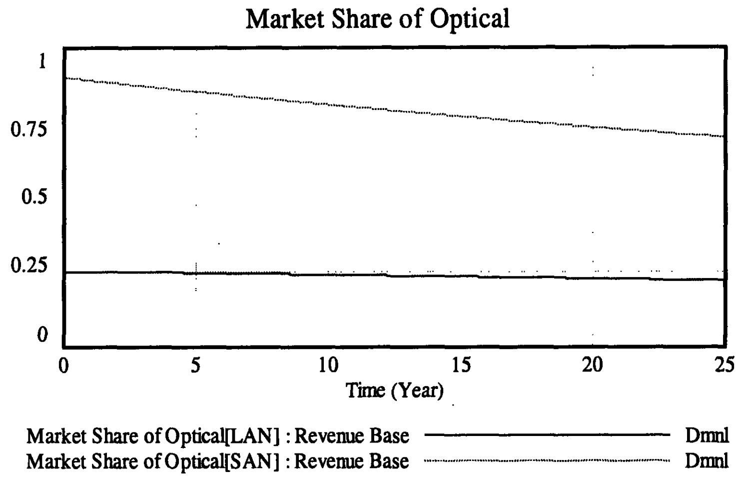

Figure 38 Base Case Market Share of Optical for the LAN and SAN markets. Since Relative Attractiveness declines, Optical becomes less likely to win market share

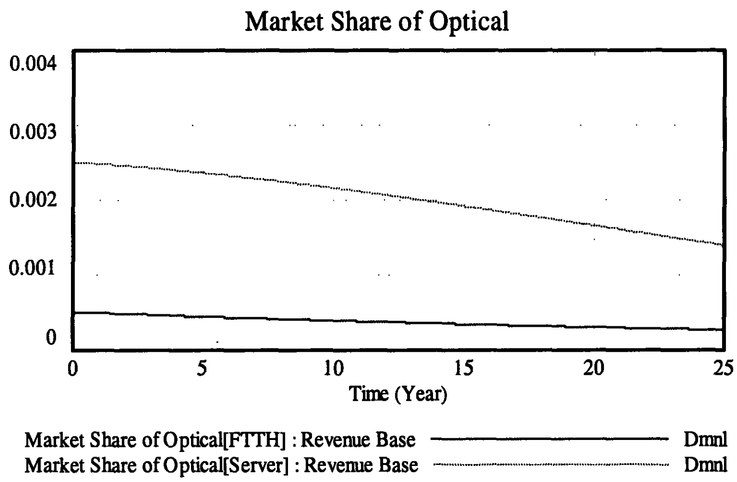

Figure 39: Base Case Market Share of Optical for FTTH and Server. Same behavior as Figure 38.

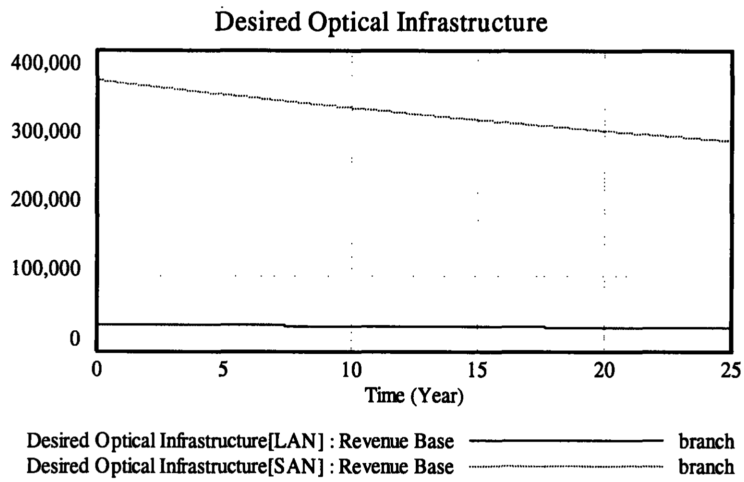

Figure 40: Base Case Desired Optical Infrastructure for LAN and SAN. Since the market share goal is decrease, so to is the Desired Optical Infrastructure.

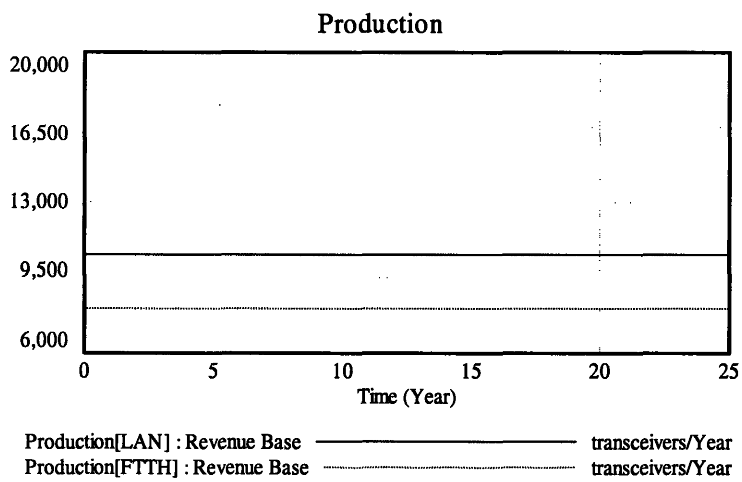

Figure 41: Base Case Production for LAN and FTTH. Production remains constant at the level of transceiver replacements.

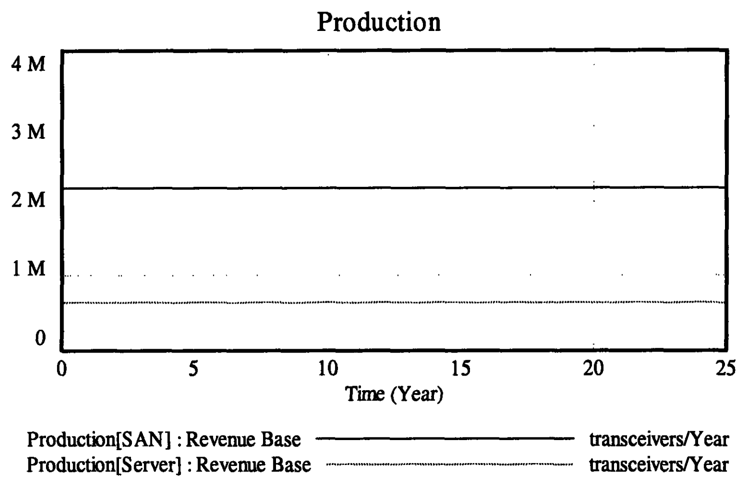

Figure 42: Base Case Production for SAN and Server. Same behavior as Figure 41

The revenues for each segment in this case remain fairly constant. It should be noted that while the model counts on replacements of the existing infrastructure, as the "Relative Attractiveness" declines, existing optical networks may be allowed to run their lifecycle, and then be replaced by other networks, resulting in reduced infrastructure and the corresponding revenues.

For this part of the model, margins are taken to be a constant over time. Efforts by firms to increase the performance of the transceivers lead to a corresponding increase in costs and greater absolute profits. It is assumed here that the existing networks and connections choose to replace existing infrastructure with the most up-to-date, an\d thus most expensive technology. The result is a constant number of transceiver produced, but at higher prices, and therefore higher revenue even though the margins remain constant.

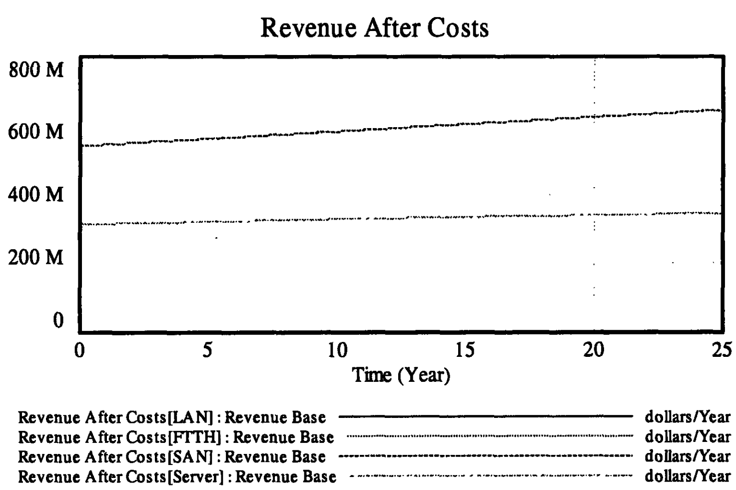

Figure 43: Base Case Revenue for all segments. Revenues do increase slightly because performance and costs increase slightly, while margins remain constant. Absolute revenues increases with no increase in margins

While SAN markets have dominated, the Base Case serves as a warning of sorts. The attractiveness of the optical SAN decreases relative to other technologies, resulting in a potential overcapacity. In this run of the model, SANs are in danger of eventually being overtaken by other technologies if R&D is not productive enough. The point here is that the lack of new volumes and resulting lack of R&D money stalls the improvement of optical SAN devices, introducing an opportunity for other technologies to gain an advantage. In other words, if the electrical communications industry enjoys greater resources and is better organized, the optical industry will suffer, or it can wait and hope that somebody introduces bandwidth intensive applications that only optical can serve effectively.

In the case of the Server market, there are many factors that are not included in this analysis. There are several technical barriers to providing optical connections for servers. First of all, current transceivers are not dense enough. That is, the XFPs and SFPs take too much room for too few bits per second. If the Server needs 25 transceivers per connection, it is easy to see how density can be troublesome. Also, an optical transceiver requires much more power than an equivalent electrical connection. This power budget can be managed better in applications where the required optical connections are much less (just one or two transceiver per connection in the other three segments). These and other technical barriers specific to server connections divert monies that could be invested in the device itself rather than the architecture of the network.

The Server data depicting revenue can be misleading. Because of the number of transceivers that would be needed for a rack-to-rack connection and the price that producers could charge for such state-of-the-art equipment, the revenue potential is rather large. However, the costs are also much higher, particularly considering the technical barriers that would need to be overcome. This model considers the costs of developing technical solutions to overcome the technical barriers by denoting a lower percentage of revenue dedicated to R&D (because many resources are dedicated to the technical barriers that are external to the transceiver). Since the success of optical server interconnects depends on solving the technical barriers, it is difficult to know when the potential of servers will be realized. Further analysis shows that the server segment could be very successful, given solutions to the barriers.

One lesson from the Base Case is that transceiver revenue can only be increased by shortening the product lifecycle through obsolescence of the optical components. Figure 44 shows the results of halving the product lifecycles for SANs, Servers and FTTH networks. While the benefits of shortening the product lifecycle are potential significant, such a reduction in the product lifecycle is difficult for three reasons;

1. The costs associated with improving devices significantly (typically with a new platform), especially if the costs are relative to the very narrow market segment that an individual firm may serve.

2. Firms have been successful in the last 10 years in selling products based on the promise of "future-proofed" networks. It is simply more difficult to convince consumer that they need a few more megabits per second than it is to convince a computer user that they need a processing chip with a few more Hertz.
3. Finally, optical networks are subject to network dynamics. The build is a one-time event. Contrast those dynamics to appliance dynamics, characterized by a continual need to replace the product with the next best thing, and it is easy to see what a huge impact these dynamics can have on the market. Again, the absolute number in the graphic are not validated – only the trends are important in this study.

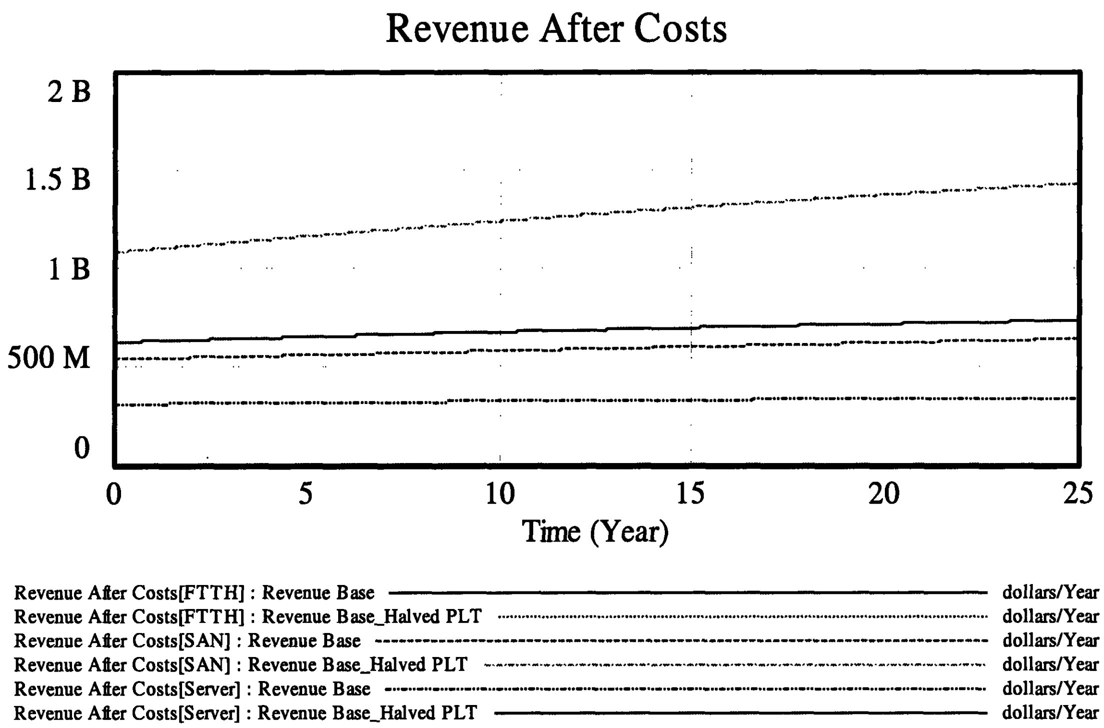

Figure 44: Base Case vs. ½ Product Lifecycle Revenue for FTTH, SAN, and Server networks. This clearly chows that reducing the product lifecycle, through a higher rate of obsolescence, is advantageous.

The case when product lifecycle is halved for LAN is particularly revealing. A shorter lifecycle allows greater revenue that enables optical LAN to challenge the current dominance of other technologies. As postulated from analysis of the dynamics hypothesis, the fixation on reducing costs is not the only way to generate revenue. Figure 45 shows the market share progression, while Figure 46 shows the enhanced revenue growth rate.

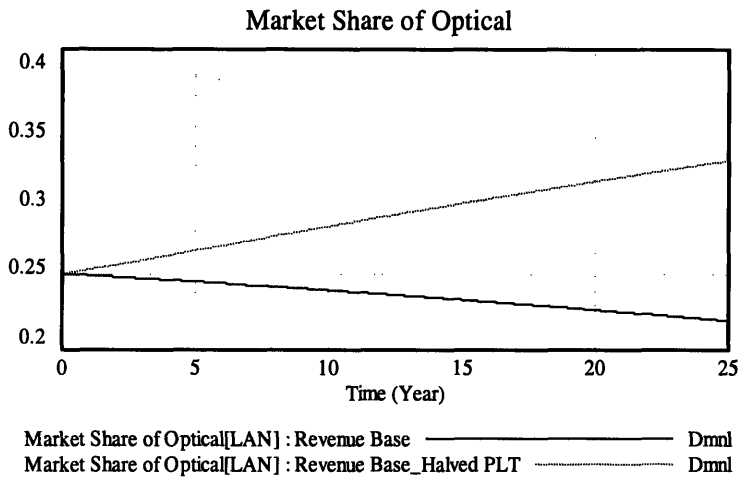

Figure 45: Base Case vs. ½ Product Lifecycle Market Share for LAN. Unlike the other segments, the ½ decrease in product lifecycle for LAN actually allows Optical LAN technology to gain on other technology. The result is a higher market share. Any of the other segments could display this behavior given the proper conditions.

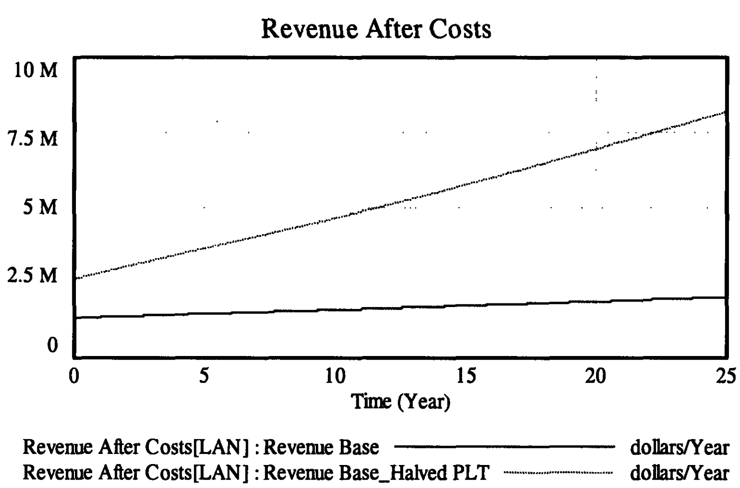

Figure 46: Base Case vs. ½ Product Lifecycle Revenue for LAN. As expected, increased market share results in higher revenues.

3.7.1.2 Increased R&D Productivity For The Revenue Model

The Base Case introduced some of the fundamental dynamics of the system. In all the segments, optical loses out to other technologies. One way to combat this trend would be focus on the effectiveness of R&D and/or increase the money put into R&D to try to win over the market. This improvement can be achieved through the purchase of advanced tools, resource sharing among industry members, efficient deployment of resources on the "correct" technologies, or other methods. The next iteration of the model introduces improved the effectiveness of R&D programs to improve BRxD.

Figure 47 graphs all the market segments as each of them begins to capture market share. For each segment, the R&D productivity has improved just to the point of "catching-on." The common characteristic is that once the attractiveness of optical approaches, and then exceed the attractiveness of competitors, optical will eventually take over the market. This effect is due to the additional revenue that feed continued R&D.

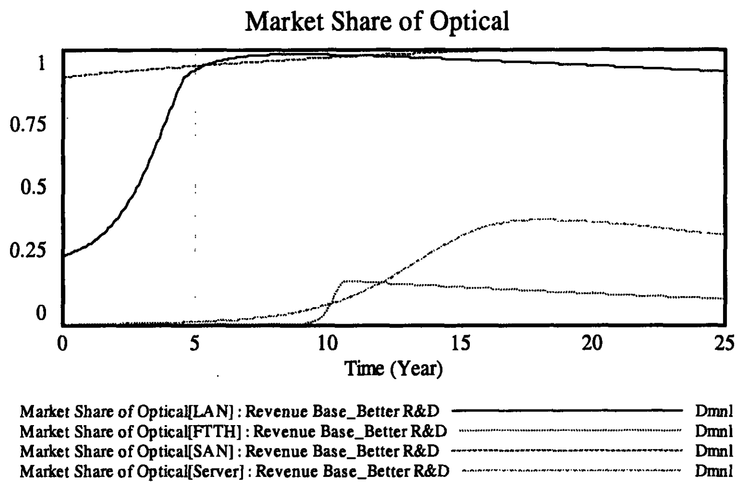

Figure 47: Better R&D Market Share for all segments. Improvements to R&D productivity allow Optical technologies to catch other technologies. All markets increase market share, showing behavior that is indicative of the market conditions of each.

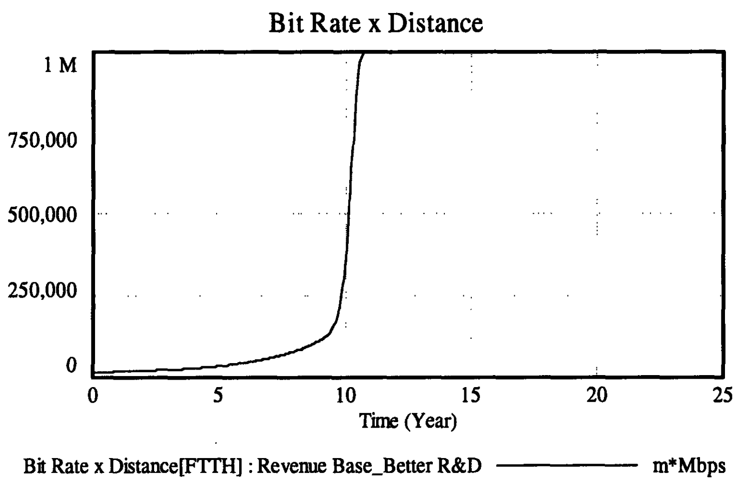

Figure 48: Better R&D BRxD for FTTH. The reinforcing effects of better R&D allow FTTH to improve rapidly. At some point, improvements in BRxD will be restricted either by physical barriers, or lack of market demand. The ceiling limits the improvements of Optical, and allows electrical to catch up. Market share will suffer, as demonstrated by the limited market share growth of FTTH in Figure 47.

One of the attractions of the FTTH market is that the potential is quite high. Once optical connections to the home become "better" than DSL and cable on a costs per performance basis, the proverbial floodgates will open and the influx of new revenue will carry optical to wide installation. The model does not account for difficulties of dealing with the complex regulatory structure of access markets or of the practical difficulties in tearing up 10 million backyards to install the fiber. Nonetheless, the potential of rapid growth is real, as shown in Figure 48. Increasing the productivity of the BRxD R&D efforts helps advance the level of penetration seen in Figure 49.

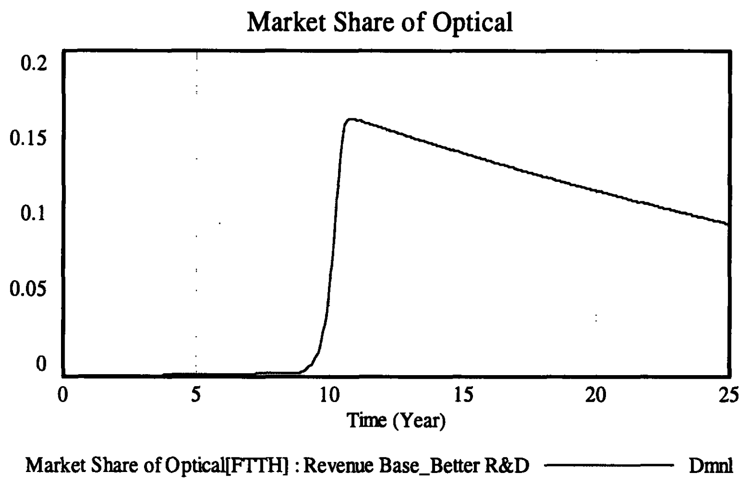

Figure 49: Better R&D Market Share for FTTH. The cap on market share growth results from an "optimal" BRxD.

There are a couple drawbacks to FTTH. The problem with FTTH is that although growth can be rapid, the market is easy to saturate, and the links do not need high bandwidth, relative to the other optical connections considered in this thesis. The result is high growth, but to a relatively low peak level. The network dynamics of FTTH also play to the detriment to the market. With long lifecycles, the "future-proof" links stay in the ground for years and decades.

