The Evolution and Adoption of Optical Interconnect Cables

by

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Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of
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ABSTRACT

Optical technologies are now ubiquitous in data communication, telecommunication, and computing networks for transmission distances beyond a few meters. The use of optical to transmit voice communication has changed the nature of the industry and been driving photonic component innovation for the past 30 years. Never before has the world demanded more data to run its collective everyday lives. Technological lifecycles have shortened and to keep pace with the rapidly increasing quantities and demands of data needs, firms are placing a stronger emphasis on the development of new technologies to replace old ones. The use of electrical interconnects has been the workhorse for data transmission for over a century and a new technology is poised to succeed it. Due to the limitation of current transmission medium, an adoption of new technology is inevitable and the question is when and what are the drivers? In this thesis, an analysis will be conducted to examine the adoption of optical interconnect cables in different lengths using different costs of new technology. These results will be used to understand how each driver affects the overall adoption of optical interconnect cables, the limitation of adoption, and a potential timeline of adoption for each length examined.

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1. – Introduction

1.1 – Statement of Objective and Motivation

Never before has the world demanded more data to run its collective everyday lives. Technological lifecycles have shortened and to keep pace with the rapidly increasing quantities and demands of data needs, firms are placing a stronger emphasis on the development of new technologies to replace old ones. The use of electrical interconnects has been the workhorse for data transmission for over a century and a new technology is poised to succeed it. That technology is the use of optical fiber or waveguide interconnects that can more effectively transmit higher quantities of data via a means of light. Due to the limitation of current transmission medium, an adoption of new technology is inevitable and the question is when and what are the drivers? In this thesis, an analysis will be conducted to examine the adoption of optical interconnect cables in different lengths using different costs of new technology. These results will be used to understand how each driver affects the overall adoption of optical interconnect cables, the limitation of adoption, and a potential timeline of adoption.

1.2 – Background

Optical technologies are now ubiquitous in data communication, telecommunication, and computing networks for transmission distances beyond a few meters. The use of optical to transmit voice communication has changed the nature of the industry and been driving photonic component innovation for the past 30 years. These optical carriers became commodities in long- and medium-distance services. As our everyday lives becomes more technology- and internet- oriented, the electrical performance at each level of the interconnection hierarchy as shown in Figure 1 will be challenged [1]. The bandwidth x distance performance metric at each level will eventually become the bottleneck of the overall system, leading to development and implantation of optical technologies closer to edge of the core.

Due to fiber optic's lower loss, higher speed, and longer reach, it has replaced copper in long distance transmission (greater than1km), which is presented in Figure 1. This is seen in the prevalent use of single mode fiber, in telephone and campus networks, and multimode (MM) fiber in data centers globally. Optical technologies are now seriously considered for distances as short as 5cm [2]. However, this thesis will concentrate on distances less than 1 meter, at the edge of wiring board.

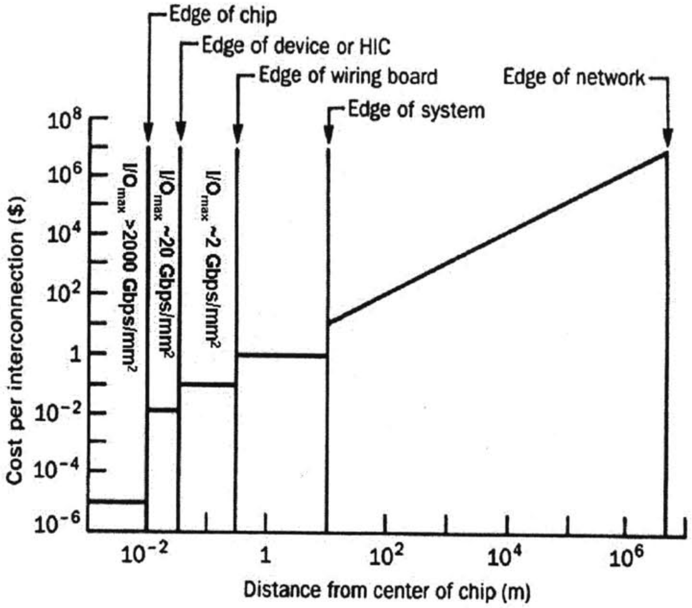


Figure 1: Required cost evolution of optical interconnects

As shown in Figure 2, the distance-bandwidth product of Ethernet communication over optical fiber is growing faster than signals traveling over twisted pair copper. This implies the system scaling will be limited by local electronic bandwidth availability rather than by extended interconnect bandwidth. Electronic-photonic convergence in electronic packaging has the potential of relieving the I/O bottleneck by allowing denser and longer interconnections between system elements. Table 1 shows a timeline from 1990 to 2030 that examines and forecasts the convergence of electronic-photonic.

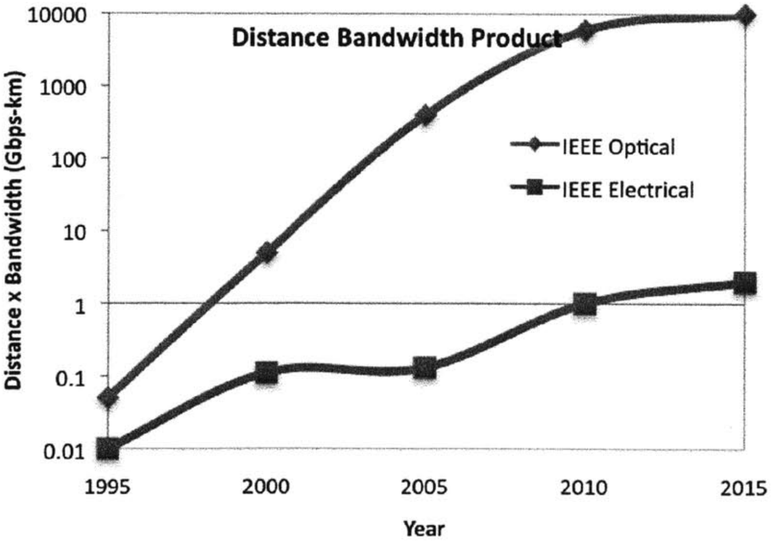
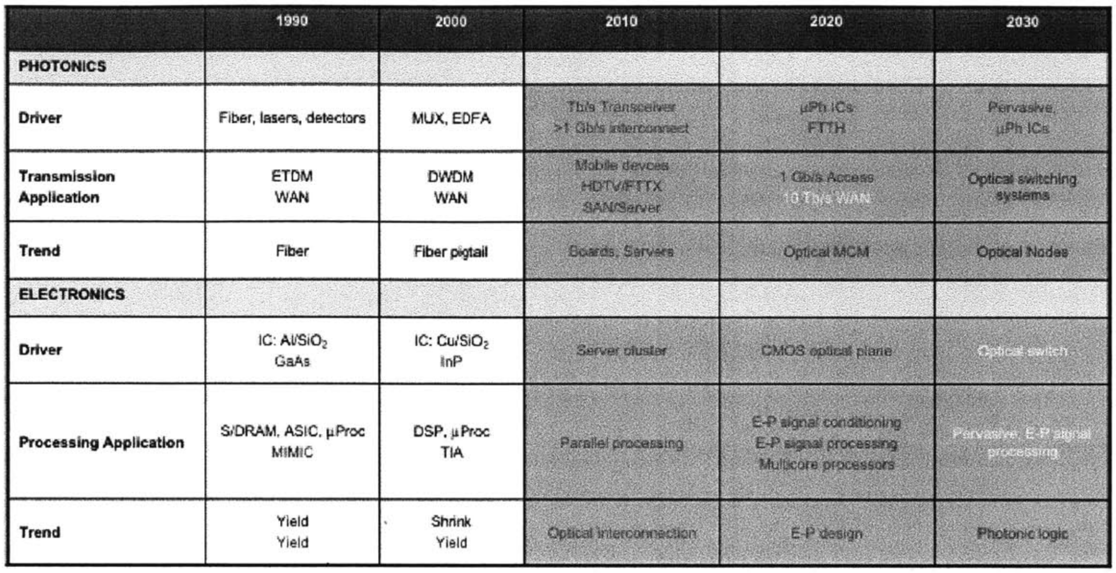


Figure 2: Distance-bandwidth product for optical fiber and electrical interconnect

Table 1: Evolution of some key communication technologies [3]



	1990	2000	2010	2020	2030
PHOTONICS					
Driver	Fiber, lasers, detectors	MUX, EDFA	Tb/s Transceiver >1 Gb/s interconnect	µPh ICs FTTH	Pervasive, µPh ICs
Transmission Application	ETDM WAN	DWDM WAN	Mobile devices HDTV/FTTX SAN/Server	1 Gb/s Access 10 Tb/s WAN	Optical switching systems
Trend	Fiber	Fiber pigtail	Boards, Servers	Optical MCM	Optical Nodes
ELECTRONICS					
Driver	IC: Al/SiO$_2$ GaAs	IC: Cu/SiO$_2$ InP	Server cluster	CMOS optical plane	Optical switch
Processing Application	S/DRAM, ASIC, µProc MIMIC	DSP, µProc TIA	Parallel processing	E-P signal conditioning E-P signal processing Multicore processors	Pervasive, E-P signal processing
Trend	Yield Yield	Shrink Yield	Optical interconnection	E-P design	Photonic logic

Communication technology has advanced rapidly through the first half of 20th century. The data communication industry has evolved from dual open space wires to hundreds of open space wires. The number of open lines routed along the city streets and into major office buildings eventually approached space limit and drove the development of twisted pair insulated copper wires. Although twisted coppers addressed the issues with space, it did not solve the fundamental problems of copper. A particular important factor is its extremely high distance x bandwidth penalty that is data rate dependent. Because of this distance x bandwidth limitation, both long distance and high data rate transmission have been replaced by optical fiber waveguides [4]. Table 2 illustrates the limitation of copper cables assuming a budget of 20dB and a transmission rate of 1bit per Hz. It is evident that the distance data is able to transmit decreases as data rate increases. From the table, one can see that the attenuation loss increases 83% from 7dBm to 40dBm when data rate grows from 1GHz to 10GHz.

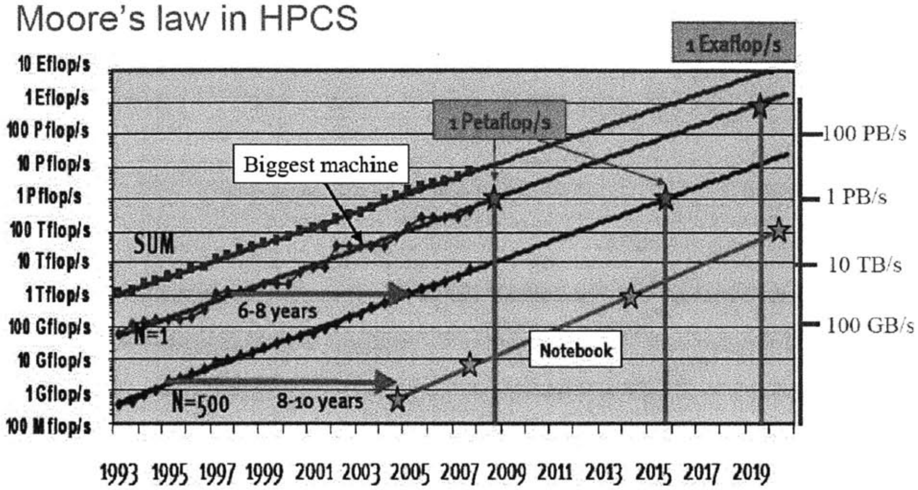
Table 2: Limit of Copper In FR-4 Circuit Boards as a Data Transmission Media [2]

Frequency & data rate @ 1 bit/cycle	Distance in meters for 20 dB attenuation	Distance X Bandwidth, Hz-Meters	Energy per bit in pJ/bit (1 volt into 50 ohms all cases)
<100MHz	Practically unlimited	$<1.5 \times 10^9$	>200
100MHz	20/1.3 = ~15	1.5×10^9	200
1GHz	20/6.7 = ~3	3.0×10^9	20
10GHz	20/40 = ~ 0.5	5.0×10^9	2
100GHz	20/310= ~0.06	6.0×10^9	0.2

Optical systems have some inherent advantages over electrical systems, especially in high speed and large bandwidth applications. The advantages include lower attenuation, lower cross talk, lower dispersion, higher bandwidth, higher density and immunity to electromagnetic interference (EMI) [5]. Well-designed optical fiber waveguides are capable of achieving negligible loss, even at high data rates. In contrast, the limit of distance x bandwidth for electrical interconnects is mainly dominated by electrical resistance and energy losses of the material. These losses are further enhanced by skin effect and the tan delta losses as data rate and frequencies increase. As a result of these losses, signal attenuates as it propagates through the medium. To combat signal attenuation, a repeater is placed periodically along the transmission lines. When the electrical wires get closer together, a variety of challenges emerge such as resistive-capacitive (RC) delay, electro migration resistance, and heat dissipation exacerbated by increased chip power [6].

This presents another opportunity for optical technology as it can carry more data in a single channel thereby reducing the number of channels required. The minimum spacing between optical fibers is an order of magnitude shorter than electrical systems, which translates to a large savings in device size, cost and power. Though the demand for data is increasing, the size of devices is decreasing, which results in a density bottleneck. Consequently, optical fiber waveguides can provide longer reach, higher data rate, higher bandwidth, higher density and lower power consumption.

Electronic transmission over copper is currently limited to distances under 100 meters for data rate exceeding 1Gbps and is continuing to shrink as data rates increase [6]. Internet growth and consumers demanding more immediate access to data have driven the demand for higher data rate. As the projection of data rates continues to increase (Figure 3), there is a rising priority to replace the copper lines with more efficient materials, such as optics, to accommodate more data at lower power for computing and communication applications. It has become increasingly attractive for medium distance (such as business access, campuses, and data centers) and moderate data rate transmission to adopt optical fiber waveguides. Performance improvements should come from new architectures (enabled by technologies such as photonic interconnection, packaging, and integration) and better operating systems rather than incremental reduction of transistor size.



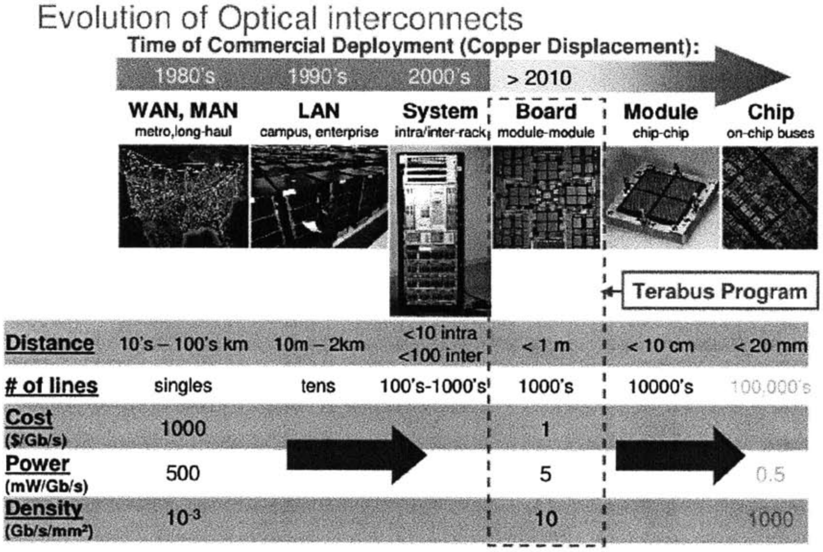
After Jack Dongarra, top500.org

Figure 3: Evolution of computer system capacity [7]

The emerging high volume applications in consumer and meter scale systems (Figure 4) will require faster, higher data capacity in smaller sizes at a lower cost and power optical links. However, optical elements continue to struggle to penetrate consumer and meter scale markets due to three fundamental issues: photonics are expensive, large, and application specific. These characteristics, which are primarily due to difficulties in packaging and interconnecting optical elements, must be eliminated through fundamental design changes if photonics are to provide a solution to the looming interconnection problems in future systems.

The high cost of optical interconnects is also a result of a lack of industry standardization. During the boom of telecommunication industry, there was excessive capital available for companies to develop new infrastructure and networks. As a result of little competition, each company developed its own optical technologies, leading to a fragmented industry with customized products [5]. To date, there are variety of form factors for optical packages and many different types of components and manufacturing processes for each form factor. Cost efficient mass production is difficult to accomplish because companies are reticent to give up their "leading" optical technologies.

Other difficulties of displacing copper with optical include risks of implementing new technology, both economic and technological risks; lack of suitable infrastructure or backward compatibility of both software and hardware to manage and support new technology; lack of supply support, especially in early stages; and electrical industry legacy [8]. Since both the technologies and infrastructures are well established for copper in the meter-scale interconnection, optical technologies face tough resistance. Culturally, the big copper players are unwilling to spend more capital and resources to replace the existing platforms. In addition, the general acceptance of the capabilities of electrical interconnect is widely accepted and well understood by the consumers, adopting optical will be perceived as an additional risks.



	1980's	1990's	2000's	> 2010		
	WAN, MAN metro,long-haul	**LAN** campus, enterprise	**System** intra/inter-rack	**Board** module-module	**Module** chip-chip	**Chip** on-chip buses
Distance	10's – 100's km	10m – 2km	<10 intra <100 inter	< 1 m	< 10 cm	< 20 mm
# of lines	singles	tens	100's-1000's	1000's	10000's	100,000's
Cost ($/Gb/s)	1000			1		
Power (mW/Gb/s)	500			5		0.5
Density (Gb/s/mm²)	10^{-3}			10		1000

Figure 4: Evolution of Interconnects and their performance requirements [9]

1.3 – Figure of Merit (FOM)

The focal design parameter is maximizing distance by bandwidth per installed dollar. For the past decade, the technology requirement for the cost performance market, such as computer (PC, notebook, and netbook), blade server, processors, game consoles, and small routers and servers, has been driving the package technology innovation. The issues for this market have always been speed, heat dissipation, reliability, and cost. However, with the rising mobile markets, such as cell phones, smart phones, portable personal and video devices, and tablets, form factors (size and device shape), weight, and time to market have become increasing important. Due to these emerging demand, the industry have agreed on a new figure of merit for interconnects become is described as

$$FOM = \frac{R \times G}{A \times \$ \times J} \qquad \text{Equation 1}$$

Where R is the reach in meters, G is the data rate through the link in Gbps, A is the maximum area of the interface per link in m^2, \$ is the cost in dollars per link, and J is the energy required in Joules or Watts per 1 Gpbs data transmitted. Therefore the FOM has a unit of Gbps/m-\$-W.

1.3.1 – Attenuation and Dispersion

In an optical system, signal integrity is the most basic issue in interconnections and it is affected by two major optical characteristics: attenuation and dispersion. Attenuation is dependent of both bit rate and wavelength and it is examined as power loss. Because of attenuation, received signal is weakened and is subject to noise interference. Figure 5 validates the wavelength dependency of attenuation, though it is important to note that SM silica-glass fiber always dominates MM fibers with lower attenuation coefficient at any given wavelength.

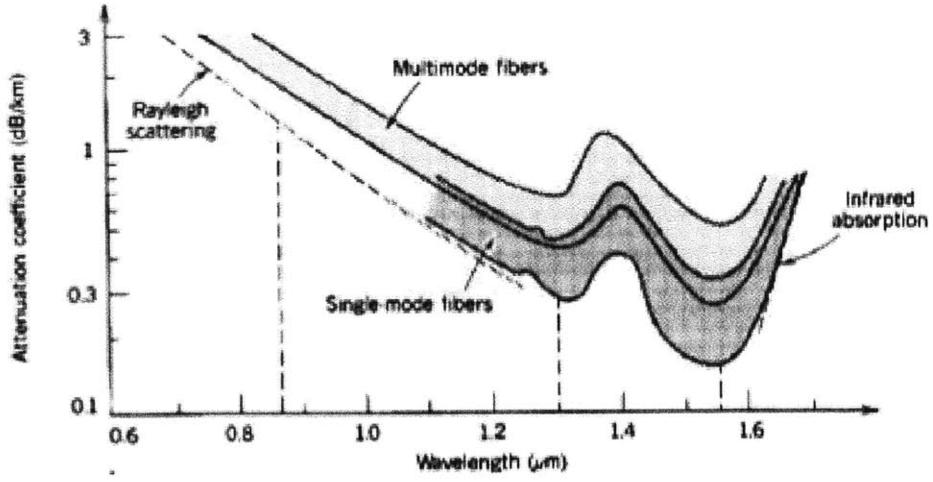


Figure 5: Wavelength dependence of attenuation coefficient of silica-glass fibers [10]

Moreover, dispersion also contributes to the weakened signal. Dispersion causes the energy light pulse to spread in time, widening the pulse width as the signal transverses down the channel. The spreading creates two issues affecting signal integrity. The first is that is a higher signal to noise ratio and the second is a higher bit error rate. Because the pulse is spread out, it reduces the peak signal strength and leads to higher signal to noise ratio. Moreover, it also increases the probability of two pulse overlapping, which leads higher bit error ratio [11]. Figure 6 represents the two different regimes and limiting factors. When the received power is weaker than the received power sensitivity, the system falls in the attenuation-limited regime. On the other hand, if the received pulse becomes greater than bit time, the system rests in the dispersion-limited regime. While the main design parameter is the product of data rate and distance, depending on the application (longer reach or higher data rate), the device design will differ. A general rule of thumb of design rule is to give the power received a margin (6dB) above the receiver sensitivity while keeping the maximum allowed pulse width below a fraction (1/4) of the bit time interval. Figure 7 shows the maximum distance at given bit rates for four most commonly used fiber materials that operate in dispersion-limited regime.

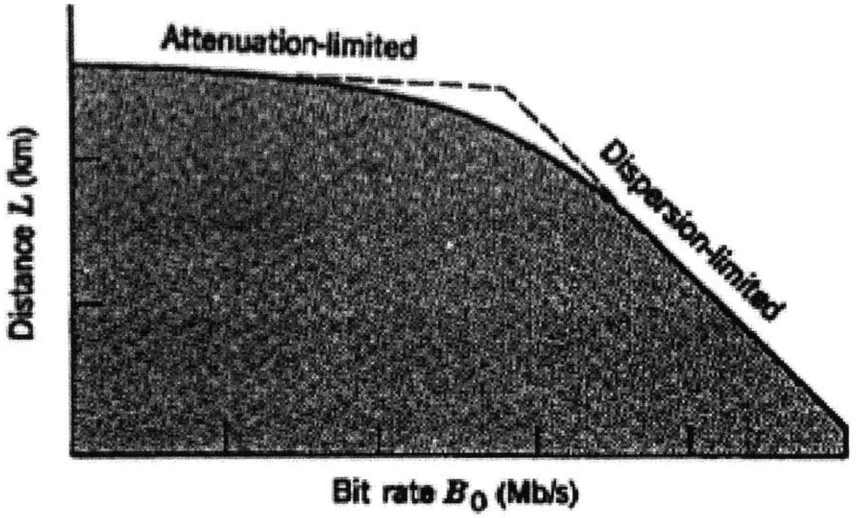


Figure 6: The relation between distance and bid rate for interconnection optimization [10]

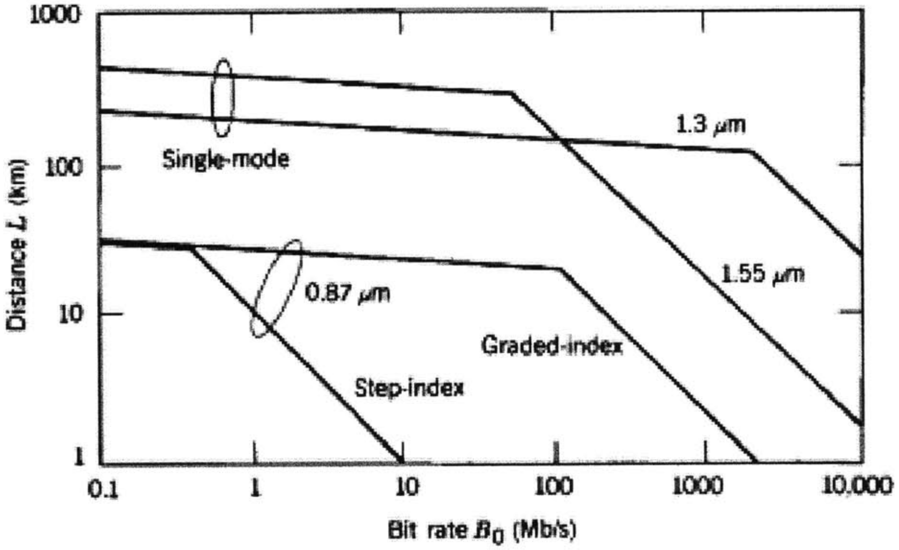


Figure 7: The relation between distance and bid rate for four different fiber materials [10]

1.3.2 – Single Mode vs. Multimode

Figure 8 shows the state of the art for data transmission utilizing various technologies in early 2011 for various data rates and distances. Depending on application, the figure illustrates each technology's limits and feasible combinations of distance and bandwidth.

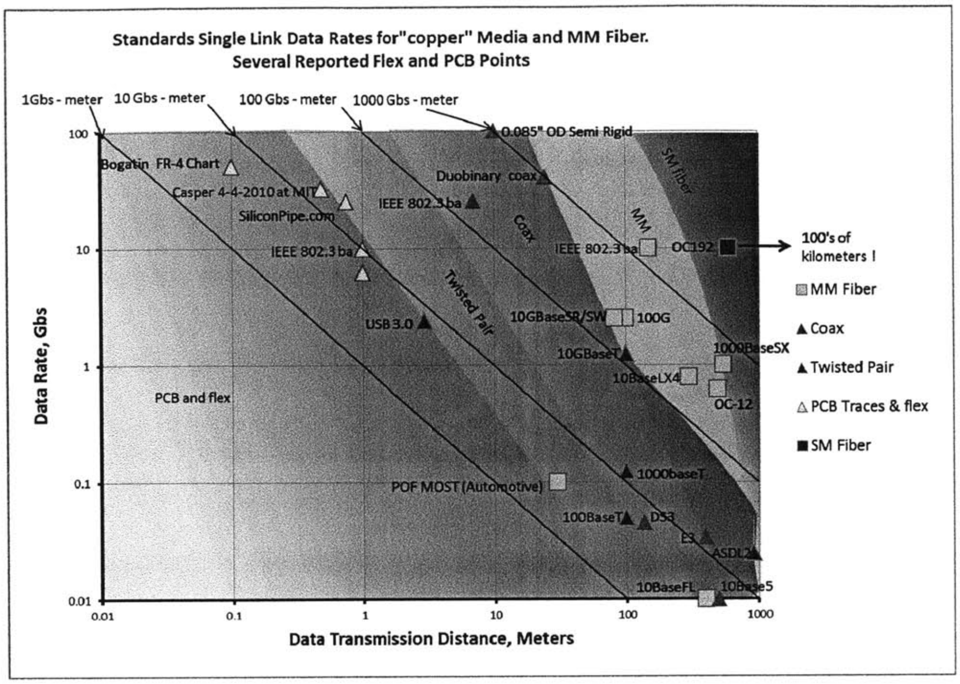


Figure 8: Standards single link data rates for optical and electrical [12]

According to the Figure 8, optical technologies have already replaced electrical in several areas. When data rates are 10Gbps or higher at distances over 10 meters or when data rates are 25Gbps or higher at distances shorter than 1 meter, optical technologies are the medium of preference.

