

Third Edition

Handbook of Fiber Optic Data Communication

A Practical Guide to Optical Networking

Casimer DeCusatis



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Handbook of Fiber Optic Data Communication

Preface to the Third Edition

SONET¹ on the Lambdas²

(by C. DeCusatis, with sincere apologies to Milton³)

When I consider how the light is bent
By fibers glassy in this Web World Wide,
Tera- and Peta-, the bits fly by
Are they from Snell and Maxwell sent
Or through more base physics, which the Maker presents
(lambdas of God?) or might He come to chide
“Doth God require more bandwidth, light denied?”
Consultants may ask; but Engineers to prevent
that murmur, soon reply “The Fortune e-500 do not need
mere light alone, nor its interconnect; who requests
this data, if not clients surfing the Web?” Their state
is processing, a billion MIPS or CPU cycles at giga-speed.
Without fiber-optic links that never rest,
The servers also only stand and wait.

As this book goes to press, I am pleased to say that the world of optical data communication is well established and continues to thrive. Mature technologies combined with high-volume, low-cost manufacturing have made high-performance optical data links more affordable than ever before and have turned some of the early technologies into commodities. Applications for fiber-optic networking have grown significantly. This goes beyond Internet and Web traffic to encompass areas such as disaster recovery, video distribution, massively parallel clustered computing, and networked storage. (Large corporations now boast multi-terabyte, petabyte, or even exabyte databases interconnected with their core business functions.) The distinction between datacom and telecom technologies continues to blur, with the encapsulation of traditional data center protocols over

¹Synchronous Optical Network.

²The Greek symbol “lambda” or λ is commonly used in reference to an optical wavelength.

³The original author of the classic sonnet “On His Blindness.”

metropolitan and wide area networks designed for voice traffic. Network convergence and the triple or quadruple play for service providers have entered common usage, but the unique requirements of data communication networks remain (including very low error rates, long unrepeatable distances, ease of use for untrained staff, and an unprecedented combination of high reliability and low cost in demanding environments). These many developments, coupled with the continued success of previous editions, led to the decision that the time was right to update this Handbook once again.

Since the first edition was published over 10 years ago, I have tried to continually incorporate feedback and comments from readers to improve this book and ensure that it continues to provide a single, indispensable reference for the optical data communication field. Previous editions had experimented with a two-volume set of Handbooks. But you, the readers who make use of this book every day, have consistently emphasized the importance of having a single volume as your one-stop reference source. In this edition, I have taken your advice and have returned the Handbook to its original design. This one book contains an overview of the entire optical data communication field, broken down into basic technology, link design, planning, installation, testing, protocols, applications, and future directions.

A great deal of new material has been added, and many familiar chapters have been updated to reflect new types of optical components, connectors, cables, and other devices. Some legacy applications that are not as widely used have been edited to their essential material only, such as FDDI and ESCON. Others have been expanded, and we have added the latest updates to Fibre Channel/FICON, InfiniBand, and SONET/SDH. Some technologies that were just emerging when the previous edition was published are now commonplace; among these are pluggable small form factor transceivers. Completely new chapters deal with issues that did not exist when the last edition was published, including Enhanced Ethernet for the data center, silicon photonics, and nanofibers. Throughout I have tried to maintain a focus on practical applications. This edition includes about a dozen case studies that either provide numerical examples of the principles discussed in the text or discuss real-world applications using grid computing, triple-play networks, optically interconnected supercomputers, and other areas. Our industry is just beginning to see the promise of all-optical networking emerge—application-neutral, distance-independent, infinitely scalable, user-centric networks that catalyze real-time global computing, advanced streaming multimedia, distance learning, telemedicine, and a host of other applications. We hope that those who build and use these networks will benefit in some measure from this book.

