Microphotonics:
Hardware for the Information Age

A Vision of Communications

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Acknowledgements

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## Definitions

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<th>Abbreviation</th>
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<tr>
<td>DVR</td>
<td>Digital Video Recorder</td>
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<tr>
<td>I/O</td>
<td>Input/Output</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>MSO</td>
<td>Multiple Systems Operator</td>
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<tr>
<td>MTBF</td>
<td>Mean Time Between Failures</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
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<td>REA</td>
<td>Rural Electrification Act</td>
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<tr>
<td>VHS</td>
<td>Video Home System</td>
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<td>VoIP</td>
<td>Voice over Internet Protocol</td>
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A Vision of Communications

Learning from History

Accepting Electricity
The modern world of the late 19th century thought the best uses for electricity were as a sideshow amusement to animate disembodied animals, and a medical curative. Forty years after Edison invented the incandescent lamp, the American populace was still resistant to the use of electricity as a replacement for “safe” gas lamps. Electricity was unreliable, poorly maintained, demanded special lamps for proprietary (company) sockets, and had a low MTBF. Worst of all, for the investment community, there was no clear path to achieve a cost-effective mass market as so few people had electric lights. On 28 December 1879, the headline of the New York Times read, “EDISON’S ELECTRIC LIGHT, Conflicting Statements as to Its Utility.” In 1884, Scientific American ran an article that read in part, “the novelty of the new light has worn out, and the extent to which it is being introduced as a substitute for gas is little noted except in the reports of the companies.” Clearly, the foregone conclusion about the benefits of the electric light, and the meteoric market for electricity that surrounded it, simply never happened.

It would take a combined, visionary effort on the part of the local municipalities, federal government, and private industry to achieve the realization of a mass market that now—125 years later—is woven inextricably into the fabric of modern society and shows no sign of diminishing. That vision culminated in the Rural Electrification Act. Beginning in 1936, the Congress allocated over $375M—an amount roughly equivalent to $50B today—based upon the belief that electrical access was important to the future of the US and that the government needed to assist in making electricity available to as many homes as possible. This was especially true in rural areas where fully 90% of farms were without access to electricity. This act on faith by the government was a remarkably prescient commitment. The REA became one of the most successful programs of its type in US history. Within twenty years, the tables were turned—almost 90% of rural agricultural areas had access to electricity.

Reaching Critical Mass

Through the lens of history, the implementation, standardization, and adoption of electricity is an interesting anecdote. Yet today, in certain areas of technology, notably in optical communications, we may be looking at a surprisingly similar situation.

As the transmission medium has changed from twisted pair to coaxial cable to satellite, transmission capacity has grown exponentially. Today, a single commercial fiber is capable of speeds in excess of 1 Tb/s [1]. Photonics has yielded a performance/cost value that has increased at a rate of two orders of magnitude every 10 years. This means that as a measure of value by capacity, photonics has outperformed silicon integrated circuits; however, it has not had as significant an economic payoff for its industry as silicon, nor has it become the “killer technology.” One possible reason is that measure of capacity alone is not sufficient: as
Metcalfe’s Law states, “The value of a network is proportional to the square of its number of users” [2].

Until a critical mass of users is reached, a change in technology only affects the technology. Once critical mass is attained, however, social, political, and economic systems change. This is what authors Downes and Mui call the Law of Disruption [3]. For instance, it took about 10 years for radio to reach critical mass in the United States and even longer for television; recently, Internet and mobile phones have experienced the same trend (Figure 1). Yet each of these technologies transformed family, economic, and political structures once they reached critical mass.

![Figure 1. Technology penetration in the United States](image)

**The Marketplace**

Ronald H. Coase gave us the first lucid explanation of transaction costs in a 1937 essay titled "The Nature of the Firm" [6]. His discovery eventually won him a Nobel Prize. Coase concluded that firms are created because the additional cost of organizing them is cheaper than the transaction costs involved when individuals conduct business with each other using the open market. Firms should conduct internally only those activities that cannot be performed more cheaply in the market or by another firm. Thus, a firm will expand precisely to the point where "the costs of organizing an extra transaction within the firm become equal to the costs of carrying out the same transaction by means of an exchange on the open market."
These are key reasons why the classic strategy rules will no longer apply. There will be no more sustainable competitive advantages—only temporary ones. Firms will outsource, deplete their physical assets, and morph into new configurations and relationships with other firms to lower their transaction costs. Those who cling to the industrial models of the past will find life very difficult in the marketplace of the future.