The evolution of interconnects will continue to migrate from electrical to optical as data rate increases. It is important to note that when talking about optical technologies replacing copper, it implies that copper is being replaced by multimode (MM) optical fiber. However, one major issue with MM is high dispersion loss. The large core diameter of MM fibers[1] allows light to travel in different directions and results variation of path length and high dispersion loss. In order to maintain data integrity, a resonator is placed to compensate propagation losses [13]. The longer the fiber the greater the dispersion, causing signals to overlap and unreadable. As a result, more power is required to compensate such loss. The current MM technology is able to support a distance-bandwidth product of 1Gbps x 1km. Beyond that, single mode (SM) fiber optics will be more practical.

Another tradeoff that is not represented in Figure 6 is the device size. In the short distance interconnections, the device is expected to have more function at a smaller size. Therefore the size of the

---

[1] Usually 125 microns with a 50-62.5 micron inner core.

cross-section connectors becomes a concern when scaling the MM fibers. Replacing copper wires with MM fibers allows transmission over longer distances due to reduced loss while providing the same bandwidth density. Scaling of data rate is achieved by increasing the number of multimode fibers. Problems arise as the number of fibers continued to increase as the fiber cross-section for the connector will eventually exceed the size of the port.

On the other hand, the small core diameters of SM fibers allow light to travel in only one direction, eliminating dispersion problem. Moreover, SM fibers with wavelength division multiplexing (WDM) provide a higher bandwidth while maintaining a constant cross-section. WDM allows many optical channels to pass through the same cross sectional area, thus adding data capacity while keeping the cross-section constant. As a result, SM optical fibers can support distance-bandwidth product of over 1000Tbps x 1km data transmission [14]. Therefore, adoption of MM and SM optical waveguides have realized higher bandwidth transmission for board-to-board and chip-to-chip interconnect. Figure 9 demonstrates the evolution of transmission medium. As data rate or modulation frequency increase, the evolution of interconnects will not only move from electrical to optical but, more specifically, from electrical to MM fibers and eventually to SM fibers.

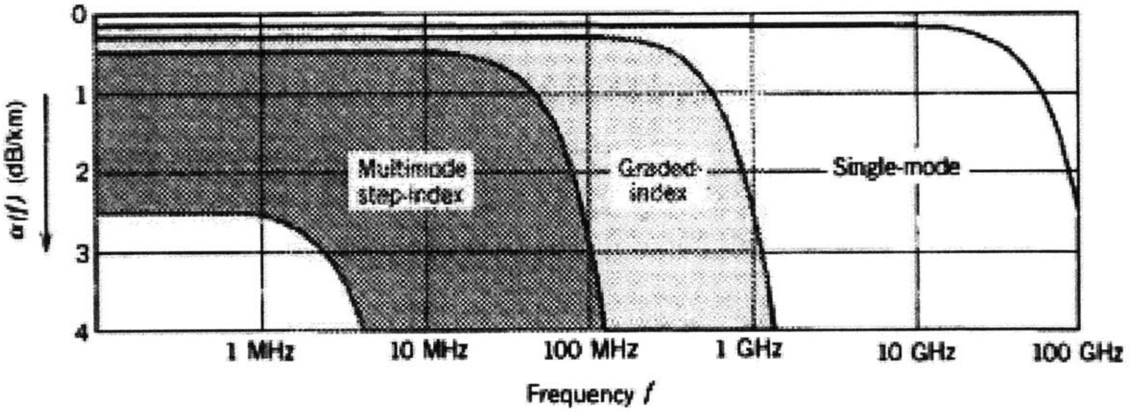
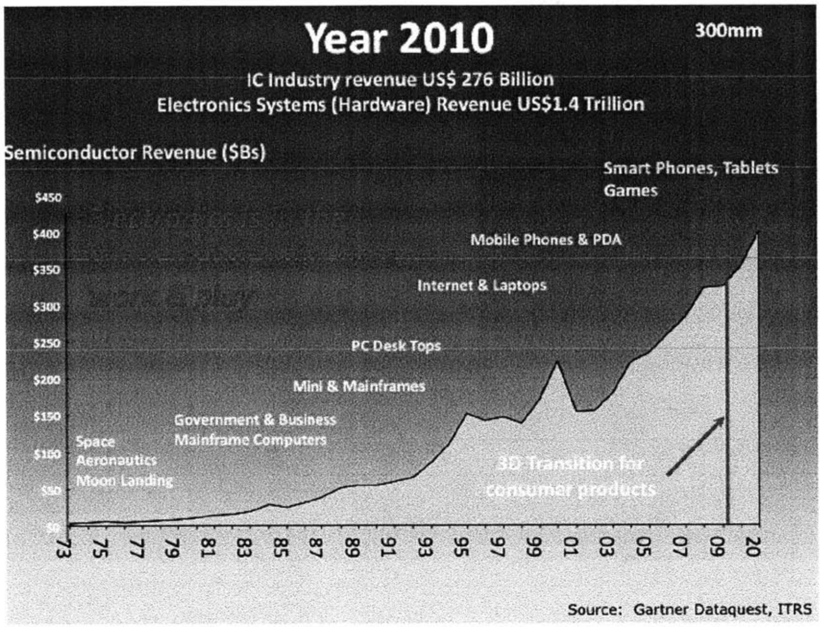


Figure 9: Typical attenuation coefficients (dB/km) as a function of the modulation frequency [10]

1.4 – Market Sizing

Requirements ranges from 1 Gbps, transport in cell phones, to 10 Gbps, transport in home entertainment, to 100 Gbps, transport in home computers, gaming consoles, and communication clusters, and up to 100,000 Gbps in super computer systems have led to an unprecedented market opportunity [15].

In today's information technology society, the use of integrated circuits (IC) (whether optical-electronics or pure electrical) is inevitable in our daily lives. Applications range from large and immobile data centers to small and mobile devices. At the Spring MPhC Meeting, Bill Bottoms, from ITRS, indicated that IC industry revenue in 2010 was approximately US$276 billion and is expected to continue to grow in the future (Figure 10). The projected industry revenue will increase by more than 50% in the next decade, mainly driven by consumer demand in smart phones, tablets, and gaming systems.



Source: Gartner Dataquest, ITRS

Figure 10: ITRS industry revenue projection through 2020 [16]

Figure 10 indicates the total electrical systems hardware revenue is $1.4 trillion. The main market driver for interconnects is derived from portable consumer electronics products including cell phone, smart phone, tablets and digital cameras. From 2008 to 2009, the portable consumer device market declined by 7.3% to $290 billion in 2009. This decline was due to the financial crisis in 2009, recovery is expected in 2010 and is estimated to grow at 5.5% per year through 2015 as show in Figure 11 [17].

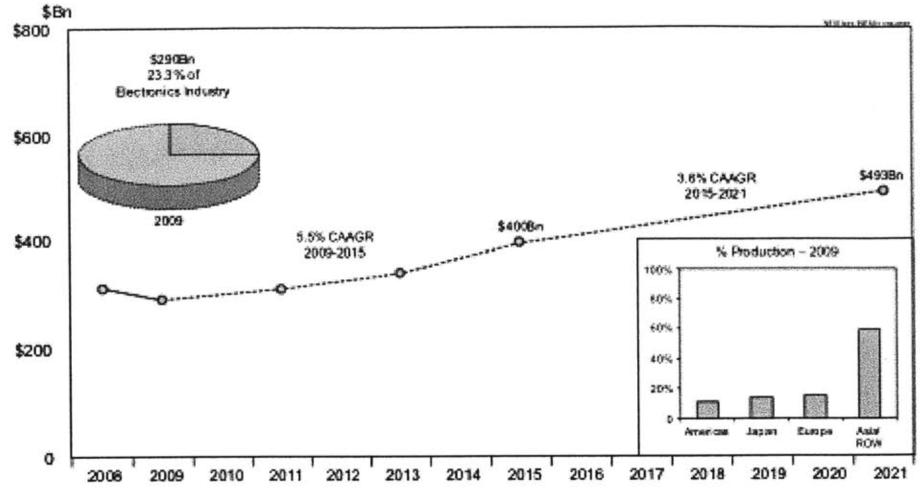


Figure 11: Portable consumer electronics market projection through 2021

Another major driver is the growth in computer and office equipment sector, which includes personal computers, high performance computers, computer peripherals, storage systems, and office equipment. Figure 12 shows the iNEMI's market projection of this sector. The computer and office equipment totaled $411billion in 2009, accounting for 33% of the total market. It is expected to grow at an average rate of 3.3% per year to reach $500billion in 2015.

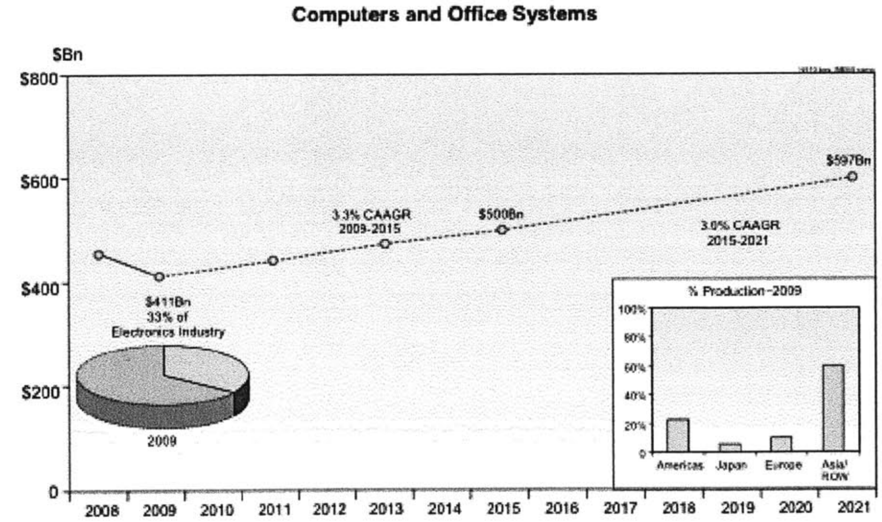


Figure 12: Office and computers equipments market projection through 2021

Along with the growth of the consumer electronics and computer and office equipments markets, the interconnect industry is also growing rapidly. As shown in Figure 13, the electronic connectors market without cable assemblies has achieved total revenue of $109 billion worldwide and will grow by 23.5% to $135 billion in 2010.

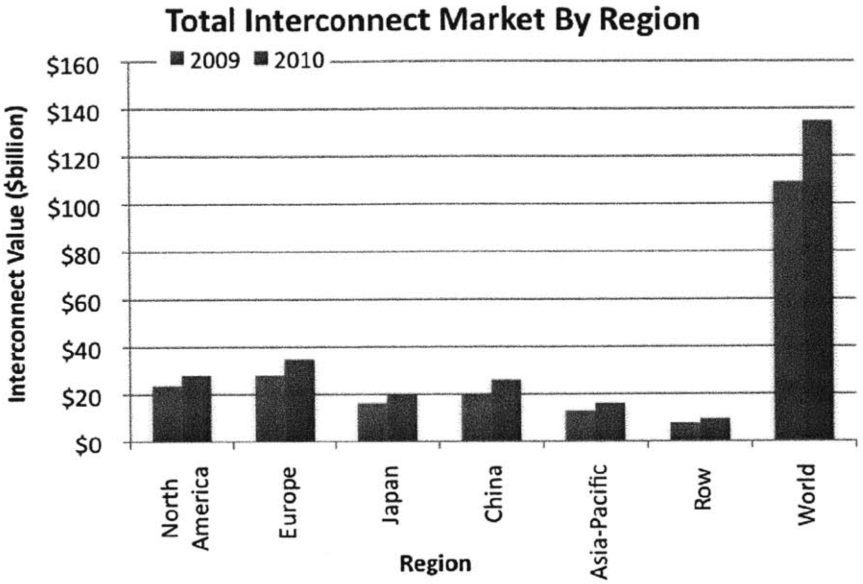


Figure 13: 2009 and 2010 Total Interconnect Market by Region [18]

Compared to hundreds of billions in the electrical interconnect market, the optical interconnects market is significantly smaller. In 2004, the overall photonics component industry totaled $2.5 billion [19], which included interconnects and other components such as laser and LED. As data rate rises, optical interconnects continue to displace copper for shorter distance applications, from telecommunication distances of hundreds of km to on chip distances of a few millimeters, which are placed in consumer electronics including portable devices. This can be seen in Figure 14 wherethe optical interconnects market is $1.3 billion in 2010 and will almost triple to $3.5 billion in 2015.

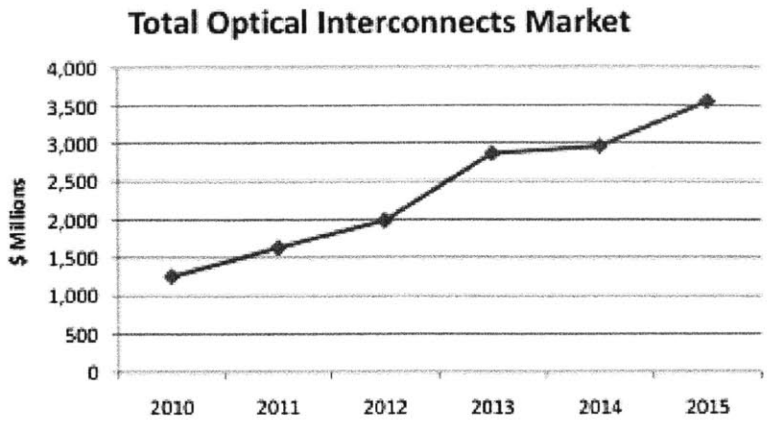


Figure 14: CIR projection of optical interconnects market [20]

Currently, the total addressable market (TAM) of optical interconnects is 10% of the total interconnect market. As data rate continues to increase, optical interconnects will be needed in shorter distance and will start taking portions of the electrical interconnect. In terms of the portable consumer electronics market, consumers are trending towards higher bandwidth for high-definition handheld displays and higher transmission speed between devices. This presents an opportunity for optical interconnects to be adopted in this market. Moreover, because camera image quality has increased dramatically in the past decade, the time it takes to transfer the file between devices also gets longer. Optical can provide a faster speed for higher quality and larger load of data transmission between devices, presenting another market opportunity. Smaller devices with longer battery life are two other important criteria in the portable device market. This offer another opportunity for optical because of its ability to reduce interconnect footprint and reduce power consumption.

In the office and computer equipments market segment, there is also a significant potential market opportunity for optical interconnects. Figure 15 illustrates the potential TAM for optical interconnects in higher performance computers. As the rise in bandwidth demand pushes optical closer to board, the potential market increases dramatically [21].

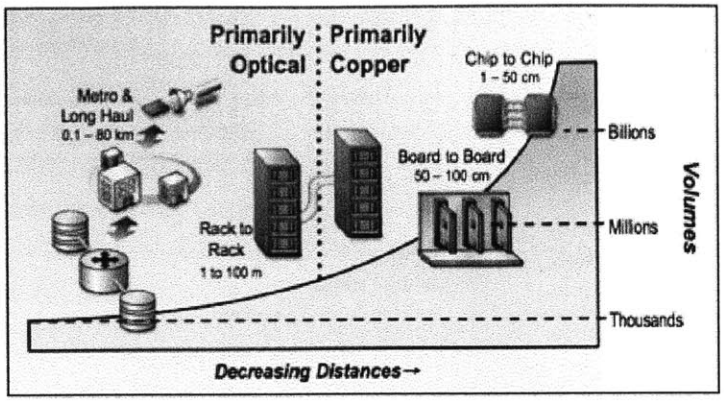


Figure 15: Potential optical interconnect volume in HPC

Figure 16 presents the optical and copper cost per Gbps transmission. At short distances, the cost of electrical cable is more attractive. As cable lengths increases, repeater is added to compensate losses, driving cost of using electrical cables higher than optical. The distance between repeaters also depends on the actual data rate. At higher data rates, loss is amplified due to a skin effect, thus shortening the distance between repeaters. As a result, the two cost lines in Figure 16 intersect at shorter cable length, which will also push the adoption timeline earlier.

Figure 17 is a cost comparison between copper and optical cables based on distance-bandwidth product. The tradeoff will be between data rate and distance. At 1Gbps, the crossover point is at around 180 meters and quickly drops to 10 meters when data rate is increased by an order of magnitude whereas at 40Gbps. The crossover point is at short as 0.1 meters.

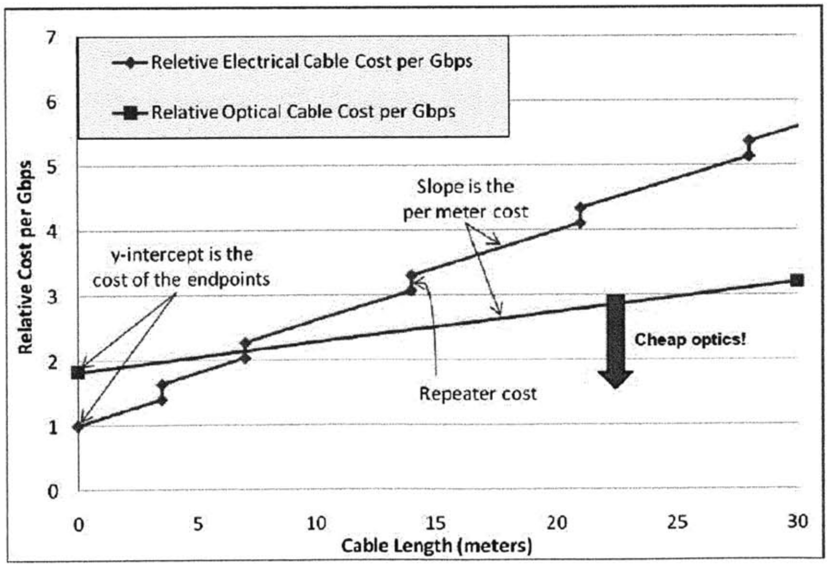
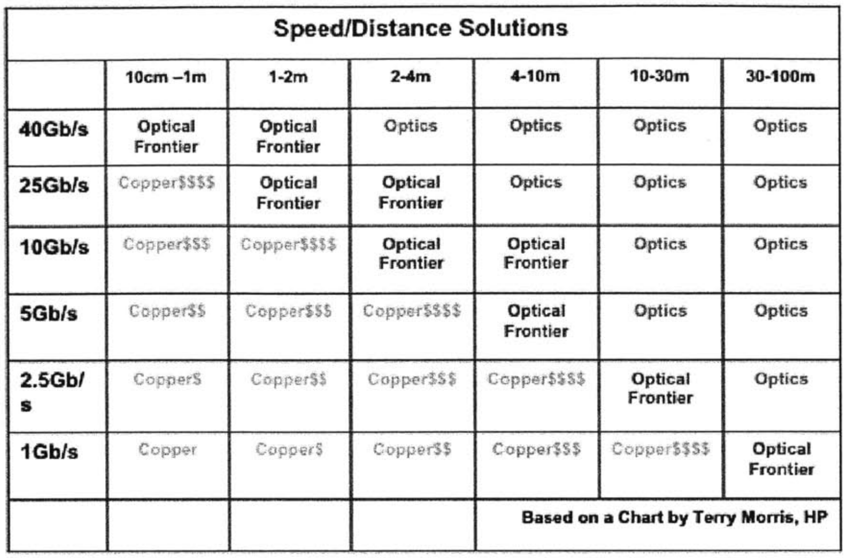


Figure 16: Cost of copper and optical per Gbps transmission with distance [2]



Speed/Distance Solutions

	10cm –1m	1-2m	2-4m	4-10m	10-30m	30-100m
40Gb/s	Optical Frontier	Optical Frontier	Optics	Optics	Optics	Optics
25Gb/s	Copper$$$$	Optical Frontier	Optical Frontier	Optics	Optics	Optics
10Gb/s	Copper$$$	Copper$$$$	Optical Frontier	Optical Frontier	Optics	Optics
5Gb/s	Copper$$	Copper$$$	Copper$$$$	Optical Frontier	Optics	Optics
2.5Gb/s	Copper$	Copper$$	Copper$$$	Copper$$$$	Optical Frontier	Optics
1Gb/s	Copper	Copper$	Copper$$	Copper$$$	Copper$$$$	Optical Frontier
				Based on a Chart by Terry Morris, HP		

Figure 17: Cost comparison between copper and optics by distance-bandwidth product [17]

2. –Evaluation Attributes

2.1 – Bandwidth

2.1.1 – Bandwidth Scaling

Scaling of the optical-electronics technologies has suggested a1cm interconnect length with a bit rate greater than 1Tbps at the chip level [1]. Originally, the main consideration of an interconnect was its performance in bandwidth x distance. However, over the last few decades, additional considerations have surfaced. The increasing demand for portable devices such as mobile phone, tablets, netbooks has sparked the need to consider for smaller sizes, lighter weight, and lower power consumption. The reduction of transistor size and utilization of parallelism have enhanced the performance of electronic circuits and enabled the industry to hold to Moore's law. However, the trend of processor frequency scaling has reached a plateau due to issues such as cooling and power densities. As the device size decreases along and signals increase in frequency, a higher electrical field shielding is required. Higher shielding can be achieved by increasing the minimum spacing between pin counts while keeping the overall device size constant. As a result, either the pin count needs to be reduced or the area connecting the pin count to board must be decreased in order to continue the trend of both reducing size and increasing data rate.

Despite tremendous improvements in electronic capabilities in the past 50 years, two issues that remain are conventional electrical interconnects are resistive-capacitive (RC) delay and increasing power dissipation with increasing data rate. RC delay is an issue because it hinders further improvements in electronics IC speed. Thus, it is difficult to meet the rising bandwidth demand. As bit rates are projected to increase (Figure 3), the challenges facing conventional interconnects present new opportunities for photonics interconnects across the interconnect market.

While the desired data rate per I/O is projected to increase exponentially (Figure 3), the size of the devices is expected to decrease. As a result, I/O bandwidth density becomes an increasing concern. As a rule of thumb, the estimated data capacity is composed of memory bandwidth per instruction-cycle, data bandwidth between processors, and the I/O bandwidth requirement. Each of these are about 1Byte/FLOP, 0.1Byte/FLOP and 0.05Byte/FLOP. Using this rule of thumb, the required I/O pins on a chip will exceed 10,000 with the assumption of 4 instructions per cycle at a clock frequency of 3GHz and I/O bandwidth of 10Gbps. This is well over the limit of available pins for 128 cores on a 400mm^2 die. Therefore, *bandwidth density is the key limiting parameter for system scaling* [22].

2.1.2 – Bandwidth Density

Bandwidth density is a key limiting parameter for system scaling and is driven by the increasing I/O requirements of ever more powerful processing systems.

Optical interconnects are utilized when data transport between system elements is more effective with optical links than with electrical links. Electrical-optical-electrical (E-O-E) interfaces are placed between optical and electrical devices. E-O-E interfaces convert electrical signal to optical for data transmission and back to electrical signal for data processing. These point-to-point links may include multiplexing of the source signals to take advantage of the optical transport properties. As required bandwidth scaled beyond a single fiber performance, multiplexing or multiple channels will be needed. The three most common multiplexing methods utilize electrical Time Domain Multiplexing (TDM), optical Wavelength Domain Multiplexing (WDM), or physical Space Domain Multiplexing (SDM). Figure 18 demonstrates how a WDM system works, and shows that the bandwidth can be scaled linearly. According to International Technology Roadmap for Semiconductors (ITRS) 2010 projection [23], the required bandwidth density will grow by a factor of 4. One of the major advantages of multiplexing is its ability to provide higher bandwidth without increasing the actual number of channel counts, thus leading to higher bandwidth density.

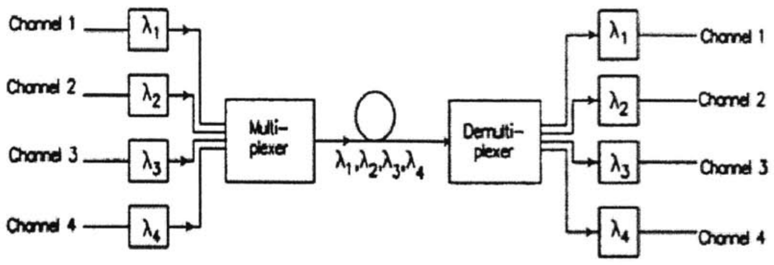


Figure 18: Schematic of point-to-point WDM system. Total capacity is defined as bit rate (Gbps) per channel x the number of channels ($m(l_m)$)

The increasing demands of bandwidth will drive the transition from electrical to optical signaling for future meter scale compute systems. As mention previous section, there is a minimum required spacing between the pitches due to electrical shielding. With device size shirking and data rate rising, either the pitch count needs to be reduced or the pitch size needs to be reduced. Figure 19 shows the contact pitch in millimeter for various electrical interconnect methods and applications projected by ITRS. Since there is little change in the dimension of the pitches, the change in bandwidth density will also be limited. This will eventually become the bottleneck of I/O scaling in the future system.

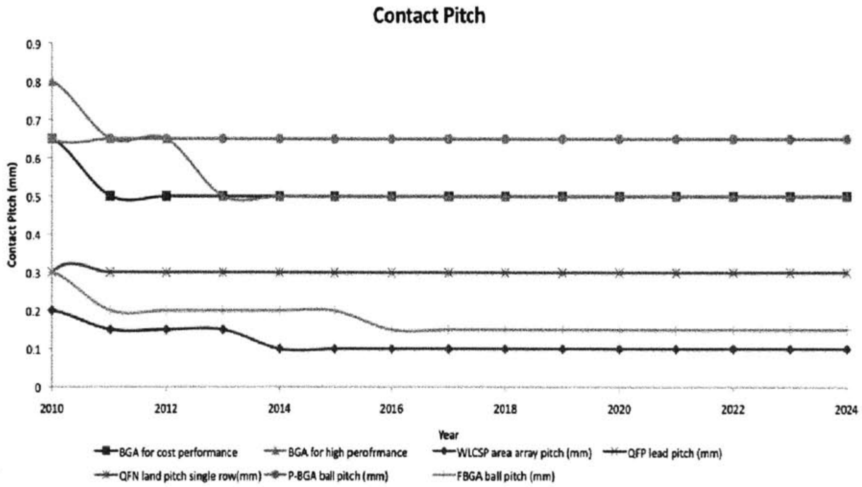


Figure 19: ITRS projection of contact pitch size [23]

2.1.3 – Definition of Bandwidth Density

In order to understand the analysis, bandwidth density must be specified. There are different measures of bandwidth density: contact bandwidth density, transport bandwidth density, and escape bandwidth density. Figure 20 presents a graphic definition of these bandwidth densities. Each will be further described in the following sections.