With better BRxD R&D productivity, optical SAN markets are able to maintain and expand the dominance over other technologies, quickly achieving 100% market share. The increase in market share for the LAN (Figure 50) is characterized by a competitive market that fights back to compete. The rate of increase for the costs and performance of other technologies is lower than optical LAN at the start, resulting in the penetration of optical. However, later in the period, competitors begin to turn the tide as optical reaches the upper limit to performance. The decline in the R&D budget that slows the rate of improvement below that of others is shown in Figure 51.

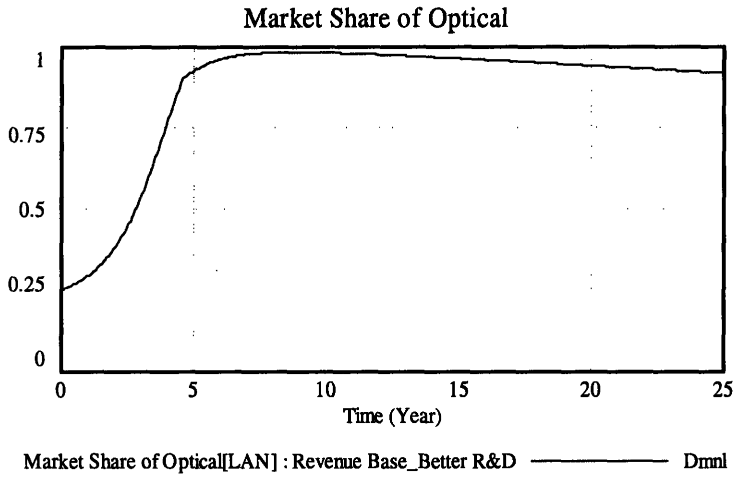

Figure 50: Better R&D Market Share for LAN. This shows the results of backing off R&D once full market penetration (or close to it) is achieved, particularly in a competitive market such as LAN.

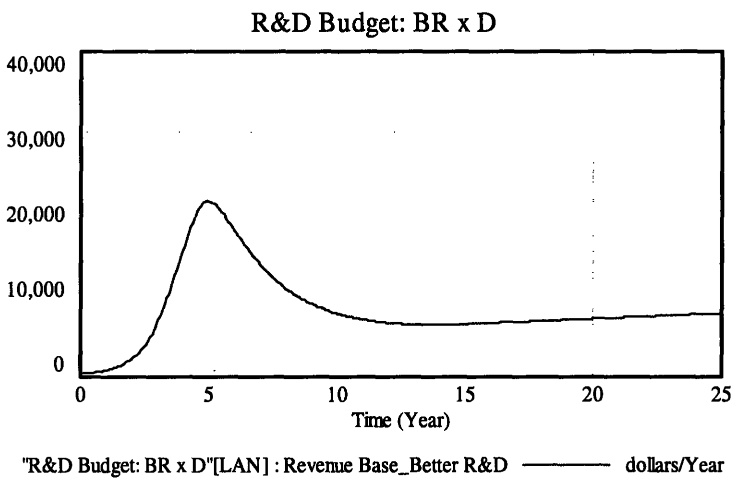

Figure 51: R&D Budget for BRxD for LAN. As market share approaches 100% (Figure 50), investment is decreased, resulting in the deterioration of market share.

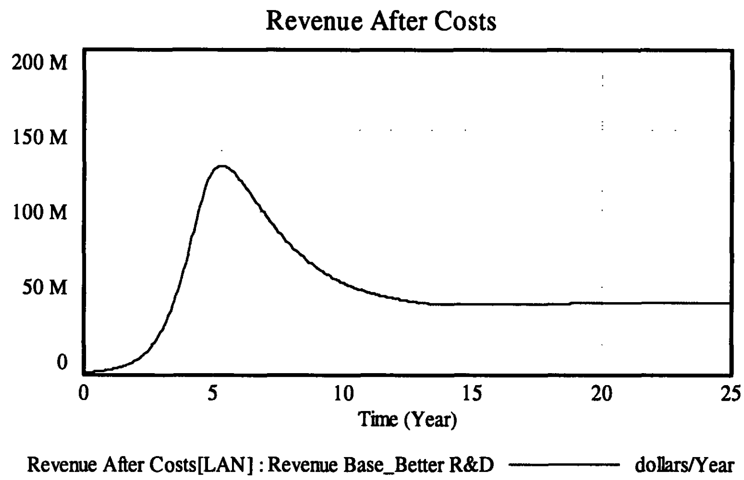

Figure 52: Better R&D Revenue for LAN. Also playing into the reduction in R&D investment is the market saturation effects. At 100%, growth slows and revenue levels. See text for further explanation of this important behavior.

The revenue graphic (Figure 52) demonstrates some important dynamics of the long product lifecycle market. The distinct peak and flat future revenues reveal a lot of the market. The period before the peak is the incubation time necessary for new products to gain market acceptance. In that time, the existing technology generation, or the legacy technology dominates the market and the new product must fight to gain markets. Once it does gain the advantage, there is a peak followed by a downturn that corresponds to the end of the build up. Incubation time is costly to firms, and standardization could be a way to avoid that period because the standard would make the next generation transceiver ready-made for the infrastructure. The hope would be that the downturn at the end of the build is not relevant because the next generation would be arriving on the market. This story illustrated the importance of product obsolescence.

In essence, standardization can enable an obsolescence mindset. The market segment with the most sales would be able to lead the industry in the technology advancement. This constant release of newer and better standardized devices means that if, say, the Server market has the most sales and drives the market to meet its demand, the less technological advanced segments will "piggy-back" and save millions of R&D dollars. The resulting ease by which network providers can obtain better performing devices creates an obsolescence culture in that the technology will increase more rapidly than otherwise because of the additional industry-wide resources contributing to each segment. All segments will want to take advantage of the improved product by trying to convince their customers that they need to have it.

Server connections exhibit the same connection limited behavior that was seen in the FTTH market, albeit at a much greater bit rate. It is impossible to know where that limit is, particularly for the bandwidth-hungry server connections, but the point is that at some bit rate, there will be no further benefit to increasing performance, allowing other technologies to catch up. The difference here is that the revenue level for servers does not show the peak revenue behavior corresponding to the peak market share that is pronounced in the FTTH and LAN markets (Figure 53 and Figure 54).

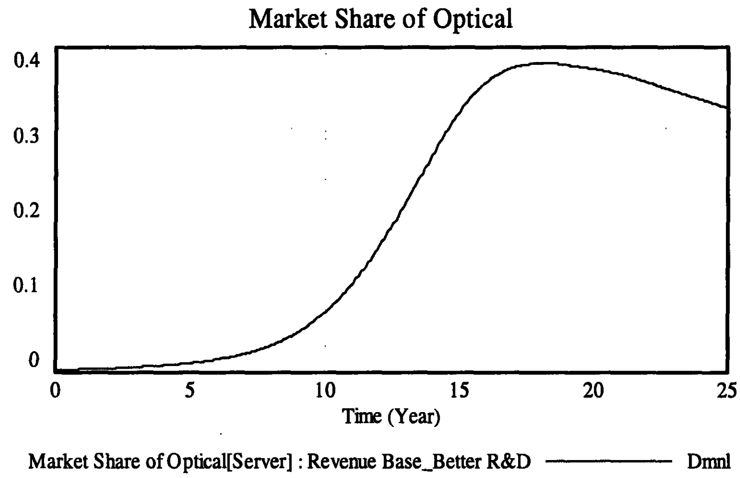

Figure 53: Better R&D Market Share for Server markets. The market share is limited by an "optimal" BRxD, much like in the FTTH market.

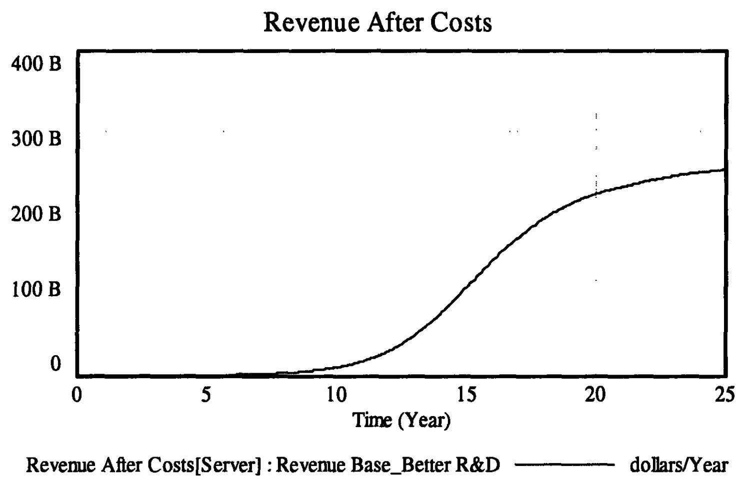

Figure 54: Better R&D Revenue for Server. Capture of even 40% of the market results in an enormous revenue increase for the Server market. Also, notice there is no drastic peak and decline. This is due to the shorter product lifecycle that enables a continuing renewal of the market.

The lack of a peak in Server markets is a result of the short product lifecycle that allows a rapid turnover of devices. Essentially, the market completely recycles itself over a short time. Figure 55 helps to understand this phenomenon in terms of separate technology generations. Each generation cycle is represented by a peak and a decline, with each commanding a bigger market. If the generations are close enough in time[41], the markets experiences a steady increase in sales, and revenue. Figure 56 shows a similar illustration for a market segment with longer product lifecycles. The space between generations is large enough that the bump of each individual generation is well defined.

The peaked behavior of the revenue cases above are problematic in that they disrupt supply chains and alter capacity utilization for producers. As experience has shown, building to accommodate a peak can be very costly during a valley. Shorter product lifecycle is one way to reduce the potential of peaks in the market. Another way to avoid the peak behavior in the figure could be to extend to additional markets so that the peak could be sustained for longer periods. Standardization could provide an avenue to additional markets help equilibrate the market. Section 3.7.2 addresses that possibility.

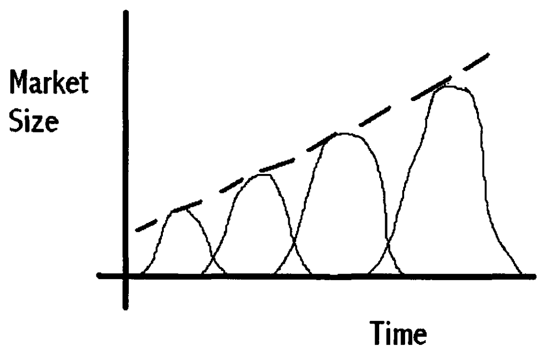

Figure 55: Short Product Lifecycle Dynamics

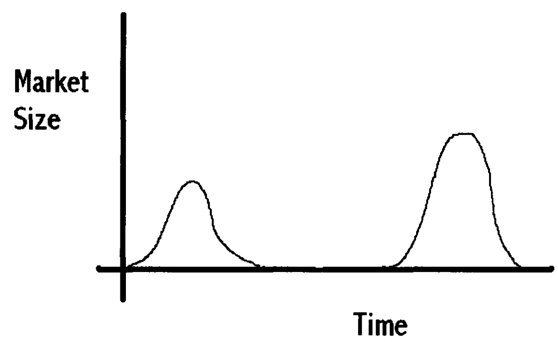

Figure 56: Long Product Lifecycle Dynamics

Improving the performance of R&D efforts can also be managed by increasing the revenue dedicated to R&D. The effects of this policy results in the same behavioral changes that results from improving R&D productivity. In fact, actual policies for improving R&D results would likely involve both measures.

3.7.1.3 <u>*The Need for Volume For Revenue Model*</u>

This section uses the model results to illustrate the final lessons of the Revenue Loop. Volume has been discussed as an important parameter to helping the optoelectronics industry back to health.

In the growth case, the demand for broadband expands to saturation points in each segment. The additional volumes (assuming optical maintains market share) infuse the industry with enough new revenue to propel the improvements in BRxD and costs. Figure 57 and Figure 58 show the increase in

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[41] Typically, a new technology generation every three years is an adequate spacing to avoid the period of drastic decline. The three years assertion is based on observations from other high tech industries.

addressable markets. This is not the increase in optical demand, just in the number of potential customers that can access optical networks.

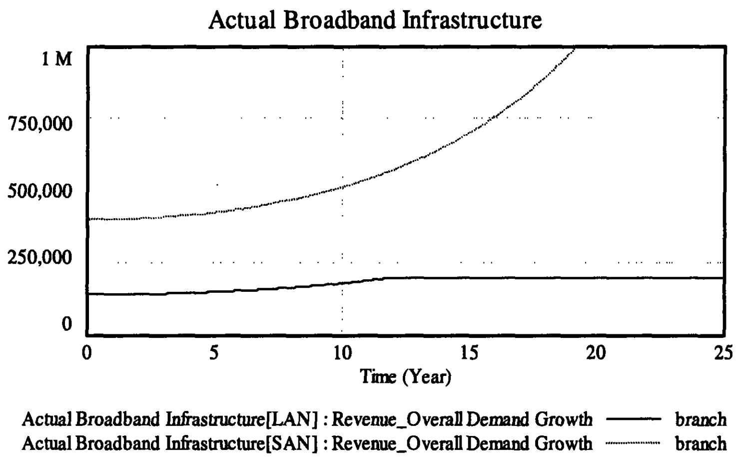

Figure 57: Increases Demand Broadband Infrastructure for LAN and SAN markets. The effects of increasing overall demand for broadband (in terms of links, not BRxD per link)

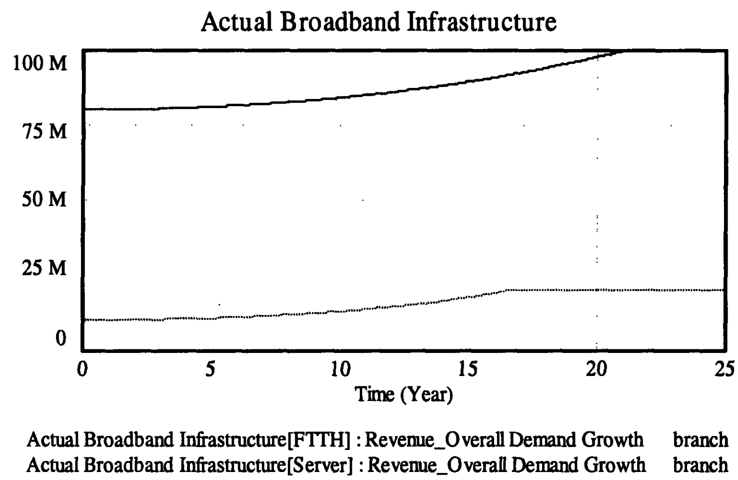

Figure 58: Increases Demand Broadband Infrastructure for FTTH and Server markets.

In the first version of this case, R&D productivity does not increase, resulting in only moderate growth in the optical share of the growing broadband market. Figure 59 shows the total industry revenues in both the Base Case from above and the case when product lifecycles are halved. Fueled by nothing but higher a bigger broadband "pie," revenues outperform previous cases. The growth case does shown in the figure does not include any measures that would makes the optical solution more attractive to other technologies, and the market share of each segment remains constant.

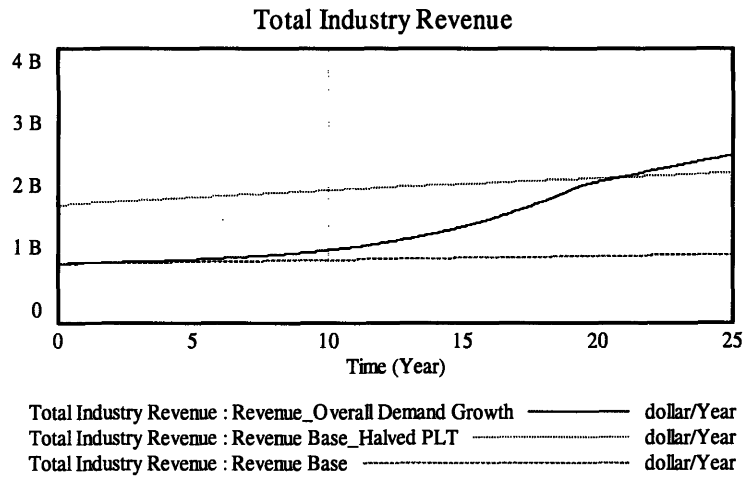

Figure 59: Base Case vs. Demand Growth vs. ½ PLT Comparison Industry Revenue for all segments. The sum total revenue for all segments is considerably higher for both increasing in broadband demand and reducing product lifecycle. These two cases represent two potential policies for increasing revenue.

When R&D is made more productive and optical begins R&D dollars to make significant improvements to the devices. Under exactly the same conditions that resulted in lagging markets in section 4.7.1.1, with additional volumes, the industry can thrive. In this case, increased volumes work to improve the attractiveness of optical and the total revenues dwarf any other case. Figure 60 shows the market share improvement in each segment and Figure 61 shows the resulting revenue.

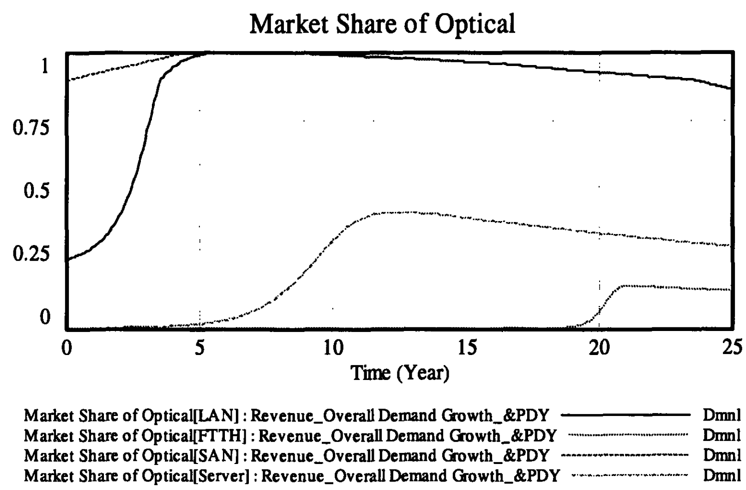

Figure 60: Base Case vs. Demand Growth vs. ½ PLT Comparison Market Share for all segments. The combination of increasing overall demand and improving R&D increases revenue not just from additional sales, but also from increased market share won via device improvements funded by revenues from additional sales.

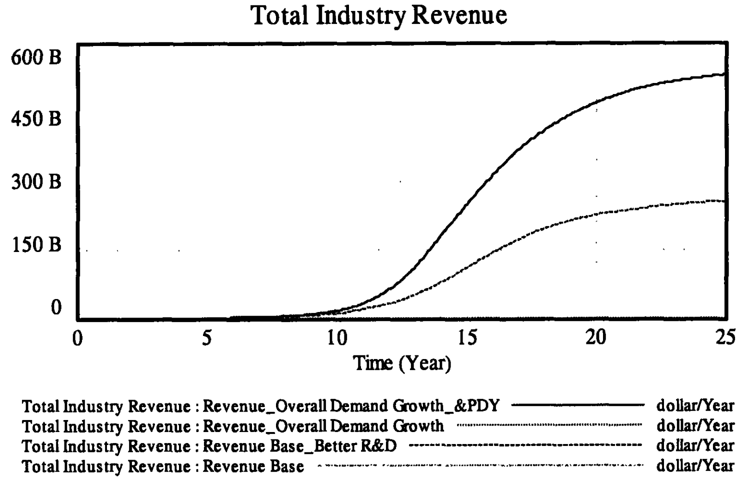

Figure 61: Base Case vs. Demand Growth vs. ½ PLT vs. Better R&D Comparison Industry Revenue for all segments. Improving R&D is an effective route to improved revenues.

Firms are generally interested in boosting volumes to capture more revenue. The scenarios offered in this section do not address two important drivers for revenue, 1) The volumes captures not just through overall broadband market growth, and 2) cross-segment leverage of volumes. This thesis proposes that producers can generally go about gaining volumes in two ways; 1) standardization to capture cross-segment volumes, or 2) Capture of volume through gained market share. Another way to sell more transceivers is to shorten the product lifecycle, thereby avoiding peaks and valleys, as shown above. The next section begins to address the effectiveness of standardization.

3.7.2 Standardization Model Analysis

The next phase of modeling builds in the effects of standardization. There are two different ways that a standard can affect the industry. First, under standardization, there will be only one dedicated platform, all but eliminating the expensive costs of creating a new platform. Currently, each company is struggling to develop newer and better devices to out-compete the rest of the firms. The development of a new platform for transceivers can be the most costly R&D expenditure[42]. Eliminating new platform development costs leaves more resources to improve other functions of the transceiver such as bit rate and costs.

Another way that standards can affect the industry is that firms can leverage volumes across segments, thereby expanding the available addressable market to each manufacturer. As it stands now, one production line has a potential market limited to the systems that support that device. As the analysis

[42] Comment from discussions at the May 4, 2004 CTR Conference

of the revenue model hinted, adding volumes can generate enough revenues to support the industry and provide additional monies for R&D that will allow optical to capture more of the broadband market.

The standardization model introduces the two affects of standardization described above. The "Need to do Something" is linked to the "Capacity Utilization" as stipulated in the dynamic hypothesis of section 3.5.3. Given a policy of standardization, the "Need" is converted to a driving force for reducing the number of platforms. As the number of platforms falls, the model is affected in three ways, 1) the ability of manufacturers to reduce costs is enhanced, 2) each platform receives a higher R&D budget as industry revenue is split among fewer technologies, and 3) since the market becomes more commoditized, margins are reduced.

3.7.2.1 The Base Case For The Standardization Model

Just as in the revenue model in the last section, the analysis of the standardization model begins with the base case. All the parameters have been left the same as the revenue base case, with the only the added standardization structures added.

Figure 62 shows the reduction in the number of platforms due to a high "Need to Do Something." The result of each segment gravitating to a single standard is seen in the corresponding market penetration of each segment (Figure 63). Figure 64 shows the relative total industry revenues (the sum of all four segments).

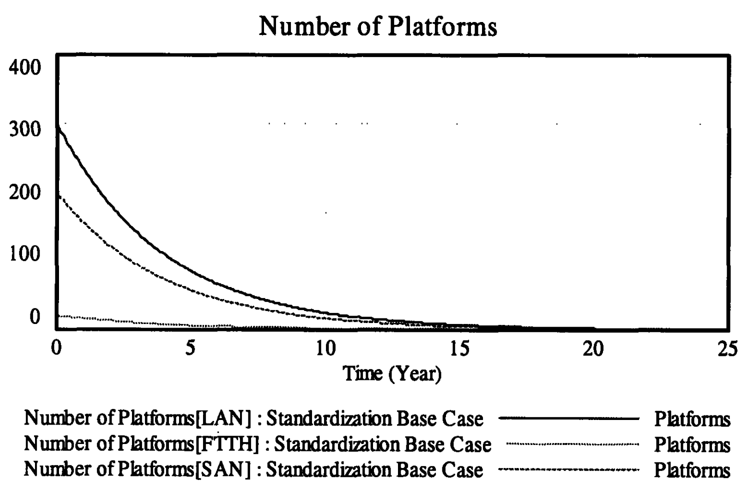

Figure 62: Standardization Case Platforms for LAN, FTTH, and SAN markets. Efforts to standardize reduce the total number of platforms.