**Early Adoption**

In communications, connectivity and capacity are equally important. In addition, as with integrated circuit electronics, connectivity growth is incompatible with discrete component technology. Photonics holds great promise, but it does not yet have an economic microclimate in which to grow properly. As Professor Lionel Kimerling, Director of the Microphotonics Center at MIT, said recently, “we have to shift the demand curve outwards.” The key is to remember the lessons of the “Early Adopter” rule: “When you are on the cutting edge, it is important to stay behind the blade.”

**Creative Solutions**

We need to learn from other industries that have depended upon creative solutions during times of unclear and changing technical paths, user dynamics, and multiple types of hardware platforms. We can turn to computer games as an example because there is no more computationally demanding application in common use today. Not only are games written to integrate with hardware not yet available when development begins, but they also have to incorporate fast, 3D engines; complex, multi-layer graphics; multi-channel sound; machine logic; dynamic I/O; latency caching; and many other features—all operating in real-time. That means a screen update at least 24–60 times a second, which to achieve requires elegance over horsepower.

Early games had to operate within severe processor, graphics, and memory constraints. Developers had to learn numerous tricks to overcome or work around the limitations in hardware. For instance, in the mid 1980s, the Commodore 64—the first decent personal computer for games because it had a built-in sprite generator running at the blazing speed of 1 MHz on a 6502—had 16-bit addressing but only 8-bit registers, so you had to go through an inelegant, but necessary, process of writing alternate high and low bytes to address memory. In home PCs, there has not been reliable floating point processing available until the Intel Pentium series. Up until then, you had to use integer math or fixed point unless you wanted to write your own floating point math routines which, by not being incorporated in hardware, were hopelessly inefficient. Nevertheless, during these days of underpowered hardware, games were made, and device limitations were overcome, because there was a slow but demonstrated market. Success favored those creative minds who could build great games with the limited tools of the moment, while simultaneously creating for future hardware that usually did not exist at the time of initial programming. That took guts as well as brains. It was no accident that many software developers perished or were acquired while others survived and flourished. Competitive success was not derived from brawn, but from creative solution.

Today’s developers are often at a disadvantage as they attempt to use brute force techniques to solve subtle problems with powerful tools and hardware, instead of conceiving elegant solutions.
And when everybody has the same tools, the playing field favors the skilled team. Technology advances alone do not guarantee success: it is the education process along the way that enables creative solutions and rarely does one party ever have all the answers. Historically, those who rely upon others to lead in great technical undertakings do so at their own peril. One need only look at the likes of an initially successful entrepreneur such as Guglielmo Marconi to understand the consequences of complacency and failing to understand the importance of continuing to invent the future. Marconi lost his business advantage when he failed to appreciate other potential uses for wireless than telegraphy [8].

**Shifting Perceptions**

In 1981, many believed that Hayes Smartmodems, running at 300 baud and based upon the same Bell 103 signaling standards that were introduced twenty years earlier, were satisfactory—that is, until the novelty wore off and the Bell 212 phase-shift keying yielded 1200 baud at less cost. We stayed there until the end of the 1980’s with universal 2400-baud modems, which gave way to 9.6K, the 1991 Suprafax 14400, and over the next few years, the 28.8K, then 33.6K and the alleged(!) 56K baud modem of the late 1990s. We share this sense of communications history because we experienced it empirically. Our children, however, take interconnection for granted and they expect nothing less than maximum speed and horsepower. For the Baby Boomers and most of Generation X, speed and connection was an evolutionary advance; but for the following generation, connection is merely a tool—like electricity. The future of a technology is written in its history.

**Identifying Potential Markets**

Technology history demonstrates that content drives platforms. There should be no doubt that thin wall screens connected to on-demand video servers will drive the market for high speed wideband. The same content driver economics will follow for telepresence, medical and high-resolution imaging, photonic cryptography in secure communications, the conversion of libraries to searchable text, VoIP, and real-time interconnected games networks, to name a few. Additionally, the new economics of Long Tail theory—where the 80/20 rules of distribution no longer apply—will come into play as the economy is transformed to one that pays for moving bits rather than atoms.

As the technology develops, other, “out of demand curve,” markets will arise, such as the replacement of copper with fiber in aircraft in order to increase communications capability while simultaneously reducing weight. We have to be sensitive enough to recognize and feed these new markets in order to stimulate the demand necessary to ultimately supply them with the infrastructure and interconnection devices they will require.