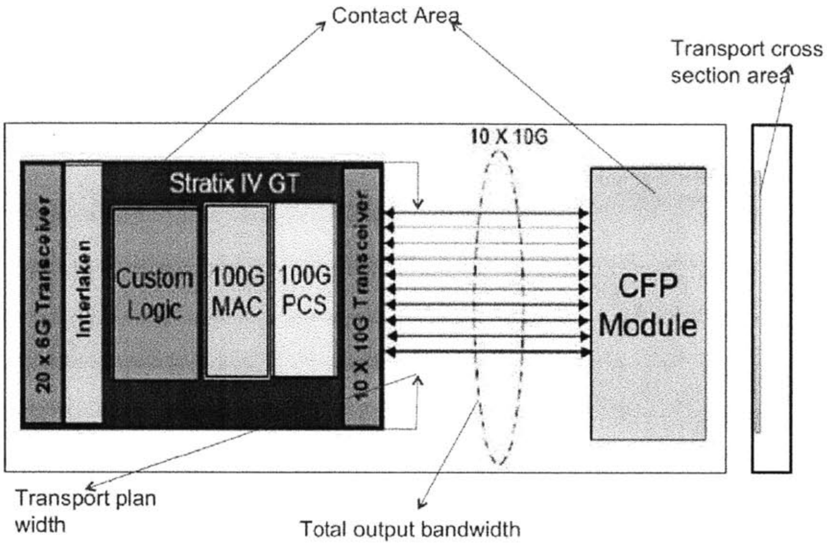


Figure 20: Graphical description of bandwidth density [24]

2.1.3.1– Contact Bandwidth Density

Contact bandwidth density is defined as aggregate bandwidth or total output bandwidth divided by the surface area between two components. For example, the contact bandwidth density between a ball grid array (BGA) package and the underlying printer circuit board (PCB) is equal to the bandwidth at that interface divided by the contacted surface area. It should be noted that the contact bandwidth density for short links is measured in Gbps/mm^2. Since it depends on surface area, contact bandwidth density is unaffected by the number of signal layers.

2.1.3.2– Transport Bandwidth Density

Transport bandwidth density is defined as bandwidth connecting two regions divided by the width of the connection. For example, the transport bandwidth density of a data bus between a CPU and memory is equal to the bandwidth of that data bus at that interface divided by the plan-viewed width of that bus. In contrast to contact bandwidth density, transport density scales linearly with the number of signal layers and is measured in Gbps/mm.

2.1.3.3– Escape Bandwidth Density

At the device boundary, transport bandwidth density is also called escape bandwidth density. Escape bandwidth density defines the bandwidth allowed to cross the perimeter of the contact area and *determines the total bandwidth of the device.* The higher the transport density, the higher the total device bandwidth and it must scale non-linearly with contact density to enable full escape bandwidth. Given equal total bandwidth device bandwidth, the required escape bandwidth density increases with decreasing device size because the area width of the connection is smaller.

2.1.4 – Projected Bandwidth

It is evident that over the last ten years, the demand for greater bandwidth per end user has been increasing. The main drivers of this trend come from the rising demand for music and video downloads as shown by a reported 60% increase in music downloading from 2005 to 2006 [25]. The advent VoIP services, which require much greater bandwidth than text, email, or normal web-browsing has also contributed to an increased demand. . According to Organization for Economic Co-operation and Development (OECD) 2007's report, the projected available bandwidth per end user for different market segments is presented in Figure 21. Neilson's Law, a conservative estimate of bandwidth growth, predicted a 50% increase per year in an end user's available connection speed. Following Neilson's law, the expected bandwidth to the end users will reach 100Mbps in 2013 and 1Gbps in 2015. As indicated in Table 2, the maximum distance that a signal is able to travel in a copper cable is around 15 meters at 100Mbps while dropping to 3 meters at 1Gbps. With fgrater than 500 meters being the typical "last mile" distance between router boxes and homes, the industry can expect an increase in fiber optics deployment (such as FiOS) in 2013 and completely ultimately displace copper by 2015. By 2021, the projected data rate per uses will grow to 10Gbps. At this data rate, one should expect a wide spread of optical interconnects between the device edges to routers since copper will be limited at 50 centimeters. The continued increase in bandwidth not only furthers the need to adopt optical cable connections into home networks, but eventually to the computer core (ie. chip-to-chip connection). Figure 22 shows a modification of Figure 1, which includes a rough estimation of adoption timeline according to the bandwidth growth projection in this section.

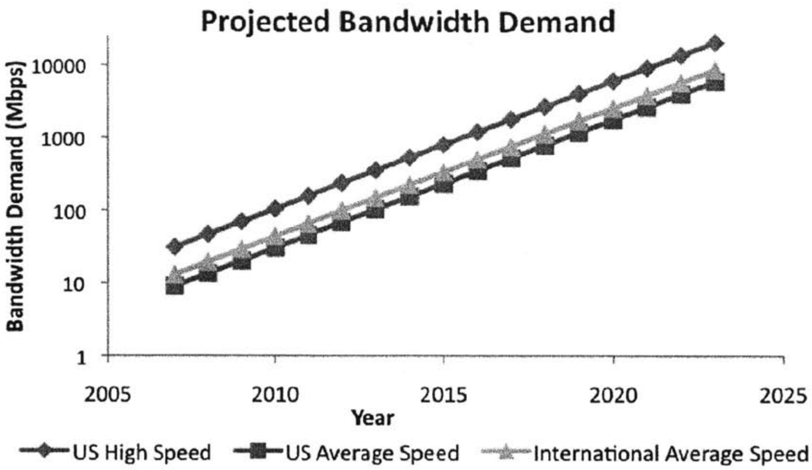


Figure 21: Projected bandwidth per end user

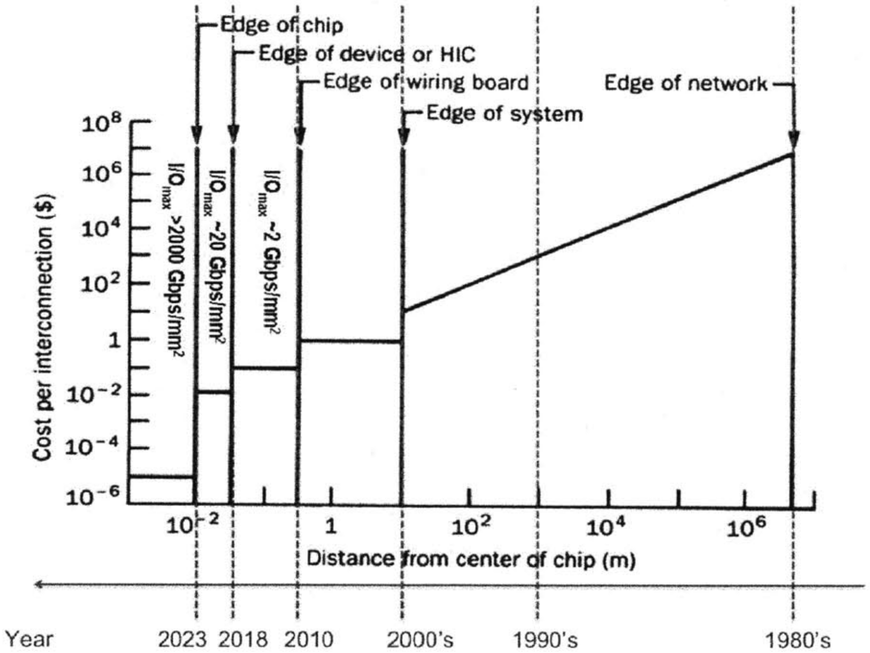


Figure 22: Projected adoption timlne based on bandwidth per end user

2.2 – Power

Energy consumption is the new performance metric that will drive electronic-photonic integration closer to the core.

Energy consumption has gotten tremendous amount of attention in the past decade because of global CO_2 emissions. With increasing data demand, power consumption in the interconnect will eventually become the bottleneck in the integrated circuit design. Energy consumption by information technology is already trending towards an unsustainable fraction of the world's electric power generation and is expected to increase with scaling. This has been, and continues to be, a major concern at the system level. An example is demonstrated by the power consumption of IP routers in Japan. Figure 23 presents Japanese projection of annual router's energy consumption. If the gross power generation in Japan stays constant at 2005's level, the total power consumed by routers alone will exceed the total power supply by 2020. One must remember that routers are not the only source of energy consumption. Considering other daily sources of energy consumption, the energy consumption of routers must scale down by factor of 3 or 4 in order to be sustainable [26].

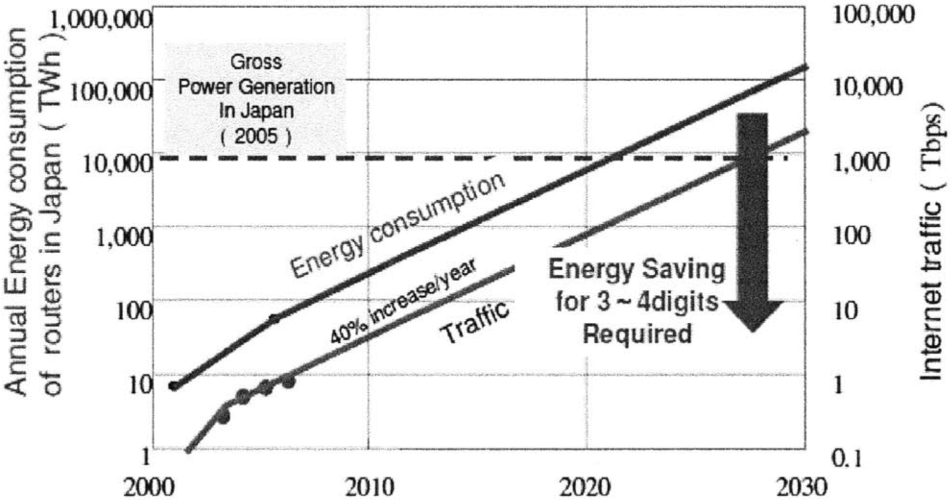


Figure 23: Projected energy consumption of routers in Japan

As the demands for higher-definition video contents and faster streaming capability by end users continue to grow, the performance of the processors is also expected to improve. Integrated circuit scaling has enabled such requirements in processing capability. Following the trend predicted by Moore's Law, the performance requirement is achieved by doubling the number of transistors on ICs every two years. The doubling of transistors will also cause power consumption to double every 18 months. As a result, not only is power consumption an issue in high-end routers, but also will eventually become an issue in the low-end in-home routers. In particular, it has also become an issue at the device and chip level.

At the chip level, heat dissipation is another major issue, and is particularly visible in microprocessor (MPU). As device size continues to shrink, the area available for heat dissipation also diminishes. Currently the performance of MPU is limited at 4GHz because the chip will not be able to dissipate additional heat when operating beyond 4GHz. A particular concern at the device level is the power consumption in portable device. In this sector, a major performance metric is the lifetime of single charged battery. Major industry players have identified the need to reduce the power consumption by at least an order of magnitude while still providing more functions [15].

In conclusion, it appears that energy consumption, rather than physical dimensions, will be the deciding factor that brings an end to conventional scaling.

2.2.1 – Data Rate Independent of Power Consumption

The electrical interconnects power consumption is greatly dependent on the length of the transmission and data rate. In electrical wires, power efficiency decreases with distance due to noise, skin effect, cross talk, and material resistance. As a result of high loss nature of copper wires, repeaters or signal amplifiers are installed in electrical interconnect to maintain signal integrity, which drives the overall power consumption up. For simplicity, one can assume that the power scales linearly with the number of transistors. Therefore, the advantage of optical interconnections consuming significant less power than electrical interconnections during data transmission is much more evident in higher data rates (Figure 24).

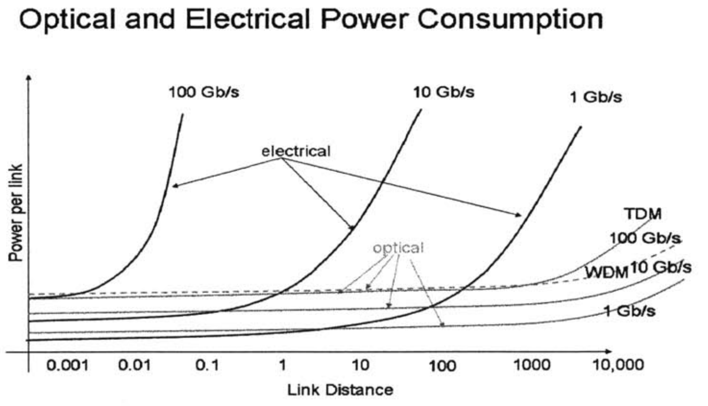


Figure 24: Schematic of the power dissipation of optical and electrical channels over distance and bit-rate

Contrary to electrical, optical interconnects power consumption is only slightly dependent of transmission length but is independent of data rate [27]. Although studies have shown that for a non-modulated optical transmission, a higher data rate results in more lasers being used, which drives the power consumption up. However, this is not the case for a modulated laser such as vertical cavity surface emitting laser (VCSEL). Since the current box-to-box optical interconnect market uses of arrays of VCSEL as its laser sources and is coupled into MM fibers, one can assume optical interconnects is not data dependent.

As shown in Figure 24, the power requirements needed for electrical links to maintain signal integrity rise with pre-emphasis and equalization during signal processing and the use of transmission lines. Typical commercial high-speed serial I/O links consume close to 20mW/Gbps while research-grade consumes around 10mW/Gbps [28]. The demand for higher data rates will push the figure inward, resulting in greater power consumption or shorter distance. Alternatively, as shown by the optical curves, the power to maintain signal integrity remains very flat in applications and typically only rise in large distances. In conclusion, because of the negligible frequency dependent loss, optical interconnects offer a promising solution to the I/O bandwidth and power issues.

2.2.2 – Dispersion as Power Penalty

Although optical technologies achieve higher power efficiency during data transmission, losses are incurred through other sources. The sources of energy loss are the power for driving lasers, transmission through the waveguides, connectors, couplers, and the reception of by the photodetectors. As mentioned in chapter 1, resonators are placed in the device periodically in order to compensate for the dispersion loss of MM fibers. The power required to drive these optical components increases with data rate and will consume substantially more power from the optical source than electronics, which offset the efficiency gained from data transmission. The most significant amongst these sources of energy loss is the slope efficiency (ratio of output power to pump power in the efficiency) of the laser light source. This effect naturally raises the overall amount of power dissipation locally and in the overall system. Table 3 presents the state of loss incurred in each component.

Table 3: Sources of optical interconnects inefficiency and estimate [29]

Transmission Loss (silica)	**0.3**	**dB/km**
Coupling Loss	0.1	dB
Laser Slope efficiency	50%	(0.3mW/0.5mA)
P_{min} at receiver [2]	0.025	mW
Connector/transition loss	0.5	dB

---

[2] Minimum power required for a signal to be detected by a 10 GHz receiver with the signal-to-noise ratio of 20 and 10^{-12} BER (bit error rate).

To account for the losses described above, one can treat dispersion as power penalties. If the device is operating at attenuation-limited regime indicated in Figure 6, the power received by the receiver depends on the power of the source, power loss in connectors (P_c), fiber dispersion loss (a x L), and margin required above receiver power (P_m) (Figure 25). By treating dispersion as power penalty, the attenuation-limited and dispersion-limited can be combined, which makes the power calculation much simpler.

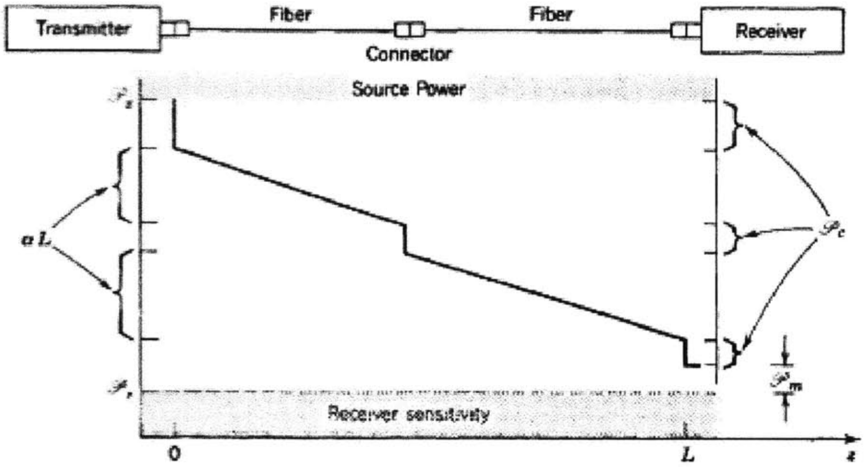


Figure 25: Power budget of an optical link operating in attenuation regime

Currently, the most common use of laser source is vertical cavity surface emitting laser (VCSEL). Most VCSELs operate at 850nm with a 3.3V of voltage drop. Each VCSEL can provide bandwidth between 10Gbps to 20Gbps and the power consumption of VCSEL ranges from 3dB to 15dB depending on the data rate [28]. The data rate of VCSEL is largely constrained by temperature and average current level. Thus, equalized modulations are placed to monitor the current and ensure stability of data rate. However, the tradeoff between stability is power consumption and device size penalty. According to the study by Palermo, due to relatively fixed size of the synchronization, there is a 90% area penalty for each equalizer, thus limiting the VCSEL's ability to shrink any further. In terms of power penalty, each equalizer tap results in a 25% increase in multiplexer power consumption. Figure 26 compares the energy efficiency of the optical transceiver to the electrical counterparts. It is evident that optical technologies are more favorable, as they use less power for higher data rates [28].

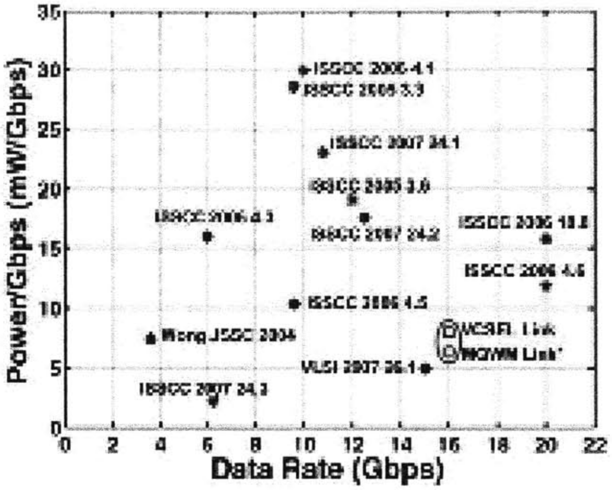


Figure 26: Optical link power consumption versus data rate

2.2.3 – Link Budget

The link budget is an important driver for the photonic interconnection in short distant data transmission. The link budget accounts for all the power losses (and gains) from transmitter through the medium to the receiver. The higher the link budget the higher the loss. For short-distance application, the current glass waveguide technologies incur significant link budgets, which are dominated by coupling losses, bend losses and crosstalk. Propagation loss is not a big factor for glass waveguides because it is essentially zero over the distances up to 100 meter.

Therefore, bending and coupling losses dominate the limit of glass waveguides link budgets.

Power consumption of an electrical system increases as the required data rate increases. At the Microphotonics Center (MPhc) meeting, it was stated that optical interconnections incur a minimum loss of 10-20dB due to E-O-E conversion at the interfaces. And in short distance transmission, the optical loss falls approximately to zero with silica fibers having a propagation loss less than 0.3dB/km beyond the interface. As a result, optical solution for short distance data transmission becomes relevant when the electrical loss become more than 20dB.

By itself, excess dissipation in systems is undesirable. But, adding additional power to an existing local high dissipation region gets compounded in the system. To improve efficiency, an external power supply can be employed in an optical system. This would allow the dissipation to be located away from the processing die and, through the use of optical modulators, result in a reduction in dissipation. The use of an optical power supply would reduce power dissipation via connector loss and also share its output amongst a large number of modulated channels to ensure that the system has minimum propagation.

2.2.4 – ITRS Power Projection

Figure 27 gives the ITRS projections for allowable power per MPU chip, with the use of heat sinks, for both cost performance and high performance. Although the number of transistors is increasing, the power consumption per chip is expected to stay relatively constant or slightly decrease. The power consumption is driven by higher operating frequencies and higher interconnects capacitance due to closer electrical wiring. Historically, the increase in frequency is offset by the reduction in power supply (drive voltage) in order to keep overall consumption constant. This is, however, no longer the case because the ability to lower drive voltage has reached its limit due to minimum power dissipation inherent in the material properties. The new approach by the industry is to target lower capacitance since

$$P = C \times V^2 \times f \qquad \text{Equation 2}$$

Where P is power, C is capacitance, V is drive voltage, and f is the operating frequency.

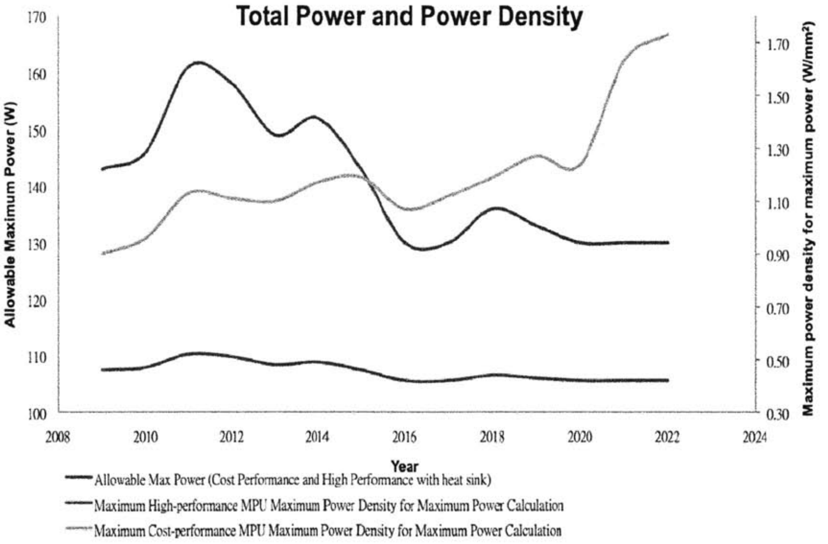


Figure 27: ITRS projection of allowable max power and power density per chip

2.3 – Cost

Similar to other industries, the optical-electronics interconnects industry is largely driven by cost. Cost reduction is necessary to accelerate the market growth. While the cost of wafer processing for optical-electronics industry is important, packaging is a more significant factor as it contributes 60-80% of the total manufacturing cost of an optical-electronics device [30]. The challenge of the package cost comes from strict requirement of process control, material purity, and precision in component alignment. These concerns can be reduced as the assembly process shifts from manual towards more automated processes. However, a fully automated assembly process has yet to be realized because of lack of standardization in packaging. In the past, the market for optical-electronics interconnects packaging has always been high margin with small unit since most of the products were custom ordered. Thus, leading to a lack of standardization.

ITRS and iNEMI have identified *the importance of the reduction in cost-per-function as the transistors per chip doubles every two years in order to keep the cost-per-chip (packaged unit) approximately constant.* Figure 28 shows the projected increase in number of functions per MPU chip and the cost of each chip through 2024. When looking at the figure, there are two things to keep in mind. First, cost per MPU is the product of affordable packaged unit cost per functions and the number of functions. Since the number of functions (transistors) is projected to double every two year, the cost per MPU encounters a spike in the graph every two years. Therefore, data points are used every two years instead of every year. Second, the cost per low performance MPU does not fall below zero. It is, however, an extremely small number (~$0.05) after 2017. It is interesting to note that the cost per chip for cost performance application is expected to drop to less than $1 per package even though the number of functions is expected to rise to 6184 by 2016 [23]. In order to compete with these packages, optoelectronic packages must be able to provide higher functionality at a lower price.

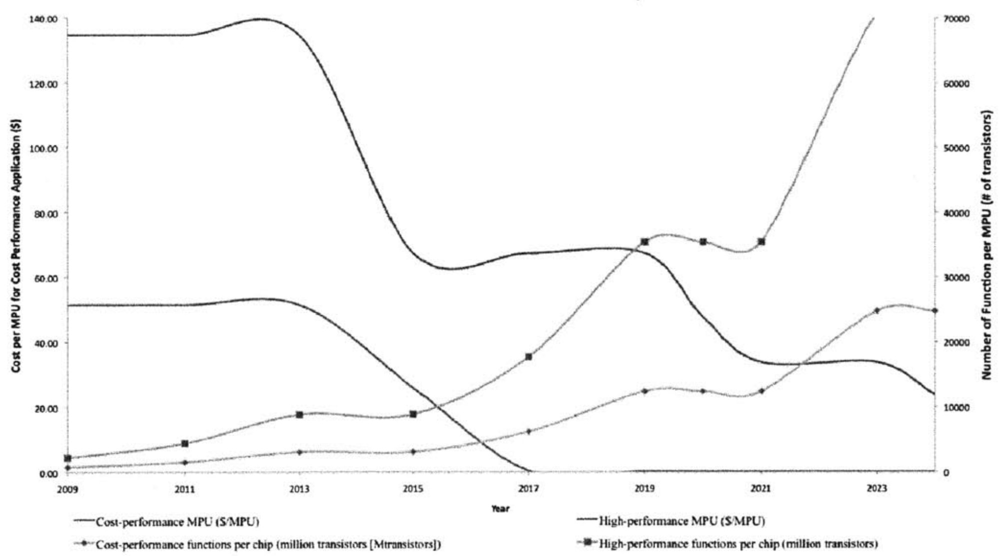


Figure 28: Affordable cost per MPU and number functions per MPU

For the on-circuit board and on-to and off-of chip data transfer applications such as short-range LAN, FTTX, and active optical cables, the cost of optical-electronics links are also expected to fall significantly in order to be affordable for the end consumers. Figure 29 illustrates such reduction trend. Optical links are costing around $5 per link. In order for optical to be competitive to electrical, the projected cost must dramatically decreased by a factor of 5 in 2013 and by a factor of 100 by 2024 [23].