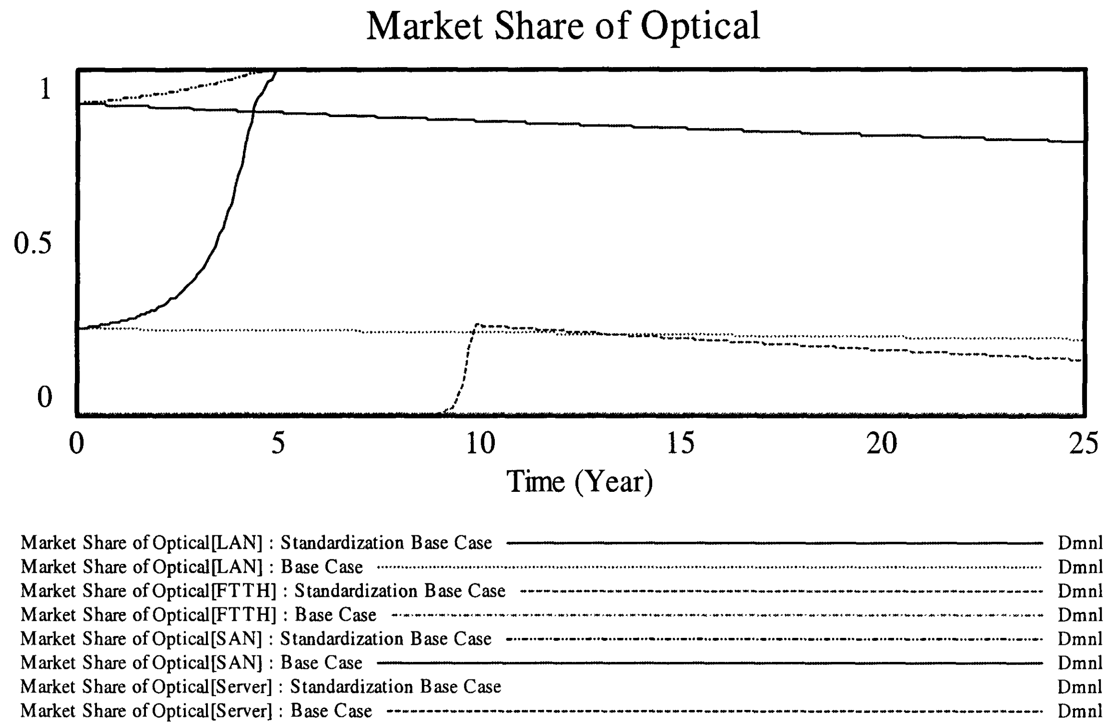

Figure 63: Standardization vs. Base Case Comparison Market Share for all segments. In all segments, standardization is better for market share than non-standardization.

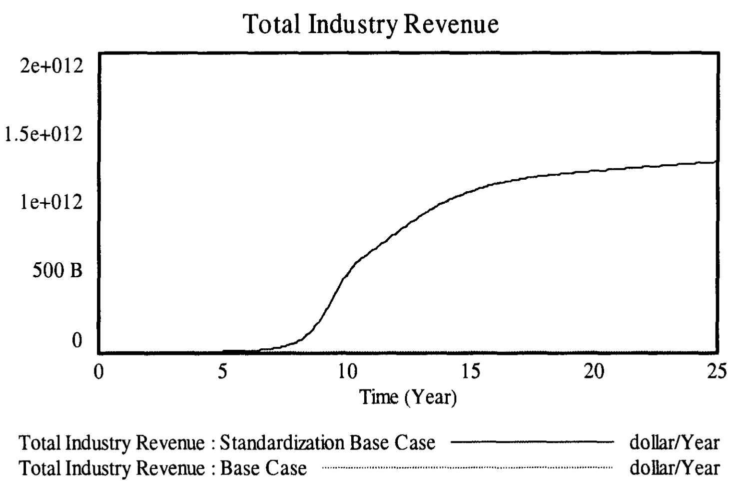

Figure 64: Standardization vs. Base Case Comparison Industry Revenue for all segments. Revenue is drastically improved. Beware of the lack of calibration in the models that may exaggerate (or understate) the actual increase.

The server market tends to dominate the industry once it overcomes the technical barriers of implementation. The costs of overcoming those barriers could be restrictive and slow the penetration of optical. In the case where the server market does not take-off, the industry revenues still eclipse revenues without standardization, however, the severe peak is prominent as the product lifecycle of transceivers in the non-server markets is relatively large (Figure 65).

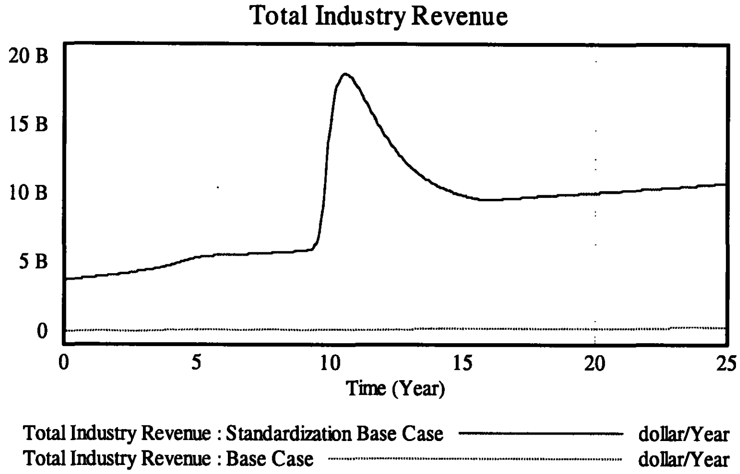

Figure 65: Standardization vs. Base Case Comparison Industry Revenue without Server markets. As the Server markets become huge compared to the rest of the segments, this figure excludes Servers. The peak and decline are characteristic of long product lifecycle markets.

The non-calibration of the model means that the server market may not be large enough to eradicate the peak-dip behavior even if it does take-off. That is, this model makes no claims to an accurate quantitative analysis of the total addressable markets. As an example, the SAN market also has product lifecycles short enough to avoid a stark peak. In the total industry view in Figure 65, the non-peak behavior of SAN is overcome by the peak behavior of FTTH in particular and does not affect the total industry behavior. Also, the small bump in the Standardization Base Case line in Figure 65 is due to the peak in the LAN revenues. While care has been taken to try to be estimate the relative sized of the markets, the strength of this and other segment relative to each other could be inaccurate. The important points of this model is that 1) long product lifecycles tend to introduce revenue peaks followed by steep declines, and 2) standardization of transceiver that gives producers greater access to volumes and enhanced R&D productivity[43] can boost revenue by a significant amount.

The other policy option is that standardization is not accepted as a solution to return the industry to health. In this case, low capacity utilization is met with further efforts to differentiate and an increase in transceiver platforms. The result of this action is a further erosion of the market share as compared to the Base Case, in which there no movement at all on the number of platforms (Figure 66 and Figure 67).

[43] Standardization enhances R&D in two ways, 1) more resources per platform as the number of platforms decreases, and 2) continuance of learning curves as the technology builds off of past transceiver designs, network compatibility, power conditioning, etc. The common components can magnify the incremental improvements and provide a "jump-start" for each generation.

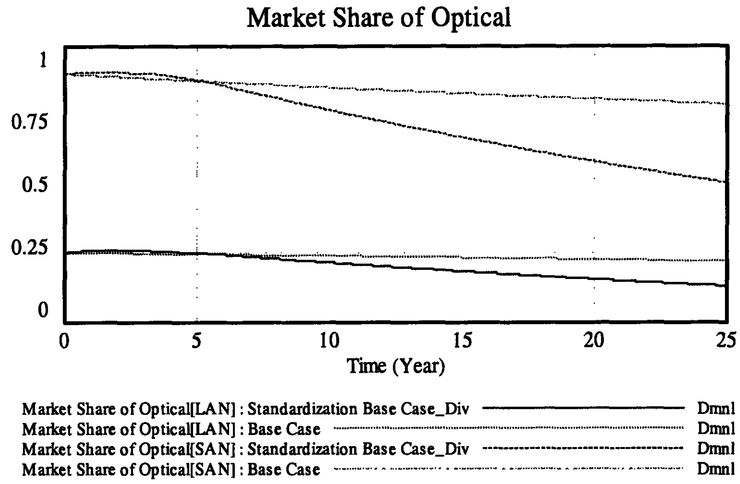

Figure 66: Standardization vs. Divergence Market Share for LAN and SAN markets. Comparing a standardization policy to the current dominate policy, differentiation to win market share. In the Base Case, divergence accelerates the downturn in market share.

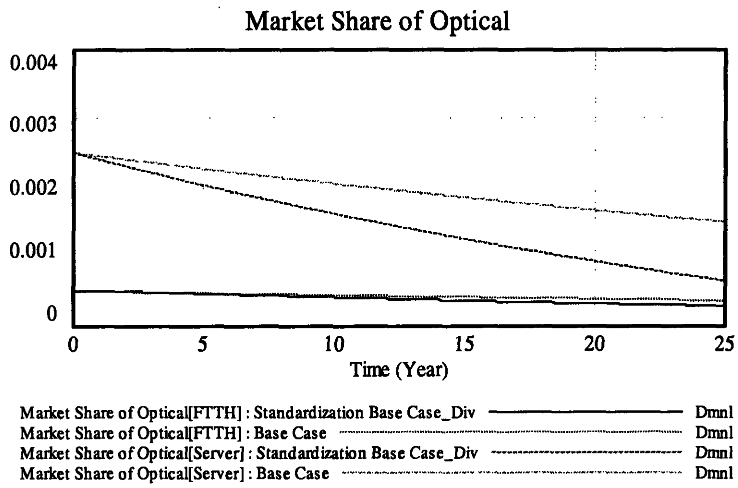

Figure 67: Standardization vs. Divergence Market Share for FTTH and Server. Same behavior as Figure 66

The SAN market segment provides a clear display of the difficulty in getting the industry to follow a path to standardization. The revenue graphic in Figure 68 shows that initially, the revenues are greater if the industry continues to diverge. This phenomenon is present in all segments, the length of time that the non-standardized revenue stays above the standardized path, and the amount by which it exceeds the standardized path is different for different segments with different parameters. That period of lost revenues is a powerful barrier to implementation, as there is no guarantee for the firms that the period will pass and standardization will reap the significant revenue increases suggested by the model.

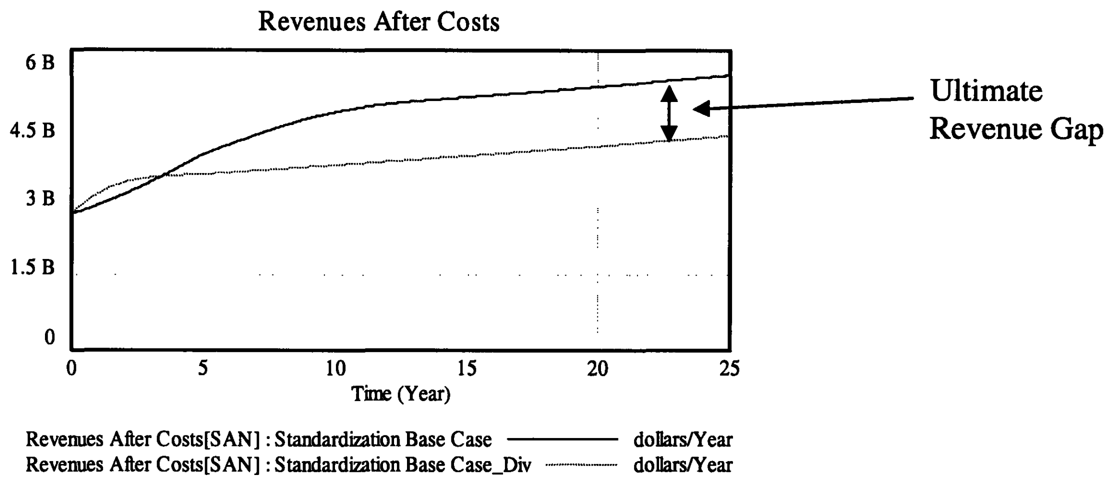

Figure 68: Standardization vs. Divergence Revenues for SAN market. The initial period of higher revenue in the divergence case is a strong barrier to implementation of a standard.

In the SAN example in Figure 68, the eventual revenue gap is not large because optical already owns most of the segment. In other segments, the eventual margin between standardization and non-standardization is very large, for example, Figure 69 shows the same graphic for LAN. Because of scaling, the period that revenue falls below that of non-standardization cannot be seen.

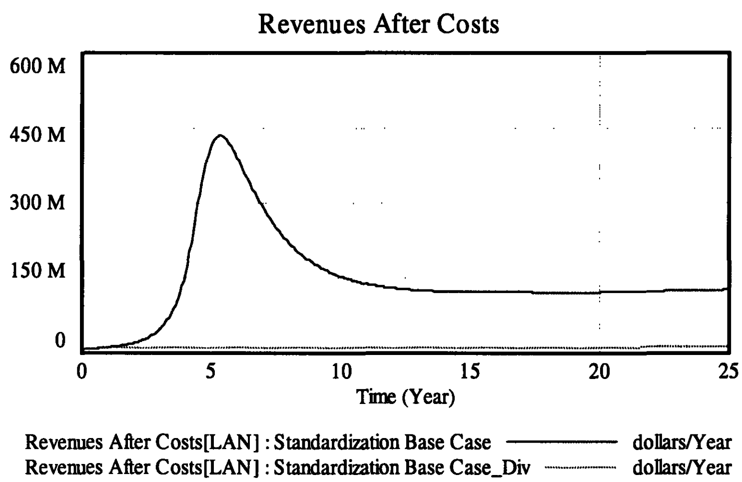

Figure 69: Standardization vs. Divergence Revenues for LAN markets. Ultimate Revenue Gap is larger here due to greater increase in market share than for SAN in Figure 68.

The model has not been developed to adequately portray the cross-segment convergence of transceiver designs. However, since the model is more concerned with relative behavior, the market as a whole can be represented in any one of the individual segments by realizing that the number of platforms can be industry wide as well as inter-segment. There are more difficult technical challenges in reducing the number of platforms across segments which may make it more difficult to reduce the number of platforms, but the same vast improvements in revenue can be scales to the industry level and provide a useful depiction of the industry.

3.7.3 Summary of Insight For Model Analysis

This analysis section is replete with insight for the industry. The following includes some of the important points.

Revenue Model Analysis:

- The Base Case simulates the industry with no new broadband demand (in terms of links and connections). In this case, only product replacement provides revenue. That revenue must suffice to infuse the R&D sector with enough resources to improve the devices to the point that optical can gain markets share.
- Because replacement is the only source of revenue, shorter product lifecycles can provide additional revenue and help boost R&D resources.
- The LAN market demonstrates the potential of reduced product lifecycles. The LAN segment in this model was able to increase market share, and thus realize a new driver for growth in achieving effective demand growth.
- One way to try to emerge from a stagnant market is to either increase the productivity and/or to commit greater shares of revenue to the R&D effort.
- FTTH has a high and rapid potential for increased revenue. The problem with FTTH is that the relatively low broadband demand per link makes it more difficult to emerge above other technologies since copper-based and wireless networks can provide low bit-rate connections at very low costs. Also, FTTH suffers from market dynamics that are characterized by a one-time build and long product lifecycles.
- Product life cycles can be illustrated by the peak-valley behavior of revenues when achieving market penetration. A typical lifecycle consists of an incubation period that lasts until the new technology can catch the incumbent. The peak follows as the market converts to the newer, better technology. Once the market has been captured, the revenues dip and flatten.
- Shorter product lifecycles puts the peaks close enough together that there is effectively no valley experienced by the industry.
- Peak behavior can disrupt the supply chain and capacity management. Reduction in product lifecycle is potential solution to this disadvantageous dynamic.
- Optical could also ride an increase in overall broadband demand (in terms of links and connections) as a source of additional revenue even without increasing market share.

- To reduce the product lifecycle, networks need to introduce obsolescence. Obsolescence is achieved by developing customer services, at the edge of communications networks, which requires greater performance from the network. This growth in "edge functionality" requires upgrades to the network and provides shorter product lifecycle. The first step to that mindset is an increase in the broadband per link, which would lead to a desire for better links. This broadband per link variable is not included in this model, but the consequences could be vital to the success of optical.

Standardization Model Analysis:

- Standardization, without any other policies to spur growth, can drastically improve the performance of the industry
- Revenues with an effective standardization policy can generate revenue many orders of magnitude greater in this model, lead by a very large Server segment that
- Given the uncertainty of the success of Server segment overcoming the technical barriers, the relative revenues were considered with no growth for the Servers. The result is still a significant increase in revenues
- The long product lifecycles common to network components still create a large peak in the overall industry even with standardization.
- With no standardization policy, the number of platforms grows greater, with the result of a poorer performing industry.
- All segments show an initial period where the revenues for the standardization path are lower than the revenues with no standardization policy. This initial period represents a difficult barrier to implementing standardization as firms are reluctant to give up revenue.
- Cross-segment standardization is not treated explicitly in this model. However, each segment could be considered an analogy for the entire industry, with the number of platforms representing the variety across the industry rather than across just one segment. The lesson learned can be applied to the industry as a whole.

3.8 Summary

This chapter presented the role of standardization analyzing the optical communications industry. The results of the analysis show that standardization has clear economic advantage over the current industry paradigm. There are barriers to implementing a standardization policy that have been mentioned in this chapter and in the previous chapters. The next chapter offers further support of standardization as a credible path toward growth by comparing the experiences of other relevant industries that have incorporated standards into the market. The final chapter then offers potential solutions to the industry woes based on this analysis.

Chapter Four: A Historical Perspective

The problems discussed in the previous chapter focused on lack of volume and the high costs of optical components as the major contributors to the current state of the industry. Members of the NGT TWG wonder if standardization can be instituted as the key to securing the volumes and allowing manufacturers the flexibility to enact cost saving measures that will bring down the costs of the transceiver. This chapter presents validation for looking at standardization as a solution by proposing a generic path to growth and fitting that path to other industries that have experienced growth in the last 150 years.

4.1 Four Phases of Development

Is his book, *The Innovator's Solution*, Clayton Christensen proposes that profit accumulation occurs at the point in the supply chain where the technology is "not quite good enough" to met the needs of the customers. Once that technology advances to meet product requirements, firms must be able to identify and take advantage of the next profit making link in the supply chain. In terms of the ability to carry the numerous available network services, the transceiver has become "good enough" to meet the needs of mainstream customers. The success of the transceiver industry is evidenced by the observation that any optical component supplier can provide roughly the same level of performance for any network service. Full exploitation of the next profit making sector cannot materialize until there is significant standardization in the transceiver industry.

The current state of the industry illustrates the need to seek opportunities to converge transceiver designs. This paper presents a generic representation of the path to standardization that can also be applied to other industries as they matured from small, fragmented cottage industries to fully integrated industries. The development of today's optical transceiver market can be illustrated as a four phase process that began with the first period of significant growth in the industry and continues with the efforts to standardize that are just now mobilizing. The four phases have been developed for this thesis by drawing on Christenson's theory of innovation as well as a matrix of business types that contribute to the growth of the economy proposed by the Boston Consulting Group[44] (see Table 5).

4.1.1 Take-off Phase:

Phase one, the "take-off" phase, was ushered in by the perfection of fiber technology at Corning and Lucent Technologies that allowed long distance transmission without restrictive attenuation and

[44] The Boston Consulting Group proposed a matrix of business types that contribute to the growth of the economy as whole to formulate its strategic planning consulting practice.

dissipation. In the take-off phase, companies were able to enter the "specialization" category of the Boston Consulting Group's matrix (Table 5) in which there were many approaches to achieve advantage, corresponding to the number of firms and the variety of solutions within those firms. In specialization, these approaches are largely differentiated giving each firm sizeable competitive advantage in its niche market. In this phase, many firms enjoy high margin and relative health. The transceivers in the take off phase fit into Christensen's "not quite good enough" stage if supply chain dynamics.

Table 5: The BCG Matrix of Business Types

Number of Approaches to Achieve Advantage	Many	Fragmentation	Specialization
	Few	Stalemate	Volume
		Small	Large
		Size of Advantage	

4.1.2 Overshoot Phase:

Phase two is characterized by "overshoot." The rapid, unconstrained growth of phase one results in the proliferation of transceivers that leads to a divergent industry.[45] The overshoot phase took root as transceiver solutions became good enough, and firms overshot the market by producing more improved products that were beyond the technical necessity of the market. This gave rise to modulated architectures that brought more and more divergence among network providers as firms continue to try to maintain competitive advantages in niche markets. Eventually, every supplier could provide essentially the same performance for every network application. Margins disappear due to heavy competition.

In the overshoot phase, the industry entered into the BCG's "fragmentation" category. Fragmentation is characterized by the wide variety of firms offering individual options for technical solutions, yet with a fairly uniform level of performance across all the approaches. The consequence of residing in the fragmented category is that profitability is uncorrelated with market share. Performance is based, rather, on the ability of the firm to exploit market structures and achieve a competitive advantage[46].

[45] Fine, Charles and Whitney, D. *Is the Make-Buy Decision Process a Core Competence?.* IMVP Working Paper, MIT, http://web.mit.edu/ctpid/www/Whitney/morepapers/make_ab.html. Here, the authors describe the cyclical tendency of industries to integrate and disintegrate. Integration is synonymous with vertical integration, while disintegration refers to a more modular market structure where the supply chain is broken and dispersed among independent firms. Some of the drivers toward disintegration sited by the paper that apply to the transceiver market are; 1) the focus on niche markets where high margins are possible, 2) the organizational rigidity, or resistance to change, that sets in once a market position is established, and 3) the difficulty that would be inherent in managing product development across a larger number of different network architectures

[46] Hax and Majluf

Profitability in this environment is generally poor and large companies have no real advantage over small firms. If the take-off phase corresponds to Christensen's "not quite good enough" stage, then the overshoot phase is the "nearly good enough" stage. Firms continue to innovate beyond the industry need in order to differentiate. What remains is a sort if technical overcapacity.

4.1.3 Cooperation Phase:

As a result of the diminishing margins experienced in the overshoot phase, the transceiver industry has entered the third phase, regarded as "cooperation." Firms have begun to realize that multi-company cooperation is required for a healthy, stable, and successful industry. This drive to cooperate is demonstrated by the heightened interest in legitimizing solutions using multi-source agreements (MSAs)[47]. Cooperation begins the movement to BCG's "volume" category. Without the ability to differentiate product performance, this category represents the only way to increased profitability. It is important to note that a volume strategy requires a reduction in the number of approaches, or equivalently a reduction in the number of firms. This trend toward consolidation could be very important for the strategic choices of many current firms. The industry needs to be well coordinated so as not to restrict the movement to the next profit accumulation point on the supply chain, as theorized by Christensen. The limited number of MSAs and the lack of cooperation across market segments suggest that the transceiver industry still has a ways to go before it can leave this stage of development and enter the next phase.