An undertaking such as this would not be possible without the concerted efforts of many contributing authors and the publisher's supportive staff, to all of whom

I extend my deepest gratitude. As always, this book is dedicated to my mother and father, who first helped me see the wonder in the world; to the memory of my godmother Isabel; and to my wife, Carolyn, and my daughters Anne and Rebecca, without whom this work would not have been possible.

Dr. Casimer DeCusatis, Editor
Poughkeepsie, New York
August 2007

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Part I

Technology Building Blocks

Computers Full of Light: A Short History of Optical Data Communications

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To those of us who grew up in the electronics era, optical communications is a new technology. But if you look back, you can find that the age of telecommunications started not with the well-known electrical telegraph, but with optical telegraphs that first came into use in the late eighteenth century. The new age of optical communications has been powered by two new technologies invented in the mid-twentieth century—lasers and fiber optics.

The shift to optics coincided with the change from analog to digital transmission in the telephone network and with the growing importance of computer data transmission. Historians of technology state that technology evolves and that evolution is evident in the changes that have combined optical and digital technology, both on large and small scales in the global telecommunications network.

1.1 THE OPTICAL TELEGRAPH

The idea of telegraphing signals to remote locations emerged long before scientists had any idea how to control electricity. The first telegraph proposals were for semaphore-based systems that relayed signals between a series of stations. The operator of one would spell out a message as a series of characters, which the operator of the next would view through a telescope, write down, and relay to the operator of the next. The scheme was labor-intensive, but at the time labor was cheap, and it could send signals much faster than horses.

The oldest recorded proposal for an optical telegraph dates from March 21, 1684, when English scientist Robert Hooke described “a way how to communicate one’s mind at great distances” to fellow members of London’s Royal Society. Hooke suggested that the towers display light-colored characters at night and dark

ones during the day, so that they could be easily seen, and he proposed coding the symbols to prevent eavesdropping.¹ It was a remarkably prescient idea, but it would take a century before the first practical system was built.

The impetus for success came from the French Revolution, which left France in turmoil and surrounded by enemies. Optical telegraphs had been demonstrated by then, but only over short distances. Claude Chappe and his four brothers set themselves to the far more ambitious task of building a national optical telegraph network. After some false starts, in March 1791 they succeeded in sending signals between two French towns and made a point of having local officials confirm the demonstration.

The Chappe brothers then asked the revolutionary government to fund their plans to build an optical telegraph network. Claude moved his experiments to Paris, and his brother Ignace was elected to the new Legislative Assembly, where he became a member of the Committee for Public Instruction. Those connections helped the Chappes gain support as they refined their technology. First they tested a pulley-driven array of five sliding panels that offered 32 possible combinations, enough to spell the alphabet plus a few other symbols. Later they shifted to a semaphore with two arms on the ends of a longer horizontal beam, as shown in Fig. 1.1.

To prove their design would work, the Chappes built a demonstration system spanning two segments, one of 15 kilometers (km) and the second of 11 km, and on July 12, 1793, they transmitted a 26-word message in 11 minutes, incredibly fast by the standards of the time.² Two weeks later the government agreed to build a 15-station line spanning 120 km from Paris to Lille. That system began operating less than a year later and grew steadily because the war-torn country needed to keep in touch with its frontiers. The system survived the fall of Napoleon and the restoration of Louis XVIII, and ultimately other countries built their own optical telegraphs, as Gerard J. Holzmann and Björn Pehrson recount in a fascinating book titled *The Early History of Data Networks*.³

Optical telegraphs launched the age of telecommunications, but by the 1830s a competitor had emerged—the electrical telegraph. The new electrical systems were cheaper to build and operate and could transmit signals at any time, not just when the sun was shining and the air was clear.

Optical communications was not entirely forgotten in the years that followed. In 1880, Alexander Graham Bell demonstrated the “Photophone,” an optical version of the telephone that modulated the intensity of reflected sunlight with voice signals. The Photophone fascinated Bell, but it could not compete with his earlier

¹Gerard J. Holzmann and Björn Pehrson, *The early history of data networks* (Los Alamitos, Calif.: IEEE Computer Society Press, 1995), pp. 35–38.