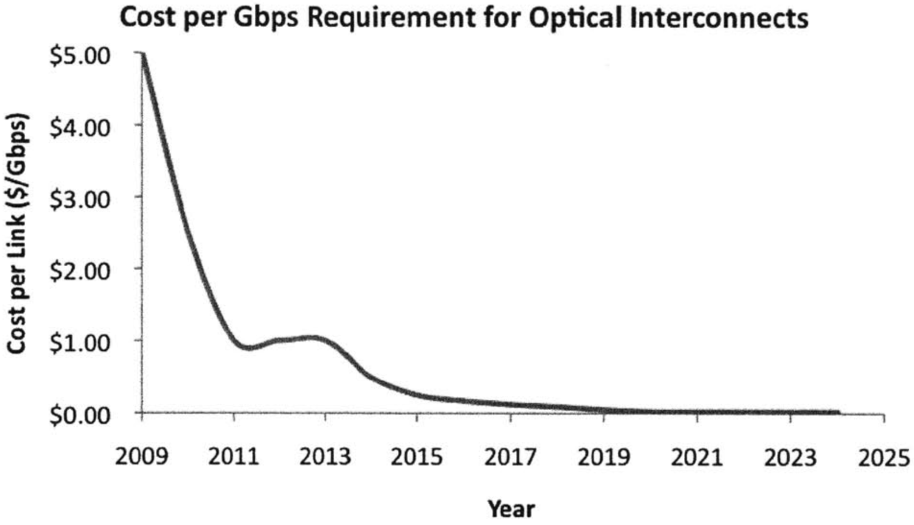


Figure 29: Required cost of optical interconnects

2.3.1 – Standardization is a Barrier to Cost

While there have been advances in standardizing some applications of optical interconnects, there remain significant variations in product platforms, specifications, manufacturing, design and quality. In order to be adopted commercially, it is crucial to reduce the cost of optical interconnects substantially. The standardization of PCB card cages has offered lower cost and easier management of optical wiring for shorter optical interconnections. Similar to electrical circuit boards (ECB), PCBs allow optical waveguides to be laid automatically on the card. The automated system reduces the probability of wiring error and increases overall yield while reducing cost [31].

2.3.1.1 - Lack of Standardization

During the last half of the 20th century, the evolution of packaging has been independently developed by the major OEM's such as IBM, Bell Labs, Siemens, Hitachi, and NEC. In an attempt to develop standardized packaging technology, a group named SEMATECH was established but was disbanded at the end of the century [17]. As packaging became more critical to the advancement of interconnect technology, recent industry effort such as multi-source agreement (MSA) have been made in order to agree on a standardized transceiver module platforms. In addition, industry consortium such as the International Technology Roadmap for Semiconductor (ITRS) and International Electronics Manufacturing Initiative (iNEMI) have identified that the lack of standards is significantly slowing the implementation of technology and growth of interconnect markets. Thus, efforts have been made to standardize in areas such as final assembly process and components material choices.

All optical solutions have higher performances in bandwidth density and power consumption for long and short length data transmissions. Presently, most applications of optical transmission are for long length data transmissions where the price and the dimensions of the device are not a design concern. However, in short length data transmissions, the cost and the size of the device are important factors. Currently, the price of all optical solution for short length data transmission is too high to be commercialized in all but the most specialized markets. Companies such as Intel and IBM already produce photonic-chips at relatively low costs, therefore, the key barrier to realizing necessary link costs is not the chip itself, but due to optoelectronic packaging and integration. As concluded in the previous chapter, the high cost of optical-electronics packages comes not only from the difficulty in precise alignment, between optical sources and transmission medias, and to prevent scratches and dust accumulation on the device. More importantly, the high costs come from the lack of a standard in the optical-electronics industry.

Lack of standardization is one of the major concerns of the optoelectronic industry, and has contributed to the high cost of optical packaging. Because of how the industry has evolved, the majority of packages are customized and targeted at discrete, single channel, components. This is evident in the variety of packages in the market. Even the three most commonly used optical-electronics packages in the market (TO, Butterfly, and mini-DIL) make up only 39% of the packages while the remainder continues the trend of being custom built. Figure 30 is a pie chart that describes such phenomenon.

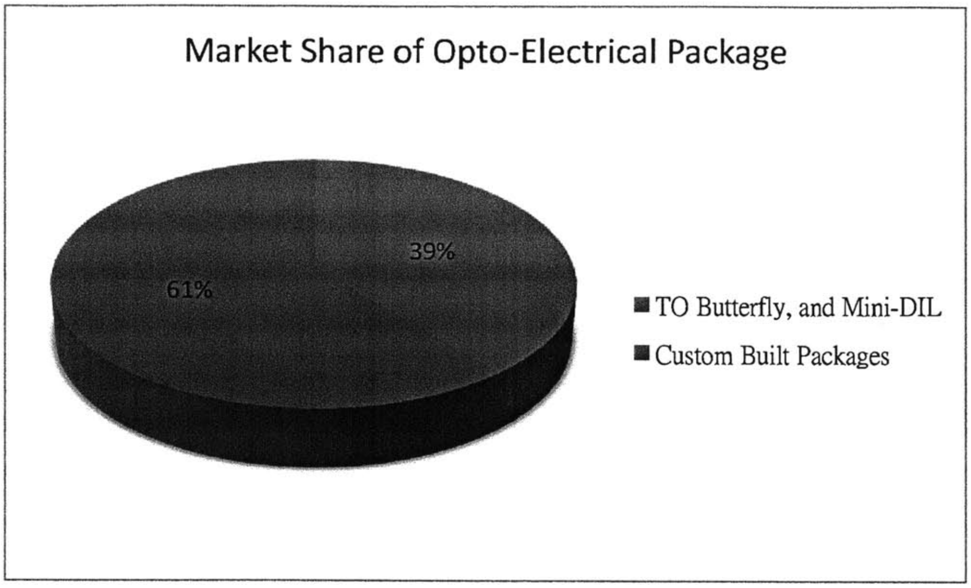


Figure 30: Proportion of market share for optical-electronics packages.

Lack of standardization is also seen in the transceiver modules market, which has no standard form factor. Table 4 lists several types of transceiver packages and the number of variants for each. The large number of variants is driven by customized solutions that are application specific. This complexity makes it difficult to negotiate and manage optical links and may marginalize the efficiency gains of the modular approach.

Table 4 Number of different types of transceiver package available in the market

Form Factor	Types
SFF	143
SFP	96
GBIC	20
XFP	5
MSA	50
Other	17

To enable high volume electronics-photonics integrated circuit (EPIC) chip production, a packaging standard must become established [32]. As the standard is being defined, there are two levels of consideration that are required. First, the incumbent technology needs to be improved upon and not replaced until new technology and costs present a more attractive standard. Second, the capability of the platform to deliver performance at the projected cost point.

Both optical and electrical packages must be considered for the high-density meter scale applications. For the packaging technology to be dominated in the market, the choice must anticipate the evolution of the highest volume and lowest cost.

2.3.1.2 - Standardization Analysis

Several studies have been conducted at MIT during the past 10 years to answer the question of whether standardization is necessary for the optical-electronics industry. In 2004, Michael Speerschneider published a thesis that examined the drivers and barriers to industry standardization [5]. System dynamic analysis and loop diagrams are conducted to understand the importance of standardization and include factors such as revenue, product variety, transceiver costs, and capacity utilization. His models showed standardization has led to significant increases in revenue due to the enhanced market penetration that was spurred by greater concentration of industry resources for fewer platforms (Figure 31). Therefore, he has concluded that although standardization is essential, current efforts to establish a standard are not adequate. A true convergence will only occur with the effort of all regulators, industry players, and consumer markets.

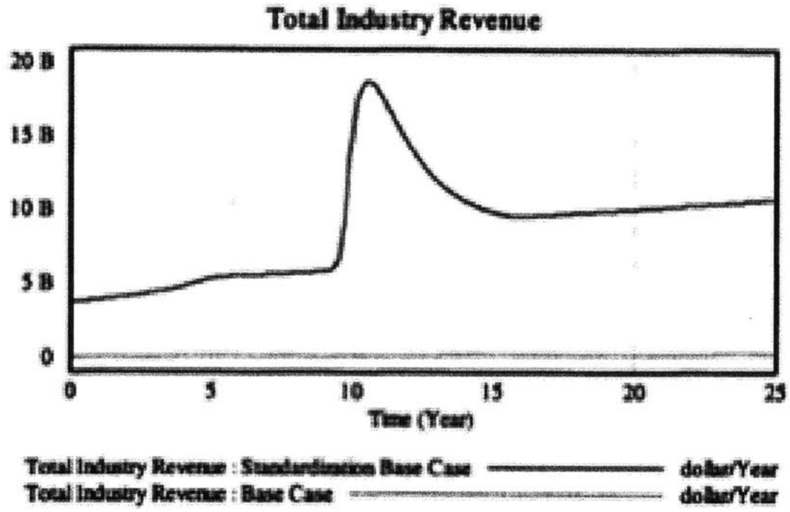


Figure 31: Standardization vs. base-case comparison for industry revenue

Similar to the standardization of LAN, 3 or 4 packages standards will be specified by either the regulators or the industry players, the market will eventually adopt to the more superior technology. Amongst the packages that need to be considered are, the incumbent (Butterfly and TO-can type) technologies, Leaded Electronic Packages (DIP, PLCC, QFP), Leadless Electronic Packages (Ball Grid Array (BGA), QFN, Chip Scale Package (CSP)), and System in a Package (SiP). The functions and performances of different packages will be further discussed in Chapter 3.

Jerry Hausman, an Economics professor at MIT also conducted a standardization analysis in 2004 [33]. Similar to Speerschneider, he also concluded that it takes more than one industry segment for the development of one standard transceiver platform to take place. An important yet slight different conclusion Hausman had made was that without volume (market or consumer demand), whether standardization takes place or not would not affect the industry. This is due to the low pricing elasticity of optoelectronic product. Hausman argued that since the cost of components account to only a small percentage of overall system cost, reducing the price of transceivers would not have significant impact in demand (Figure 32). On the contrary, market opportunities should come from creating new market applications in order to have larger impact on demand. Because of this, Hausman is uncertain about the effect of standardization. He argued that whether the outcome of standardization is favorable or unfavorable would remain as a debate for the industry. This is an interesting and important finding because it could contribute to the reason why standardization is happening so slowly across the industry.

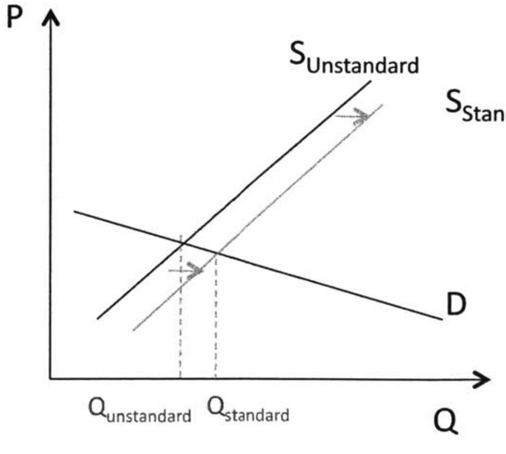


Figure 32: Supply and demand curve demonstrating Hausman's theory

Identified by the technology-working group in Microphotonic Center, the most significant factor contributing to IC industry's success is the ability to coordinate vertically across the supply chain. The efficient allocation of human and capital resource for research and development has not only helped the industry standardize the final product form factors, but also and more importantly, standardize and optimize manufacturing processes. This offers a cost entry point to penetrate the market. As the working group also pointed out, optical should learn from its electrical counter part and work together across the supply chain. In order for optical to compete with electrical, three key issues must be addressed: first, mature-and-growing markets that sell more than 10 million units per year must be identified. Second, a viable, high-volume, and low-cost manufacturing platform must be defined. Lastly, a common infrastructure for design, manufacturing, and integration must be developed [15].

2.3.2 – Installation and Maintenance Cost

There are two different criteria that need to be defined before deploying interconnects:
The first is determining the type of interconnect (electrical or optical) and the second is the type of module (fixed mounted or flexible pluggable). The cost of each module depends on the product applications.

Pluggables can be advantages in terms of their design flexibility, ease of assembly, and cost. However, because the devices are fabricated and assembled afterwards, additional spacing is required. In addition, other tradeoffs include device performance, density, and signal integrity challenges. As a result, the device sizes are typically larger than embedded modules. On the contrary, an embedded module can provide higher performance with smaller device sizes since the devices can be designed and precisely assembled with automated machines. This, however, increases the cost and since the components are designed, manufactured, and mounted all in the same process, it reduces the device overall flexibility.

In the long distance application, optical interconnect is the most conventional medium used to send optical data over fiber networks from varying objects to the transport infrastructure. Connections between the equipment rely on optical modules and transceivers that were connected to the installed fiber. It's important to note that trained optical technicians were needed to manage the process. Since form factor (size of the device) is not as important of a consideration for long distance interconnects, pluggable modules become more attractive method since it is cheaper and easier to manage. However, in a short distance application, smaller form factor become a more important consideration while reconfiguration and maintenance are done much less frequently, an embedded transceiver module seems to be a better method in this application.

The use of pluggable modules running on a fixed infrastructure provided a simpler to manage and more flexible configuration capability than existed with board level transceivers based on discrete components. The success of modules, especially hot-pluggable modules, in the datacom field provided the impetus for the development of telecom capable pluggable modules based on the same form factors. Shorter reach applications have benefited by adapting the concept of using transceivers connected to facility transport fiber to modules, which incorporate the transport medium as part of the specific installation.

2.3.3 – Product Cost

Similar to the metric for power consumption, the parameter used to measure link costs is $/Gbps. The cost of functionality is impacted by the product of optical, electrical, and transceiver bandwidth. The cost of a link scales weakly with distance when data transmission is beyond 1m. However, as optical interconnects are driven closer to the core (below 1m), the cost of optical per length is determined by number of architectural changes, interfaces, and coupling cross talk.

One important issue to keep in mind is that the cost of interconnect is a time and context dependent factor. Currently, cost of photonic interconnect is still relatively high because of packaging issues (a discussion of these packaging issues are further discussed in the optical packaging paper). Those costs, however, can be normalized to specific combinations of power, speed, and size of the components.

Although increasing demand in capacity has driven photonic interconnects closer to the core, the adoption will only occur when a series of synergies exist. Those synergies begin once costs drop to a price point where customers are willing to pay and industry adoption of a photonic standard is enacted.

3. –Packaging Analysis

3.1 – Challenges and Opportunities

Packages and assemblies allow the integration of various electrical, mechanical and optical components. Since packaging cost is the key contribution to optoelectronic's total cost, the trend in the assembly industry is important to the evolution and adoption of optoelectronic industry.

Customer demands, corporate issues, and government regulations determine the trend in packaging technology strategy and development. Some factors influencing the customer trend include smaller device size, higher performance in functionality, power and cost, and higher reliability. Because of this, many packaging technologies, especially consumer portable devices, are trending towards an ever increasing product density, functionality integration, and miniaturization for many applications.

Newer and more integrated technologies have enabled the industry to deliver what was demanded by the end users. Some challenges to future manufacturing economies have been indentified by the industry. For example, the continued pressure to reduce the cost per pin,while the numbers of pins used continues to grow, has made it more challenging to deliver cost-effective solutions. Also the varieties of assembly components and processes have also become increasing concerns to the industry. The complexity will only increase as more functions are integrated into a smaller device size.

3.2 – Standard Package Attributes

The main goal of standardizing packaging options is to leverage the high unit volume at both the board-to-board and board-to-chip levels. This has a particularly strong effect on optoelectronics industry. The concern remains at the composition and/or layout of electrical and optical I/O. Until the industry has moved completely away from electronic, the device must be able to accommodate both electrical and optical I/O, which result in the need to negotiate both electronic and optical I/O for any standardized packaging will.

Another goal of standard optical packages is to increase yield, performance, and reliability while simplifying the manufacturing process to decrease costs. There are several commercialized technologies that currently contain both electronic and photonic I/O. In this chapter, performances and requirements of various standardized electrical and optical packages will be presented and an analysis of whether the current packages can reach performance requirement will further be conducted.

3.3 – Electrical Packages

In the optoelectronics interconnects industry, the shift from through-hole technology to surface mount technology (SMT) has achieved higher performance and lower cost while continue to miniaturize the device size. Figure 33 shows the comparison between the two technologies. SMT is a board packaging technique, which solders the lead pins and components directly onto the surface of printed circuit boards (PCB).

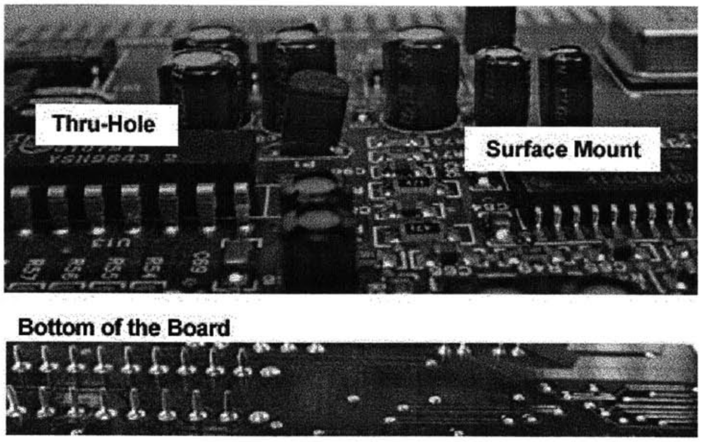


Figure 33: Schematic comparison of through-hole technology and surface mount technology [34]

Since SMT eliminates the need to drill holes on the board, it speeds up and increases the yield for board manufacturing. In addition, SMT provide more efficient board design because it freed up the space underneath the board, allowing the closer layer placements and higher bandwidth density [35]. Since surface mount packages are much smaller than through-hole, higher chip density is also achieved. Another significant benefit of SMT compared to through-hole mounting technologies is its performance is guaranteed at high performance. Although through-hole packages are able to meet required data rate, the reliability starts to deteriorate when aggregate bandwidth is greater than 1Tbps. Consequently, SMT packages are usually used for high density and high performance requirement applications while through-hole packages are generally used for less complex and less costly applications.

A study done by IC Insight has indicated that in order to keep pace with the accelerating demand for smaller, faster, yet less expensive product, new packages must be an integral part of chip design and production process rather than a last step during the assembly [36]. Figure 34 presents a pie chart that summarizes the forecast market share of each type of packages in 2015.

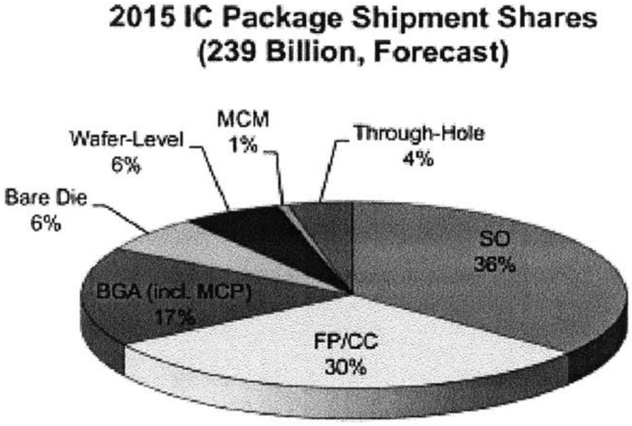


Figure 34: Forecast package shipments by package types [36]

3.3.1 – Leaded Packages: Dual In-Line Packages (DIP) and Quad Flat Pack (QFP)

Dual in-line package (DIP), presented in Figure 35, was one of the first types of memory packaging. DIP is a conventional through-hole package with leaded electronic pins. The number of leads may vary from 8-68 and they are generally longer because they need to go through the holes on the board and a recurring problem arises because the pins are easily bent [37]. Moreover, since the users are unable to replace the DIP if it is faulty, the entire board will need to be replaced when one DIP goes bad. This leads to very high yield requirements and high maintenance costs.

There are many different types of DIPs depending on material used. Figure 36 shows another type of electrical packages, quad flat packages (QFP). QFPs are a type of surface mounted packages and their lead pins are generally shorter because they do not need to go through any hole. Although most DIPs have been replaced by QFPs, DIPs were the most popular technology in the 70s and 80s.

Both DIPs and QFPs are commonly used for low cost, moderate density and moderate power applications. These packages can also support different features. For example, packages with ceramic bodies and metal plugs enable high dissipation applications.

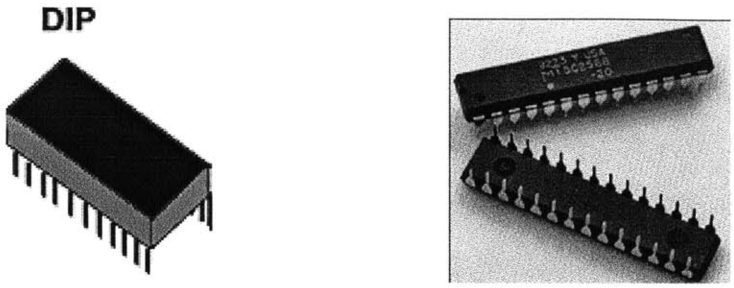


Figure 35: Schematics of DIPs

Figure 36: Schematics of QFPs

3.3.2 – Leadless Packages: Ball Grid Array (BGA), Quad Flat No-Leads Package (QFN), and Chip Scale Package (CSP)

3.3.2.1– Ball Grid Array (BGA)

Ball grid arrays (BGA), quad flat no-leads packages (QFN), and chip scale packages are all different types of surface mount packaging technology. BGA packages evolved from pin grid array (PGA) packages [37]. Although both BGA and PGA are used to provide hundreds of pins on the package surface, BGA uses solder balls instead of pins. The pins are placed on the PCB with the same pattern as the solder balls. The two are aligned perfectly and stuck together with thermal adhesion.

As the number of pins increases and device size shrinks, the allowed spacing between pins becomes smaller. It becomes more difficult to maintain the increase in pins without having them touch. BGA packages provide a solution for this problem.

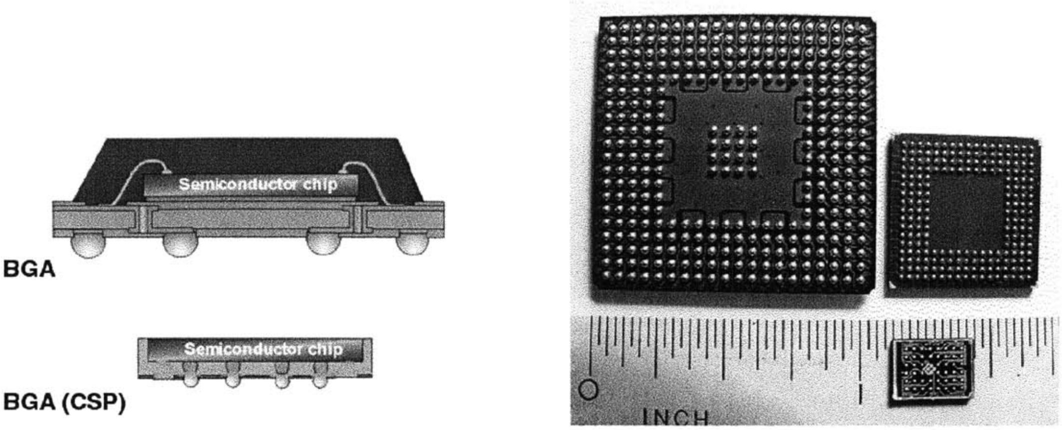


Figure 37: Examples of BGA packages [38]

BGA packages transfer heat more efficiently than leaded packages because BGA packages have lower thermal resistance. This provides an advantage in preventing the package from overheating compared to PGA. Because of the low thermal resistance, heat generated in BGA packages can easily flow to and dissipate from the circuit board. To further assist with thermal dissipation, metal lid BGA packages are used. In addition, since the distance of interconnects between the BGA packages and the PCB is short, it not only provides BGA a size advantage over PGA, but it also allows BGA packages to have lower inductances and better performance.

On the other hand, since the ball grids solder connections cannot be examined visually, it causes an increase in inspection cost. The defected solder connections that are removed cannot be reused and a consistent manufacturing process is required [37]. Another disadvantage of BGA packages is that if the coefficient of thermal expansions between BGA and PCB are not matched correctly, it can cause solder joints to fracture and lead to device malfunction. Figure 38 shows a schematic of the joint fracture [39]. Therefore, it could cause a problem in industry with high reliability requirements such as aerospace and automotive industry.

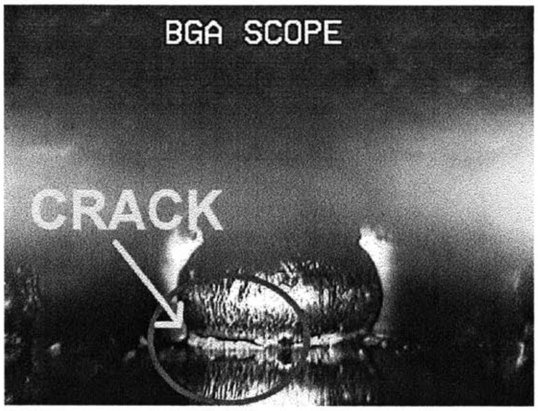


Figure 38: BGA solder joints fracture caused by thermal and/or mechanical stress [40]

Despite their disadvantages, BGA packages are still the most widely used in the interconnect-packaging industry such as handheld markets, low-cost low-end consumer electronics and memories, and cost performance applications. Variants of BGA include fine pitch BGA (FBGA), plastic BGA (PBGA), flip-chip BGA (FCBGA), molded array process BGA (MAPBGA), and micro-FCBGA. Different types of packages are fabricated depending on the application. For example, FBGA has the greatest contact density in conventional packages is usually used in handheld applications since they require smaller device size. Currently, the total thickness of FBGA is as thin as 100mm with 60mm cores in high volume manufacturing while 50mm and 35mm remains too costly to achieved high volume manufacturing [23]. PBGA is another example, which is an excellent packaging technology for mid-to-high performance devices that require low inductance, high reliability, and easy to mount at a relatively low cost. Typical PBGA size ranges from area of 15x15mm to 40x40mm with greater than 1000 I/O available.

Compared to QFPs, BGAs, including the cheapest PBGAs, are still relatively more expensive. This is especially true at lower pin counts such as 250 or lower. As a result, BGAs are generally used in mid-to-high performance market applications while QFPs target low-cost low-performance market applications [41].

3.3.2.2– Quad Flat No-Leaded Packages (QFN)

Quad flat no-leaded packages (QFN) are another kind of miniature packages that provide improved thermal dissipation at very low cost through metallic heat spreader. Lead frame carriers have thrived in the past decade through their low cost and good reliability products. However, unlike BGA packages, QFN packages only allow contacts to be placed around the edges of the package rather than on the bottom. Thus, QFN packages cannot provide as high of interconnect density as BGA packages. Figure 39 presents schematics of QFN packages. Although recent development such as multi-row has enhanced their interconnect density and performance capability for QFN packages, BGA still dominates the packaging market.