4.1.4 Standardization Phase:

The final phase, "standardization" is the finalization of the cooperation where one standard for the technology has emerged and provides the platform on which the industry can evolve. Obviously, the transceiver industry has not entered this phase yet. This roadmap study aims to guide the industry as it moves from the cooperation phase to final standardization. The mechanisms for arriving at a universal standard could be the domination of a technically superior design, specific regulatory action, attrition of other competing standards due to lack of resources and/or mismanagement, or a combination of all these mechanisms. Chapter five will provide recommendations on how to achieve technically efficient solutions as well as regulatory measures that could help the industry along this path. Attrition of inferior standards and network mismanagement may also have a role, but those forces are more difficult to orchestrate.

[47] Taken from the comments of Next Generation Transceiver TWG chairman Michael J. Schabel (Lucent) at the October 10, 2003 meeting.

4.2 Industry Comparisons

The path to standardization outlined above can be validated by demonstrating how well it fits to other industries that have achieved growth. In addition, such a comparison could give insight into the possible paths to the standardization phase. For these reasons, it is instructive to look to other standardized industries to form intuition about the consequences and results of market dynamics in developing industries.

Formulation of a transceiver platform is not a simple matter of deciding on common characteristics of the device itself, but it must also fit into the needs of the optical network of which it is a critical part. The following is a review and comparison of the Railroad, Ethernet and IrDA cases and how they might relate to the transceiver case. Railroad and Ethernet are examples of network–based industries that needed standardization of the basic infrastructure as a mechanism to support further growth. The IrDA case represents the standardization of particular components. Following each case is a discussion on how the case maps onto the transceiver case, and any insights the comparison might offer.

4.2.1 Railroad[48]

The railroad industry has become ingrained in the US economic landscape. Like all major industries, its emergence did not occur overnight. In the 1820s and 1830s railroads filled a niche market that served short, local markets. Rail competed with steamboats and canals as the expanding US economy increased the need for transport of raw materials and agricultural products. By the 1850s, rail began to dominate thanks to a more flexible technology, favorable iron tariffs allowing cheap imports, growing domestic and foreign demand for foodstuffs, raw materials and finished products, and the entrepreneurial relentlessness of railroad leaders. The first take-off of growth, coincided with the federal land grants of the 1850s.

The decades following the take-off were marked by intense competition among local railroads. The scope of operations for rail lines expanded as rails attempted to capture market share by serving emerging economic regions in the Midwest and the west. This unconstrained competition resulted in overcapacity as multiple lines served the same centers.

The independent regional carriers were intensely competitive, but as the networks expanded beyond narrow geographical regions, the rail leaders recognized the danger of excessive competition and moved to standardize the basic network features, including gauge, signaling, ticketing, and inventory control. As railroad companies saw dwindling margins due to intense price wars as competition

[48] Adopted largely from *Emerging Infrastructure: The Growth of the Railroad* by Amy Friedlander. Corporation for National Research Initiatives, 1995 and *The American Railroad Network* by George R. Taylor and Irene D. Neu, 1956.

increased, leaders soon determined that the marginal costs of adding more throughput to the existing rail was much less than building new track to move into new markets. Therefore, the period of the 1860s and 1870s saw the development of measures that would optimize productive capacity of the existing physical infrastructure, including efficient scheduling and cooperation with competing firms. The significant increase in throughput enabled by allowing competing firms to use the track made standardization of the rail gauge a critical development.

In 1862, Congress specified the standard gauge at 4 feet 8.5 inches[49]. It took some twenty years for the standard to become more or less universal. Many local networks attempted to build non-standard gauge for either competitive advantage or for technologic reasons (the gauge was thought too narrow to support the increased power of locomotives). Ultimately, the standard took effect when it became increasingly difficult for the deviants to secure supplies as the suppliers did something that made the nonstandard impractical (go back to the reference to complete this thought)

The take-off phase of high growth in the railroad industry in the 1850s is similar to the growth of transceiver market in the 1990s. As railroads competed to capture new markets independently, so too did optical network providers. The period during and after the Civil War provided unlimited resources for railroad companies as emerging economies relied heavily on the railroad for transport of goods. This is analogous to the seemingly unlimited resources that poured into the telecommunications industry during the 1990s. In both industries, that economic windfall provided the feeling that high margins could support sustained profits, resulting in relatively independent technology. Thus, railroads developed with each company installing its own basic system features (gauge, signaling, and inventory control). Likewise, the optical network industry developed with each firm incorporating its own transceiver specifications (wavelength, form factor, network service). Both periods represent the overshoot phase as the end result was too much capacity for the market to support.

Interoperability also became a concern for optical network providers as margins shrank. Just as railroad companies realized the need to standardize gauge to physically allow all competing firms to use any track, the optical network providers need to move toward a more uniform optical components to make it physically convenient for all service providers to use any network. Thus, the cooperation phase is entered, somewhat reluctantly.

The railroad case offers some insight into the path of final standardization for the transceiver industry. In the coordination phase for the railroads, competing firms recognized the importance of working with one another. They realized that further growth was not in out-competing in terms of

[49] One explanation of this standard is that it was adopted from George Stephenson in early rail work in England. Therefore, it is held as a long term technology transfer from England. Douglas J. Puffert. "The Economics of Spatial Network Externalities and the Dynamics of Railway Gauge Standardization," *Journal of Economic History.* 52, 1992.

offering independent routes, but rather in the expansion of services and goods provided by the existing network. Optical component suppliers are beginning to recognize the need for such standardization of the network infrastructure. Future profits will come from the services provided via the network and increased demand for optical communications, not in the ability for a particular network provider to provide service to a narrow customer base. As cooperation continues, the railroad case also illustrates the limited role of regulatory standardization. Regulatory action can set a standard, but market forces must enforce those standards, highlighting the importance of thoughtful and careful consideration of regulatory measures. If the transceiver industry continues a path similar to the railroad, supplier strength will ultimately complete the standardization process. One of the key questions for the roadmap study will be to assess the ways in which the industry can arrive at a transceiver platform without the pain of 20 years of tight competition to find the ultimate standard.

4.2.2 Ethernet[50]

The early days of computer technology brought the desire to connect computers together as a way to increase the usefulness of the new technology. Before the advent of minicomputers and personal computers (PCs), mainframe computers constituted the only computer category. These large and expensive machines were rarely co-sited and therefore wide area networks (WAN) were developed to connect multiple mainframes in different geographical areas. The defense oriented Semi-Automated Ground Environment (SAGE) and its civil counterpart, the Semi-Automatic Business-Related Environment (SABRE) were two of the first networks and introduced some of the important features that would make the more localized local area network (LAN) possible.

Increased number of mainframes and the advent of minicomputers introduced the need for LANs to connect an increasingly dense computer landscape. Early entrants in the LAN market were at a decided disadvantage. They first movers entered the market before IBM had launched its PC and could not anticipate the enormous impact that PCs would have on LAN markets. Once the PC was introduced in 1981, a high growth phase took shape. During the next few years, multiple firms entered the market and the variety of LAN technology expanded. Table 6 shows a selection of the LAN companies that entered the market by 1985.

Clearly, the proliferation of LAN companies was potentially problematic to widespread communication. In the late 1970s, a few firms realized that LAN was poised to explode and they initiated a standards process that aimed to create an industry-wide LAN standard. Two independent initiatives set out to achieve the standard, and eventually they merged to form one project. At this point, IEEE 802 was

[50] Adopted largely from *The Triumph of the Ethernet* by Urs von Burg. Stanford University Press. 2001

born. The interested firms and individuals could not agree on one standard and eventually settled on three; Ethernet, Token Ring and Token Bus.

Once the standard was in place, the Ethernet standard attracted suppliers that formed a complex community that shared information and joined in collaboration while fiercely competing with one another. Of course, other LAN technologies still existed, even outside of the three designated in the IEEE 802 standard. Proprietary networks and technologies that outperformed Ethernet in specific niche markets challenged the Ethernet standard. Eventually, these technologies fell to the market power of Ethernet or to mismanagement.

Table 6[51]: Selected LAN Companies Between the Late 1970s and the mid-1980s

Firm	*Network Name*	*Year of Introduction*
Datapoint	ARCnet	1977
Network Systems	HYPERchannel	1977
Xerox	Ethernet	1979-80
Zilog	Z-Net	1979-80
Amdax	Cablenet	~1980
Ungermann-Bass	Net/One	~1980
Apollo	DOMAIN	Early 1980s
Contel Information Systems	Contelnet	Early 1980s
Applitek	UniLAN	Early to mid 1980s
Fox Research	10-Net LAN	Early to mid 1980s
Orchid Technology	PCNet	Early to mid 1980s
Corvus	CONSTELLATION	1980
Nestar	Cluster/One	1980
Prime Computer	Primenet	~1981
Digital Microsystems	Hinet	1980-82
Codenoll Technology	Codelink-20	~1981
	Codelink-100	~1981
Corvus	Omninet	1981
InteCon	InteNet	1981
Proteon	Pronet	1981
Sytek	LocalNet	1981-82
Wang	Wangnet	1981-82
Kaypro	KayNet	~1982
Syntrex	Synnet	1982
Concord Data Systems	Token/Net	~1983
Gateway Communications	G/Net	~1983
3M	LAN/1	1983-84
Apple	AppleTalk	~1984
Centram	TOPS	1984-85
IBM	PC Network	1984-85
NCR	PC2PC Network	1985

Much as the introduction of the PC helped boost LAN technologies, the development of chemical vapor deposition (CVD) process for preparation of optical fiber revolutionized the telecommunications

[51] Urs von Burg. *The Triumph of the Ethernet.* Table 4.1, page 101.

industry[52]. The process enabled long distance data transmission without restrictive attenuation. This development helped pave the way for the "take-off" phase in the optical transceiver industry, just as the PC initiated "take-off" for the LAN market. It is interesting to note that Corning's optical fiber developments came a full decade before what could be considered the take-off phase of optical communications, which suggest that there were other factors that facilitated the growth of the industry. However, the fiber technology made it possible to begin to consider the use of optics as a serious competitor in the communications industry.

Just as the proliferation of LAN technologies created a potential hazard for the future of inter-communication, the proliferation of transceiver flavors has created a barrier to further development of the industry. This "overshoot" phase is common to both industries. The initial attempts at standardization correspond to the ongoing attempts of the transceiver industry to codify a standard for transceivers. Much as the IEEE created three standards for LAN, the IEEE and other bodies have introduced various standards for transceivers in the form of multi-source agreements (MSA).

Ethernet has emerged as the recognized standard for the LAN industry, and in that respect, the LAN experience can teach something about what might be expected for transceivers. Ethernet's power to attract suppliers and the waning of competing technologies allowed the standard to dominate. Perhaps the same process will prevail for transceivers. In an analogous case, the formal standards process would dwindle the acceptable product offerings to something more manageable, and various market forces would drive the industry to a single standard. This is much the same path that the railroad industry followed toward final standardization.

4.2.3 IrDA

The previous two examples have dealt with the path to standardization from a nascent technology. It is also instructive to look at how an industry might standardize a component. In the railroad and LAN examples, the standardized entity was physical infrastructure and a network service, respectively. The transceiver, while part of a network, is also an optoelectronic component. Because the transceiver component is composed of various technical parameters, the standardization path may differ from a purely physical parameter such as railroad gauge, or a network service such as LAN (no real physical component). The case of the IrDA can provide insight into the basic requirements for component standardization.

[52] Fine, Charles and Kimerling, Lionel. *Biography of a Killer Technology.* OIDA Future Vision Program. July 1997.

Infrared Data Association (IrDA), a consortium of communications industry members, has developed the universal platform for air link datacom. The platform is used in a variety of applications including computers, PDAs and cell phones. There were four key elements in the IrDA development that permitted the standard to emerge. The first element was to minimize or simplify functionality. The IrDA platform eventually included only an LED, photodetector, and a preamp. Integrating the devices with drivers, integrated circuits and other commodity chips ultimately lead to decrease interoperability and higher costs. The design also incorporated commodity components to reduce investment costs and ensure compatibility in the package. The third element was to develop an accepted package solution. Finally, the IrDA platform could not have survived without the creation of high volume expectations.

Importantly, the factors that have been identified as the drivers to success for the IrDA included, 1) The lack of legacy infrastructure for air link, 2) no requirement for alignment beyond die-attach, 3) the architectural solution had minimal impact on the design, and 4) the total addressable market was 1-10 million parts.

The factors for the success of IrDA present a problem when the case is compared to the transceiver industry. 1) There IS a legacy infrastructure. In fact, there are two, copper telephone wire and cable have already been widely distributed into all segments of the network, 2) All transceiver designs in the market today require active alignment, which is a critical, and costly, part of assembly process. 3) The difference between architectural solutions[53] could impact the design of the transceiver platform. 4) To date, no studies on the total addressable market for a transceiver platform has been conducted. This will be a part of the roadmapping effort. The conventional wisdom from TWG members has indicated that addressable market will be an issue, and the roadmap will likely include a plan to expand the existing market potential.

Perhaps the most important insight extracted from the IrDA standard process is that standardization did not occur according to the sequence of phases identified in this paper. The take-off phase progressed only after the cooperation and then standardization phases were complete. Initially, it was feasible to install the air link standard into PCs with such negligible cost increase that there was no justification needed. Thus, the IrDA enjoyed enormous volume guarantees, making investment easier to justify, without showing a true application. Eventually, the technology made its way to more salient applications including PDAs and cell phones, thereby facilitating the analogous take-off phase.

The divergence of the IrDA path from the four phase developmental path may suggest that the proposal is fatally flawed. There are two reasons that the four phases should still apply to the transceiver

[53] Architectural solutions could include packet-switched versus circuit switched networks, passive or active systems. In addition the extent to which WDM or TDM is deployed could have a significant impact on the design requirements for a transceiver platform. Part two of the four part roadmap study addresses the extent of the possible impact.

market; 1) Other industries have followed a very similar path, if the mechanisms have differed somewhat, and 2) the transceiver market has already reached the overshoot phase and has therefore diverged from the IrDA path in an important way. The IrDA example is a special case that cannot be applied directly to the transceiver industry. However, there are some important insights that should be considered when developing the transceiver roadmap.

Since volume is of such critical importance for transceiver standardization, perhaps it would be beneficial to develop a standard that can easily be installed into potential market segments, as the IrDA was able to accomplish. A low cost transceiver that could be cheaply and benignly installed into personal electronics, automobiles, and other untapped but potentially substantial volume markets could provide a valuable volume lever. This possibility should be considered when developing a standard transceiver platform.

Chapter Five: Standardized Transceiver Design

The previous chapters in this thesis have systematically made the case for standardization. The first chapter described the system and provided a fundamental understanding of the basic components of the system. The second chapter defined the OEM industry and identified the proliferation of transceiver varieties as a potential barrier to reviving the optical communications industry. One way to rid the industry of the plethora of transceiver flavors is to implement a path toward standardization that would intelligently identify the most likely platform and formulate policy that will guide the industry to that platform. Chapter three then used System Dynamics to provide a proven method of analyzing markets and testing policy decisions. The modeling process showed that standardization could in fact lead the industry from its current stagnation and increase revenues and volumes for the OEM industry. To bolster the claims that standardization is a reasonable path, chapter four documents three related industries that have used standardization to achieve substantial and prolonged health.

The path to standardization is strewn with many technical obstacles that must be considered in any policy decision. It is not a trivial matter to implement a single platform that can be interchanged across segments. This section identifies the numerous technical difficulties in going to a single standard and proposes a solution that could serve as a basis for developing a standard transceiver. The design presented in this section was developed by a MIT project group as part of course 3.46 *Optical and Optoelectronic Materials*. The group was composed of the author of this thesis, Kelvin Chan (Electrical Engineering), George Whitfield (Materials Science and Engineering), and Emily Zhang (Materials Science and Engineering)

5.1 Problem Definition

The fragmented state of the optical communications industry restricts the ability of optical component manufacturers to take advantage of large product volumes. In this thesis, four market segments have been identified as key to future growth. The challenge is to define a standard transceiver that can accommodate the bit rate x distance performance parameter for each of these segments.

1. Local Area Network – 10 Gb/s, 15 km
2. Broadband Access – 1 Gb/s, 1 km
3. Storage Area Networks (SAN) – 40 Gb/s, 25 m
4. Server Buses – 1 Tb/s, 1 m

5.2 Key Issues

In designing the standard transceiver, there are several key issues. The first issue is the choice of device architecture. There are many ways to design a transceiver, among the architectures to consider are;

- Discrete design with laser and receiver manufactured separately, hermetically sealed in a TO-can, and then inserted into a "box." The box could have the accompanying electronics, or just have leads from the device to be connected to the electronics set best suited for the particular use (similar to the design in Figure 6 from chapter two).
- Silicon Optical Bench (SiOB) based solution that utilizes the integrated circuit capabilities of silicon and bonds the laser and receiver to the SiOB. The waveguides, or the light paths connecting the laser and the receiver to the optical fiber interface, are integrated with v-grooves or some other method that allows for easier alignment.
- A monolithic design that enables production of laser, receiver, and waveguides in one production step. The electronics could be internal or external to the device.
- In all cases, materials systems must be chosen that meets all the requirements of the design in the most cost effective way possible. Common materials systems include Indium Phosphate (InP), Silicon (Si), Gallium Arsenide (GaAs), and others

In addition to architecture, the wavelength of the communications is a central parameter. A suitable wavelength of depends on the bit rate and distances required for a transceiver that serves all four segments. Not all material systems can transmit and receive all wavelengths. Therefore, the correct material system must be selected for the standard device.

To illustrate the issues involved with building a standard transceiver, engineers may use a figure of merit that provides measure of the quality of the design. The measure could be quantitative, but the figure of merit generally serves as a qualitative way to balance the trade-offs inherent in device design. For the standard transceiver device, the figure of merit will include the following parameters:

$$FOM = \frac{Speed}{\#\ of\ Connections * Dimension * Power * Costs}$$

Speed here refers to the technically feasible bit rate, number of connections refers to the number of waveguide couples within the device and the connections to the fiber running between devices. Dimensions if footprint, or the size, of the device and is important as there is no reason to believe that optics will follow a trend toward miniaturization similar to the trends in electronics. Power incorporates both the capabilities of the output laser power as well as the lowest detectable power for the detector.

Power requirements for lasers might get down to 10 mW, while transistors use about 0.1 mW[54]. This is a potential problem for power needs at the optical central offices and boxes.

And candidate for a standardized transceiver must also consider scalability of the design. The scalability refers to the ability of the device to readily adapt to the growing broadband requirements. The bit rates specified above are the expected performances of the devices in the next five years. Beyond that, data rates could grow exponentially, rapidly dwarfing even the high bit rate given.

There is also a general consideration for device costs, including materials, processing, and packaging costs. As identified throughout this document, costs are a central concern for the optical communications industry. The standard transceiver must be compatible with current processing techniques that can be employed for large scale production. The figure of merit applies to the entire transceiver. There are separate figure of merits for each component within the transceiver.

5.3 Preliminary Decisions

The first step of the design process was to decide on some of the basic specifications of the standard transceiver and the network. The FOM and physical restrictions served as a guide.

5.3.1 Wavelength

The most basic decision for a standard transceiver is the base wavelength that should be used. Light is generally sent through silica glass optical fiber at 1550, 1310 or 850 nm wavelength light. Scattering of the light particles at 850 nm is relatively high, but the lasers are much cheaper to produce. Therefore, 850 nm involves a trade-off between expense and distance. Since a standard transceiver must be able to send information at greater than a gigabit per second and 850 nm light is generally used for much slower data rates, it is not practical to make the trade-off for 850 nm light. Figure 70 shows the relationship between bit rate and distance for 850, 1310, and 1550 nm light through silica (SiO_2) optical fiber. Notice that for 850 nm light, anything greater

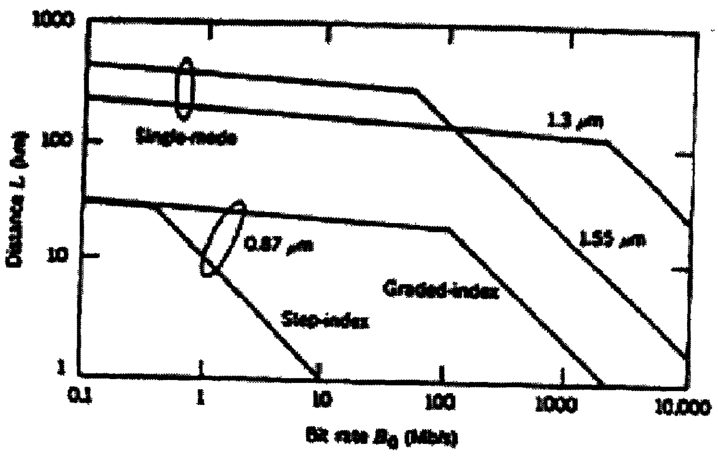

Figure 70: Attenuation and Dispersion of Optical Signal in Silica Fiber. 1310 nm supports the highest bit rates, while 1550 nm supports the longer distance communications

[54] Jeff Kash, IBM. Presentation at the October 10, 2003 NGT TWG meeting.

that 1 Gbps will not travel very far. Since 3 of the 4 market segments considered in this thesis are at or above 1 Gbps, 850 is not an available option despite the costs advantages.

Figure 70 suggests that 1550 nm light is superior for transmission in the 100s of kilometers, however, for shorter distances, 1310 accommodates higher bit rates[55]. 1310 and 1550 nm light are both candidates for a standard as both correspond to low points in the attenuation spectrum of light through silica glass fiber and both are used for medium to long range communications. 1550 nm light marks the absolute minimum for attenuation and suffers the least from scattering and absorption (Figure 71), however, a 1550 nm laser is also more expensive than a 1310 nm laser. Because of the added costs of 1550 lasers, and the data rate limitations of 1550 nm light, it seems reasonable to use 1310 nm light as the standard for optical communications.

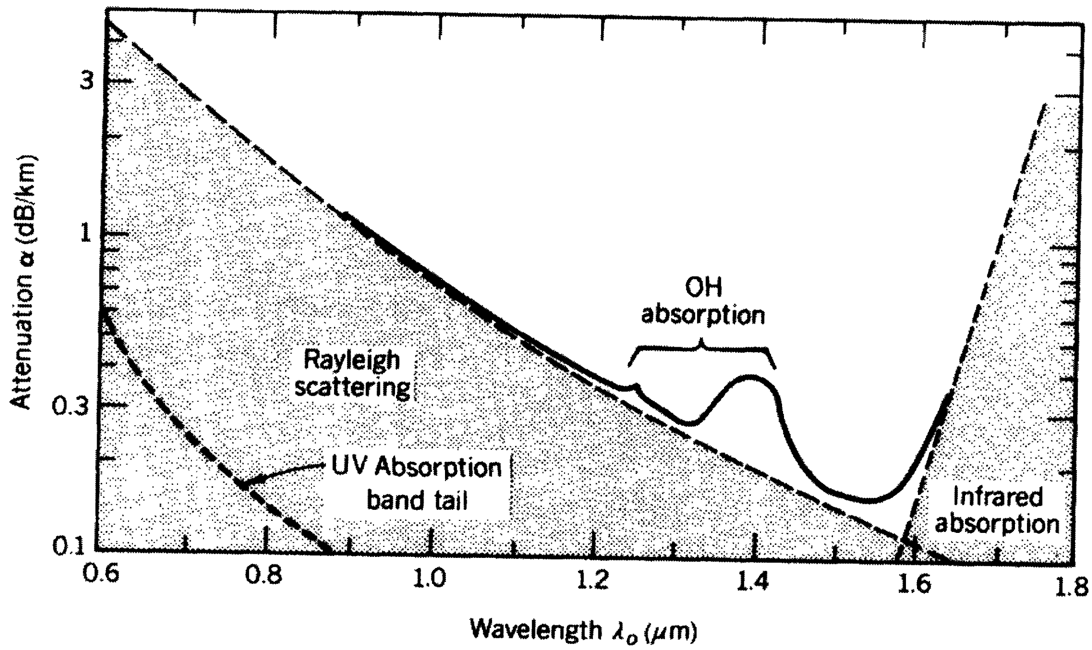

Figure 71: Dependence of the Attenuation coefficient of silica on the wavelength. There is a local minimum at about 1310 nm, and an absolute minimum at 1550 nm, making both these wavelength strong candidates for communications.