²Ibid., p. 61.

³Holzmann and Pehrson, *The early history of data networks*.

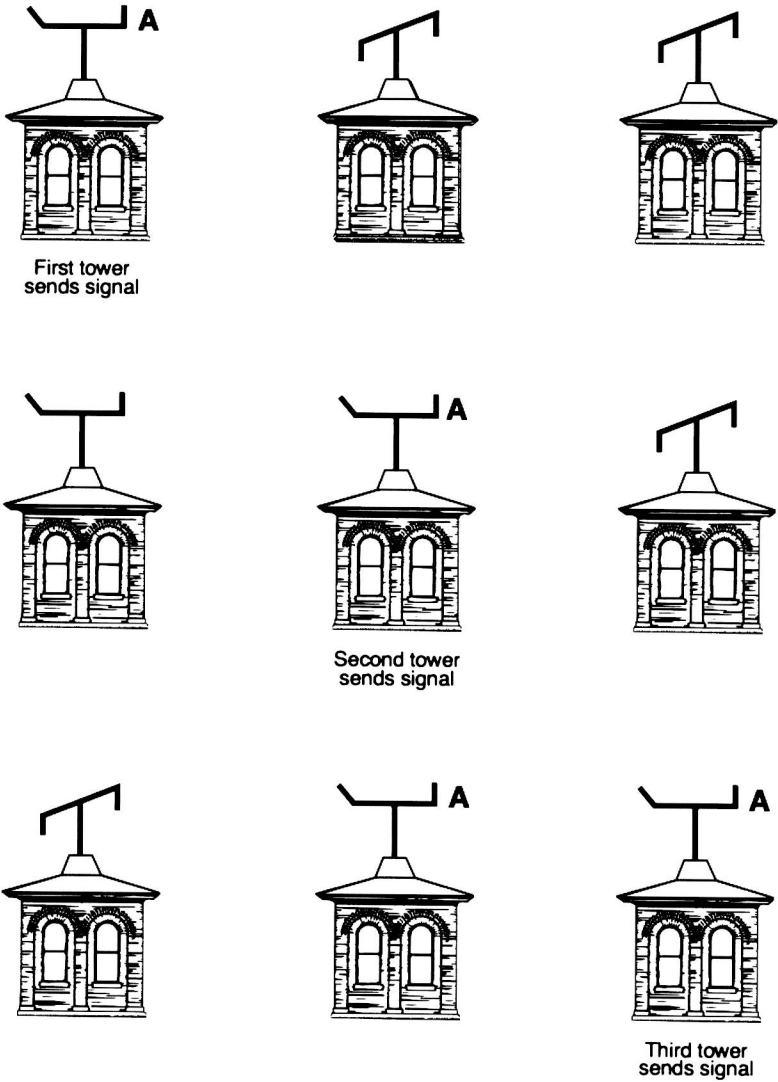


Figure 1.1 Signal transmission along a series of Chappe-style optical telegraph towers.

invention, the wired telephone. Like the electrical telegraph, the wired phone could transmit signals day or night, regardless of the weather.⁴

1.2 LASERS REVIVE OPTICAL COMMUNICATIONS

The birth of the laser launched the new age of optical communications. The first step on the path to the laser was the 1954 invention of its microwave counterpart, the maser, by Charles Townes, then at Columbia University. The amplification of stimulated emission from material contained in a resonant cavity made the maser oscillate at the frequency of the stimulated emission. Importantly, maser output was coherent and limited to a narrow range of frequencies.