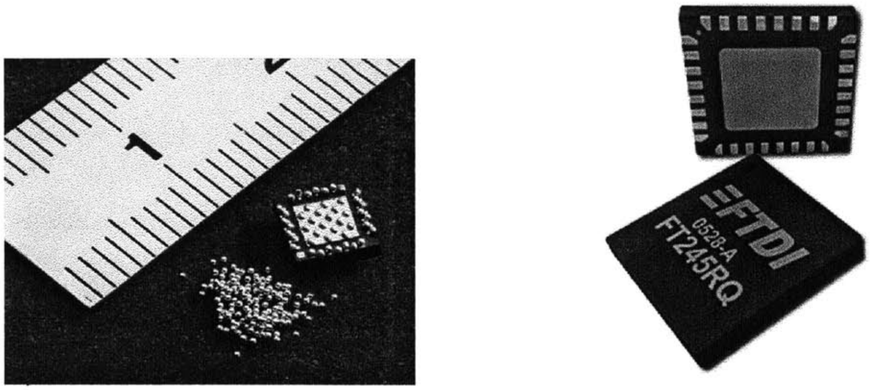


Figure 39: Examples of QFN packages

3.3.2.3– Chip Scale Packages (CSP)

Chip scale packages (CSP) are the smallest packages available in the market. CSPs are a volume-efficient packaging method and minimize the packaging overhead. Since CSP only specifies dimension requirements rather than defining how a package is constructed, CSP comes in many different forms: wire-bonded, flip-chip, BGA, or leaded. The size of CSPs are typically no more than 1.2 times the die dimensions. Because of its small package size, CSP has to be single-die and direct mounted to PCB. Moreover, CSPs use external electrode bumps on the bottom, which provides sufficient area for electrical contacts [11]. These contacts allow for moderate pin count and high interconnect contact density.

Advantages of CSP include smaller device size and lighter device weight, which are extremely important in today's world as consumer demand smaller and more mobile applications. Moreover, since the construction of CSPs is not specified, they present an opportunity to choose its own architecture and combine the strengths of various packaging technologies to improve electrical performance, contacts density, and cost. CSPs are popular in mobile industry such as cell phone, laptops, tablets, and digital camera because its size and weight reduction.

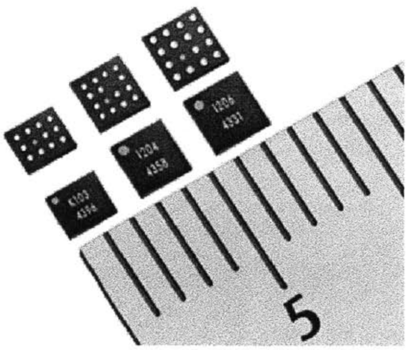


Figure 40: Schematics of SCPs

3.3.2.4– System in Package (SiP)

Figure 41 illustrates a schematic of a system in package (SiP), which assembles a combination of multiple active and passive electronic components in a single package or module [23]. With multiple components on a single module, SiPs can provide multiple functions to a system or sub-system depending on its application. While taking advantage of existing miniaturized packaging technologies such as stacked-die, horizontal placement, or embedded manufacturing technology, SiPs provide a reduced size packaging compared to conventional multi-chip modules. SiPs are typically mounted on PCB with solder ball connectors similar to BGAs.

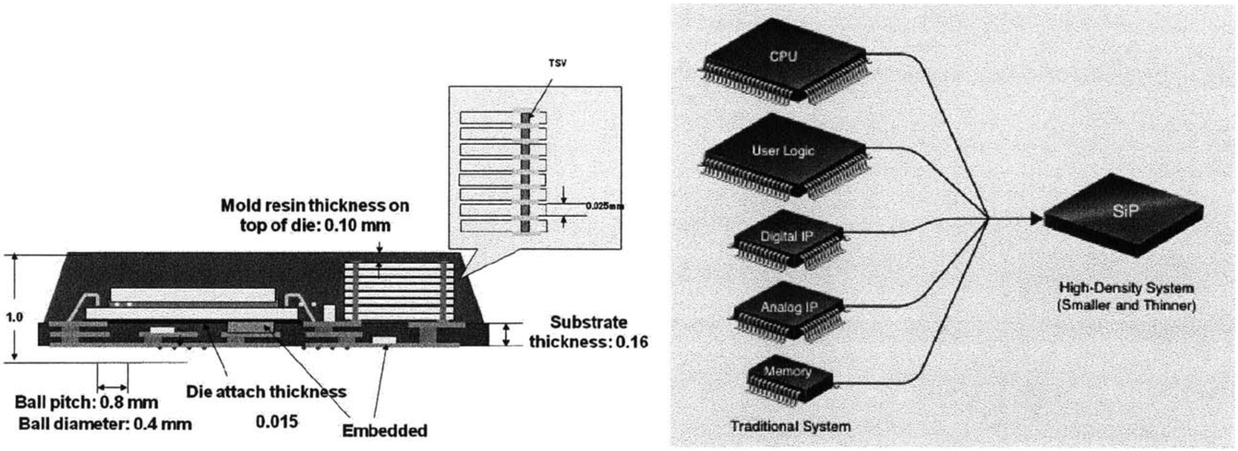


Figure 41: System in a Package (SiP) schematic

Due to SiP's ability to integrate multiple functional chips into one package, it enables smaller form factors, higher density chip-to-chip connections, and cost reduction in the package level. Moreover, in the board level, SiPs also reduce the complexity and footprint of PCB design. That makes SiPs especially valuable in applications such as mobile applications and high performance processors with near-by memory [17].

Despite of the benefits, SiP's technological challenges remain to be solved. Because all of the chips are integrated into one package, one single defective chip will cause the package to be malfunction even if all the other chips are working. This reduces overall product yields and increases production cost due to a higher precision standard, testing, and defective product costs. Another challenge with SiP design is heat dissipation. Aside from issues with manufacturing and testing, power delivery and cooling for stack of chips become much more complex than to a single chip. As the pins get closer together, power supply noise and losses also increases due to electromigration [23, 42]. Moreover, when logic chips are stacked, the total current that needs to be delivered to the stack increases, which exacerbates the power delivery issue. Figure 42 maps out the roadmap for SiPs technological requirement for the next 20 years. The number of pins is excepted to grow from 2200 to 3700 in 2024 for cost performance application and from 3350 to 6543 for high performance application.

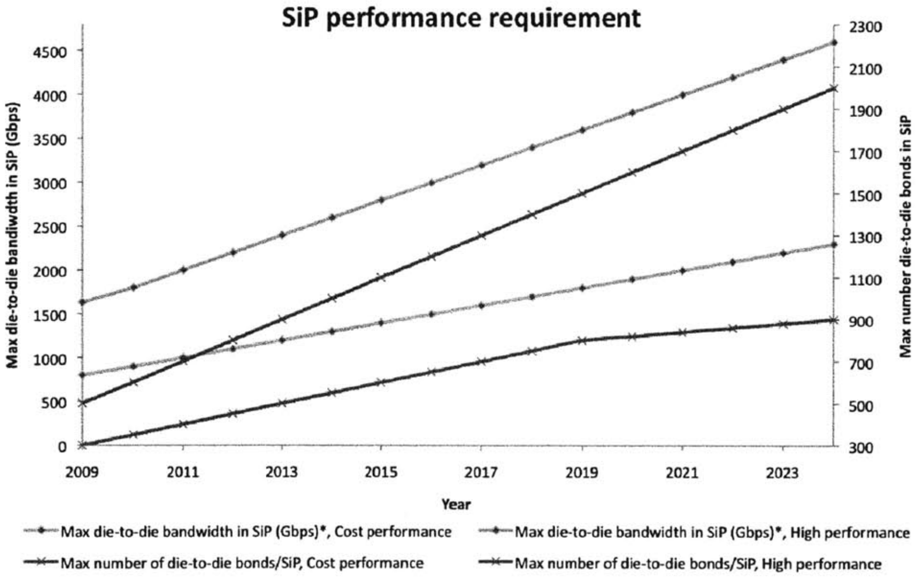


Figure 42: SiP die-to-die bandwidth and number of bond requirement [23]

3.3.2.5– System on Chip (SoC)

Figure 43 presents an alternative technology to SiP, system on chip (SoC). As the name described, system on chip is a type of single chip system that integrates a variety of components into a single chip or IC. Similar to SiP, SoC can provide multiple functions through a single chip. Because of this, SoC enables a smaller device. Another advantage of SoC comes from simpler and easier packaging. As a result, SoC is more cost effective in large volumes because it has higher yields in manufacturing. However, due to the performance limitation of single chip, SoCs application is often limited to less powerful applications such as external memory such as Flash or RAM. When running more powerful and complex systems, SiP is usually preferred. Table 5 presented the pros and cons of SoC and SoP, each approach has specific advantages and both will be used in the future.

Figure 43: System on a chip (SoC) schematic

Table 5 Comparison of SoC and SiP architecture [23]

<table>
<tr><th colspan="3">Market and Financial Issues</th></tr>
<tr><td><i>Item</i></td><td>SiP</td><td>SoC</td></tr>
<tr><td>Relative NRE cost</td><td>1×</td><td>4-10×</td></tr>
<tr><td>Time to Market</td><td>3–6 months</td><td>6–24 months</td></tr>
<tr><td>Relative Unit Cost</td><td>1×</td><td>0.2–0.8×</td></tr>
<tr><td colspan="3"></td></tr>
<tr><th colspan="3">Technical Features
PROs and CONs</th></tr>
<tr><td colspan="2">SiP</td><td>SoC</td></tr>
</table>

PROs	CONs	PROs	CONs
Different front end technologies; GaAs, Si	More complex assembly	Better yields at maturity	Difficult to change
Different device generations	More complex procurement & logistics	Greater miniaturization	Single source
Re-use of common devices	Power density for stacked die may be too high	Improved performance	Product capabilities limited by chip technology selected
Reduced size vs. conventional packaging	Design Tools may not be adequate	Lower cost in volume*	Yields limited in very complex, large chips
Active & passive devices can be embedded		CAD systems automate interconnect design	High NRE cost
Individual components can be upgraded		Higher interconnect density	
Better yields for smaller chip sets		Higher reliability (not true for very large die)	
Individual chips can be redesigned cheaper		Simple logistics	
Noise & crosstalk can be isolated better			
Faster time to market			

* The cost advantage is only applicable when the SoC has good yield

3.4 – Optical Packages

The electrical packages described in the previous section are packages that are currently available in the market for electrical interconnects. They can also be considered for packaging optical I/O elements. BGA based packages are most likely to be used for optical packages because BGA packaging allows for greater area interconnect, which enables efficient power dissipation from the dies. Better power dissipation has become an increasing concern since power increases exponential with chip performance. Another advantage of BGA based packages is its cavity down package configuration. The configuration frees up more vertical space for optical signal sources such as VCSEL. This allows the source to be co-mounted in the cavity within the IC, saving space and increase manufacturing costs.

One of the mainstay solutions for optical coupling from devices to fibers is the butterfly style package that helped to increase the reliability and reduce the loss. Another option was the use of TOSA and ROSA modules. Since both TOSA and ROSA modules are low cost, cooled packages with coplanar RF interfaces and socketed optical connections, they enabled integration of smaller form factor transceivers without sacrificing overall device performance. The third option was coaxial TO-can style optics, with either coplanar ceramic or glass feed-through RF interfaces, is another option for 10Gbps operations.

3.5 – Optical-electronics Packages

As the number of transistors on a chip increases, the number of pins necessary to support I/O signal transport also increases. One issue with electrical packaging is that although the slow increase in maximum pin count has allowed a reduced contact density (pin-to-transistor ratio), a large fraction of this pin increase is used to supply more power to increase noise immunity rather than data transport. Over 2/3 of increased pins are used to provide power and reduces the number of pins available for signal I/O. With the majority of the increased pins dedicated to power, simply increasing the number of pins for parallel interconnects is not sufficient to satisfy the increased in I/O demand. Figure 44 shows that the required bandwidth per pin needs to increase in order to compensate for the decrease in pin count.

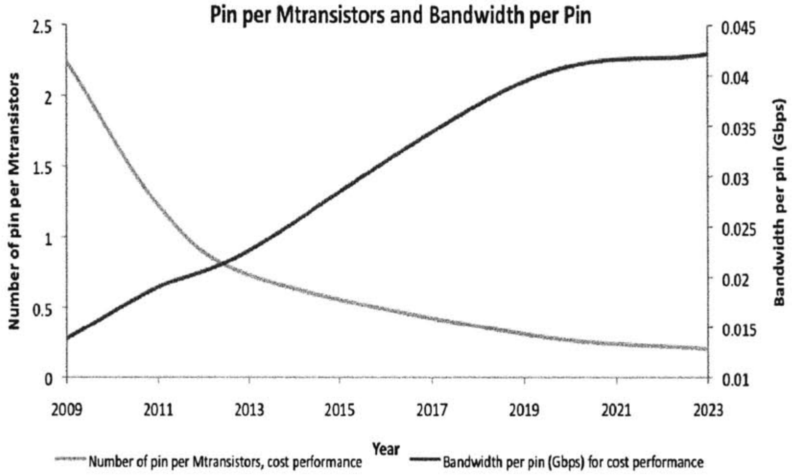


Figure 44: Number of pins per million transistors and bandwidth per pin

Optical technologies are able to integrate multiple channels in a single I/O pin to save on pin count and efficiently increase the information density. This contributes several advantages over metal wire for signal transmission including small loss, almost frequency dependent, low cross talk, short latency, reduced power consumption (Figure 24), and very high data rate per pin through CWDM or DWDM technologies.

Issues such as the lack of standardized optical-electronics packages remain because standards, like ANSI and IEEE, do not specify details for an optoelectronic transceiver package. As a result, many companies have agreed upon common packages agreements, such as the multi-source agreement (MSA) for 10 Gbps Ethernet in the recent year [43].

3.5.1 – Butterfly Packages (BTF)

Figure 45 is a type of pluggable optical package that is widely used in the industry and are called butterfly packages. The name butterfly came from the physical structure of the package with two series of leads sticking out on each side. Butterfly packages are can-and-cover type arrangements of optical subassembly and are essentially a type of through-hole packaging. Its packaging characteristics include positioning the distributed feedback lasers (DFB's), tilting mirrors, and various optical components. The assembly of butterfly packages can be a single process or components are produced separately and assembled at a later time. The optical components inside the package are wire-bonded to the leads of the butterfly and sealed with a hermetic sealing.

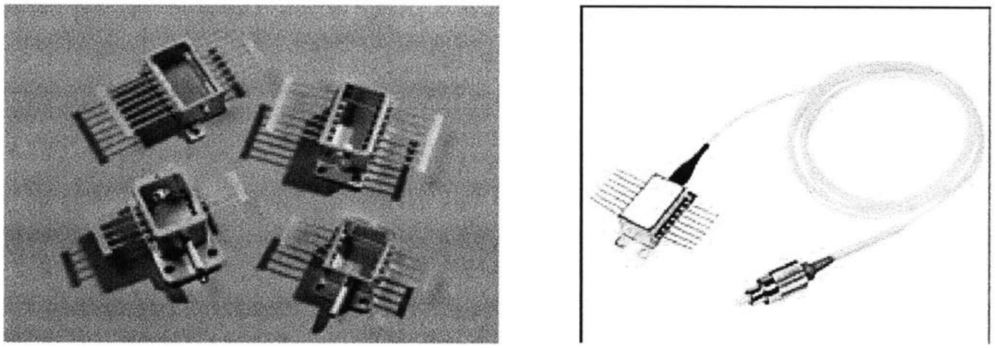


Figure 45: Examples of butterfly packages [44]

As shown in Figure 46, the optical connection is established through the optical fiber inside a feed-through tube on the walls of the butterfly packages. The optical fiber has to be aligned accurately to the optical components inside the package in order to get maximum coupling [45]. Hermetic sealing of the components is also crucial to maintain the reliability of the packages.

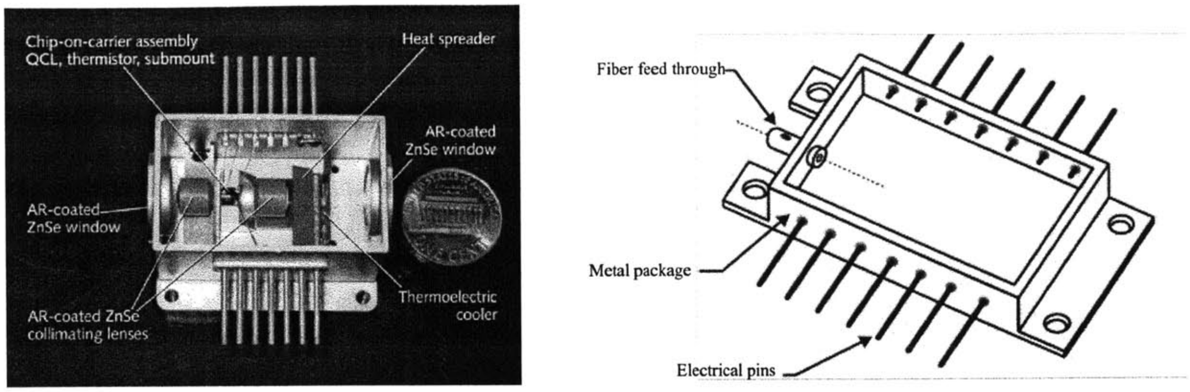


Figure 46: Components layout of butterfly packages [45]

An advantage of the butterfly package is its ability to thermal stability. While the use of DWDM enables higher bandwidth with lower pin count, the bandwidth performance is highly dependent of temperature fluctuation. The ability to control temperature has provided a solution to this issue. The butterfly packages are generally custom designs and have led to many variant packages in the industry. There are two primary applications of butterfly packages. The first is when the components needed to be mounted on a Petlier cooler for temperature control and, the second, iswhen many devices needed to be mounted in a single hermetic envelope.

3.5.2 – Transmitter Optical Subassemblies (TOSA) and Receiver Optical Subassemblies (ROSA)

Figure 47 and Figure 48 illustrate the schematic transmitter optical subassemblies (TOSA) and receiver optical subassemblies (ROSA) packages that are designed for small pluggable modules such as XFP transceivers or SFP transceivers. Each TOSA and ROSA contains the basic elements such as socket for the optical connector ferrule in order to enable its design functions. As a result of lack of standardization in packaging industry, there are hundreds of different types of TOSA and ROSA that are available for different form factor transceivers, which is presented on the top of Figure 48.

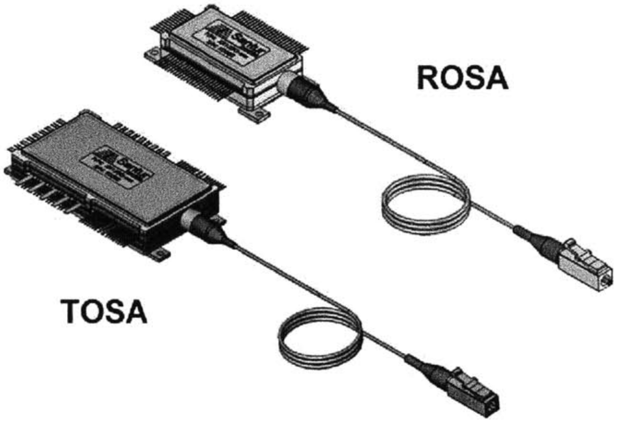


Figure 47: Schematic of PD100 TOSA and ROSA (10Gbps x 10 channels each) [46]

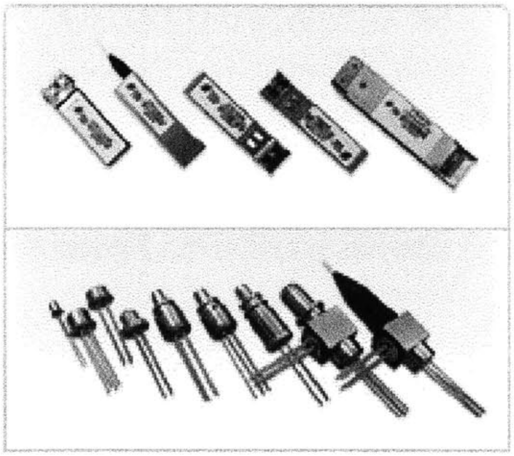


Figure 48: Top represents examples of transceiver packages and bottom shows TOSA and ROSA

Although no standard has been established, industry has been trying to move to converging to an agreeable level of conformity. For example, industry leaders, Bookham Technology, JDS Uniphase, North Light, T-Network Inc., and TriQuint Optoelectronics have formed a multi-source agreement (MSA) for standardizing 1550 nm 2.5Gbps cool TOSA and ROSA in July 2004 [47]. Other companies such as Fujisu Quantum Device Ltd., Mitsubishi Electronic Copr., and 3 other Japanese companies have also established a compatible source of 10Gbps TOSA and ROSA for the use of 10Gbps XFP MSA modules. MSA agreed on a standard form factor transceiver to support TOSA and ROSA and interface compatibility [48]. This is, therefore, an important step for the industry since it enables the reduction of system developer's cost while expanding performance and functionality of a standardized package. Although there are some agreed upon standards, there are still tens of different types of TOSA and ROSA packages in the market. Therefore, more effort should be made to expedite the pace to standardization.

3.5.3 – Optical BGA

Butterfly packages are essentially a type of through-hole packages. As shown in Figure 45, the pins that are sticking out on the sides are similar to the pins in DIP, which is illustrated in Figure 35. As discussed in the previous section, SMT electrical packages can also be used to package optical components. As the performances of the components inside the device continued to improve, it required more and denser electrical solder balls for power delivery, heat dissipation, and information transmission. However, at one point, most likely in high-level integration, the increase in density will hit its bottleneck. The rise in the solder balls will not be able to keep up with performance demands and would prompt a switch to optical balls/pins. When that happens, one would need to consider the use of optical pin. However, several questions remain. Can we have optical-pinned BGA? How would it be done? What would it look like?

3.5.4 – MicroPOD – An Industry Example

Figure 49 illustrates the 2011 optical-electronics packaging state of the art, MicroPOD. The package is an example of a miniature embedded parallel optics module and is descended from MiniPOD but with a higher interconnects density and smaller footprint [49] . MicroPOD's size is as small as 8.2x7.8mm with 12-channel parallel optics transmitter (T_x) and receiver (R_x), providing an unprecedented density. MicroPOD was developed by Avago Technologies together with IBM and USConec [50]. Parallel interfaces, in contrast to single-channel connectors, contain multiple lanes within the connector, providing higher bandwidth without increasing the number of I/O. Therefore, MicroPOD enables higher density interconnects with superior signal integrity and thermal performance.

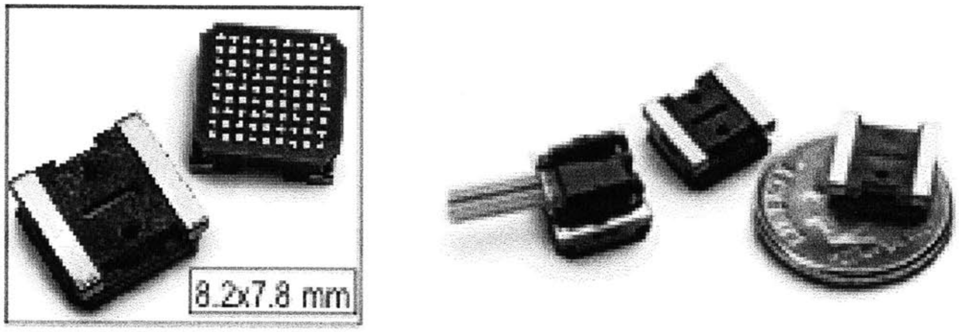


Figure 49: MicroPOD – Avago's next generation embedded parallel-optics module in scale

Each of the 12 channels supports a capacity up to 10Gbps and provides an aggregate demand of 120Gbps while consuming power less than 125mW [50]. MicroPod features separate T_x and R_x modules in order to maximize board layout flexibility. Figure 50 shows a dense tiled group of 8 MicroPOD, which provide a total bidirectional aggregate bandwidth of 960+960 Gpbs in less than $3in^2$ of a board area [49]. A top-attached optical connector with convenient slots for optical routing enables the dense tiling of the MicroPOD.

MicroPOD meets the specifications of both IBTA 12xQDR Infiband and IEEE 802.3ba 100BASE-SR10, thus it is very versatile. The main application of MicroPOD is in next generation supercomputers powering scientific researches such as climate modeling and drug design. MicroPOD also brings value in high performance routers, switches, and other cloud computing equipments. As businesses, research institutions, and governments increasingly rely on high performance computing, the performance of super computer must also be improved [51]. One particular factor is bandwidth density as discussed in chapter 2. MicroPOD is able to scale to 10s to 100s Gbps and 10s Tbps of connectivity bandwidth per core while still maintaining reasonable power consumption and device size. Since MicroPOD modules consistently provide superior performance in both air-cooled and water-cooled system, they are currently used in world's fastest supercomputers such as Power7-IH.

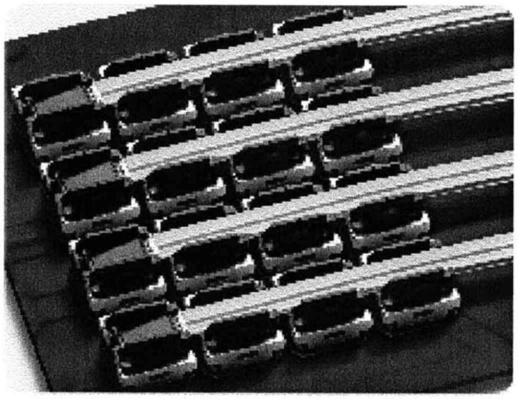


Figure 50: MicroPOD – A dense tiled gourp of 8 MicroPOD (T_x and R_x)

3.5.4.1– FOM of MicroPOD

In chapter 1, the figure of merit for an interconnect was identified as

$$FOM = \frac{R \times G}{A \times \$ \times J} \qquad \text{Equation 1}$$

From the equation, understand simple calculation can show the superiority of MicroPOD compared to conventional copper cables. MicroPOD is able to provide a maximum aggregate data of 120Gpbs for distance up 100 meters. Given the dimension of MicroPOD, area is calculated to be 63.96mm^2. There are two modules in each of the package. The power consumption is estimated to be 25mW/Gbps assuming 1.5W per module [2]. Using an estimated cost of $316 per MicroPOD, the FOM is around 1,425 Gbps/meter-joule-dollar.

3.5.5 – Active Optical Cable (AOC) – An Off-Board Connection

Active optical cables (AOC) are optical-electronics cables that connect to the conventional electrical interfaces while using optical cables to transmit data between the connectors. AOC use an electrical-optical transceiver to convert electrical information into optical to improve speed and distance performance of the cable without sacrificing capabilities of current standard electrical interfaces. Therefore, AOC is an example of pluggable optical-electronics packages.

To date, AOC is most commonly used for double date rate (DDR) and quad data rate (QDR) at 10Gbps per link. The future demand of AOC is driven by eight data rate (EDR) at 20Gbps per lane, hexadecimal data rate (HDR) at 40Gbps per lane, and four and ten channel Ethernet cables at 40 and 100Gbps respectably.