5.3.2 Transceiver Architecture and Detector Material System

Low cost are important to the success of optical networks, and cheaper, more straight forward manufacturing is needed to lower costs, the 3.46 design group decided that the transceiver design should incorporate monolithic processing wherever possible. Monolithic processing requires just one production step as multiple components are grown with one technique. Silicon is by far the most advanced materials

[55] Data rates for 1550 nm light are restrained by a higher susceptibility to material dispersion.

system and is relatively cheap and abundant. Therefore, the design group also decided that a standard should move toward silicon based components.

With silicon as the base, the choice for the detector materials system is straight forward. Germanium detectors are advanced and can be produced easily and cheaply[56] on silicon, making it a natural choice for the standard transceiver. Detectors using compound semiconductors using group III and group V materials (III-V semiconductors) can also be used, however, the processing is more complicated and therefore more expensive, and Si compatibility would be problematic.

Ge detectors can absorb 1310 nm light, however, absorption of 1550 nm light requires bandgap engineering involving strain, altering the composition, or operating under different temperature environments. Bandgap engineering can make 1550 nm silicon detectors possible, and 1550 nm is not ruled out based on the detector limitations.

5.3.3 Data Management

Section 1.2.2 of chapter one explains the concepts of wave division multiplexing (WDM) and time division multiplexing (TDM). Since one of the concerns for a standard receiver is scalability, the design should take advantage of WDM technology. TDM may be a simpler technology, but WDM can provide much higher effective bit rate. In addition, TDM can be used in conjunction with WDM, utilizing both techniques. The standard transceiver should incorporate WDM, and TDM can be added as needed.

At this point, the protocol structure of the network can be considered to be external to the transceiver. Configuring the devices for IP versus ATM or Fibre Channel protocols can be programmed through the associated software. For now, the electronics are assumed to be independent of the protocol and require no different process to accommodate whatever software is used on a per-network basis.

5.3.4 Optical Fiber

Fiber can be engineered to accommodate one single mode or multiple modes of light. A mode is a resonance path through the fiber that one wavelength can occupy. As light bounces off the fiber walls, only certain paths that produce constructive interference between the reflected and incident light are allowed. If the fiber diameter is small enough, only one path is allowed, resulting in a single mode fiber. Larger diameter fiber supports multiple paths and is multimode. Employing a WDM architecture requires filtering structure at the transceiver that combine the multiple wavelengths for transmission down one fiber, and then separate the wavelengths at the receiving end. Because multimode introduces added complexity, these filtering structures are conducted at single mode conditions (See below). If multimode fiber is used, the fiber to waveguide couple will convert a multimode signal to a single mode signal. This

[56] Kimerling, Lionel. *The Next Killer Technology.* Silicon Microphotonics

couple would introduce enormous loss due to modal mismatch. Since power is a critical consideration for the standard transceiver, and because less loss means the laser output power can be lower, a single mode fiber should be used to connect all network links if WDM is employed. In single channel communications (just one wavelength), multimode fiber is possible, and may be efficient in some low bandwidth applications.

The advantage of multimode fiber is that it is less costly and the alignment is easier because the diameter is larger. The costs of fiber, single or multimode, is a small part of the total network costs[57], so the cost is not a significant concern. The easier alignment can be significant and techniques to enable more efficient alignment of single mode fiber are being developed. There are other reasons to go to the single mode fiber architecture, as discussed by Frank Levinson at the October 10, 2003 NGT TWG meeting.

5.3.5 Laser Material System

The laser is problematic as there are no silicon compatible materials systems that can produce 1310 nm light (or 1550 nm light). Compound semiconductor lasers have proven successful and reliable. Keeping in mind the emphasis on monolithic integration, Indium Gallium Arsenide Phosphorous (InGaAsP) semiconductors can be grown on an Indium Phosphate (InP) substrate and an InGaAsP/InP system for lasers has potential as a transmitter solution at 1310 nm.

5.3.6 Waveguide

The transceiver now has two basic materials systems that must be combined onto one device. The detector is to be grown on a Si substrate, while the laser will be on InP. Integration of these two systems is treated in the architecture section below. Waveguides serve to direct light as it moves from the laser, to the multiplexer (combining multiple wavelengths onto one fiber) and ultimately to the fiber couple. A similar waveguide system is needed for the silicon detector substrate.

For Si, the waveguide technology is well developed. A SiON waveguide can be deposited to provide adequate index contrast to confine the light (see waveguide section below). The waveguides for the InP substrate can be composed of InGaAsP. In both cases, the waveguide can be monolithically grown onto the respective substrates.

5.3.7 Initial Specifications

Based on the preliminary decisions in the previous sections, it is possible to deduce some initial conclusion about the performance specifications of this standard transceiver. The design should employ

[57] Where can I get reference for this?

the highest performing capabilities that are not too complex for reasonable implementation. Given the current demonstrated capabilities of InGaAsP lasers, the operation bit rate will likely be about 20 Gigabits per second (Gbps).[58] Using WDM to decrease the number of fiber connections the design should incorporate five laser (and therefore 5 detectors) to satisfy specifications for all segments. This specification requires 1 laser to be utilized for Broadband Access, 1 for LAN, 2 for SAN and 5 for Servers.

5.4 Component Optimization

Once the basic parameters of the systems were selected, each component within that system was analyzed to achieve optimal operation. Although there are many subsystems within the standard transceiver, the design presented here focuses on optimization of the laser, the modulator, the detector, the coupling, and the architecture.

5.4.1 Laser

The laser is likely to be the major bottleneck in establishing a standard transceiver because it represents the central function of optical communications and therefore is a key focus of product improvement. In order to encourage obsolescence in the optical industry, the product must be sufficiently upgradeable. The challenge is to design a standard that achieves the goals of universality within the OEM industry, yet still allows competition and innovation that yield year-to-year improvements in performance that justifies and encourages short product lifecycles. Some of the major issues in optimizing a standard laser include;

- Material system with bandgap compatible with emission of 1310 nm light
- Production of five lasers with 5 different wavelengths for each transceiver
- Power considerations for lasing and modulation

5.4.1.1 Laser Design

To assess various potential laser designs a laser figure of merit was formulated.

$$\mathrm{FOM}_{\mathrm{Laser}} = \frac{(\mathrm{Gain})(\mathrm{Responsivity})}{(\mathrm{Threshold\ Current})(\mathrm{Spectral\ Width})(\mathrm{Power\ Dissipation})}$$

[58] Kimerling, Lionel. *The Next Killer Technology.* Silicon Microphotonics

Gain is a measure of the quality of the laser as a generator photons,[59] the threshold current refers to the injected current at which gain occurs (that is, the current at which absorption = emission) and is the key parameter for laser characteristic, responsivity is the ratio of optical power increase to the electric current increase (above threshold). The spectral width refers to the range of wavelengths for which emission is greater than absorption (gain is wavelength dependent) and the power dissipation is the power needed to generate the required injection current for lasing.

As noted above, InGaAsP is a good candidate for the laser material system because the technology is relatively mature and because the InGaAsP emits photons at around the 1310 nm wavelength. Most communications grade lasers use a double heterostructure as shown in Figure 72[60].

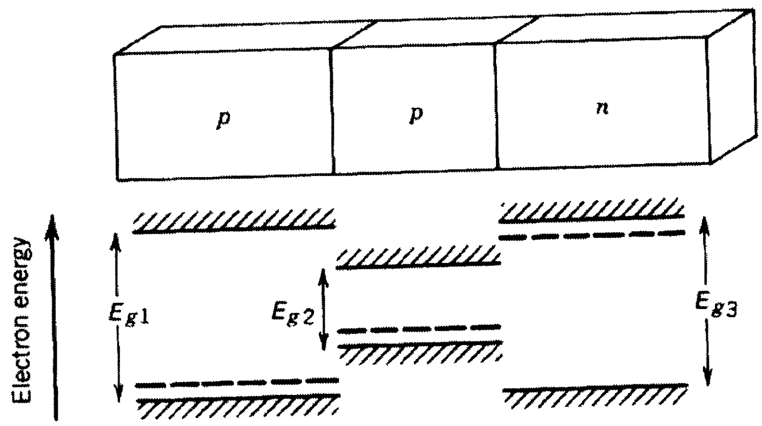

Figure 72: p-p-n Double Heterojunction structure

The difficulty in choosing a laser design is that the architecture of the transceiver calls for five laser, each emitting photons at a slightly different wavelength. The wavelength of a III-V semiconductor laser is generally determined by the bandgap, or energy band between the highest valance band and the lowest conduction band. In considering laser design, four different designs were considered and analyzed for practicality as a standard transceiver laser; 1) Inclined MBE, 2) Index-tunable cavity, 3) Ring

[59] Light incident on a semiconductor interacts with the material according to the energy of the band-to-band transitions. Provided the wavelength energy is greater than the lowest transition energy, the photon can be absorbed by the material. In the case of sufficient energy, the photon of light can either be absorbed, promoting an electron to a higher energy band and creating an electron-hole pair, or it can create additional photons by stimulating electron-hole recombination. Gain occurs when the probability of creating additional photons is greater than the probability of photon absorption. The difference in the probabilities, and thus the success of the laser as a photon generator, it termed the "gain."

[60] Lasing occurs when the population of conductance band electrons outnumbers the valance band population of electrons. A p-n junction is a junction between a p-type semiconductor (excess holes) and an n-type semiconductor (excess electrons). The excess holes attract the electrons and vis versa resulting in a region of

resonator, and 4) Quantum well intermixing. The four processes examined here represent four ways of altering the bandgap to achieve a monolithically grown WDM transmitter.

Molecular Beam Epitaxy is a method common for growing compound semiconductors. The constituent elements are thermally evaporated in effusion cells, producing a molecular beam that is deposited on a heated substrate. The advantage of MBE is that the growth rate is on the order of Angstroms per second, meaning that the thickness of the layers can be controlled almost to the atomic layer. A typical MBE growth chamber is shown in Figure 73.

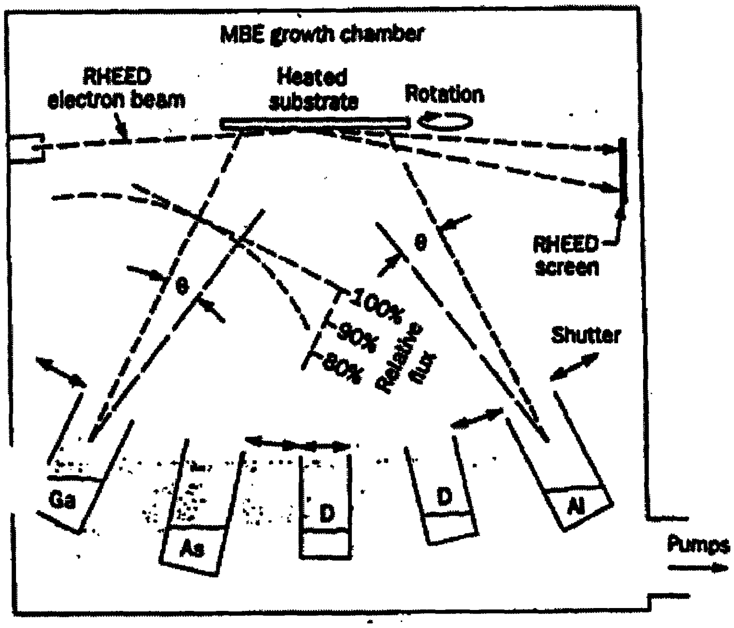

Figure 73: MBE Growth Chamber

The concept of loading InP substrates on an incline in the MBE chamber is an attempt to exploit the fact that output wavelength can be altered by varying the thickness of the InGaAsP active layer. Inclined MBE is problematic because it would be very difficult to control composition uniformity throughout the incline, and thickness uniformity throughout the batch. One wafer would consist of many laser assemblies and each assembly would have a different range of layer thicknesses.

The index-tunable cavity design is formed by coupling the InGaAsP laser to an InP cavity, the design can utilize the electro-optic effect to change the refractive index of the cavity. Changing the refractive index changes the wavelength, making the cavity a different effective length. The cavity would act as a resonance cavity and select out a specific wavelength depending on the strength of the electric field and the corresponding change in the refractive index.

The advantage to the index-tunable cavity is that identical lasers and cavities can be grown on the InP substrate. Tuning the lasers is accomplished by applying a differential electric field at each cavity.

The disadvantages include more difficult electronic integration and increased power requirements as the laser *and* the cavity need to be energized. In addition, because the cavity acts as a filter, much of the output laser power is lost, and there could be a need for additional amplification.

The ring resonator is a concept that would combine the lasing and the multiplexing functions in one structure. Ring resonators have been used to couple and decouple multiple wavelengths for WDM transmission. By incorporating the laser into the ring, the costs of growing the laser and the WDM functions separately can be saved. One section of the ring would be injected with carriers to promote gain, while another part would be subject to an applied voltage to use the electro-optic modulator[61]. The difficulty with this design is that laser gain would be lost because part of the active region would not be available for carrier injection, thereby increasing the current requires for gain (threshold current). In addition, it would be difficult to separate the desired modes from the laser spectrum with the ring, and multiple rings would likely be needed, all but eliminating the advantage of combine the ring filter and the laser in one structure.

5.4.1.2 Quantum Well Intermixing Design

The laser designs above proved difficult and would not be practical for incorporation in the near future. In designing the laser light-emission system of the standard transceiver, the use of quantum well intermixing (QWI) is proposed. QWI is a processing technique that facilitates high-throughput monolithic integration of quantum well lasers of different peak emission wavelengths. In this method, the band structure of each quantum well is different across the laser chip, although the core and cladding layers of all of the lasers together only need to be grown in a single step. After epitaxial deposition, diffusion is induced within each of the structures, causing the core and cladding materials to intermix. This intermixing effectively decreases the width of the core, which increases the structure's band-gap along with its emission frequency. Reports in literature have shown that by varying the amount of diffusion that occurs at each laser element, it is possible to control a range of emission spectra on a single chip.[62]

In order to induce diffusion within the quantum well structures, ion implantation is performed to create defects at the cladding surface, and then the structures are annealed to activate vacancy-based diffusion and heal defects at the materials surface. To vary the level of diffusion among each element, the

[61] The electro-optic effect stipulates that a voltage changes the refractive index of the material. Altering the refractive index changes the effective length of the ring and thus creates destructive interference in the ring. Bringing the ring into and out of resonance results in the on and off behavior for modulation.

[62] S. Charbonneau, P.J. Poole, P.G. Piva, M. Buchanan, R.D. Goldberg, .V. Mitchel, ***Bandgap tuning of semiconductor Quantum Well laser structures using high energy ion implantation***, Nuclear Instruments and Methods in Physics Research B, vol. 106, pp 457-460, 1995.

ions are implanted through a variable thickness SiO_2 mask, which is fabricated by gray-mask photolithography and a reactive ion etch (RIE). As light is passed through an optical mask of varying opacity, it strikes a negative photo resist with varying intensity. The subsequent RIE of SiO_2 through the photo resist penetrates the oxide to varying depths.[63]

A major concern about this process regards the effect of defect creation and material intermixing on device performance and reliability. It has been shown that after a low-energy ion implantation step of 1.5×10^{12} As ions/cm2 and RTA that shift a laser's output wavelength by 26 nm, the threshold current and light-emission vs. injection current relation are essentially unchanged. In a second ion implantation of higher defect generation at 10^{14} as ions/cm2, a shift of 100 nm was affected while the threshold current was only increased by 15%.[64] These results indicate that a large level of variation in band structure is achievable, while still preserving device quality. Separate tests additionally estimated lifecycles of QWI lasers in excess of 25 years, which is sufficiently reliable for the expected level of use of the standard transceivers.[65]

Based on an reported threshold current of 160 mA in a ~135 μm^2 QWI laser device structure[66], an assumed external quantum efficiency of 0.4, output wavelength of 131 nm, and a waveguide index of 3.1, a typical output power (at 170 mA operation) of the laser is estimated at 1.2 mW from the following formula:

$$Po = \eta_{ext} (I-I_{th})\, hc / (qn\lambda)\,.$$

As seen in the power budget analysis below, this exceeds the estimate of minimum required output at the laser source, ensuring transmission of the signal.

The final consideration for laser design concerns the power dissipation and its effect on the heat budget of the device. The design calls for five 20 Gbps laser in the Server Bus case. Calculations below specify that the source optical power must be 0.78 mW. Under the assumption that the lasers are 50% efficient, that would mean that about 0.78 mW of power is lost to heat. This results in fewer than 5 mW of heat generation when all five lasers are operational. A rough estimate of the power dissipation of the accompanying electronic processors is on the order of Watts[67], 1000 times greater than the 5 mW

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63 S. L. Ng, H. S. Lim, Y. L. Lam, Y. C. Chan, B. S. Ooi, V. Aimez, J. Beauvais, and J. Beerens, *Generation of multiple energy bandgaps using a gray mask process and quantum well intermixing*, Jpn. J. Appl. Phys., pt. 1, vol. 41, pp. 1080–1084, 2002.

64 V. Aimez, J. Beauvais, J. Beerens, D. Morris, H. S. Lim, and B. S. Ooi, *Low-energy ion-implantation-induced quantum-well intermixing*, IEEE J. Select. Topics Quantum Electron., vol. 8, pp. 870–879, 2002.

65 J.-P. Noel, D. Melville, T. Jones, F. R. Shepherd, C. J. Miner,N. Puetz, K. Fox, P. J. Poole, Y. Feng, E. S. Koteles, S. Charbonneau, R. D. Goldberg, and I. V. Mitchell, *High-reliability blue-shifted InGaAsP/InP lasers*, Appl. Phys. Lett., vol. 69, pp. 3516–3518, 1996.

66 V. Aimez, J. Beauvais, J. Beerens, D. Morris, H. S. Lim, and B. S. Ooi, *Low-energy ion-implantation-induced quantum-well intermixing*, IEEE J. Select. Topics Quantum Electron., vol. 8, pp. 870–879, 2002.

67 Finisar 2 Gbps pluggable SFP transceiver (http://www.finisar.com/optics/FTRJ1619P1xCL.php) uses a typical electrical supply current = 230 mA, and a supply voltage = 3.5 V, given a supply power of about 1

generated by the laser. There is no reason to think that the power dissipation from the laser array would contribute significantly to temperature concerns in the transceiver.

Power is also required for current injection and other functions of the laser. Given that a laser typically requires on the order of 10 MW, it is easy to see that multiple transceivers demand more power than is readily available. The server will need approximately 5 lasers for every connection at each end. That is 10 lasers for every server. Many server connections also employ multiple connections to provide redundancy that ensures reliability and security. Some of the larger server stations contain 100s of servers. It is easy to see that the power needs for these stations can grown very rapidly and the may outstrip the available grid power. The broader infrastructure issues are not treated in this thesis, but will be important as optical connections move into the server market segment.

5.4.2 Modulator

The modulator is responsible for producing the light pulses that become the bytes[68] of information to be sent through the fiber communication lines. Modulation can be done either directly or indirectly. Direct modulation involves directly turning the laser on and off. Indirect modulation allows the laser to function continuously will an external modulator blocks the emitted light according the data stream. Direct modulation is less complicated and requires fewer materials structures, however, indirect modulation is capable of generating much higher bit rates.

The standard transceiver design emphasizes monolithic integration as a way to reduce manufacturing complexity and to reduce uncertainty in coupling efforts. The modulator for the QWI laser must then be compatible with growth in the InP substrate that supports the laser. There are two main issues that need to be addressed for the modulator.

- The modulator and the QWI laser, along with the waveguide should be monolithically integrable.
- The modulator needs to be coupling to the laser active region as well as the waveguide

5.4.2.1 Modulator Design

Direct modulation reaches a technical limit at about 10 Gbps. Part of the reason for the technical limit is that directly modulated signals are susceptible to chirp. Chirp is when the wavelength of the emitted light varies through the each pulse. In direct modulation, chirp arises from the change in refractive index resulting from the change in applied electric field (electro-optic effect) as the laser is turned on an off. There are also relaxation oscillations, or rapid variations in the light output just after the

---

W. We might expect that a 20 Gbps device would require more power. Clearly, the estimated 5mW for laser operation in the Standard device is not significant.

[68] A byte is a single "on" or "off" piece of data. Similar to electronic 1s and 0s, the optical equivalents are pulses and non-pulses. Eight bytes make up a bit which is the foundation of digital communications.

laser has been turning on[69]. These oscillations restrict modulator speed as the bit rate cannot be faster than the time it takes to equilibrate the pulse. The standard transceiver, then, should utilize external modulation.

One potential design for InP modulation exploits the Quantum Confined Stark Effect (QCSE)[70]. The design utilizes an identical double stack active layer.[71] By using an identical active layer for the laser and the modulator, the design is more cost effective because it only requires one epitaxial process, and coupling loses become almost negligible. The design uses two different quantum well structures in the identical active regions (Figure 74). The laser quantum wells are narrower and therefore are pumped stronger and dominate the gain. The modulator section is separated from the laser section by electrical isolation. An electric field is applied in the modulator section and the QCSE changes the effective bandgap of the modulator section to dominate the absorption.

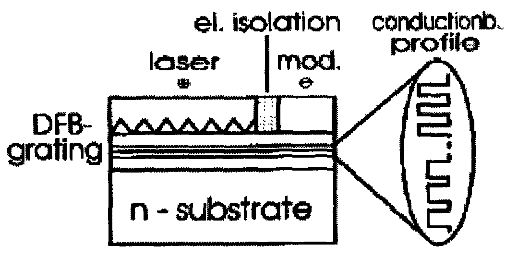

Figure 74: Identical Cavity Modulator/laser

The design in this case will be adjusted to fit the QWI laser by growing just one laser quantum well, rather than the multi-quantum well design shown here. The design can still have 3-5 modulator quantum wells[72]. The modulator has been demonstrated to work at about 25 Gbps.