The next logical step was to extend the maser principle to the much higher frequencies of light waves. The team of Townes and Arthur Schawlow and, separately, Gordon Gould, working by himself, both proposed similar designs for a laser, essentially solving the same physics problem and coming out with the same answer. However, it was Theodore Maiman, working at Hughes Research Laboratories in California, who succeeded in making the first laser on May 16, 1960.⁵

Optical communications was a key application envisioned by laser developers. As a coherent oscillator, the laser was analogous to the coherent oscillators used in radio communications, but because light waves had much higher frequencies, they promised much higher transmission capacity. Maiman's demonstration opened the floodgates to a series of experiments, first with the ruby laser Maiman had invented and later with the helium-neon gas laser invented at Bell Labs. Initial tests showed that laser beams could be modulated in intensity to carry a signal and that they could travel many miles through clear air. However, further tests eventually revealed that fog, clouds, or precipitation could attenuate or block the beam, making long-distance signal transmission unreliable through open air.

Short laser links through the air did work reasonably well. The National Aeronautics and Space Agency (NASA) considered them to replace umbilical communication cables connecting spacecraft waiting for launch with mission control. Businesses considered lasers for short links through the air between buildings that did not require the Federal Communications Commission license needed for microwave transmission. However, costs were long an obstacle.

NASA went so far as to test lasers for transmitting signals between ground and space or between two spacecraft, but the results were discouraging. In December 1965, astronauts tried to send signals between the Gemini 6 and 7 spacecraft when they were simultaneously orbiting the Earth. They pointed a

⁴Jeff Hecht, *City of light: The story of fiber optics* (New York: Oxford University Press, 1999), p. 80.

⁵Jeff Hecht, *Beam: The race to make the laser* (New York: Oxford University Press, 2005).

hand-held transmitter, which contained four semiconductor diode lasers pulsed at 100 hertz to carry voice signals, between the two satellites. But the connection worked only briefly, probably because it was hard to aim the narrow beam at the other spacecraft. Later, NASA and the Air Force spent millions of dollars trying to develop high-speed laser links between satellites, but pointing and tracking proved insurmountable problems until recent years.⁶

With its primary interest in long-distance transmission, the telecommunications industry decided that the best approach was to develop an optical waveguide to carry laser signals. The logical approach seemed to be an optical version of the hollow metal waveguides similar to those used for microwave transmission—specifically the hollow circular guides that Bell Labs and others were developing to transmit frequencies around 60 gigahertz (GHz), called millimeter waves. Phone companies were running into the capacity limits of the chains of microwave towers that carried long-distance traffic at frequencies of a few gigahertz, so they were trying to move to higher frequencies. Millimeter waves were not transmitted well by the atmosphere, so phone companies planned to transmit them through buried waveguides. Bell was convinced that millimeter waveguides were the technology of tomorrow, but the parent AT&T was the country's monopoly carrier, so Bell had the luxury of planning for the day after tomorrow.

Metal pipes with reflective linings turned out to absorb too much light to transmit laser beams long distances. However, Bell Labs developed an ingenious scheme to repeatedly focus a laser beam through “gas lenses” formed periodically along the waveguide, so that the light would not touch the walls of the tube. It was a challenging and expensive system, but in theory it promised low loss, and Bell had plenty of time and research dollars.

1.2.1 Solid Optical Waveguides and Fiber Optics

Money was not as plentiful at Standard Telecommunications Laboratories (STL) in Harlow, England, although it was owned by the International Telephone and Telegraph conglomerate. STL was blessed with a visionary engineer heading its research programs—Alec Reeves—who in 1937 had invented pulse-code modulation, the basis of converting analog signals into digital form for transmission in modern networks. That invention had been so far ahead of its time that Reeves's patent had not earned a penny in royalties.

STL engineers experimented briefly with hollow optical waveguides, but the results were not encouraging, and so Reeves decided that STL should not pursue an expensive technology that was better suited to the wide open spaces of the United States than to smaller Britain. Instead, he turned his attention toward a

⁶Jeff Hecht, Reflections: Lasers as space-age technology, *Laser Focus World* 30, 8, pp. 45–47 (August 1994).