The most common deployment of AOCs is in large data centers and switches and core routers. Campuses and companies with the needs to connect two devices over 20-30m have also started seeing the switch to AOC. With the advent of 10Gbps and above interconnection, not only does the distance for copper interconnects shorten to 3m but the cable also becomes too heavy and large to manage [21]. Consequently there is a stronger push to adopt AOC in shorter distance applications such as personal computer, external hard-drive, and consumer electronics. These new market applications are the key to the development of AOC as the market size are measured in hundreds of million.

AOCs provide a standardized platform for the insertion of new optical technologies, such as silicon photonics, and integrates with electrical connectors. Unlike patch cables, AOCs permanently bundle the optoelectronic transceivers with optical fibers while relying on the electrical connector as the pluggable interface. The pluggable feature of AOC brings two key values. First, it removes the need for specialized optical installation and allows the link performance to be managed at manufacturing. Secondly, since these active cables are compatible with existing electrical infrastructures, it does not require new architectures, making adaption cheap and easy.

The standardization of the electrical performance achieved by AOC does not only result in rapid cost reduction (Figure 54), it also allows innovation in transceiver design and packaging. Though replacing copper with AOC in the electrical socket has made the implementation easier and cheaper, AOC also has certain disadvantages. The conventional architecture for electrical sockets is designed for high loss copper and draws a substantial amount of power. While plugging the AOC into the socket achieves longer reach, the amount of power being drawn remains constant, which results in an oversupply of power for the AOC. Another disadvantage of AOC is its bandwidth limitation. Since the information has to eventually convert to electrical signal, the data rate is limited at the electrical interface, which is about 10-20Gbps. Therefore, to fully take advantage of photonics interconnects, a new architecture must be designed.

Different companies have different approaches to implementing AOC, but since *the device interface is defined at the electrical level*, the details of the optics inside the cables do not affect the performance as long as the electrical interface specifications are met. This allows vendors to optimize designs according to their technologies and to provide an accessible market for innovation. However, this also the problem of driving costs higher since the components inside the connecters are not uniform and manufacturing processes are not standardized.

3.5.5.1– Quad Small Factor Pluggable (QSFP) AOC

Relatively recently, the MSA had agreed on Quad Small-Factor Pluggable (QSFP) transceiver packaging in order to support a mild degree of parallelism for high-speed applications [43]. QSFP AOCs are developed to provide thinner cable with less loss. The main applications are for server, switches and end users in data centers. QSFPs are short-reached optical transceiver packages and present a key enabler for the AOC market to emerge. The QSFP AOC consists of 4 bidirectional parallel optical data links. Using 850nm VCSEL as its light source, each link provides a data rate from 1-10Gbps. Through the use of Coarse Wavelength Division Multiplexing (CWDM), QSFP can provide an aggregate 40Gpbs capacity. Taking advantages of low-cost and low-power-consumption of VCSELs, QSFPs consume only 1.3W for 40Gbps. Compared to a traditional SFP transceiver that consumes 600mW for 10Gbps (which equals to 2.4W for 40Gbps assuming no other modulation needed), an optical QSFP is almost 50% more power efficient than traditional transceivers [52]. QSFP AOC is designed with internally terminated optics, thus eliminating the need to clean optical connectors, which offer an added value of cost and reliability.

3.5.5.2– C-Wire

The C-wire developed by Finisar is another example of AOC that is designed based on the CXP from factor. C-wire encompasses 12 Tx and Rx bidirectional MM cables. With 10-12.5Gbps data rate for each link, C-wire provides an aggregate capacity up to 150Gbps. Applications of C-wires include InfiBand, 100G Ethernet, data centre, and high-performance computing.

3.5.5.3– Thunderbolt

Intel collaborated with Apple to develop Thunderbolt, which is also known as Light Peak. Thunderbolt is a connector that is based on the miniature version of display port (DP). Thunderbolt technology consists of a dual-protocol port, PCI Express and DiplayPort, with dual-bi-directional channels per port. Each channel can carry a data rate of 10Gbps, Figure 52 shows a schematic of thunderbolt including the connector interface connector and the inside the connector. It also utilizes 850nm VCSELs as its light sources. Thunderbolt is compatible with DisplayPort devices and provides advantages such as lower latency, faster data and display transfer, and lower power consumption all on a single channel.

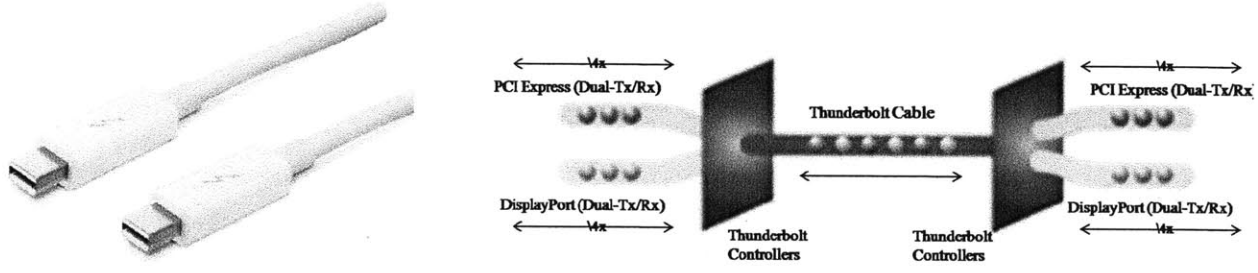


Figure 51: Schematic of Thunderbolt (left: interface of thunderbolt; right: cables inside) [53]

3.5.5.4– USB 3/HDMI

HDMI and USB ports have become two of the most common interfaces for connecting two electronics, such as computer to TV. As the demand for HDTV and BluRay DVD increases, the need for HDMI cables also increases. The most common application for HDMI AOC and USB AOC are in high-end entertaining systems. A few examples are large-format HDTVs, such as 240 Hz LCD plasma, higher-end DSLRs, and extensions of high-resolution digital graphic data and multichannel audio data transmission between two devices that are over 40 meters apart.

3.6 – The Dominant Packaging Technology

Because there is no standard package, tradeoffs occur when choosing the best package technology. For example, in chip packaging, BGA is better than QFN for high performance application but it remains too expensive for low-cost low-performance sector. Table 5 presents a good comparison between the two packaging technologies. Due to its ability to integrate more functions in SiP, the packaging solution is also better in high performance application while SoC will be preferred in low-cost low-performance applications or in portable applications that require smaller device size. In terms of cables, it can be argued that performance requirements can be achieved by increasing the number of electrical lines, or number of chips, with more accurate modulation rather than switching to optical cables or packages. However, the tradeoff comes with increasing power consumption and bigger and heavier cables (larger chips or larger optical lines).

The application for optical-electronics interconnects can be divided into 2 segments, signal processing or signal transmitting. Signal processing generally requires high level of integration while signal transmission requires a much lower level of integration. Depending on the application, the level of integration would be different. This chapter had analyzed different package technologies and their most prominent applications. There has not been one package technology that satisfied cost, device size, bandwidth performance, power and thermal issues. Although there have been efforts to standardized packages, it is proving difficult to come to one standard package to meet requirements across all applications.

4. –The Adoption of Optical Cables. How and When?

This chapter will examine the electrical and optical markets. An analysis will also be conducted to understand whether the two markets will converge, or overlap, and the events that would precipitate the change. However, this analysis will focus on the adoption of an off-board optical technology via AOC. Off-board optical technology will be more immediately deployed with a considerable market size. Moreover, AOC was selected for this analysis because there is greater existing comparable technology (electrical cable). AOC is a box-to-box fiber optic interconnect that consists of both transceivers and cables and can be plugged into existing ports without designing a new system. Because of its plug-and-play format, the risk of adopting AOC for the end users is low. They do not need to incur additional cost would be able to enjoy the benefits of higher bandwidth, smaller or thinner devices, and lighter weights from optical fiber technology. Thus, AOC is a design innovation rather than technology innovation. As a result, AOC meets the need for introducing the new technology.

It should be noted that all of the packages discussed in chapter 3 were on-board packages that are placed inside the box, with the exception of AOC.

Advances in photonic components and integration will not only simplify optoelectronic packaging, but also allow cost-effective short-reach AOC implementations. These advances will simultaneously provide decreasing sizes of the end terminal elements and the opportunity for increased system I/O bandwidth density.

The number of optical cables available in an AOC is a function of the combined number of light sources (VCSELs) found inside the AOC. The optical cables can be either multiplexed or non-multiplexed and the material can be either polymer or silica. The choice of multiplexing decreases the number of cables found inside an AOC with the level of multiplexing. The material choice also affects the analysis since different material has different refractive index and thus different loss. If polymer fibers were chosen, a graded index is necessary to minimized dispersion loss and support higher data rate. The use of graded index, however, limits the ability of the optical channel to 10 Gbps. For simplicity, the optical fiber inside of an AOC is assumed to be silica and without multiplexing in this analysis.

4.1 – AOC Market Size

According to Hausman [33], standardization is important for cost reduction, but without market demand, it is hard to increase unit sales. Therefore, in order to understand the adoption, one must first understand the market sizes of the product.

In 2009, CIR consulting conducted a market analysis in the total global active cable optical (AOC) market. As shown in Figure 52, its results show that, the market is forecasted to grow to around $1.5 billion by 2014. Across the sectors, data center equipment constitutes the biggest market value at $835 million. Currently, optical technologies have been used for intra-data center connections with reach between 10 meters to 2 kilometers. Figure 53 shows a bandwidth projection for network and server I/O. Even with a conservative projection of doubling every 24 months, the bandwidth requirement per I/O is expected to exceed 10Gbps in 2010 and reach 100Gbps by 2018. As the traffic in the data centers is multiplied and data rate grows to 10Gbps and beyond, it becomes increasing difficult for copper cables to deliver a cost-effective and power efficient performance. As a result, low-cost and high-power-efficiency AOCs have started replacing copper cables in the last 10 meters that connect servers to the TOR switch [54]. As indicated in Figure 15, the unit volume of cables increases exponentially with decreasing distance; thus, there is a tremendous market opportunity for AOCs as they start replacing copper in the final 10 meters. Other sectors include PC interconnects, home theaters, and digital signage.

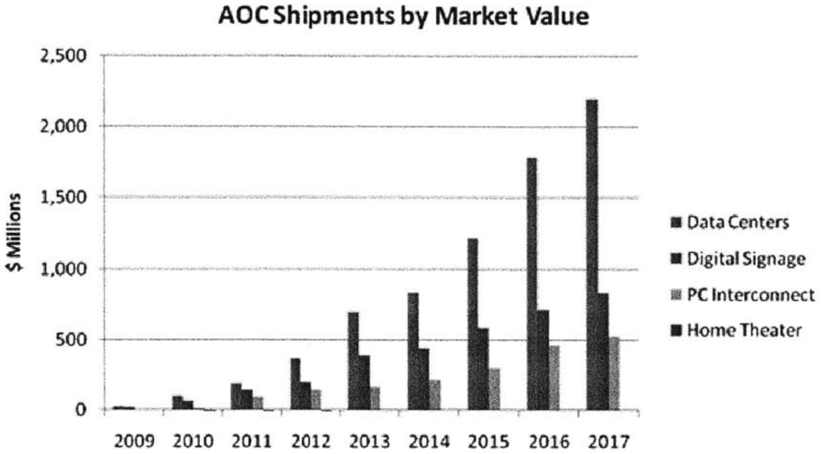


Figure 52: Forecasted AOC market value in 2014

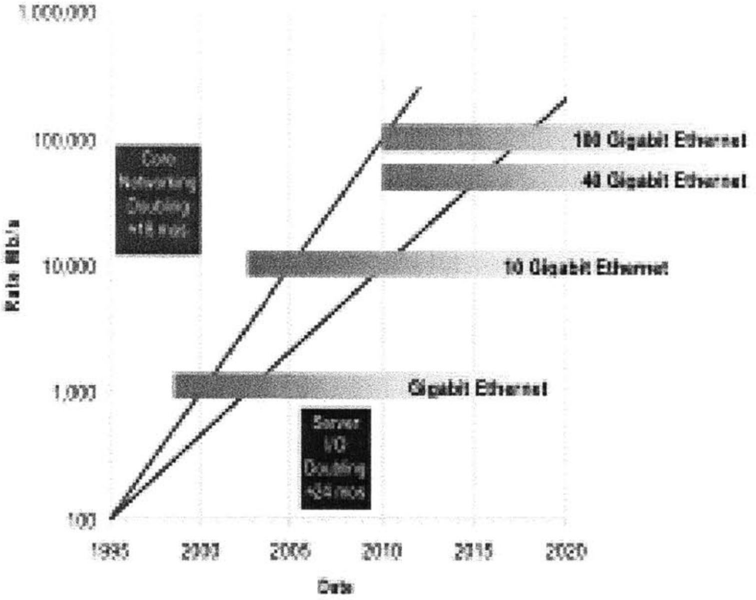


Figure 53: Bandwidth trend for networking and server I/O [54]

Tom Rossi of Solution by Design has predicted a much faster market growth, achieving $2.45 billion with personal computer markets occupying roughly 56% of the total market [55]. Figure 54 demonstrates Rossi's AOC market projection through 2014. The total market revenue is estimated to be $2.45 billion and unit demand is expected to increase 40 times to 48 million cables by 2014. In addition, though the market is projected to grow by a factor of 18, the cost per cable is anticipated to drop by 33% due to technological improvements and volume discounts achieved by economies of scale. Despite its limitation in power and bandwidth density, AOC will be the dominant approach to short distance optical links for the next 5 years due to the fact that AOCs are more reliable, cheaper and easier to implement when compared to other optical solutions.

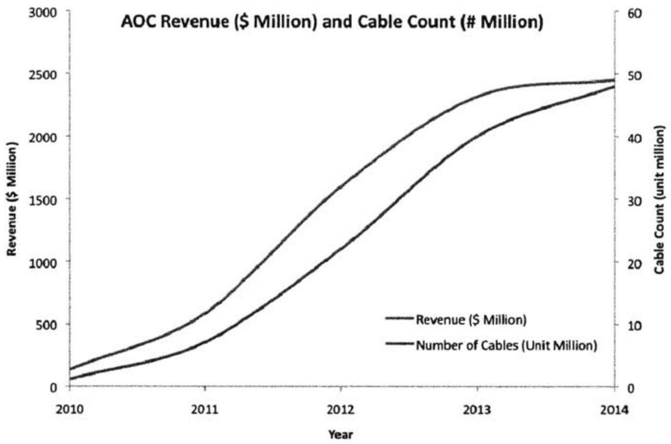


Figure 54: Projected AOC market revenue and cable count through 2014

The rapidly rising high performance consumer applications are the main driver of the AOC market. One major value creation of AOC is its ability to provide higher speed while consuming less power. Also projected by Rossi, Figure 55 illustrates the projected market share by AOC's link speed. The AOC market was dominated by 10Gbps links with $154 million in revenue and 70% of the market share [55]. This number is expected to shift dramatically by 2013 with the revenue for 10Gbps links expected to almost double but market share falling to 11% as majority of consumers begin demanding 20Gbps data rates.

Through 2013, the 40Gbps and above links will remain a small fraction of the overall AOC market because there is low demand in the consumer market. It should be noted that although small, among the 40Gpbs interconnect market, AOC dominates over copper.

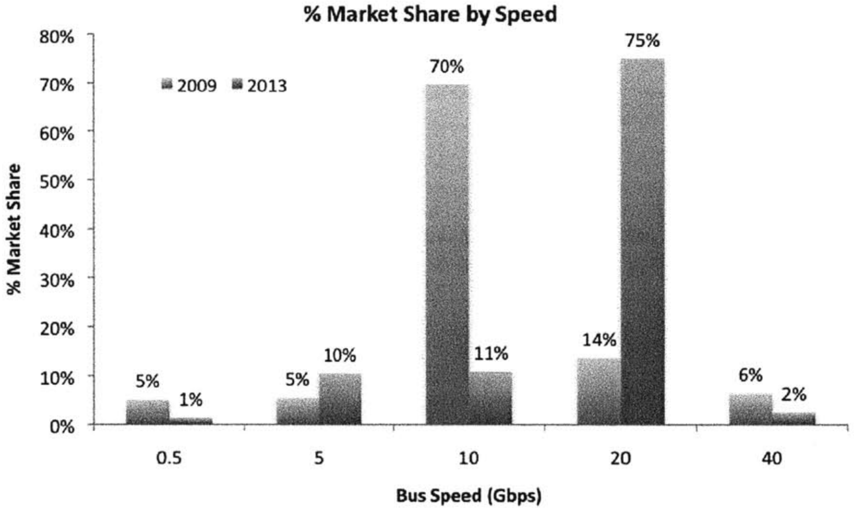


Figure 55: Projected market share percentage by bus speed

4.2 – Adoption Loop

Figure 56 illustrates a causal diagram of the adoption of circle. The demand of the development of technology is driven by business needs. As is the case for most technology sectors, new solutions are often highly customized until a dominant technology becomes the standard. Once the standard has become more widely adopted, manufacturers are able to leverage standardized processes to improve production, and enable economies of scale that drive costs down. The reduction of cost will eventually translate to the increase in the availability of product and higher adoption rates in both consumer and business sectors. The increase in consumer adoption leads to the increase in the expansion of consumer applications, thus creating stronger consumer demand signals. As consumer demand signals evolve, businesses will react and change their technology strategies and ultimately restart the circle of adoption again.

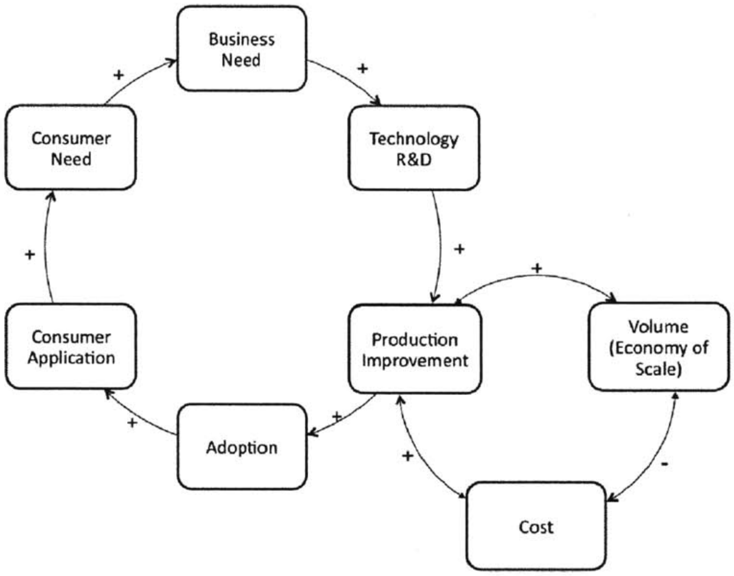


Figure 56: The circle of adoption

4.3 – Scenario Analysis – Data Center

In the past, the exponential growth of bandwidth has driven data center to bundle multiple 10Gbps links in a parallel configuration to meet such needs. Table 6 presents the IEEE standards for different 40Gbps/100Gbps, where 4 or 10 of the 10Gbps links are grouped together, Ethernet links and their maximum distance available depending on the medium [56]. This approach has led to improvement in both cost and volume in 10Gbps links and allowed consumers to adopt applications that require higher bandwidth.

Table 6: Standard physical implementation determined by 802.3ba

Standard	Medium	Reach (m)	Design Configuration	Copper
40GBASE-KR4	CAT6	1	4 x 10 Gbps	Y
40GBASE-CR4	Twin-ax Cable	7	4 x 10 Gbps	Y
40GBASE-SR4	OM3 MMF	100	4 x 10 Gbps	N
40GBASE-LR4	SMF	10000	4 x 10 Gbps	N
100GBASE-CR10	Twin-ax Cable	7	10 x 10 Gbps	Y
100GBASE-SR10	OM4 MMF	150	10 x 10 Gbps	N
100GBASE-LR4	SMF	10000	4 x 25 Gbps	N
100GBASE-ER4	SMF	40000	4 x 25 Gbps	N

As this bandwidth demand continues to rise, higher level interconnects need to scale from 10Gbps to 100Gbps with the bottommost server interconnects also demanding 10Gbps. Although bundling has been the solution in the past, it has led to load imbalance, which made it difficult and costly to scale. As a result, a new technology that is able to support 40Gbps, and eventually 100Gbps, on a single channel would be required in the near future. Because of the billion-dollar potential market of the bottommost interconnect, indicated in Figure 15, this analysis will be conducted through understanding the adoption in the sector for bottommost interconnects. Specifically, since the last 10 meters of this market sector are still mostly copper interconnects, a scenario analysis will be performed to understand how cost, power, and area of the data center will be affected by purely scaling with copper or entirely with optical. The analysis for purely optical is further broken into 3 different scenarios: keeping module costs constant, 80% learning curve (20% cost reduction), and 49% learning curve (51% cost reduction). Learning curve is referred to the efficiency gained from repeating a task. When a new process or activity is implemented, maximum efficiency is unlikely to be achieved immediately. Repetition of the task would help achieve higher efficiency over time until reaching the maximum, leading to a lower cost. This is also known as the experience curve effect. It is widely observed that in manufacturing industries, the cost of manufacturing will decrease by a constant amount whenever the production volume doubles, typically between 10-25%. An 80% learning rate means the cost of the product will fall by 20% of its previous cost (or become 80% of its previous cost).

4.3.1 – Understanding the Effects of Area, Cost, and Power

Since optical is a relatively new technology, cost of optical components is expected to decrease due to learning curve effect. The cost of copper cables is expected to increase as bandwidth rises due to higher loss and larger core diameters, thus requiring more materials and more expensive handling. However, in this analysis, cost is kept relatively constant, representing the upper-bound, or best case scenario for copper.

In terms of power, both copper and optical are estimated to scale relatively linearly with bandwidth. An important factor to take into account is heat dissipation. As the power of cables continues to increase, there needs to be higher capability for heat dissipation, thus driving power for cooling higher. The power consumption of copper also scales relatively linearly with distance. Since most loss occurs during signal transportation for copper, the longer the distance, the higher the power requirement. On the contrary, the power consumption of optical does not scales with distance. Optical has minuscule propagation loss. Because most optical loss occurs at the interface where optical signal is converted into electrical or when electrical signal is converted into optical, power consumption for optical is distance dependent.

For the scaling of area, both copper and optical are also assumed to scale linearly with bandwidth. For copper, it is assumed that each copper cable is connected to two connectors, which will scale at the same rate as cable increase. However, this should represent the worst-case scenario since a connector can have multiple channels of cables, the rate of area increase should be flatter than the bandwidth growth rate. For optical, we assume each connector can connect up to 12 cables. Although technology can improve throughout the roadmap and the optical connectors might be able to host more than 12 cables in the future, the following analyses do not assume this case.

Currently, CAT5E, the earliest IEEE standard for gigabit Ethernet, cables are the most widely used copper cables in the data center. Although faster types of copper cables have surpassed CAT5E, CAT5E will be the focus of discussion in this analysis. According to a Cisco data center report [57], a CAT5E copper cable can provide a maximum data rate of 1Gbps for a maximum distance of 100 meters. One can also examine the figure of merit of interconnects to understand why the scaling of copper is unsustainable. Traditionally, the figure of merit has always been

$$FOM_{old} = L \times B \qquad \text{Equation 3}$$

where L is the distance or reach in meter and B is the bit rate in Gbps or GHz. It does not take into account for the increase in area, cost, and power consumption caused by the increased bandwidth-distance product. These factors have drawn more attention recently as the effects of these factors have become increasingly more significant. As a result, a new figure of merit was developed over the years and is described in chapter 1 $FOM = \dfrac{R \times G}{A \times \$ \times J}$ Equation 1.

To understand the effect of these factors, one can examine the following situation. Supposed the data center wanted to scale the 1Gbps to 10Gbps for 100 meters. In this case, 10 CAT5E cables will be required. With the assumption that there is no extra power needed to drive the synchronization of the 10 cables and bundle the 10 cables without incurring extra waste in space at the same time, scaling to 10Gbps for 100 meters with CAT5E will require 10 times greater area, 10 times higher cost, and another 10 times more power consumption.

For comparison, an alternative solution, such as optical interconnects, can be reviewed simultaneously. In this case, one can choose between the IEEE standards: OM3 or OM4. Since CAT5E, which has low performance but is also the least costly compare to other twisted copper standards, was chosen for the copper case, one should also choose OM3 who has a poorer performance but also has a lower cost than

OM4. OM3 is a laser optimized MMF that utilizes 850nm VCSEL as its light source. The MMF cable has a core diameter of 50μm and a cladding diameter of 125μm. Because optical fiber is a newer technology, it will cost more than copper cables. Part of this cost is offset by the decrease in power consumption in optics and a shrink in optics cable size, and thereby keeping the FOM slightly smaller than copper. In addition, OM3 is able to transmit data rate of 10Gbps for as far as 220 meters, thus one OM3 cable alone would be sufficient to support the 10Gbps signal transmission through 100 meters fiber, avoiding the 1000 times of FOM reduction. This gap will only multiply as the data rate requirement continues to increase. When the data rate is increased to 100Gbps with 100 meters transmission distance, it will require 100 CAT5E cables, resulting in a 1 million times reduction of FOM while it will only reduce OM3's FOM by a factor of 100 times. The widening of the gap is illustrated in Figure 57 where the figure of merit of copper started higher than optical because of its lower cost and its ability to meet the bandwidth demand without sacrificing much of distance. However, as bandwidth rises, the rate of reach penalty for copper becomes more significant than optical, and results in a much lower bandwidth-distance product.

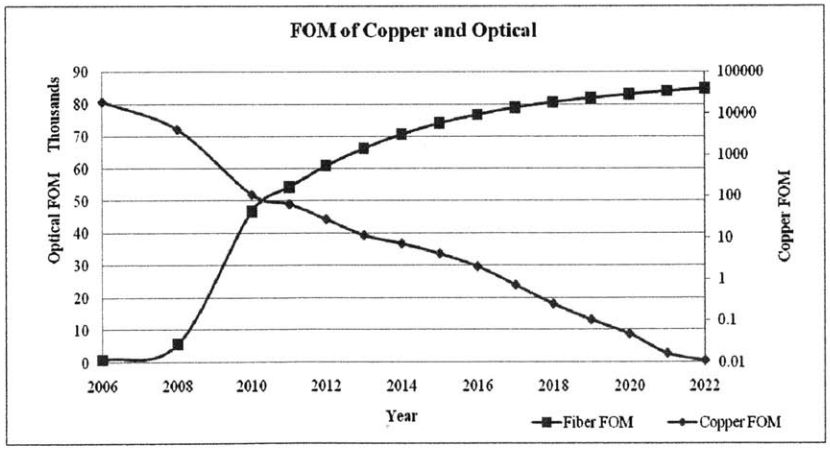


Figure 57: FOM of copper and optical given increasing bandwidth

An analysis of figure of merits was conducted by examining four different scenarios that were mentioned above in order to investigate the scaling of the interconnects and to further understand how, and when, the increase in bandwidth requirement will drive the adoption of optical technologies. Besides scenario analysis on figure of merits, cost analyses for different scenarios are also examined in order to better understand the rationale behind the slow optical adoptions. Questions such as "why hasn't optical already been widely adopted?" or "why hasn't optical been adopted faster?" might arise.