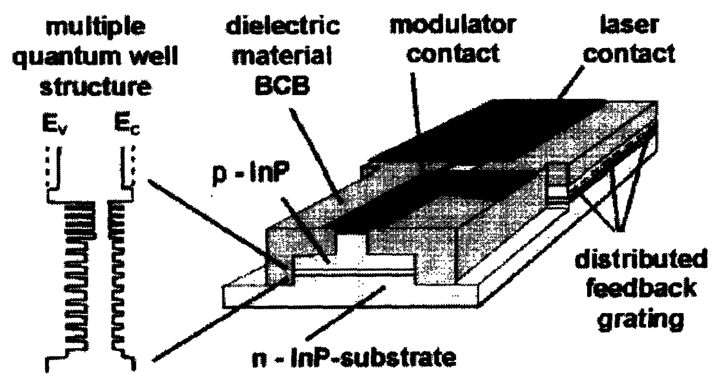

Figure 75: Implementation of Identical Cavity Modulator/Laser

[69] *Optical Modulation* Beginners Guide from www.lightreading.com
[70] QCSE is explained in most advanced photonics textbooks. For now, it is enough to understand that the QCSE shifts the absorption edges of the bandgap upon application of an electric field. The effect serves to lower the bandgap.
[71] B. Stegmueller, C. Hanke. *Integrated 1.3 umDFB Laser Electroabsorption Modulator Based on Identical MQW Double-Stack Active Layer With 25GHz Modulation Performance.* IEEE Phot. Tech. Lets., Vol. 15, No. 8, August 2003
[72] Further work could be done to test the QWI concept in a MQW, DFB laser structure. If that is shown to be a workable solution, the design can employ MQW (and enjoy the associated gain benefits).

5.4.3 Detector

The detector will receiver the incoming light and convert it to electrical signals that can be processed by modern software and applications. Issues for the detector for the standard transceiver include;

- Compatibility with silicon substrate for monolithic integration
- Appropriate absorption characteristic that include the 1310 nm light used in the standard.
- Capable of detection of at least 20 Gbps to correspond with the modulation capabilities.
- The signal to noise ration of the detector must be high enough that the detector can differentiate between data and noise
- The minimum detectable power will ultimately determine the output power required from the laser.

5.4.3.1 Detector Design

As one component of the monolithic process, the detector design uses a Ge on Si architecture to take advantage of Si integrated circuitry that is more common and cheaper than other materials systems.

The design adequately fulfills the main concerns for the detector design. Ge detector can be effectively grown on Si. The lattice mismatch of Si to Ge is about 4%, resulting in a minimal lattice strain and associated defects[73]. In addition, the bandgap energy of Ge is 0.66 eV for the indirect gap and 0.8 eV for direct gap. Absorption at the direct gap is desirable because the quantum efficiency is greater. According to the expression E = hc/λ, the corresponding wavelength is about 1550 nm. Any shorter wavelength, including the 1310 nm telecommunications wavelength, would be higher in energy, and the Ge detector will absorb the signal.

The design seeks to maximize the signal to noise ration, or the ratio of the incoming signal power to the power of the noise.

$$\frac{S}{N} = \frac{Power_{signal}}{Power_{noise}} = \frac{i_s^2}{i_n^2} = \frac{(P_{light} R_{esp})^2}{(i_{n,shot}^2) + (i_{n,thermal}^2)}$$

The noise current in the photodetector comes mostly from shot noises and thermal noise. Shot noise arises from the statistical nature of the production and collection of photoelectrons when an optical signal is incident on a photodetector. These statistics follow a Poisson process:

[73] For crystalline structures, the lattice parameter refers to the average distance between atoms of the crystal. If the difference between the lattice parameter of the crystal substrate and lattice parameter of the structure to be grown on the substrate (lattice mismatch) is too great, the resulting strain will introduce defects and could fatally disrupt the integrity of the structure.

$$i_{n,shot}^2 = 2qIB$$

where q = electron charge: $1.6*10^{-19}$, I = average diode current, B = bandwidth. The average diode current is the sum of the signal current, the background current and the diode dark current. The dark current is equal to the reverse bias leakage current, given by the following equation

$$I = q * ((n_{ip}^2/N_a)(D_{ep}/L_n) + (n_{in}^2/N_d)(D_{hn}/L_p)) A$$

Where q is electron charge, n_{ip} is the intrinsic carrier concentration of in the p region, N_a is the doping in the p region, D_{ed} is diffusivity of electrons in the p region, n_{in} is intrinsic carrier conc. in the n region, N_d is doping in the n region, D_{hn} is diffusivity of holes in the n region, L_p is recombination length of holes in the n region, and A is diode area.

Thermal noise arises from the creation of electron-hole pairs from thermal energy. The higher the temperature, the greater the probability that electrons in the valance band will absorb enough heat energy to be excited into the conductance band. Thermal noise current is expressed by the following equation:

$$i_{n,thermal}^2 = \frac{4kTB}{R}$$

where k = Boltzman's constant, T = temperature, B = bandwidth, R = resistive load.

Signal current is the power of incident light multiplied by the responsivity of the photodetector. Responsivity is an expression of the current produced in the detector for a given signal power and is one of the most important parameters in characterizing a detector.

$$R = I / P_o \quad (A/W)$$

Responsivity can be calculated from following formula:

$$R = \eta q/h\nu$$

Where η is quantum efficiency, q = electron charge, h = Planck's constant, ν = the frequency of incoming light. Quantum efficiency is an expression for the percentage of incoming photons that are actually absorbed by the detector material, and can be expressed as:

$$\eta = (1-R)T(1-\exp(-\alpha w))$$

where R = reflectivity, T = charge collection efficiency, α = absorption coefficient, w = width of depletion region. A large α is important in achieving high quantum efficiency and therefore high responsivity.

The bandwidth of the detector (or the speed of detection) is determined by either the transit-time spread or the RC time constant. Photons that are absorbed create an electron-hole pair by promoting an electron in the valance band into the conductance band. The electrons and holes travel to the electrodes and the signal is registered. The hitch here is that electrons travel faster than holes. The difference is termed the transit-time spread and the maximum speed that the detector can receive is the related to that transit-time spread. The transit-time spread is determined by the slowest moving charge carrier, the holes. τ_{tr} is the time it takes for a hole to drift one half the depletion region, and can be expressed as;

$$\tau_{tr} = w/v_d$$

where w = I-layer thickness, v_d = drift velocity of holes. The bandwidth is then defined as;

$$\text{Bandwidth} = 1/\tau_{tr}$$

Response time can also be limited by the resistance and capacitance of the detector. Once the electrons and holes are creates, they must travel through the semiconductor material to the electrodes, then they must travel through some distance until they reach the connector wire. There is resistance and capacitance associated with that trip and too much resistance could disrupt the signal. The resistance of the trip through the semiconductor is given by

$$R = L/(\sigma^* t^* w)$$

where R = resistance, L = length of detector, σ = conductivity, t = thickness, w = width

Conductivity is calculated by:

$$\sigma = ne\mu$$

where n = number of carriers/cm^3, e = electron charge, μ = mobility

The bandwidth of the detector could be increased by making the depletion layer thinner. This would reduce the difference in transit time between electrons and holes (shorter distance, so shorter time). While it may be desirable to achieve higher bandwidth, thinning the active region would not come without tradeoffs. As discussed in the next section, the standard transceiver design proposed here uses evanescent coupling to the waveguide. The coupling efficiency of this design depends on the length of the couple interface and the thickness of the depletion layer. A thinner depletion layer would require a longer interface and hence greater series resistance, increasing the RC constant.

As the next section shows, the waveguide-to-detector coupling area required to achieve greater than 90% coupling efficiency is small enough that the speed response will never be limited by RC time constant, but instead by carrier transit time

As a preliminary example, a Ge detector with a 1μm depletion region and 300 by 300 μm area has a responsivity of 0.33A/W[74] and response time of 50ps, corresponding to a 20GHz bandwidth.

A good rule of thumb is that a SNR of about 20 is desired to achieve good distinction between noise and signal. With the values for the noise current and responsivity as discussed above, the expression for SNR can give the minimal detectable power (P_{min}) for the detector.

[74] Responsivity is related to the quantum efficiency and gives the ratio of strength of the output current and the input laser power. This factor determines the output power needed to produce the minimum detectable signal at the detector given all the losses in the system.

It is also necessary to consider the upper limit on power to which the detector will respond. Charge carriers within the depletion region contribute towards a screening of the electric field, which degrades device performance when the carrier concentration in the depletion region approaches the doping levels of the p+ and n+ regions. Since it takes an average time of τ_{tr} for generated carriers to escape the depletion region, its steady state carrier concentration is:

$$n = R\, P_o\, \tau_{tr} / qV_i$$

Where R = responsivity, P_o is optical power, the transit time τ_{tr} = 28 psec, q is electron charge, and the volume of the i-region $V_i = 2\text{x}10\text{x}10$ μm.

5.4.4 Coupler

Light signals in the standard transceiver will originate in the laser active region and will terminate in the detector. In between, the light must pass from laser to modulator, modulator to waveguide, waveguide to fiber, back to the waveguide in the receiving device, and finally waveguide to detector. The design incorporates several mechanisms for each of these transfers. The issues involved with coupler design include;

- The first issue for the coupler design is its structure. From past experience, there are a couple different schemes that can be used. Comparisons of these schemes are summarized in the Appendix, Table A-1.
- Material for waveguide will be chosen to be compatible with detector material in terms of being lattice matched and index matched (InP for laser structure, Si for detector).
- As indicated in the figure of merit above, reflections at the interface and at the boundary should be minimized.

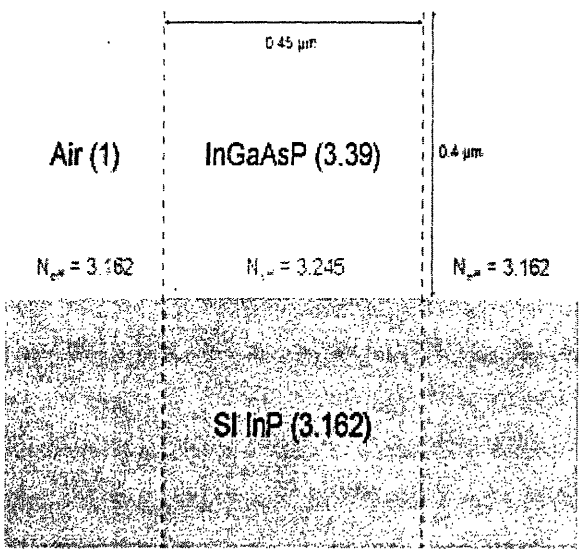

Figure 76: InGaAsP Waveguide

5.4.4.1 Coupler design

Based on the considerations listed in Appendix IV, the design will for the detector to waveguide and the modulator to waveguide will be evanescent coupling. The main advantages to this design is that alignment difficulties are not as restrictive, it is easier to fabricate (no re-growth process step) and it is possible to make the detector-waveguide and modulator-waveguide interfaces of high quality, thereby reducing the reflection loss. Since the detector design above is not capacitance limited, the wider longer detector (and thus larger interface area) is not worrisome.

The coupling design must enable the light to pass to the absorption layer of the diode with the smallest possible loss. The figure of merit hints that the insertion loss will be determined by R_{int} and R_{bound}. Analysis of the reflectivity parameters requires further examination of the waveguide/detector structures.

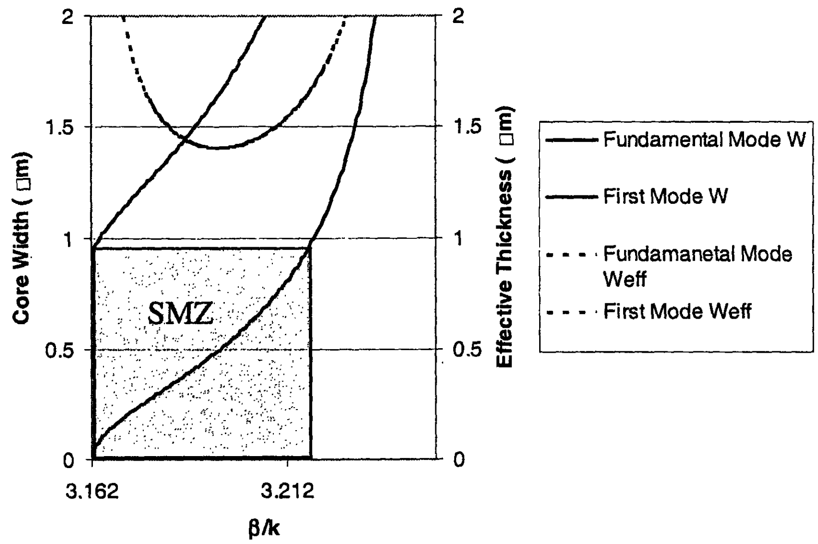

Figure 77: Effective Thickness Measurements for InGaAsP Waveguide of 0.4 μm Height

The waveguide for the laser InP substrate was chosen to be a raised-strip channel with a high-index strip on the top of a low-index substrate (Figure 76). The materials for the strip and the substrate are $In_{0.65}Ga_{0.35}As_{0.75}P_{0.25}$ (refractive index = 3.39) and semi-insulating (SI) InP (refractive index = 3.162), respectively. $In_{0.65}Ga_{0.35}As_{0.75}P_{0.25}$ is lattice matched to the SI InP substrate and has a band-gap wavelength of 1150 nm. Therefore, it does not absorb 1310 nm light. Using the effective-index method as described in Tamir,[75] the single-mode dimensions were calculated. The design group decided to use a channel height of 0.4 μm because slab-mode calculations indicate that this thickness provides the best confinement. At a height of 0.4 μm, maximum confinement occurs

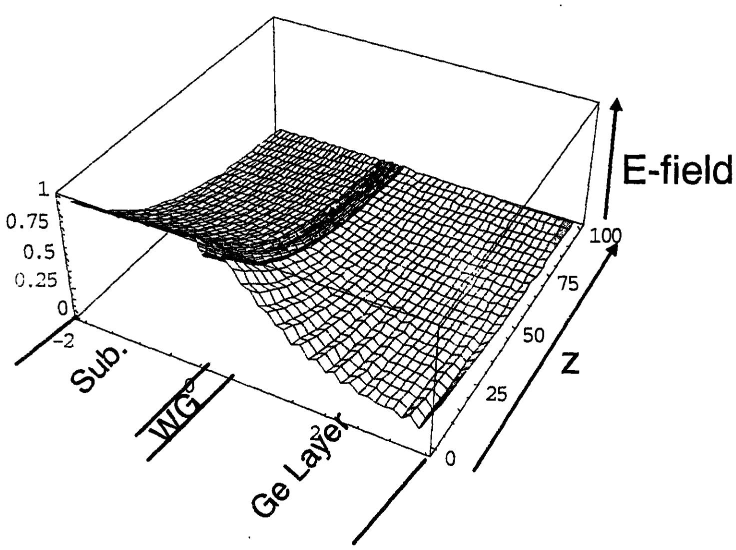

Figure 78: Electric Field Plot for Ge Detector

[75] T. Tamir (Ed.), *Guided-Wave Optoelectronics*, Springer-Verlag, NY (1990)

at a width of 0.5 μm, as represented by the effective thickness in Figure 77.

The waveguide for the Si detector substrate is similar to the InP design. The Si-based substrate will use a slab-waveguide with a low-index cladding layer on the top of a high-index raised waveguide. The materials for the cladding and the waveguide are SiO_2 (refractive index = 1.46) and Si (refractive index = 3.48), respectively. SiO_2 is an amorphous material, so lattice matching is not an issue. Si and SiO_2 are transparent to 1310 nm light as shown in Figure 79.

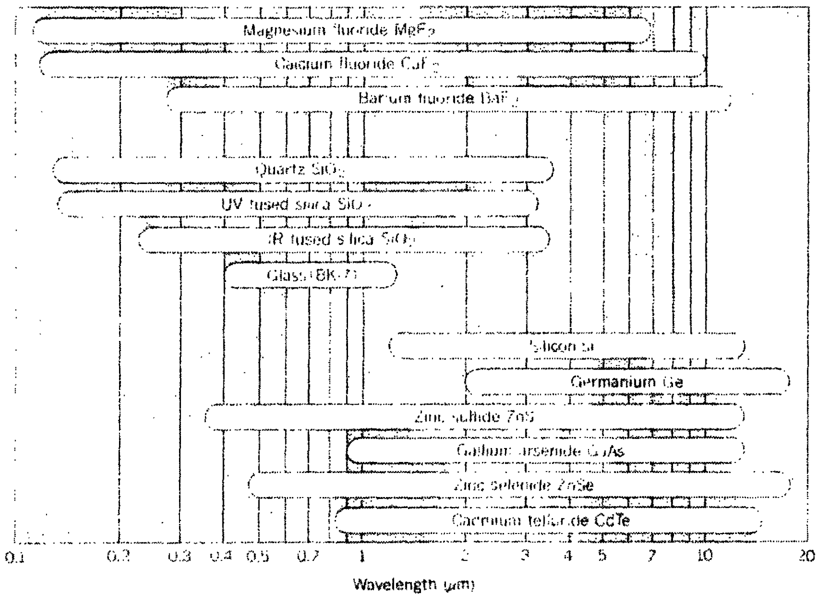

Figure 79: Spectral bands within which selected optical materials transmit light

A signal from the waveguide must be coupled into the detector described above. As the coupling is evanescent, the waveguide couples the light up into the detector. For the waveguide to detector couple, the light goes through the detector materials to the active region where photons are absorbed and carriers are generated. The length of the detector is determined by the coupling efficiency. We treat the coupling as a three-layer model—substrate, waveguide, and the Ge layers. Using a Mathematica program,[76] the waveguide-detector coupling was simulated. Figure 9 shows the maximum electric field-detector length plot. It takes approximately 5 μm for 99% absorption. Since the detector speed is not limited by the capacitance of the detector, there is no concern about the length of the couple on a RC limit basis.

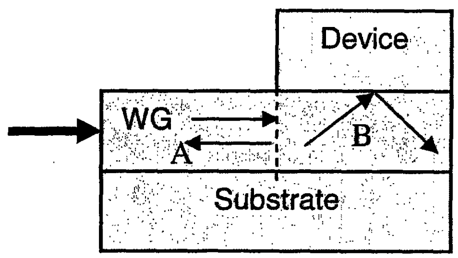

Figure 80: Schematic of reflection surfaces in evanescent couple

[76] D. Ahn, Mathematica Program (2004).

Reflection can create loss whenever there is a change in refractive index, or when there is an imperfect boundary. For the waveguide couples to the modulator and the detector, reflection occurs when light passes from the waveguide to the device section (denoted A in Figure 80 and again at the interface of the waveguide and the device (B in Figure 80). The interface reflection is minimized in the modulator design because the refractive index contrast in low (InGaAsP = 3.39, InP = 3.2) and the interface surface is very clean due the closely lattice matched. Ge and Si also are relatively well lattice matched, (4.0 and 3.5 respectively). For both device couples, therefore, large reflection is not expected, and the associated system loses will be minimal.

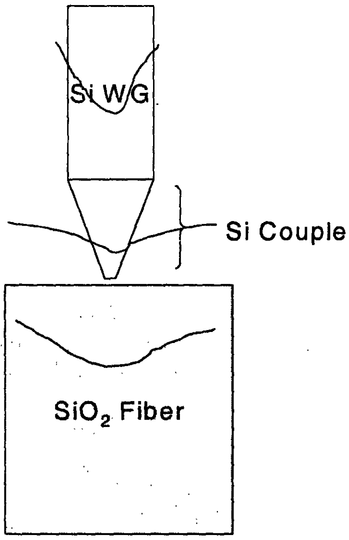

Figure 82: Adiabatic Taper Design. Shift in mode is gradual, reducing loss

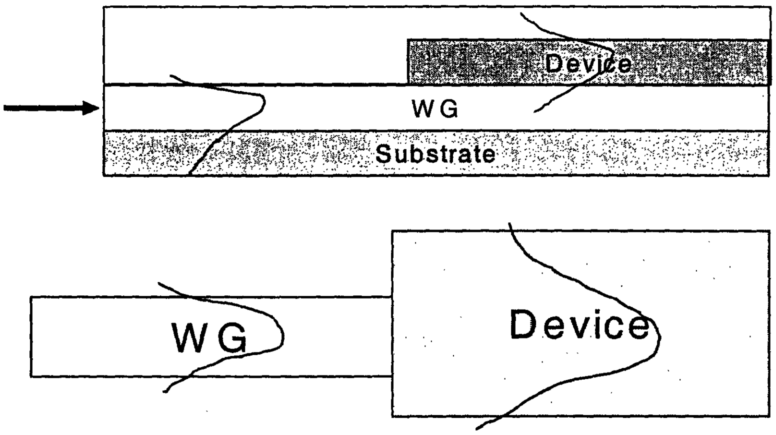

Figure 81: Generic illustration of modal mismatch. In the top figure, the mode shifts as it moves from waveguide before it enters the device area, to the device after it enters the area. The shift results in loss. In the bottom figure, the difference in size of the modes is demonstrated, also resulting in loss.

The final source of coupling losses that will be considered here is the effects of modal mismatch. Modal mismatch loss occurs because the dimensions of the waveguide and the device are different and the transfer from one size mode to another results in losses. Figure 81 shows a generic illustration of modal mismatching. To combat this loss, the couple could be design with an adiabatic taper as shown in Figure 82. The nanotaper has been shown to result in a coupling efficiency enhancement ($T_{with\ taper}/T_{without\ taper}$) of 7 to 8.5[77]. This improvement would be more significant in a higher index contrast system.

Other couples in the transceiver can be designed to minimize coupling losses. The modulator to laser couple benefits from the identical active layer design. Since the active layers of the modulator and the laser are grown in the same process, the coupling loss in nearly zero. The waveguide to fiber couple

[77] Almeida, Vilson, et. al. "Nanotaper for Compact Mode Conversion" School of Electrical Engineering, Cornell University. New York. December 13, 2002.

can be problematic, however, the nanotaper concept that can be used to minimize that loss. The fiber nanotaper features a high misalignment tolerance, and very low modal mismatch loss.

5.4.5 Architecture

The device architecture is now built around the set laser, detectors and waveguide requirements outlined above. Partitioning of transceiver functions, device layout and waveguide scheme are all important to the standard transceiver design. The standard transceiver must have;

- Robust design to achieve all technical specifications
- Process steps that can achieve mass production with high yield
- Minimal number of fiber and waveguide connections.

5.4.5.1 Architecture Design

The architecture design shown in Figure 83 was chosen for its ability to meet the requirements of the four market segments with minimal mechanical contacts. This design uses state of the art technology and allows for modest scalability in the sense that any laser (and some detector) advances can be incorporated into the package. The modulator structure used for this design is capable of speeds up to 25 Gbps, however, 40 Gbps InP modulated lasers have been demonstrated[78,79]. Ge/Si detector technology is relatively new and might also accommodate 40 Gbps. Allowing for unforeseen technology advancement in laser design and (perhaps more importantly) electrical interconnect capabilities, the design could allow transmitters and receivers up to the material dispersion limit for bit rate, perhaps approaching 100 Gb/s. These improvements could increase the bit rate of these devices by a factor of 5. Given continued exponential growth in the demand (double ever 2 years) for broadband, this would extend the life of this standard by some 4 or 5 years. The effects on the limitations on the scalability of this design cannot be guessed. However, true scalability might lock in material systems and current IC technology.