It has taken DVRs over ten years to achieve consumer traction for a host of marketing, economic, and infrastructure reasons, but now that a nexus has formed with MSOs getting into the act, DVR sales are taking a dramatic upswing. This is the tip of the high-speed iceberg. We need to pay attention to it because technology history teaches that once critical mass is achieved, markets will move at a rapid, nonlinear rate.
Predicting the Future

Any forecast about the promise of a communications technology must include an appreciation of its place within the larger communications ecosystem in which it will exist. This ecosystem comprises key elements such as transmission, distribution, switching, processing, storage, and display. Development of a viable communications infrastructure requires that those elements scale together. Photonic technology holds great promise for realizing this coordinated scaling within future high-speed communications—from the chip level through board interconnects, to enterprise and long haul. The key is to identify commonalities that drive scale and build the technical infrastructure necessary to enable optical technology to replace electrical devices. As the end-to-end infrastructure becomes increasingly optical, network latency will decrease to the point that communications become perceptually instantaneous to users. Optical networks will enable sophisticated applications such as transmission of “presence” in teleconferencing, computer-assisted surveillance, instant access to multimedia, real-time weather telemetry in navigation, and cost-effective Lidar for autos. The implications are enormous.

Today, digital networks operate at greater capacity and speed; but despite the fact that optical fiber has been used since the 1980s, current networks are still limited by the electrical interconnects at their termini. The opportunity to advance the speed of communications lies in replacing these slower components with photonic equivalents. The realization of optical transmission networks will allow any connected individual to access vast computational resources. Unbounded applications, not dependent upon local storage or processing, will be limited only by the imaginations of those who create them. Many of the current economic and distribution barriers between intellectual property owners and end-users will evaporate. Ubiquitous computing and communications will revolutionize medicine, education, and social interaction.

The effect of such technology on transportation, commerce, education, entertainment, social interaction, and government will be dramatic. For instance, one only needs to look at the world ten years ago to understand the social impact of the cell phone. The shift to a real-time wideband network promises the same dramatic social effect. Many enabling components already exist in laboratories. The demand created by new long-haul networks will allow them to be applied on a commercial scale. With the advent of this new communications infrastructure, 21st century society will be witness to a renaissance of applications spawned from the ability to extend computer-moderated information directly to the end user in real-time. Third generation applications will fuel the information vehicles. Photonics will speed the underlying highway.
Making Preparations

Dealing With Reality
Such a future, however, will come neither cheaply nor completely without technical problems. While optics is the preferred method for transport, a mix of optics and electronics will be utilized until electronic components are replaced by pure optical or hybrid devices. Barriers to the adoption of these technologies are not technical, but economic, given the scale and life cycle of the present infrastructure. A visionary program such as the REA (discussed earlier in this chapter), applied to the communications infrastructure of the country, will yield the realization of a society where the flow of information will be in real-time, and all electronically accessible material stored anywhere will be available to anyone with access to the interconnected network. This capability will initially be most affordable to government and the military, but trickle-down will result in new applications to benefit the private sector. Once standardized and widely available, the link to the user will be complete.

Getting There
The “Second Adopter” theory says that it is acceptable to wait and catch up after learning from the mistakes of others. But there are inherent risks to second adopters:

1. Instant acceleration does not exist.
2. How great is your corporate moment of inertia?
3. How long will it take to ramp up?
4. In a highly competitive field, if the window of opportunity is missed, the chance of becoming a leader is small.

There is a practical path to realizing economically justifiable photonic processing. Along the way, we will have to reduce device footprint, lower power consumption, and target high-volume markets in order to attain economies of scale. Achieving this will demand integration, standardization, and perhaps most importantly, cooperative vision. We must never forget that technical superiority alone is not the driver of success. Anyone who doubts that need only look at the recent history of the Sony Betamax standard versus VHS. The purpose of standardization is not to diminish individual creativity; it is to provide a critical mass of support technology necessary to even the playing field. There has to be a way to implement that in the microphotonics industry.

As most are well aware, the power of open architecture has historically been demonstrated over proprietary systems. A few instructive examples of closed architecture not protecting the business interests of the corporate developer are Commodore who, despite R.J. Mical’s brilliant design and the first sprite generator, lost its preeminent sales position in personal computers and Apple Computer, whose market penetration still hovers in the single digits, despite the success of the iPod. It was the Wintel platform that created the basic PC market. Now it is the applications and specialty products that drive it. The PCs have become the blades.
We must also ask ourselves the question, “What is the risk of waiting while others determine the safe path?” If history is any judge, the risk is substantial. The photonics industry needs to create the underlying microclimate in the optical ecosystem to allow organic growth to occur. It needs to develop the optical communications razor and blades scenario. If the industry can achieve that all-important critical threshold, it will grow. If it does not, it will sputter and fail to gain the traction necessary to justify continuing development in a competitive market that cares more about the content and applications than the underlying technology. Such a critical project will require an evolving, but nevertheless massive, rebuilding of the communications infrastructure. As such, community action through neutral mechanisms will be necessary in order to advance the common goals. The opportunity is great, but, as with so many other great opportunities, today’s actions will decide its future.
References