In all four scenarios, the following common assumptions that were made. The initial bandwidth requirement is 10Gbps in 2010 and will increase at a 50% rate each year. Different distances will be examined: 10 meters, 1 meter, and 5 centimeters.

The goal of this analysis is to understand how cost reduction result from standardization would affect the adoption of new technology.Thus it is very important to keep in mind that the only variable that was changed is cost of optical connectors and modules. As new technology advances, optical power efficiency may and most likely will improve, which would result in an earlier adoption timeline. However, for the purpose of this study, variables such as power efficiency and other technology advancements were kept constant. A potential future work can be to examine how the reduction of optical power consumption would affect the adoption.

4.3.2 – Scenario 1 – Scaling by Copper (CAT5E)

4.3.2.1– Assumptions

This scenario looks at scaling all the interconnects from 1Gbps to 10Gbps per link by using only CAT5E copper cable. For the CAT5E cables, there are different price references due to different applications.

According to an interview with Dick Otte from iNEMI, he has estimated a CAT5E cable cost of $0.05 per meter. In terms of other components associated with the copper interconnects, he has also anticipated a cost of $2 per SERDES. From another interview with Douglas Cannon who was formally in Amphenol TCS [58], it was estimated a connector cost of $1.5 for 2 differential pairs that are running 10Gbps each, which means the cost of connector is roughly $0.05-01/Gbps.

An industry rule of thumb for copper is its performance limitation at a data rate of 10Gbps. When the data rate reaches 10Gbps, signal can only travel as far as 3 meters in a copper cable. Beyond that, the effectiveness of copper is compromised. In order to meet the requirement of 10Gbps for 10 meters, 3-4 cable segments are needed. In addition, there are 2 connectors and 2 serializer/deserializer (SERDES) in each cable.

One important fact to keep in mind is that each of the cost is based on scaling only one of the interconnects. If one assumes 10 million interconnects in the bottommost application for an average size data center, one can get an approximate cost for scaling the interconnects (excluding other hardware costs) by multiplying cost per link with 10 million units. The number of links can be growing as well, however, since this analysis only examine the base cases, it is assumed to be constant.

Due to the RC delay and skin effect, the maximum reach length decreases with increasing frequency. Skin effect forces the current to flow only near the surface, thereby reducing the effective cross section. Since resistance is inversely proportional to area cross-section, the higher the skin effect, the lower the effective area. This led to a higher power requirement to compensate for the RC delay and I^2R losses, or a large reach penalty, if the same power input was to be maintained.

In order to compensate for cross talk and insertion loss, Corning's Lanscape report [59] has estimated a system requirement of 10-15 watts at the interface for a 10Gbps copper interconnect traveling for 3 meters. A pertinent issue with power consumption is higher heat dissipation and greater cooling requirements. The power consumption for cooling and all the other power that does not contribute to computing of the system can be estimated by power usage efficiency (PUE). It has been estimated that a well-managed data center should have a PUE factor of 2. This means that for every watt of power consumed by the server, an additional watt is being used for cooling, lighting, and administrative office power consumption. In the most cases, however, data centers are not as well-managed, and would have a PUE of 3, or even 4 for the very inefficient cases. This translates to 2-3 watts of extra power being consumed for cooling.

In the analyses, a PUE of 2 is assumed, which means the total power consumption for every increase in 10Gbps copper interconnects is assumed to rise by 26 watts (13 watts from running the servers and 13 watts from cooling). The cost of consumption is estimated to be \$0.13/kWhr. Therefore, the cost of energy can be roughly estimated to be .026kW x \$.13/kWhr x 8760hrs/yr = \$29.6 per year. For 10 meters scenario, power is assumed to be 13 watts per 10Gbps for a 3-meter link. For 1-meter scenario, this will drop to 8.5 watts per 10Gbps because it only needs to transmit 1/3 of the distance, and further down to 1 watt per 10Gbps for a 5-centimeter link.

The standard size of a CAT5E cable is 26 American Wire Gauge (AWG), which accounts for an area of 0.129 mm^2 per cable. Depending on how many cables are being bundled to meet the bandwidth demand, one can calculate the total area of the cables. The efficiency of data center is categorized in 4 different tiers, from 1 to 4 describes from most efficient to the least. Many data centers include the cost of space for powering and cooling by first calculating the power density in W/m^2 and multiplying by its Tier of functionality. This would result in a cost in terms of kilowatts. Then multiplied by \$/kWhr, one can get the total area cost. While this is how most data centers calculate their cost of space, it will not be used in this analysis because it require further assumption on efficiency, layout, and location of the data center.

Instead, this analysis will take a simple base case and look at the cost of area in terms of the area needed to install the network cables itself. Copper cables become larger and thicker as data rate increases, which are space consuming, heavy, inflexible, and hard to manage. Although the cable itself is fractional compared to the rack, cooling machines, and UPS, the more cables entail higher number of racks and thereby more space because there is a limit in the number of cables allowed in the rack. This approach to estimate area cost of network cables is considered to be conservative. Figure 58 presents a comparison between an all-electrical environment and an all optical interconnect environment. For the same data rate, optical interconnects can be fit in a box with thinner and more flexible core while electrical requires much more space as well as larger and inflexible [60]. In an Intel report, it is estimated an average data center has a cost of area of \$2,257/m^2 [61]. The total cost of area is calculated by using the following equation:

$$\textit{Total Area of Cable} \times \$ \textit{ per Cable} = \textit{Total Cost of Area} \qquad \text{Equation 4}$$

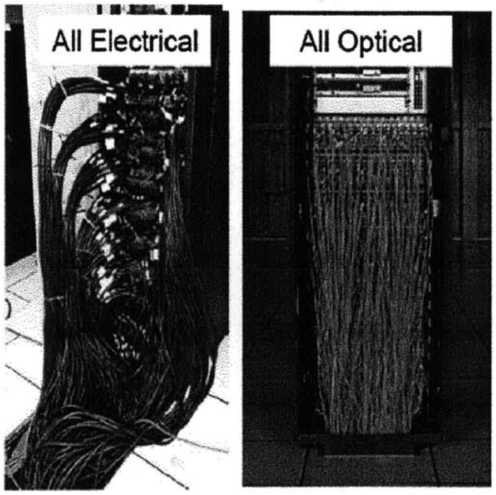


Figure 58: IBM federation switch – a comparison between copper and optical interconnect [60]

4.3.2.2– Results

Table 7 shows a summary of cost for scaling with CAT5E by changing reach. **Table 8** presents FOM analysis of the same scenario. These numbers will be compared with costs and FOM with different scenarios in the subsequent sections.

Table 7: Cost analysis of scenario 1, scaling completely with copper

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	0.22	0.50	1.13	2.54	5.72	12.87	28.95
1 Meter	0.05	0.11	0.25	0.55	1.25	2.80	6.31
5 Centimeter	0.03	0.06	0.14	0.32	0.73	1.64	3.68

Table 8: FOM analysis of scenario 1, scaling completely with copper

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	266.34	52.61	10.39	2.05	0.41	0.08	0.02
1 Meter	17371.3	3431.37	677.80	133.89	26.45	5.22	1.03
5 Centimeter	150377	29704.1	5867.48	1159.01	228.94	45.22	8.93

4.3.3 – Scenario 2- Scaling by Optical (OM3) with Constant Cost

4.3.3.1– Assumptions

The second scenario looks at the cost for a data center if it decided to scale everything with only OM3 MMF. The area that is used in this calculation is 0.0065mm^2 since an OM3 has a core diameter of 0.05 mm and cladding diameter of 0.13 mm, According to Otte's assumption, a meter of MMF has a cost $0.2, thus a 10-meter MMF will cost roughly $2 per 10-meter-link. The 2 connectors and modules at each end of the MMF are the more expensive components, with each costing $100 but can connect up to 12 cables per connector. In order to examine the effect of cost on adoption, cost of components is assumed to stay constant in this scenario. Optical cables do not encounter the same signal issues that impact copper and eliminates the necessity for SERDES. However, transceivers are needed at each end of the optical cables in order to transmit/receive lights to convert them to/from electrical signal from/to optical signals. According to iNEIMI's projection, the cost of transceivers will be around $3.50/Gbps in 2010 and will decline at 36% per year to $0.24/Gbps in 2022. It is also assumed that number of cables able to be connected to a connector will remain at 12 throughout the forecasted years. Since OM3 MMF is capable of transmitting 10 ofGbps data up to 220 meter, only one cable segment is needed for 10Gbps. The bandwidth demand will start at 10Gbps and grow by 50% each year.

According to Corning's report, optical cables at 10Gbps consume about 9 watts less than electrical. Therefore it is assumed each optical cable will consume a power of roughly 5 watts. While there is some power loss due to attenuation, it is not included in this model since the distance is so short that the effect is minimal. The 5 watts is consumed by the transceivers and used to drive the electrical-optical-electrical conversion; therefore, the power consumption does not change for 10-meter applications, 1-meter applications, or 5-centimeter applications. Same as scenario 1, the cost of electricity is assumed to be $0.13/watts, cost of space is estimated to be $2257/m^2, and a PUE value of 2 is used to conduct this analysis.

4.3.3.2– Results

Table 9 illustrates a summary of cost for different reaches when scaling with OM3 while keeping component cost constant through the projection. Table 10 presents the FOM analysis of the same scenario. The cost of scaling with optical is actually more expensive than scaling with copper, even for 10-meter reach application, if we keep the modules and connectors cost constant. However, as mentioned earlier, this is unlikely to be the case. Since optical technologies are relatively new technologies, a learning curve is likely to occur throughout the projection. The next scenarios will look at different learning curves and their effects on costs and FOM.

Table 9: Cost analysis of scenario 2, scaling completely with optical, constant case

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	2.38	2.58	2.89	3.43	6.64	13.74	29.13
1 Meter	2.37	2.54	2.80	3.22	6.17	12.67	26.73
5 Centimeter	2.36	2.53	2.79	3.20	6.12	12.56	26.48

Table 10: FOM analysis of scenario 2, scaling completely with optical, constant case

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	1754.23	724.91	290.68	111.42	25.76	5.57	1.17
1 Meter	1767.65	736.61	300.37	118.86	27.80	6.05	1.28
5 Centimeter	1769.08	737.87	301.43	119.71	28.04	6.11	1.29

4.3.4 – Scenario 3- Scaling by Optical (OM3) with 80% Learning Rate

4.3.4.1– Assumptions

The assumptions in this scenario are the same as scenario 2. The bandwidth requirement is assumed to start at 10Gbps and increases by 50% each year. The three different reach distances, 10 meters, 1 meters, and 5 centimeters are also examined in this scenario. The cost of optical is \$0.2/meter, each of the connect costs \$100 and can connect up to 12 cables. However, one difference from scenario 2, it is assumed that the cost of connectors will reduce as more company start adopting optical. It is assumed that whenever the manufacturing volume doubles, the cost will drop by 20%. Despite Otte's prediction of a higher learning rate for IC industry, many industry research groups and consulting groups have indicated an average of 10-25% of learning curve in various industries, 20% is chosen to take a conservative estimation.

The power is also assume to be 4 watts/cable, cost of power is \$0.13/watts, cost of space is \$2,257/m^2, while each cable requires a area of 0.0065mm^2. Again, the calculation is for scaling per cable, therefore, cost per cable is multiplied by 10 million units of interconnect cables.

4.3.4.2– Results

Table 11 presents the cost analysis result for scenario 3 where it is scaled with OM3 with an 80% learning rate incorporated in the analysis. Table 12 is the summary of FOM analysis for the same scenario. With the benefit of 20% cost savings, one will see the advantage of scaling with optical in 10-meter applications, but not yet in 1-meter or 5-centimeter applications. The next scenario will examine a more aggressive cost saving curve and see how it will differ

Table 11: Cost analysis of scenario 3, scaling completely with optical, 80% learning rate case

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	2.38	2.58	2.87	3.32	5.00	8.63	15.43
1 Meter	2.37	2.54	2.80	2.81	4.62	7.94	13.87
5 Centimeter	2.36	2.53	2.79	2.80	4.58	7.87	13.71

Table 12: FOM analysis of scenario 3, scaling completely with optical, 80% learning rate case

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	1754.23	724.91	292.78	170.59	34.84	9.18	2.34
1 Meter	17371.3	3431.37	677.80	136.90	26.45	5.22	1.03
5 Centimeter	1769.08	737.87	301.44	137.79	38.19	10.13	2.67

4.3.5 – Scenario 4- Scaling by Optical (OM3) with 49% Learning Rate

4.3.5.1– Assumptions

According to ITRS's projection, the number of transistors in a MPU is expected to double every two years while the cost of MPU is expected to fall by 30% every year. This means that the cost of transistor is expected to fall 51% for every time the number of transistors volume doubles. Therefore, scenario 4 will look at the cost analysis and FOM analysis of scaling with OM3 but with a 49% learning rate.

Besides having a 49% learning curve, all the other assumptions in this scenario is the same as scenarios 2 and 3. The bandwidth requirement will start at 10Gpbs with 50% increases per year, transceiver prices will start at \$3.50 but decrease at 36% per year, fiber cable costs \$0.2/meter, and connector costs \$100 each. The power per cable remains throughout different reach distances at 4 watts while cost per power is \$0.13/watts. The cost per area is \$2,257/mm^2 while the area of cable remains 0.0065mm^2 per cable.

4.3.5.2– Results

Table 13 presents the cost analysis of scaling with optical cable but with 51% cost reduction for components. Table 14 shows the FOM analysis for the same scenario. Optical becomes much more competitive in this scenario at both 10-meter and 1-meter applications. However, at 5-centimeteres this saving become minimal because we are assuming each optical cable can provide a maximum data rate of 10Gbps, when it exceeds 10Gbps, a new cable would be needed. With data only needed to transmit over 5 centimeters, the loss for copper becomes so small that it would make sense to transfer the data with copper rather than optical. Unless SMF with WDM is utilized in a waveguide, or the cost of copper raw material or cost of energy rise dramatically, copper will cost less than optical in distances less than 5 centimeters.

Table 13: Cost analysis of scenario 4, scaling completely with optical, 49% learning rate case

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	2.38	2.58	2.84	2.29	3.14	4.38	6.78
1 Meter	2.37	2.54	2.79	2.19	2.90	4.10	6.16
5 Centimeter	2.37	2.54	2.79	2.18	2.90	4.10	6.16

Table 14: FOM analysis of scenario 4, scaling completely with optical, 49% learning rate case

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
10 Meter	1754.23	724.91	296.10	178.57	58.17	20.03	6.38
1 Meter	1767.65	736.61	300.94	179.00	63.30	21.52	7.18
5 Centimeter	1769.08	737.87	301.46	179.93	63.89	21.69	7.27

4.3.6 – Comparison

Different scenarios were presented and compared in the previous sections. This section will look at comparison and impact between different scenarios whiling keeping the distance constant. Figure 59 shows the FOM analysis for 10-meter applications. All four of the scenarios have a decreasing figure of merit as bandwidth requirement increases. From this figure, one can see that optical is more advantageous in each of the scenarios. This means when scaling a 10-meter cable to 10Gbps, it will be more robust to scale with optical. Figure 59 validates the statement that the gap between optical and copper performance will widen as bandwidth requirement increases.

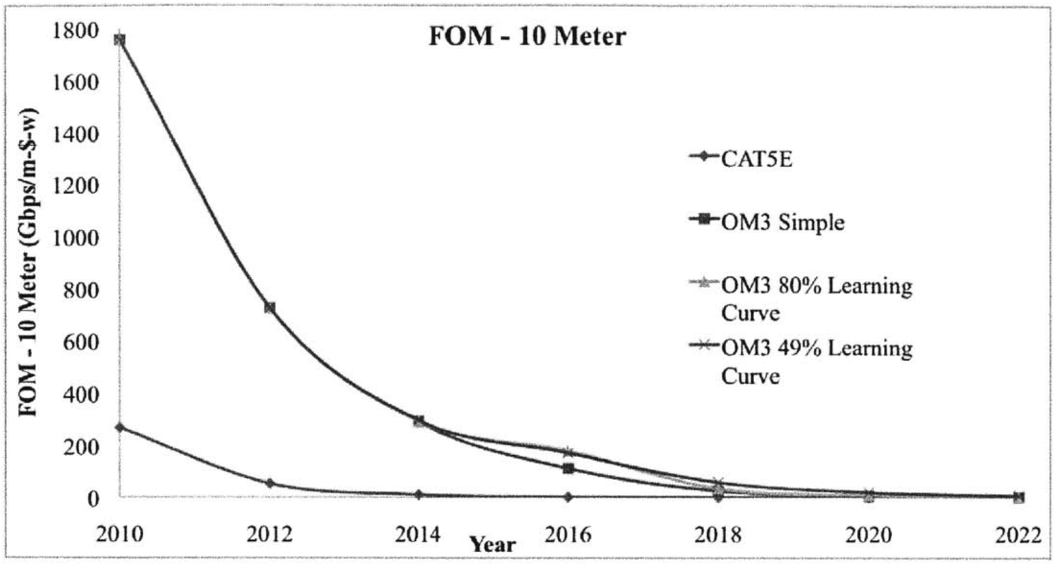


Figure 59: FOM of different scenario for 10-meter links

Figure 60 is a graphical summary of the cost analysis for all 4 scenarios for 10-meter applications. Contrary to the FOM analysis, Figure 60 suggests that it would be cheaper to scale with 10-meter CAT5E cables, even compared to scenario 4, when the bandwidth demand is 10Gbps. As the data rate continues to increase to beyond 100Gpbs (2016), it become cheaper to scale with optical cables. This coincides with Luxtera's road map [62], which stated that 10-100Gbps is the tipping point to switch to optical and that there is no readily solution to scale 100Gbps with copper. Figure 60 presents a potential adoption timeline for optical interconnects for 10-meter applications. If the bandwidth demand increases more than the predicted 50% per year, it will pushes the adoption earlier. On the other hand, if the cost of transceivers and optical components do not reduce or reduce at a lower rate, then optical adoption for 10-meter cables will be delayed.

It is important to understand the difference between FOM analysis and cost analysis before further examining the data. Since cost analysis requires many assumptions, such as the cost of electricity and cost of area, the analysis result depends greatly on the validity of assumptions. The conclusion may be different depending on these cost assumptions. On the other hand, FOM analysis does not need to assume cost for power or cost of area; thus, FOM analysis can give us a more unbiased insight to further understand the tradeoff between performance, power, and costs.

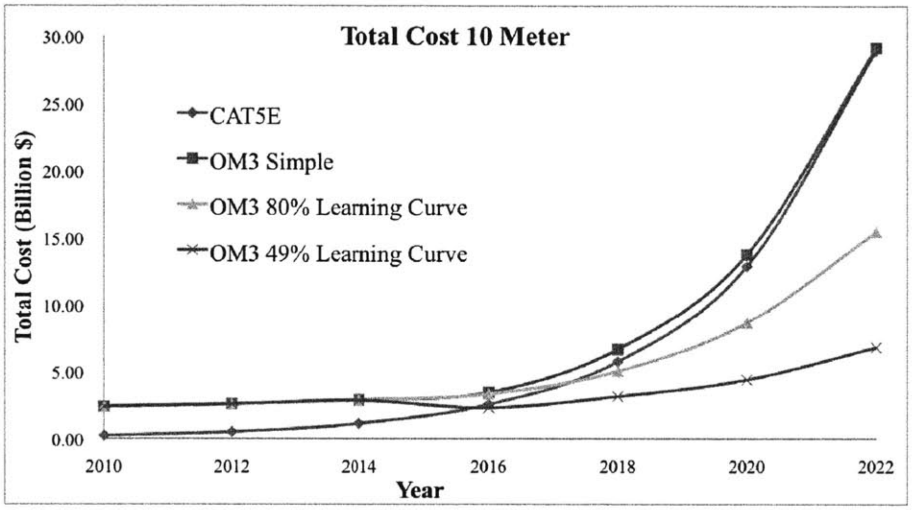


Figure 60: Total cost of scaling for 10-meter links

Figure 61 shows the result of FOM analysis for 1-meter links. It is seen that copper has a much higher FOM when the bandwidth is low, at 10Gbps. This advantage drops, however, dramatically when data rate increases to 22.5Gpbs (2012). This is because 22.5Gbps requires 23 segments of CAT5E cables to provide enough bandwidth. As mentioned in earlier sections, more cables mean more power consumption and thus leading to a lower FOM. The FOM of copper drops below optical's beyond 50Gbps (2014) indicating that optical becomes more attractive when the data rate goes above 50Gbps.

Figure 62 illustrates the result for the cost analysis for the 4 scenarios for 1-meter link. From the figure, it shows that the crossover point occurs in 2022. For 1-meter applications, this indicates that scaling with copper is going to be less costly until the bandwidth requirement reaches 1,300Gbps. Furthermore, at 1 meter, it requires an aggressive cost reduction of optical in order to compete with electrical. Keeping cost of optical components constant or reducing at lower learning rate will make optical technologies unattractive for 1-meter applications. Therefore, the optical learning rate must be at least 49% following the electrical IC industry, or else the crossover point will not occur in 2022. This is an aggressive estimate and can be risky to invest in optical for 1-meter applications. However, since optical technologies are relatively new technologies, the performance is expected to improve over the years. For example, this model looks at only the base case and does not assume an improvement in power efficiency for optical cables. If this performance improvement is incorporated, one will see the crossover point happening earlier than 2022.

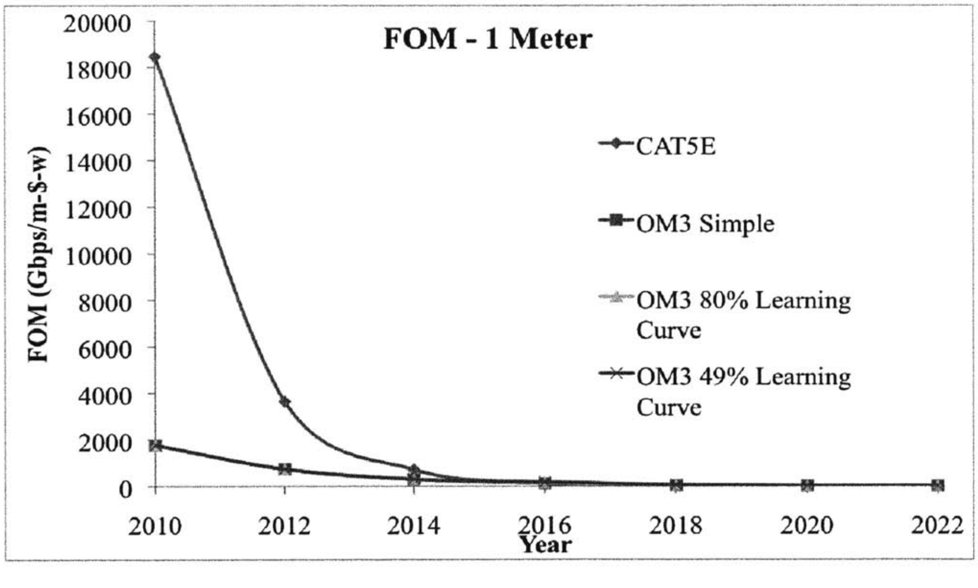


Figure 61: FOM of different scenario for 1-meter links

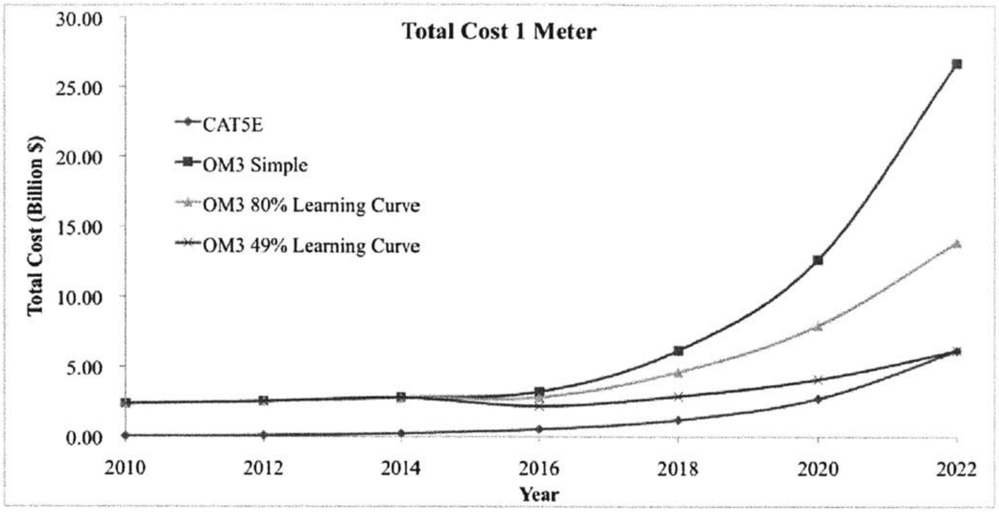


Figure 62: Total cost of scaling for 1-meter links

Figure 63 shows the result for cost analysis for 5-centimeter links. The figure is in logarithm scale because copper's FOM is far larger than optical's in almost every single scenario until 2020, Optical costs must be reducing at the aggressive learning rate (49%), or above, in order to achieve a higher FOM than copper after 2020. The reason for copper to have a much higher FOM for shorter distance is its saving on power consumption. Since most of the power/signal degradation is due to propagation loss, the shorter the distance will lead to smaller losses and thereby decrease the power consumption. On the contrary, optical's power consumption comes from the interface instead of propagation. Therefore, even in short distances, optical has to incur almost the same amount of power consumption as long distance, losing its advantage in power saving. However, as bandwidth requirements increases, optical can be more attractive once again due to the number copper required to provide higher bandwidth. Other considerations can also be taken into account for deciding between copper and optical. For example, short distance applications typically face space constraints, which makes copper a not viable solution.

Figure 64 presents the cost analysis results for 5-centimeter links. One can see from the graph, even with 49% learning rate, the cost of optical is still higher than copper. As a result, the same conclusion can be drawn from Figure 64, which shows that unless cost of optical components decreases dramatically, optical technologies will not be adopted into shorter distance applications. This is because as mentioned above, optical's power saving compared to copper becomes miniscule as distances become shorter. As a result, the high cost of optical components dominates and reduces optical's FOM in short distance. Although optical has higher bandwidth capability than copper, MMF is limited at 10Gbps per cable. While copper is also capable to provide a 10Gbps data rate at a shorter distance, the savings of optical become subtle in short distance. Therefore, in order for optical to be competitive with copper in short distance applications, the system must be all-optical to remove the extra power consumed at the interface. For further analysis, one can examine the effect and benefit of SMF and DMW in both longer and shorter distance applications.