An additional advantage to the architecture is the use of monolithic integration of devices and waveguides. While the laser cannot be easily grown on Si, the detector and waveguides have been selected so that they could be grown in a single processing step. The advantage to monolithic integration is a reduction in the processing costs and enhanced coupling efficiencies.

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78 Baeyens, Y.; Georgiou, G.; Weiner, J.S.; Leven, A.; Houtsma, V.; Paschke, P.; Lee, Q.; Kopf, R.F.; Yang Yang; Chua, L.; Chen, C.; Liu, C.T.; Young-Kai Chen; *InP D-HBT ICs for 40-Gb/s and higher bitrate lightwave transceivers.* Solid-State Circuits, IEEE Journal of , Volume: 37, Issue: 9 , Sep 2002. Pages:1152 - 1159

79 Streit, D.C.; *Monolithically integrated transceivers for 40 Gb/s applications* Lasers and Electro-Optics Society, 2002. LEOS 2002. The 15th Annual Meeting of the IEEE , Volume: 2 , 10-14 Nov. 2002 Pages:485 vol.2

All the optical components are to be grown on an InP substrate and then flip-chip bond the InP substrate to a Si substrate. Figure 83 and Figure 84 show schematics for the flip-chip bonding between the InP and the Si substrate. The lasers, the modulators, the waveguides, and the multiplexing rings are all grown on the InP substrate. This InP substrate is then bonded to a Si substrate on which driver circuitry is fabricated. In essence, the Si substrate supplies only electrical power and control signals to the InP substrate on which all the optical components are present. The fiber is to be butt-coupled with a nanotaper to the output waveguide on the InP substrate.

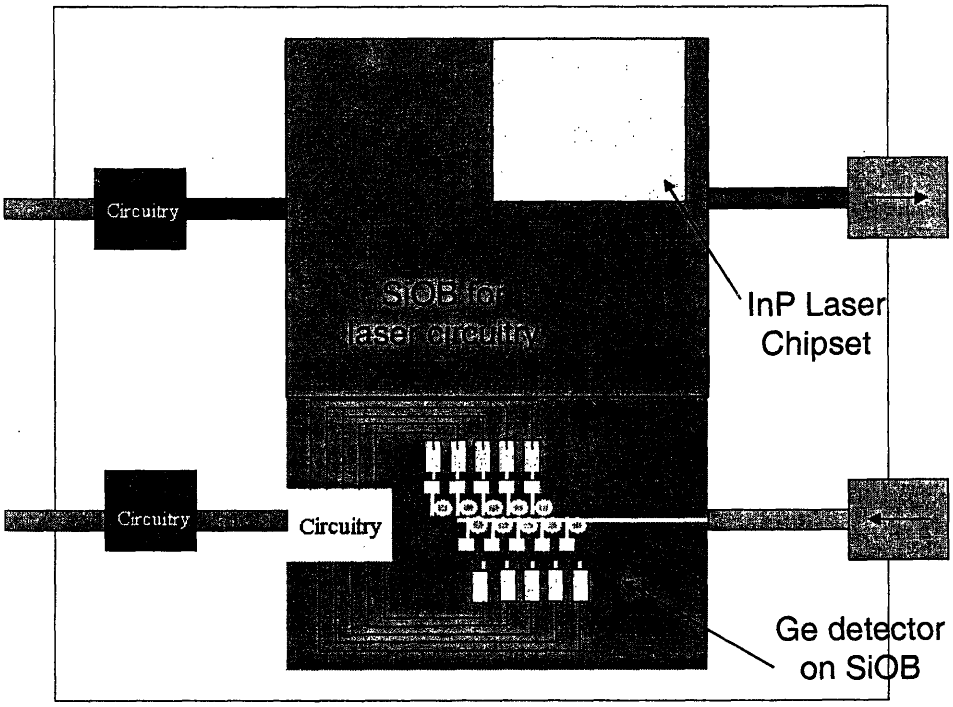

Figure 83: Transceiver Architecture for Standard. The Ge detector and corresponding waveguides and filters are grown directly on a SiOB containing the required electronics. The InP based Laser/Modulator, the InGaAsP waveguide and the filters are grown on an InP substrate and flip-chip bonded onto the SiOB. The corresponding laser driver circuits are incorporated into the SiOB and signals are relayed to the modulator through the bonding sites.

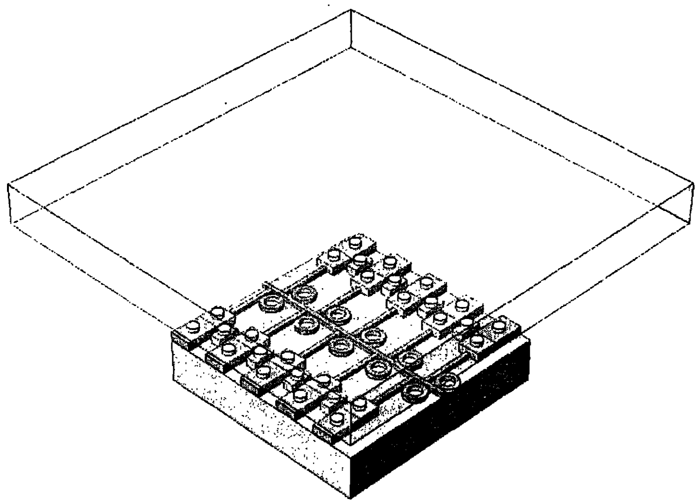

Figure 84: Reverse perspective of the Standard Transceivers transmit chip on SiOB

5.5 Summary

In this initial consideration of the standard transceiver device, the design has meet all requirements for all market segments with an eye to the figure of merit to guide in selecting design structures. Materials systems that best accommodate the required specification are chosen. The design seeks to implement monolithic integration whenever possible to decrease the variety in processes for each device. Scalability, while problematic, is reasonably addressed and the design allows for future improvements in materials technology and architecture. Table 7 gives a brief summary of the transceiver design.

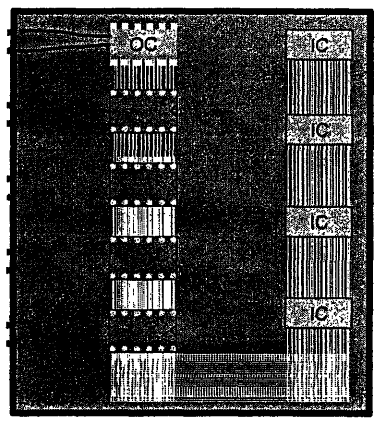

Figure 85: Server "box" with room for five transceivers

The future may bring Si based lasers, or GaAs IC that could change the standard transceiver. While the design should be robust enough to allow for significant expansion of the markets, it cannot effectively anticipate certain technology advances, nor would the design be effective if it were to effectively lock in materials systems or design architectures. As an example, we have seen the evolution of memory devices from floppy to CD and now to USB memory sticks. These standard devices change drastically with little or no disruption in daily productivity. The standard receiver should be expected to likewise evolve.

This chapter offers a very high level treatment of the main technical issues that are important in developing a standard transceiver. Any implementation policy should take the technical components of the communications industry's problems into consideration, as well as the policy and cultural components of the industry. The next and final chapter does just that and presents a proposal for policy that can pave the way for standardization.

Table 7: Summary of Basic Standard Transceiver Characteristics

	FTTH	Storage Network	Server	LAN
Fiber Length (m)	1000	25	1	15000
Bandwidth (Gbps)	1	40	1000	10
Wavelength (nm)	1310			
Fiber	Single Mode			
Detector	Ge on Si			
Laser	InGaAsP on InP – Single Quantum Well			
Modulator	InGaAsP on InP – Multi Quantum Well			
Transmitter Waveguide	InGaAsP on InP			
Detector Waveguide	Si on SiO_2			

Chapter Six: The Road to Standardization

The preceding chapters have made a case for transceiver standardization in the optical communications industry. The research completed for this thesis is a first step toward standardization, however, much more needs to be done before implementation becomes feasible, or even possible. This final chapter summarizes the results of this research and, based on those conclusions, presents a list of issues that any standardization policy needs to consider in order to be successful. Following the policy points, a stakeholder analysis is included to address what policies would mean for different players in the communications industry.

6.1 Summary of Conclusions

The optical communications industry is extremely important to the United States economy and nobody doubts that the demand for bandwidth will continue to grow. Up until now, the optical industry has been depressed by its failure to capture as much of that growth as was expected in the mid 1990s. The demand has been met by traditional copper based and wireless networks. As bandwidth demands continue to grow, it is clear that the physical limitations of copper and wireless will render optical more and more critical to the growth of the communications industry. Optoelectronic manufacturers provide the foundation of optical networks and recent economic conditions have left the industry struggling just to survive. To accommodate the inevitable position that optical will hold steps must be taken now to assure a viable and productive OEM base. In studying the current situation and a potential solution, many valuable conclusions have been reached that can help guide policy that will provide that assurance.

The late 1990s crash was simply a market reaction to the overcapacity that engulfed the industry after years of unrealized growth expectations. The overcapacity applied to both the network capacity and the manufacturing capacity. Chapter two suggests that the proliferation of transceiver designs is one of the reasons why the OEM industry has been unable to adequately adjust to changing market conditions. To meet transceiver performance demands across the telecommunications and datacommunications industries, there are nearly 600 different transceiver flavors available on the public websites of six major transceiver suppliers. The research has not deduced the difference in manufacturing processes for each of those flavors, and it is likely that many of the designs can utilized the same production line, however, the story is clear; there are enough different flavors that the manufacturing capacity is divided among many different production lines and the merging of operations is not straight forward. The results in chapter two, while striking, do not capture the entire problem as the survey of existing transceivers does not include transceivers for FTTH, nor does it include new and emerging markets that could provide a significant boost to transceiver volumes in the near future, including automotive, personal electronics, and aviation systems.

The logical progression after realizing the extent of proliferation is that standardization is a potential means by which the OEM industry could be revived. This thesis assumes that communications network providers meet their customer's demands by implementing the lowest cost solution. The proliferation of transceiver designs results in a fractured industry that cannot take advantage of economies of scale and manufacturing learning in a way that pushes down costs and allows optical to be more competitive. Standardization can enable OEMs to leverage the volume across various market segments, and within those segments, creating more cost effective manufacturing.

Chapter three uses System Dynamics to test the assertion that standardization could improve the OEM industry's performance. The following is a summary of the important conclusions from that exercise.

Pre-model Insights:

- During the boom years, manufacturing capacity grew enormously. When the market crashed and the demand declined, severe overcapacity strained the industry, and continues to do so today.
- At some point, transceiver costs will fall far enough that other network components become the costs drivers and the OEMs will not be able to drive demand further with costs improvements. One of the available options for the industry is to focus on development of new high bandwidth applications that will increase demand.
- In periods of high capacity utilization, product differentiation grows because standardization expends resources and there is no market driver to push OEMs out of the tradition differentiation culture.
- In periods of low capacity utilization, product differentiation grows because OEMs hold market share tightly and are not willing to give it up.
- Greater foresight during the boom could have lead to more effort to standardize. OEMs were less protective of market share at that time and may have been more likely to trade short term market share loses for continued health.
- One of the greatest cost advantages of standardization is the elimination of platform development from the R&D burdens of each individual firm. Resources can be pooled and fewer new platforms are needed when there is a standard platform on which all OEMs build devices.
- As firms fight for market share, sales and industry revenues are actually weakened. As revenues are further weakened, firms fight more fiercely for market share, resulting in a "death spiral" that is difficult to break.

Model Insights

- Shortening the product lifecycle helps the industry in two ways; 1) the revenue base increases as the installed transceivers are replaced more frequently, and 2) the peak/valley market behavior[80] is avoided as one technology generation is followed closely by another.
- Increasing the R&D investment and/or the R&D productivity can help optical out-compete other communications technologies, however, without shorter product lifecycles, the peak/valley behavior is still persistent.
- In the model, standardization leads to orders of magnitude increases in the revenue due to the enhanced market penetration spurred by greater concentration of industry resources on the improvement of fewer platforms.
- Continuance of the differentiation policies results in further market stagnation and less resources to improve each platform.
- The model illustrated a major difficulty in convincing OEMs to move to a standard. There will be an initial period in which the revenues for the standardization path are lower than those when continuing with the status quo. The length and depth of that period vary depending on market conditions. That initial weakening of the industry provides a formidable barrier to acceptance
- Cross market convergence is also important. In the model, each individual segment could be taken as the industry as a whole, with the number of platforms across the segment replaced by the number across the industry.

Chapter four then lays out the historical context of standardization. In the railroad industry, network components were standardized to allow a more efficient use of capacity. The Ethernet became the LAN standard over-competition began to erode the usefulness of the network because of the lack of interoperability between competing protocols, and IrDA standardization illustrated the importance of volume for new technology to take hold. Each of these industries can provide lessons for the transceiver industry and help direct standardization.

Chapter five introduces the technical aspects of creating a standard transceiver. The task is not easy and will require cooperation across the industry. One of the main concerns deals with the importance of obsolescence that was described in chapter three. A standard transceiver must therefore not restrict the development of new technologies, particularly in the laser and modulator sections. By using a SiOB for the integrated circuits and the detector subassembly substrate, the laser has some freedom to evolve. Whatever technology or materials systems that best serves the needs of the industry can be

[80] Peak/valley market behavior is undesirable as it strains the supply chain with periods of high orders, followed by lulls.

adopted at the appropriate time and bonded to the silicon base in the same manner in which the InP-based laser subsystem is in the proposed design.

6.2 Policy Considerations

The discussions in this thesis have touched on a number of different issues. Each issue is unique and affects the industry in different ways. Below are a number of concerns accompanied by some insight that follows from the research in this thesis;

1) Network Hardware – Section 1.2.1 covers the different transceivers that are used for optical communications. Subsequent chapters argue that variety only adds to the industry's problems and a standard should be developed. Proliferation of transceiver designs has handcuffed the industry and contributes to further deterioration of the health of the OEM firms. Future policy must focus on standardization within market segments and across segments if optical is to take the place of traditional communications technologies as demand for bandwidth increases.

   There is a real issue of how to handle the function partitioning in a standard transceiver. Are the electronics a part of the standard? Should the transmitter also be included in the standard specifications? The design proposed in chapter 5 includes transmitter and the basic driver circuits, and is focuses on the transceiver as a package. As new market segments are considered, including chip-to-chip, and on-chip connections, the transceiver may be reduced to simply a circuit element, with whatever laser and detector is suitable for the application laid over that circuit element. Whatever the case may be, the standard should provide rules that allow manufacturers to seamlessly insert their products into any application, and allow enough synergies that enable volume manufacturing that significantly lowers costs.

2) Data Management – section 1.2.2 describes the different methods for packaging data in a way that it can find its way through the network maze and reach the desired recipient. As the transceiver becomes standardized, competition will move from providing the lowest cost network to providing higher reliability and superior services (per Clayton Christenson's work on trends in innovation, chapter 4). Data management methods directly impact the quality of reliability and services and therefore standardization of the transceiver should not have minimal affect of the type of management that is used. The integrated circuitry of the standard transceiver should be compatible with any protocols that are developed for any segment. This suggests simplification of the transceiver driver circuits.

3) Network Architecture – As with the data management, reliability and the quality of services will depend also on network architecture. The standard transceiver should be robust enough to be impartial to topology. No particular architecture will be favored based on the transceiver. The

decision on topology will be made by network providers as they consider bandwidth demands and the power requirements and the available power sources for the network. That is, if the optical system is particularly bandwidth intensive, requiring multiple connections and transceivers, the providers may choose a topology that minimizes the number of transceivers in an effort to reduce power demands.

Each network segment has developed its own topologies, and it would prove a complex problem to try to dictate the topology that each segment must implement. There are advantage and disadvantages to each network, and it is important that network providers are free to develop their networks in the best way possible. For the purposes of this thesis, the particular network protocol is taken to be contained in the software external to the transceiver, therefore no topology is favored.

4) Overcapacity – The OEM industry faces severe overcapacity. There are two potential solutions to fill that capacity in the medium to long term. First, overseas demand for FTTH and other optical networks is still strong. A recent order for FTTH components in Japan went unfulfilled due to lack of manufacturing capacity. The hold is in the production of the laser and detector subassemblies that are produced by hand in parts of Asia. Most transceivers commercially available utilized these subassemblies. The lack of capacity in Japan illustrated the need to automate parts of production. Entering into agreements with overseas network provides in need of components could provide the volume guarantees needed to justify investment in these automation techniques.

The second way to increase capacity utilization is to learn from the IrDA case study and secure volumes without an identified market. For example, a transceiver installed in every TV, stereo, and speaker system would provide volumes and promote the development of ways to use the potential bandwidth, even if it is not used at first. The key to this strategy is low costs devices that can only be realized through standardization. IrDA was able to install its devices into laptop computers because they did not add to the costs of the computer, and it provided potential functionality that was attractive to computer suppliers and customers alike. Automotive implementation is also possible, and perhaps more so. BMW is currently installing optical networks on its high end models. The demonstration of the utility of optical at BMW could provide a concrete example of the advantages of optical.

The second strategy obviously includes cooperation with personal electronic and/or automotive manufacturers. These measures offer an example to an opportunity for OEMs to tackle the lack of demand in the industry instead of simply working to reduce costs and hoping for demand to pick up.

5) Industry Cooperation – It is vitally important that the industry come together to formulate the standard. The MIT CTR is a good start to the level of cooperation that is needed, however, to achieve universal buy-in to the path laid by the roadmap, the work and conclusions of the CTR should be

subject to industry wide review whenever possible. Publication in widely circulated industry journals is one way to achieve this review.

The other component of cooperation concerns changing the cultural norms of the OEM industry and the providers. The past industry environment put a premium on specialization and optimization. It will take a paradigm shift in corporate expectations to accept a device that may not be optimal for the desired network in exchange for a more viable components industry.

6) Regulation - Not only must the standard transceiver be somehow codified into a federal regulation, but fair competition in the market must be provided by regulators. This fair competition largely rests on control over the infrastructure. Based on other networked industries (national highway system, utilities, etc.), there are two types of network control. As in the national highway system, all lines could be controlled and maintained by the federal government. Networks also could be shared by all users. This is common in the utilities markets today, where network providers are forced to sell capacity indiscriminately to all potential users. Finally, the networks could be private and only available to the network owner, as was the case in the early days of the railroad, and is now the model that allows Verizon to begin a FTTH roll out.

   Federal control of the networks could solve many of the standardization concerns (it is easier to build the networks with standard transceivers if one entity builds the entire network), however, such control would kill the benefits and efficiencies that come with competition. Shared networks have been used successfully in the utilities industries, but strict government control is needed to curb price gouging and monopolistic practices. Private network certainly could help jump start the industry (as the Verizon case demonstrates) but regulators must be careful in controlling access to consumers. The biggest fear here is that the network owners would provide their own services and effectively block all other service providers, creating a deficiency in consumer welfare[81].

   The point here is that governments will have a vital role in the industry going forward. The level of that role needs serious consideration and will evolve over time as the industry matures. It is important that whatever the original role of government is, it does not become culturally engrained in the industry, making it nearly impossible to shift as needed.

7) Standardization – the major conclusion of this thesis is that standardization is essential. Chapter five identifies the technical challenges of that standardization and offers a high level example of the type of implementation that may be needed. The development of that standard is critical and general guidelines should be formulated as soon as possible. MSA and other efforts to form a standard by the

[81] For a further discussion of this, and other private control issues, see Owen, Bruce. *Assigning Broadband Rights.* Regulation, the Cato Review of Business and Government. Summer 2004, Vol. 27, No. 2

market force of participating OEMs are not adequate. True convergence and industry wide acceptance needs to be achieved. Again, the lessons of history can be applied. In the LAN market, regulators specified three standards and the market chose the superior design. Such a choice could work here. The road to a single standard here will be long, and providing a focus down to even 3 or 4 options, as opposed to the current situation that features a sort of free for all, will be instrumental. The purpose of the standards will be to begin to reverse the "death spiral" trends identified in section 3.5.3. Essentially, the "Gaining Market Share" reinforcing loop of section 3.5.3 should be made extremely weak, leaving the standardization loop as the stronger path.

8) Obsolescence – The standard should be made flexible enough to allow significant year-to-year improvement, resulting in shorter product lifecycles. To achieve obsolescence the transceivers need to be a) cheap enough for network providers to justify frequent upgrades, b) network pluggable to allow cheap and easy replacement with minimal network down time and to avoid the cost of a "truck roll[82]."

9) Incentives – The model has shown that OEMs may be adverse to standardization due to the initial weakening of the industry and lack of a guarantee that standardization will even bring the market back to original levels. To combat these fears, incentive programs should be implemented to help the OEMs through the initial period[83]. One of the results of standardization will be a reduction in the number of firms as the market moves toward a commodity market. Incentives should be careful not to prop up firms that should be acquired by larger firms, or that should simply fail, while at the same time encouraging the industry as a whole to follow the standardization path. The involvement of federal regulators and industry consortiums need work together to work out the incentive structure that could in clued tax relief, subsidies, or capital expenditure grants.

The policy recommendations above should serve as guidelines for implementation. More detailed policies need to be formulated with all stakeholders present. This will be a complex and difficult task, but one that is necessary if the OEM industry is to survive. The next section provides a brief analysis of the impact of standardization on the chief stakeholders.

[82] Current non-pluggable solutions require the network provider to send a technician and a truck to the site to upgrade and/or repair the transceiver box. "Truck roll" refers to the deployment of the truck to the location.

[83] Perhaps an incentive program similar to PV in Japan would be appropriate. In that case, the Japanese government covered 50% of installation costs to encourage sales. The revenues for those sales were used for further R&D that improved performance, thus making the products more attractive to consumers. The subsidy is being slowly eliminated as the industry grows.

6.3 Stakeholder Analysis

6.3.1. Optoelectronics Manufacturers

OEMs have to most to gain or lose from new policy. Continuing on the current path will promote the demise of the industry, and optical will struggle along until the demand for bandwidth simply makes optical the only choice. The problem with the "wait until they need us" strategy is that it could take to long, and most of the firms will fail and capacity will be diminished, making it more difficult to meet demand once it does occur.

6.3.2. Network Providers

Network providers are interested in providing clients with the highest level of reliability and service at the lowest costs. For many market segments, demand has not made optical technologies more attractive than traditional technologies. However, in anticipation of the growing demand for bandwidth, network providers should realize the important of a viable optical components base to supply optical networks when they do become advantageous.

6.3.3. Customers

The communications era is upon us, and there is no reason to believe that customers thirst for more accessible information will grow. Whether that information is for business, entertainment, or personal communications, there is no limit in sight to the end of the demand. New applications will be grow from the more immediate optical applications. For example, FTTH could lead to fiber-IN-the-home, including home entertainment centers and "smart" appliances. Demand will be the driver to future applications of optical, making the consumer a big player in the industry.

6.3.4. Regulators

Regulators must be on-board with any move to standardize. The IEEE standards largely set the technical specification for optical communications, including wavelength, bit rate, laser power, etc. A standard transceiver will operate at one wavelength and the bit rate and laser power will be varied according the network application. Regulatory language needs to be adjusted to reflect the nature of a network with one transceiver platform. It will be extremely difficult to essentially throw away years of regulatory development, and will require a unified directive from the industry.

One of the problems with the current regulatory structure is that Federal agencies such as the IEEE are no longer heavily funded by the federal government. Instead, they derive revenue from developing and selling regulations. This system provides a perverse incentive to produce more standards, and in fact that has been the case so far[84]. The incentive structure must be altered, and the regulators need to help realize the big picture and provide the framework for standardization to work.

Aside from control of the optical technology used in networks, regulators also have a responsibility to preside over a functioning and healthy market environment. As with all network based industries, ensuring a free and competitive flow of goods is tricky business, and the success or failure of government policy could have enormous impact on the ability of the optical communications industry to grow.

6.3.5. Competitors to Optical Networks

Copper based networks are in danger of losing enormous network market share if the efforts to improve optical succeed. It will be extremely difficult to manage this shift and careful planning is needed. The easiest way to ease the pain of copper network providers is to involve those firms in the development of optical, and in fact that is what seems to be happening. Many of the incumbent cable and DSL providers are the leader in FTTH[85]. There will be losers in this segment as the switch is made, but he transition will not be abrupt and the firm turnover

Wireless communications are in different situation, and will likely not be in direct competition with optical. Customers will continue to demand wireless services in all forms, and the technology will evolve independent of optical technology. Application where wireless will thrive: cell phones, local connectivity, etc, will not be served by optical fibers and there will be a clear distinction between the two technologies, for the most part.

6.3.6. Others

The greatest impact of the success or failure of the optical communications industry could be on the economy in general. As one of the largest sectors of the US economy, the stagnation of the communications industry could lead the country into a long recession. If OEMs are allowed to take a passive approach to improving the health of their industry, when the demand finally does arrive, and OEMs are unable to adequately meet that demand, the result will be a significant slow-down in the communications industry as well as the US economy.

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[84] A prime example of the proliferation of federal standards is evident in Angie Kelic's work regarding IEEE 803 regulation and the numerous FTTH standards that have been developed.
[85] Verizon has recently announced plans to offer optical to 1 million customers in Texas and later in Florida and California, by far the most ambitious FTTH deployment in the US to date. Announcement: http://news.com.com/Verizon's+fiber+race+is+on/2100-1034_3-5275171.html

6.4 Additional Work

1) The regulatory environment for each market is complex. A thorough review of the controlling regulations and IEEE codes should be conducted and recommendations to bring the regulatory measures into line with the standardization policy should be proposed and implemented.
2) While a standard transceiver for the four market segments that are the focus of this thesis should be possible, it may not be possible to have one single transceiver work for all potential segments including personal electronics, chip to chip, and on-chip markets. Work is being conducted to assess the total addressable markets and the standard should target the largest potential markets.
3) The extent of proliferation and the level to which standardization should be realized depends partly of the manufacturing processes. Of the 580 transceiver varieties noted in chapter 2, what is the difference in manufacturing process? How do those differences affect the ability of producers to bring down costs?
4) Modeling of the other loops in the model could be beneficial to broaden the understanding of the industry dynamics. A fully calibrated model would not be advised given the extremely complexity of the industry and challenges involved in calibrating. The effort would have to involve full cooperation of all parties that could provide the necessary data. Since these parties range across industries and industry segments, that coordination task would be nearly impossible, and the results of such an effort would be questionable.
5) There needs to be some sort of oversight committee that has the power and respect to influence the industry and the manufacturers. This committee, or organization, will be more far-reaching than the MIT CTR, and will not be a purely governmental entity. It is certainly a challenge to develop such an organization, but it is essential. Other industries have managed to organize in appropriate ways, with various levels of sophistication, including the railroad industry and, more recently, the semiconductor industry.

Appendix I-A: Survey Questionnaire

Interviewee(s):
Company:
Date:

Low Cost Technology Working Group

This survey is aimed at gaining input from the Low Cost Transceiver TWG members for discussion at the Oct 10, 2003 TWG Meeting at MIT.

Please email completed survey to Michael Speerschneider at mspeer@mit.edu. Interview must be returned to MIT by Tuesday, Oct 7th 2003.

All information collected will be kept confidential and will not be shared outside of the MIT Microphotonics Roadmapping team. What results are reported will be presented in an aggregated form such that the responses of any individual firms/participants will not be detectable.

Transceiver – Pricing Trends

Please use the following as "base-line" transceivers, to provide a point of reference:

	Data Rate	Reach	Wave-length	Form Factor
Core/Metro	10 Gbps	Up to 80 km	1550 nm	XFP or 300-pin
Enterprise	Up to 10.3125 (Gbps)	Up to 10 km	1310 nm	XFP or equivalent
Access/FTTH	1.25 Gbps	Up to 20 km	1310/1550 nm	Diplexer

I. How do you expect pricing will change over time? And, how would you like to see pricing decline? Provide an estimate with respect to today's average price.
Note: The baseline prices have not been specified intentionally in order to avoid asking for potentially sensitive pricing data.

	A.) What do you **expect** – given current industry trends?		B.) What would you **like** to see happen?	
	% Change in Ave Price 3 years	% Change in Ave Price 5-7 years	% Change in Ave Price 3 years	% Change in Ave Price 5-7 years
Core/Metro				
Enterprise				
Access/FTTH				

II. How do you think transceiver cost reduction will be accomplished over the next 5-7 years?

a. Core/Metro?

b. Enterprise?

c. Access/FTTH?

III. What do you expect the major barriers will be to achieving this cost reduction?

a. Core/Metro?

b. Enterprise?

c. Access/FTTH?

Appendix I-B: Survey Results

Methods of Cost Reduction			
	Core/Metro (LAN)	**Enterprise**	**Access/FTTx**
Internal/ Design	- Radical design change - Electronic dispersion to decrease costs - Optoelectronic integration	- Electronic dispersion to decrease costs - Increased IC integration (2) - Optoelectronic integration - Long wavelength VCSEL (2) - Removal of electronics from package	- Move from TO-can to PIC - Optoelectronic integration - Long wavelength VCSEL - Non-hermetic packaging - Packaging innovation (plastics, molding, etc.) - "Older" technologies
Manufact uring	- Decrease optical packaging costs (2) - Simplified testing - Automated active alignment	- Decrease optical packaging costs - Offshore manufacturing - Photonic assembly and packaging - Automated packaging - Automation of active alignment	- Automated manufacturing - Photonic assembly and packaging
External/ Market	- Volume - Volume in components (via datacom) - Convergence in datacom/telecom standards - System partitioning - Commonality with enterprise - Adaptation of specifications similar to other optical markets and leveraging volumes	- Volume (3) - Copper replaced by SM fiber - Synergies from FTTx/Access volumes - Increased standardization - LD, PD, and electronics cost reduction - Emergence of packaging platform, i.e. XFP	- Volume (5) - True FTTx deployment - Real services with profitable revenue model - Increased standardization

Barriers to Cost Reduction			
	Core/Metro (LAN)	**Enterprise**	**Access/FTTx**
Internal/ Design	- Lack of Technical understanding - Trouble with LD couple to SM fiber - Performance	- Lack of non-hermetic package - No confidence in VCSEL (1310) reliability	- Lack of non-hermetic package
Manufacturing	- Lack of batch fabrication process - High price of active alignment	- Lack of batch fabrication process - Lack of automated assembly - High price of active alignment	- Lack of batch fabrication process - -Lack of automated assembly
External/ Market	- Lack of consumer apps for high b/w leads to low volumes - Uncertainty over when and how quickly volume comes - Low volume decreases investment for packaging and yield - Lack of volumes (2) - Resistance to change of standards allowing electrical dispersion comp. - Resistance to change of standards allowing convergence of datacom and telecom. - Lack of customer confidence - Anticipating development of system/network architectures when upgraded to 10G leading to variability in component base	- Lack of architecture that can efficiently handle bandwidth - Low cost technologies for FTTx is unusable or too late for enterprise interface - Lack of volume (2) - Uncertain move to 10G creates confusion in market	- Lack of applications - Timing of spending on fiber based FTTx. Infrastructure upgrade too slow to justify PLC based solutions because of low volume - Lack of volume (2) - Chicken and egg dynamics - Harsh environment? - Build-out? - No Telecordia specification - Challenge of digging ditches in homeowner's yard

Appendix II: Variables for System Dynamics System Definition

Industry/Market – Communications Industry

Expenditures on Network Research & Development (R&D)
Network Profits
Operating Expenditures on Network
Capital Equipment Expenditures on Network
Number of Carriers & Service Providers
Number of Systems Companies
Demand for Increased Network Capacity (Bandwidth)
Cost of Bandwidth
Price of Bandwidth
IP traffic growth
IP revenue growth
Number of users/network segment
Total broadband customer base – consumer/business
Demand for new applications
Availability of broadband content

Industry/Market – OE Industry

TAM = total revenue

Number of OE Txr Manufacturers/Suppliers (# of competitors)
Available Capital (VC) for funding OE
Attractiveness of OE Industry to Investors
OE Industry Profitability
Total Addressable Market (TAM) for Txr in Communications
TAM for Txr in Core market segment
TAM for Txr in Metro regional market segment
TAM for Txr in Switching market segment
TAM for Txr in Routing market segment
TAM for Txr in Broadband Access market segment
TAM for Txr in Storage market segment
TAM for Txr in Servers and Computing market segment
Total Unit Volume Demand for Txr in Core market segment
Total Unit Volume Demand for Txr in Metro regional market segment
Total Unit Volume Demand for Txr in Switching market segment
Total Unit Volume Demand for Txr in Routing market segment
Total Unit Volume Demand for Txr in Broadband Access market segment
Total Unit Volume Demand for Txr in Storage market segment
Total Unit Volume Demand for Txr in Servers and Computing market segment
Total Volume/each Txr Product
Average Cost/Txr
Cost/Txr in Core market segment
Cost/Txr in Metro regional market segment
Cost/Txr in Switching market segment
Cost/Txr in Routing market segment

Cost/Txr in Broadband Access market segment
Cost/Txr in Storage market segment
Cost/Txr in Servers and Computing market segment
Demand for Txr in other "non-communications" industries
Elasticity of Demand/Network segment
Expenditures on Txr R&D
Level of complexity of supply chain
Manufacturing Capacity
Capacity Utilization

Industry-Technology – OE Industry

Number of Txr Products (Product Variety) for Communications Applications
Number of Txr Products in Core market segment
Number of Txr Products in Metro regional market segment
Number of Txr Products in Switching market segment
Number of Txr Products in Routing market segment
Number of Txr Products in Broadband Access market segment
Number of Txr Products in Storage market segment
Number of Txr Products in Servers and Computing market segment
Manufacturing Costs of Txr
Packaging Costs of Txr
Number of competing technologies for Txr
Rate of adoption of new technology
Ease of adoption of new technology (function of cost of system re-design)
Willingness to incorporate new technologies (perception)
Willingness to be flexible (compromise) on Txr performance requirements (systems requirements)
Level of Txr customization required
Demand for additional Txr functionality
Cost of Txr qualification
Length of Design Cycle
Product lifecycle
Availability of Foundry Services
Capital cost to build/maintain manufacturing/fab facilities
% cost of Txr/Total System Cost
% shift of OE manufacturing to off-shore (shift to China)

Technology – Communications Industry

Network Performance
Performance – Quality of Service
Network Scalability – Ability to Scale Capacity
Network Capacity
Network Innovations – Ability to Introduce New Services
Rate of Deployment of FTTH
Availability of new compression technologies (i.e. more bandwidth not driving increased capacity)
Availability of competing technologies (non-optical) to provide bandwidth
Level of network convergence – voice and data

Technology – OE Industry

Degree of functionality of Txr
Txr Performance – Bit rate
Txr Performance – Reach
Txr Performance – Reliability
Txr Performance – Signal Quality
Txr Performance – Thermal Requirements
Level of monolithic integration
Level of hybrid integration
Degree of functional integration
Number of Channels Required
Txr Process Yield
Txr Manufacturing Yield
Txr Packaging Yield
Complexity of Packaging Requirements (need for hermeticity)
Availability of Standard Manufacturing Tools - from other industries (e.g. semiconductor)
Requirements for Precision Alignment
Requirements for link length
Power dissipation requirements
Availability of design tools
Availability of design expertise
Product form factor – size
Product form factor – pluggable

Technology-Policy – OE Industry

Number of industry defined standards
Rate of emergence of standards
Number of Txr product standards

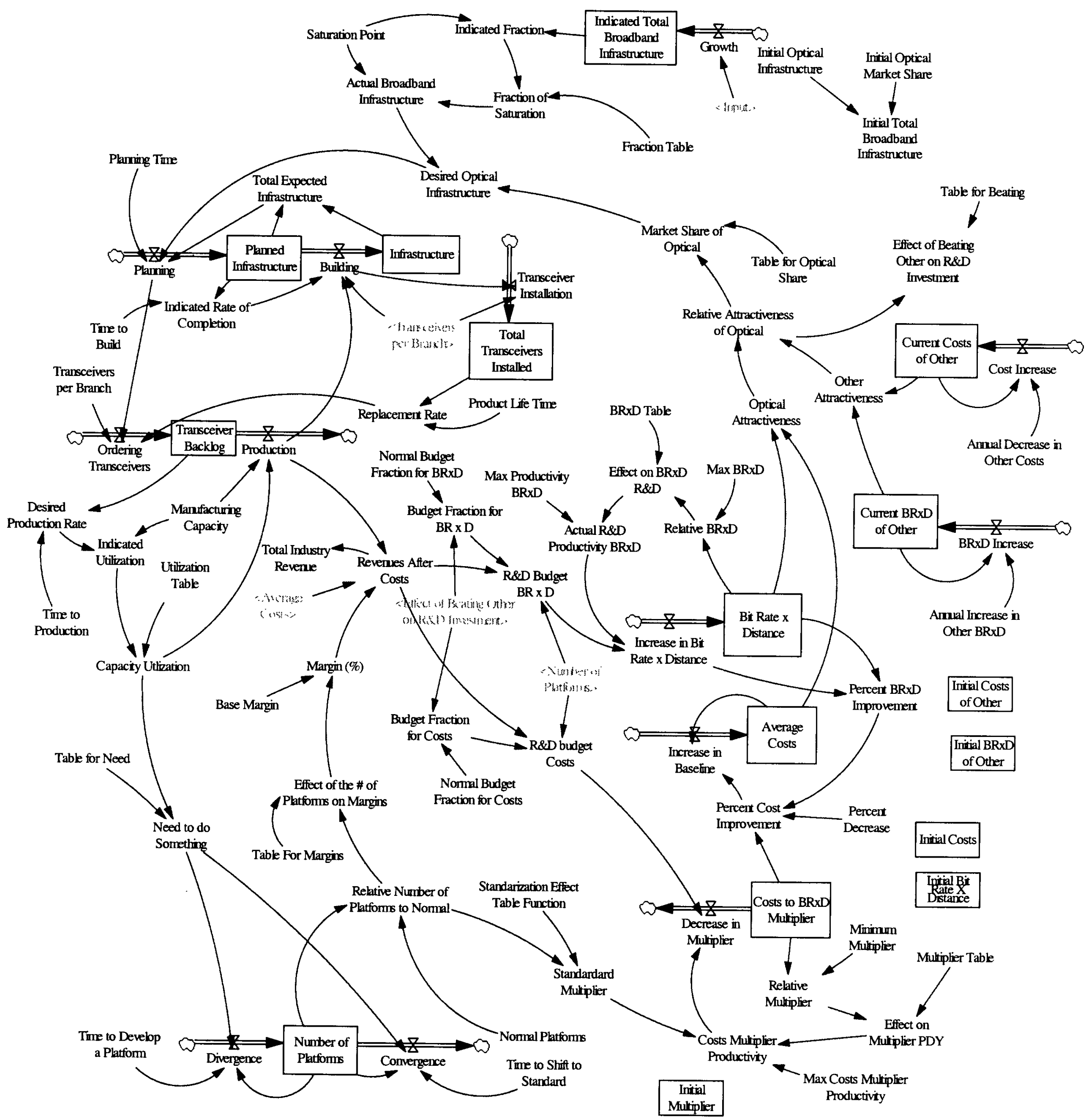
Policy – Communications Industry

Likelihood of government regulations supporting broadband

Industry-Policy – Communications Industry

Availability of funds for broadband deployment driven by policy

Appendix III: System Dynamics Model and Base Case Conditions



Base Case Variables

Variable	Value[A]	Comment
Planning Time	2 years	Time for everything that goes into planning – 1st perceive the opportunity, then arrange finance, design, get contractors, etc.
Time to Build	1.5 years	The amount of time to build once the planning is done. This time could vary, but the model showed no significant change in behavior with changing Time to Build
Transceivers per branch	6, 2, 12, 25 Transceivers	See Market Saturation Comments below
Product Lifecycle	20, 10, 2, 1 years	LAN and FTTH are essentially forever. SAN is perhaps a bit less as bandwidth demands increase. Server will be using the absolute state-of-the-art, and will see high rates of obsolescence.
Time to Production	0.5 years	Takes about ½ year to order build and deliver a transceiver. About one month to get through manufacturing and test chains, and then weeks to months to make it to the customer. This can be quite dynamic and depends on multiple market conditions (source: Michael Schabel, Lucent Technologies).
Normal Budget Fraction for BRxD	7.5%, 5%, 7.5%, 5%	Refers to the percent of revenues dedicated to R&D. FTTH and Server R&D is a little less because the "other" issues demand resources – FTTH has to overcome regulatory obstacles, and Servers have to overcome technical obstacles.
Normal Budget Fraction for Costs	10%, 5%, 10%, 1%	Same rationale as above. More for LAN and SAN because of the focus on costs reductions. FTTH and Servers have additional issues. Servers have other benefits that if they get it to work, costs would not be so much an issue. Optical Server connection would out-compete other technologies on performance alone
Base Margin	25%	Refers to the margins earned on transceiver sales. In Base Case, this remains constant. When standardization is introduced, the margins will decline.
Time to Develop a Platform	1 year	This is the time to plan and develop a new platform. Could be more, but lengthening the time does not change the behavior of the model significantly.
Time to Shift to a Standard	4 years	Generally, it should take longer for the process of getting firms together and developing an appropriate standard. Platform development is internal to each firm with fewer design arguments
Max Costs Multiplier Productivity	$1x10^{-5}$, $1x10^{-5}$, $1x10^{-7}$, $1x10^{-7}$	The productivity of the spending resources on slowing the rate of price increase. These values were chosen to fit the other parameters of the model and give meaningful results.
Annual Increase in Other BRxD	4%	Refers to the rate of increase for copper-based, wireless, and other competing communications technologies. May be low, but the model behavior would not change as the "Max Costs Multiplier Productivity" would be adjusted accordingly to give meaningful results. The important thing is to see what can happen when Optical improvement lags versus what happens when it exceeds the rate of improvement of other technologies.
Annual Decrease in Other Costs	2.5%	Same as above. The 4% to 2.5% ration is based on input by Michael Schabel, Lucent Technologies.

A: When one value is given, it the same across all segments. Four values denotes a different value for each segment, and is given in order: LAN, FTTH, SAN, Server

Current Transceiver Performance and Costs				
Segment	**Current BRxD (Mbps*m)**	**Current Costs (dollars)**	**BRxD/Costs**	**Comment**
LAN	10,000,000	500	20,000	1,000 Mbps * 10 km
FTTH	15,000	150	100	15 Mbps * 1 km
SAN	60,000	1,000	60	3,000 Mbps * 20 m
Server	20,000	2,000	10	20,000 Mbps * 1 m

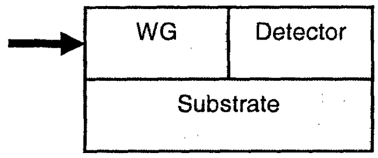
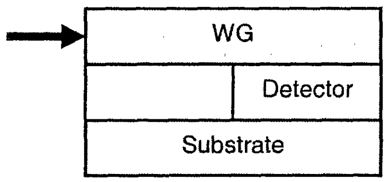
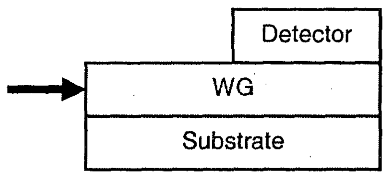
Other Transceiver Performance and Costs				
Segment	**Current BRxD (Mbps*m)**	**Current Costs (dollars)**	**BRxD/Costs**	**Comment**
LAN	200,000	10	20,000	20 Mbps * 10 km
FTTH	15,000	5	1,000	5 Mbps * 1 km
SAN	60,000	50	20	50 Mbps * 20 m
Server	20,000	100	50	5,000 Mbps * 1 m

Market Saturation							
Segment	**Initial Total Branches**	**Initial Optical Branches**	**Saturation # of Branches**	**Optical Share**	**Trx per Branch**	**Total Potential Transceivers**	**Initial Revenue Potential**
LAN	140,000	35,000	200,000	25%	6	840,000	420 million
FTTH	80 million	40,000	100 million	0.05%	2	160 million	24 billion
SAN	400,000	360,000	1 million	90%	12	4.8 million	4.8 billion
Server	10 million	25,000	20 million	0.25%	25	250 million	500 billion

Market Saturation Comments	
Segment	**Comments**
LAN	No real basis for this guess. A few thousand branches to serve a metro area, multiplied by a few metropolitan areas. Very similar to FTTH networks, but with a slightly higher bandwidth demand, leading to an estimate of 6 transceivers per branch. A couple more for added bandwidth and a couple more for added reliability.
FTTH	About 80% of homes have access to cable, telephone or some other form of broadband. There are about 100 million households in the US, giving 80 million for the initial branches, and 100 million to get to saturation. Optical serves very few homes today. Verizon's plan to role out service to 1 million customers still only amounts to 1%. There are two transceivers per branch. This depends on the network architecture and probably would be something a little less than 1 per branch.
SAN	SANs are common in urban areas and commercial centers. If there are 10 major cities in the US, and each has on the order of 10,000, we get 100,000 SANs. SANs can be quite big, but the trend has been toward smaller "mom and pop" operations[86]. The average number of connections (or branches) per SAN might be around 4. 12 connections stems from the multiple redundant lines necessary to provide reliability and security[87].
Server	Estimate comes from presentation by Jeff Kash at the October 10 NGT TWG. 10 million is about IBM's holdings. Today, optical is used in almost no server interconnects. The estimate of a saturation of 20 million says that one might not expect too many new servers, rather an enormous increase in the bandwidth demand per server interconnections. The estimate of 25 transceivers per interconnect also comes from Jeff Kash's presentation and is a function of the bandwidth requirements of servers and the capabilities of today's transceivers.

[86] Source: Interview with Michael Feldstein from EMC. Mr. Feldstein specializes in SAN installations.
[87] Also From Conversation with Mr. Feldstein

Appendix IV: Comparison of Coupling Techniques

Coupling Options			
Type of Couple	Schematic of Couple	Advantage	Disadvantage
Butt Couple		• High coupling efficiency • Short detector • Low capacitance	• Re-growth • Low interface quality • Alignment difficult
Evanescent Couple A		• High interface quality	• Re-growth • Long detector • High capacitance
Evanescent Couple B		• No re-growth • High interface quality	• Long detector • High capacitance