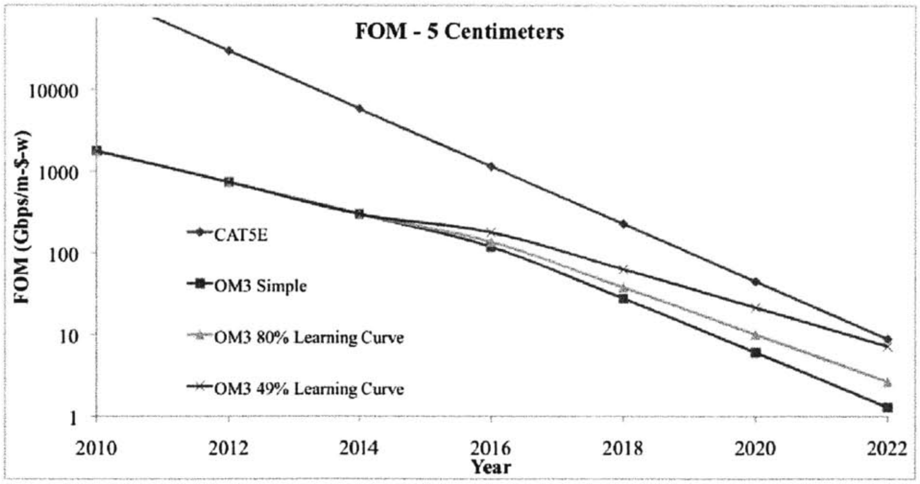


Figure 63: FOM of different scenario for 5-centimeter links

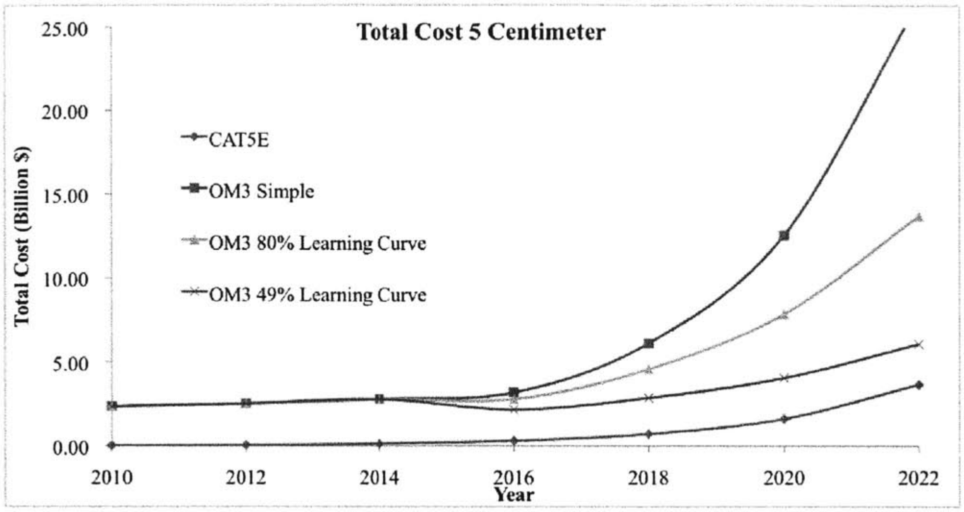


Figure 64: Total cost of scaling for 5-centimeter links

Since copper's power consumption become much smaller as it moves towards shorter distance, future research can be conducted to look at power saving due to shorter-distance and better integration for both copper and optical technologies. Many resources have been allocated in this research area. For example, Vladimir Stojanovic from MIT has been working on lower power integrated laser chip and lower power on-chip metal waveguide.

Although only the cost of reducing optical modules and connectors are explored in this analysis, the model is set up in which further analysis can be conducted to investigate other effects such as the increase in energy cost and cost per square meter on overall scaling cost. Through the scenario analyses, one can conclude that as bandwidth increases, scaling with copper becomes unsustainable, especially in terms of power consumption. In addition, although some FOM analyses do not agree with cost analyses for when the crossover occurs, a general conclusion can be observed that copper will have an advantage over optical when the distance required is shortened. Furthermore, regardless of the reach, Figure 60, Figure 62, and Figure 64 have shown that it would not have made sense to scale with optical if the cost of optical components remained constant. As a result, in order for optical's advantages to be fully recognized, standardization and thus mass production must happen in order to drive down the cost of modules and transceivers.

4.4 – The Role of Cost of Capital

4.4.1 – Adoption Impedance

Both FOM and cost scenario analyses have indicated the advantage of scaling with optical interconnects can be advantages for longer distances and higher bandwidth applications if the cost of the components is reduced. There is no question that optical can provide more robust performance, but from scenario analyses, the cost remains too high, offsetting such advantage. Besides the higher optical cost due to lack of standardization in the industry, one must understand user's habit, preference, and most importantly, the drivers behind these needs in order to answer the question that was raised in the previous chapter: "why hasn't optical been adopted faster?" According to Feldstein at the Micro-Photonics Conference in 2005, the slow adoption of optical can be attributed to 5 other factors: lack of backward compatibility of hardware and software infrastructures, incompletely supply-chain supports, lack of knowledge or skills in the new technology, strong resistance from electronics industry legacy, and the sunk cost of existing infrastructure while requiring additional cost of capital for new technology [8].

Even though in many cases, the FOM and cost analyses have indicated a better performance for optical, the switch has not happened. Because copper has been around for so many decades, the end-consumers have already invested in the infrastructure needed in placed, and they are also comfortable with the capability of the technology. Copper has been the main transmission medium for the past half of century. Regardless of the material's limit, the industry wasted significant amount of resources in research and development. Nonetheless, the industry's researches led to tremendous improvement in copper performance, and thus pushing copper's limit. As a result, copper has proven itself over the years in meeting the growing consumer demands. There is not a strong incentive for the end consumers or businesses to switch to optical since it requires more capital investment as well as inherent with higher risks in terms of performance and meeting the needs to backward integrate with the existing technology.

4.4.2 – Cost of Ownership

A transition period is required for any adoption of new technology or product. For any adoption of new technology or product, there needs to be a period of transition. In this section, cost of ownership will be examined to understand the transition from electrical to optical. Cost of ownership incorporates both initial investment and subsequent operational cost in order to provide decision makers a cost basis comparison to determine the economic value of an investment.

A major factor that hinders the transition between electrical and optical is the heavy loaded upfront investment for optical and the sunk cost of existing infrastructure. Usually, business in need for bandwidth increase is often incremental and most of the time the business would have already owned some of the bandwidth capacity. The incentive for businesses is to spend less and save more. In many cases, this incentive means looking at short-term profit and loss (P&L) for the managers because their performance is often reviewed annually. Therefore, it is a difficult decision for businesses to replace the whole existing infrastructure, as it requires significant capital investment, even if it will benefit the enterprise after number of years. Focus on the initial upfront cost and disregard the incremental cost may result in detriment of a business.

Take data center for example, the total cost of ownership (TCO) can be simplified to be

$$TCO = \frac{Initial\ Capital\ Investment + Operating\ Cost_{year}}{Traffic} \qquad \text{Equation 5}$$

In the past, the operating costs (cost of energy for servers and cost of power and cooling infrastructure) have not been significant compare to the initial capital investments (servers, machines, and other equipments). As a result, it was acceptable for the decision makers to look at only cost of initial cost of investment. Consequently, the focus has always been on driving down the equipment costs, hence adding capacity through incremental changes rather than infrastructural changes. The equipment cost is, however, no longer the case. As energy consumption scales with growth in bandwidth and cost of energy increases, the operating power becomes a major source of cost for data centers. The operating power has drawn more attention to data centers and thus shifts the attention from driving equipment costs down to focus on reducing operation cost.

To further examine the total cost of ownership, considered the scaling of 10-meter links with the 4 case scenarios that was described in section 4.3. Typical applications of 10-meter links include rack-to-rack and server-to-server interconnections. Recall that in each case scenario, servers and other hardware equipments were not included in the calculation. Therefore, by using the total cost of scaling of 10-meter links that is obtained from **Table 7**, **Table 9**, Table 11, and Table 13, one can do a quick calculation on the TCO of interconnects each year excluding hardware costs through Equation 5. The result of the TCO is presented in Table 15.

Table 15: TCO for 10-meter links

Year	2010	2012	2014	2016	2018	2020	2022
Bandwidth Requirement (Gbps)	10	22.5	50.62	113.9	256.3	576.7	1297.5
CAT5E	$22.31	$22.31	$22.31	$22.31	$22.31	$22.31	$22.31
OM, Constant Cost ($ Million)	$238.35	$114.64	$57.16	$30.11	$25.92	$23.82	$22.45
OM, 80% Learning ($ Million)	$238.35	$114.64	$56.76	$29.12	$19.52	$14.97	$11.89
OM, 49% Learning ($ Million)	$238.35	$114.64	$56.14	$20.14	$12.24	$7.60	$5.23

These numbers represent the dollar cost per each Gbps provided. From Table 15, when the bandwidth is low, copper provides a cheaper solution for transmitting the data needed. However, as bandwidth increases, optical becomes cheaper while copper remains constant. Due to the fact that growing bandwidth leads to higher loss and cross talk, scaling with copper requires better quality of cables or better cable management, and thus driving the cost up. As noted above, it is unlikely that cost of copper remains constant as bandwidth rises. Therefore, this analysis also presents the best-case scenario or upper-bound of scaling with copper. From Table 15, one can conclude that at a higher learning rate, optical becomes more attractive when bandwidth rises beyond 100Gbps (2016) while with a lower learning rate, the crossover point only happens when bandwidth reaches 200Gbps (2017). This finding agrees with the cost analysis in Figure 60.

4.4.3 – Energy Cost to Acquisition Cost Ratio (EAC)

Now consider the effect of including the hardware costs as the initial investment. As the traffic in data center continues to grow due to video on demand and other applications, the quantity and cost of energy consumption also increases. Figure 65 illustrates the increasing power density for different equipments in data center over time [61]. Moreover, the historical trend has shown that while the power density is expected to grow rapidly due to higher performance of the server, the cost of server is anticipated to remain relatively constant. As a result, the focus of TCO has shifted from initial capital cost dependent to operating cost dependent.

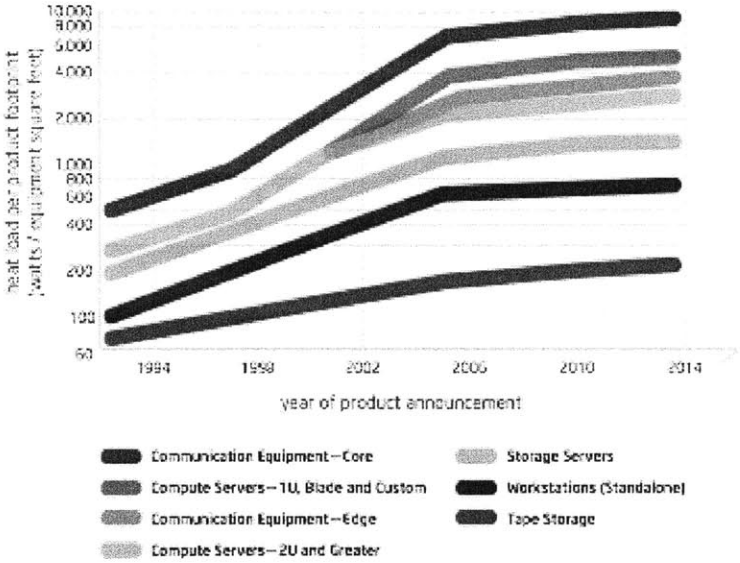


Figure 65: ASHRAE datacom power density trend chart [61]

To further understand this shift in emphasis, data centers have developed a new metric to evaluate the relative cost of servers to operation costs. The new metrics, energy cost to acquisition cost ratio (EAC), examines the ratio between 3-year cumulative energy costs to acquisition costs, and it is calculated through

$$EAC = \frac{3 - year\ energy\ \cos t}{\cos t\ of\ initial\ investment} \qquad \text{Equation 6}$$

The 3-year energy cost is must include both server power and other administrative power consumption including cooling power for 3 years. The EAC would be different depending on the efficiency design and location of the data centers [63]. When the EAC ratio is equal to 1, the 3-year energy cost is the same as the initial investment of the server, in other words, it takes 3-years to "breakeven" or become equal. Since cable is bought and installed at the beginning, it is considered as part of the initial capital. In a data center, the applications of 10-meter interconnects are used for rack-to-rack or server-to-server connection. Therefore, cost of capital includes the racks and servers. The mean (average) cost for a rack is around $1200 and a server is around $8,000 (retail price). According to Otte, one can assume a markup of 40-50%, resulting in a cost of $720 for racks and $4,800 for servers. Moreover, Intel estimated that an average size data center has 40,000 servers and each rack can hold up to 42 servers. Therefore, the total cost of investment for 40,000 servers and 953 racks are estimated to be $0.193 billion plus the cost of cable.

To understand how cost of initial investment affects the decision maker's preference to switch to new technology, one can examine the following 2 situations. In the first situation, the manager is given a choice to phase-out the old technology, which means that they are given the choice to incrementally replacing copper with optical. In the second situation, a manager is given the choice to adopt the new technology all at once at a certain year.

4.4.3.1 – Situation 1 – Phasing Out

4.4.3.1.1 – Scenarios and Assumptions

Three scenarios are examined in this situation: replacing 20% of electrical with optical every 2 years until all are replaced by optical; replacing 40% of electrical with optical every 4 years until all are replaced by optical, and replacing 80% of electrical with optical every 8 years until all are replaced by optical.

As mentioned in the previous section, there are two sources of initial capital: cost of investing in racks, servers and other infrastructure that is needed to support the new technology, as well as the cable cost since it is purchased and installed at the beginning of the investment. The sources of operation cost include energy cost and maintenance cost, in this situation, it is assumed that the maintenance cost is minuscule and thus is not included.

4.4.3.1.2 – Results

Figure 66, Figure 67, and Figure 68 present a graphical illustration of the cumulative cost of different phasing out strategies. As seen in Figure 66, if the price of optical is not expected to decrease throughout the years, it would be more beneficial for managers to wait to switch to optical technologies due to the higher initial investments. However, as learning rate started coming into place and the cost of optical components started dropping, cost of energy becomes a larger portion of total cost ownership. As a result, phasing out incrementally become more advantages. This is evident in Figure 67 and Figure 68 where the cumulative cost of phasing out with shorter period becomes less costly than waiting for a long time.

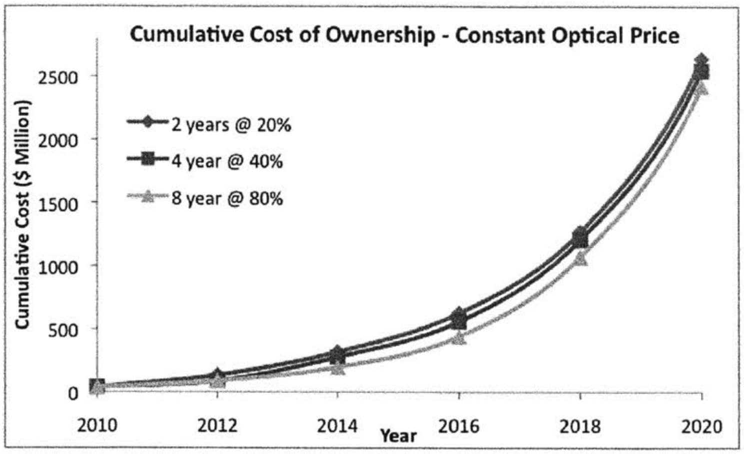


Figure 66: Comparison between different phasing out strategies – keeping optical cost constant

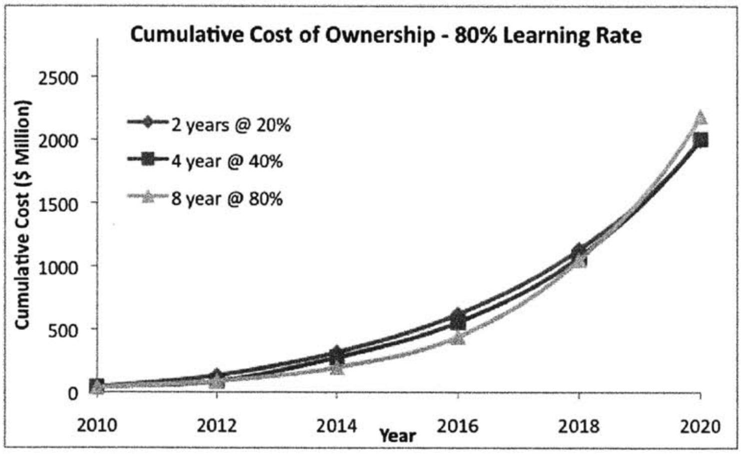


Figure 67: Comparison between different phasing out strategies – with 80% learning curve

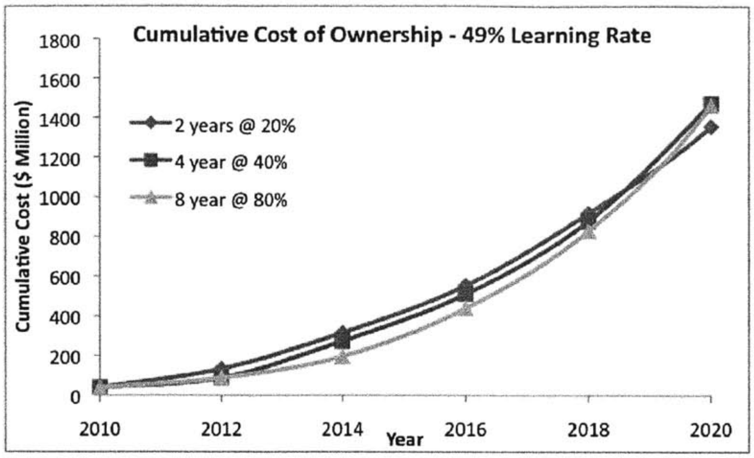


Figure 68: Comparison between different phasing out strategies – with 49% learning curve

One important fact to keep in mind is the breakeven timeline. Figure 68 indicates that even with learning rate of 49%, it will take at least 8 years for scaling every 2 years to be the total cost as scaling every 4 years. Most managers do not have a long-term vision as they are often being evaluated by their performance during that year or for the next three years. Therefore, even though it is less costly for the companies 10 years down the line, companies still are unlikely to switch to the new technology. As a result, companies wait to adopt optical technologies, which decrease the volume and lead to slower standardization timeline. Without standardization, the cost of optical components remain high, which feeds back negatively to the adoption loop shown in **Figure 56**. This negative feedback could cause a "death spiral dynamic" that is mentioned in Speerschneider's dissertation.

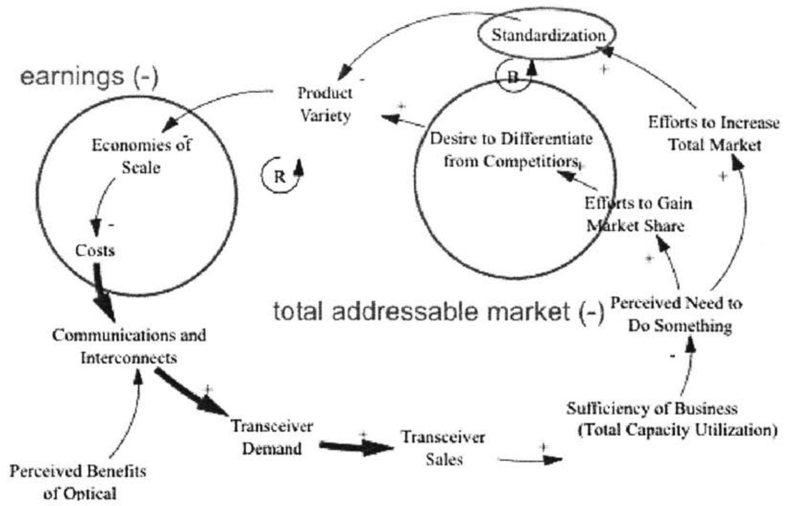


Figure 69: The "death spiral" dynamic – proliferation vs. standardization [5]

4.4.3.2 – Situation 2 – Replacing All at Once

4.4.3.2.1 – Scenarios and Assumptions

There are also 3 scenarios examined in this situation. From Figure 60, the crossover point for electrical and optical occurs around 2016, thus this will be used as a benchmark for data center's planning. In the first case scenario, the manager is risk taking and has a forward vision, thus a replacement is taken placed 2 years earlier, in 2014. In the second case scenario, the manager is more risk neutral and likes to make decisions according to the forecasts, thus the replacement occurs in 2016. In the last case scenario, the manager is risk averse and would like to wait until everyone else has tried and proven optical works before adopting it. Therefore, in the third case scenario, the replacement will occur in 2018, which is 2 years after the forecasted year.

4.4.3.2.2 – Results

Figure 70, Figure 71, and Figure 72 present a graphical illustration of the cumulative cost of different adoption timeline. All 3 graphs demonstrate that it is more costly to adopt new technology earlier. From the graphs, one can conclude that the higher the learning rate, the more expensive to adopt earlier. This is because this switching happens only in a certain year, in which case, a big investment was to be made only during that year. As a result, the lower the cost during that year, the lower the total ownership cost would be. Although many articles have indicated an increasing cost of power consumption that had shifted data center's focus from reducing equipment cost to concentrating on operating cost, the result have indicated that the current rate of saving of power consumption is not enough to justify the high upfront of switching to optical. Above noted can be the reason why adoption and standardization is occurring at a slow rate in the industry. However, future work can look at different cost of power per kilowatts hour. The higher the kilowatts hour, the higher the energy saving, which will offset the large cost of initial capital and pushing adoption earlier.

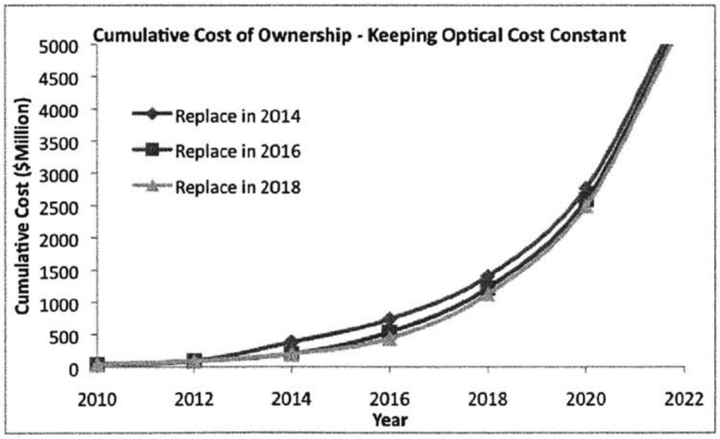


Figure 70: Comparison between different adoption years – keeping optical components cost constant

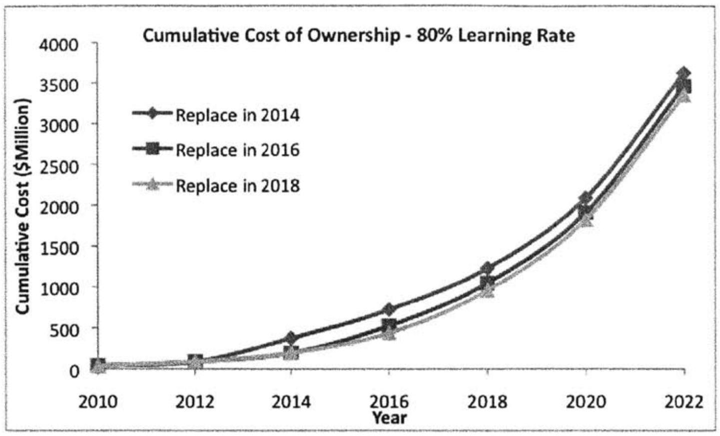


Figure 71: Comparison between different adoption years – with 80% learning curve

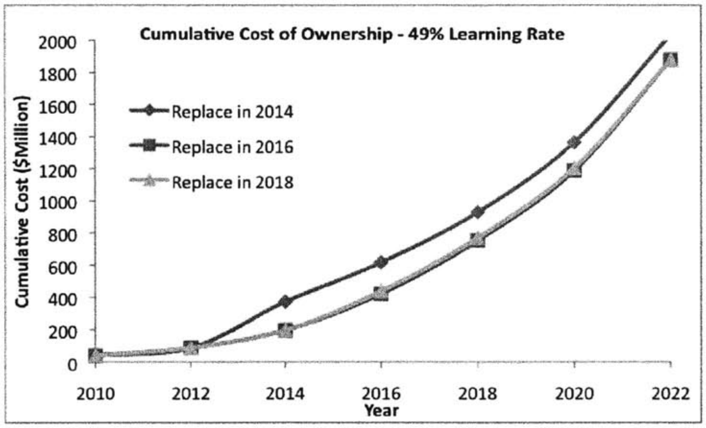


Figure 72: Comparison between different adoption years – with 49% learning curve

5. –Conclusion and Recommendation

In this thesis, we examine the adoption of optical interconnect cables in different lengths using different cost saving rate for optical components. Chapter 1 and 2 provide an overview of the interconnects market, the potential limitations of current incumbent technology, and the important drivers of new technology. Chapter 3 addresses the concern of lack of standardization in the optical industry. Chapter 4 examines costs and FOM analyses for different scaling scenarios with different lengths and their potential adoption timelines. From the scenario analyses in section 4.3, the main 3 drivers that are driving the adoption of technologies are bandwidth requirement, reach, and costs. For any distance between 5 centimeters and 10 meters, one can see that without standardizations and without cost reductions, optical will be disadvantage compared to electrical despite electrical's limitations. If the bandwidth requirement is growing at the expected rate of 50% per year, one will see gradual adoption of 10-meter optical interconnect cables starting from now and completely replacing optical before 2016 depending on optical's cost saving ability and the cost of energy. For 1-meter links, we will see an early entrant of optical in 2014 and replacing copper completely in 2022 or later, again depending on optical's learning rate and the future energy price. The adoption of optical interconnections in 5-centimeter applications will occur much later in the timeline. Although companies such as IBM has aimed to replace copper with optical in 5-centimeter applications this year, the scenario cost analysis has indicated it would not be beneficial until after 2024 and beyond. This analysis has also indicated that in order for optical to be more attractive in 5-centimeter or shorter applications, there needs to be an all-optical solution to eliminate the extra power consumed for electrical-optical-electrical conversion at the interface.

Section 4.4 points out the reasons for a slow rate of optical standardizations and adoptions. Due to the current high cost of optical, the short-sighted managers are less incentivized to adopt to new technology as it requires higher up front costs and long payback period. The high cost of optical validated Hausman's conclusion that although standardization will eventually bring cost down, it will not drive higher demand and faster adoption due to the inelasticity of demand. Accordingly, the main drivers for faster and higher optical interconnects adoption would need to come from new market applications for a different performance need more than cost need.

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