The Evolution of Optical Communications Networks since 1990

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Introduction

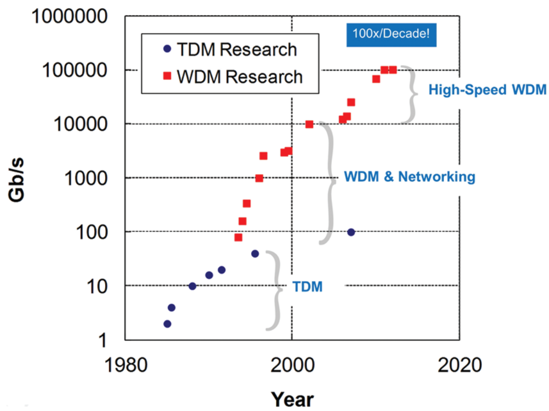
Optical communication networks have played a critical role in the information/communication revolution and in turn have fundamentally changed the world and daily life for billions around the globe. Without cost-effective, high-capacity optical networks that span continents and connect them via undersea routes, the worldwide Internet would not be possible. Optical access systems, both fiber/cable and fiber-to-the home, are also essential to bring broadband access to that global Internet to homes and businesses. Increasingly important, ubiquitous broadband optical networks provide the high-bandwidth backhaul essential for wireless access networks that enable today's smartphone users. These networks also provide the always available broadband access that will make cost-effective and energy-efficient cloud services available to all in the future.

All this has been made possible because, as capacity demand has grown exponentially following the advent of the Internet, optical technology has made possible a dramatic reduction in the cost per bit carried over an optical fiber, allowing cost-effective capacity scaling. On average, transmission capacity over a single fiber has increased at a rate of ~100-fold every ten years over the last thirty years. As a result, as traffic has grown and is aggregated at the ingress and disaggregated at egress nodes, new higher-capacity generations of long-haul and metro optical systems have been deployed at a total cost that has grown sub-linearly relative to capacity.

Of course, the advantage of the optical frequencies for communication is the inherent ability to serve as a carrier for very-high-bandwidth information. Fiber provides an extremely attractive transmission medium that offers both ultra-low loss and low chromatic dispersion. The latter results in minimal pulse spreading, resulting in low inter-pulse (bit) interference after transmission over large distances. At its most basic implementation, an optical transmission system requires an optical source whose generated dc optical signal can be modulated with information at the information bandwidth of interest, a fiber, and an optical detector and supporting electronics.

Figure 1 captures the progress of the "hero" research transmission experiments [1]. Shown is the maximum information capacity carried on a single fiber versus the year the research results were achieved. For this review, it is convenient to describe the research progress in fiber optic transmission capacity in three waves or eras. In what follows, we use those generations, each enabled by a set of critically important optical component technology innovations, to provide an overview of the advances in optical communications since 1990.

At the start of the 1990s, commercially deployed systems provided per fiber capacities of about 1 Gb/s. They were used primarily in long-haul intercity applications to carry highly aggregated voice service. At that time, increase in capacity demand was still driven mostly by population growth as well as some increase in new services such as fax. The wavelength window utilized was the minimum chromatic dispersion 1.3-μm window. To increase time division multiplexed bit rates (TDM) for fixed distance between electrical regenerations, both signal strength relative to noise and quality of the detected signal with respect to pulse-to-pulse



▲ **Fig. 1.** Reported research transmission systems experiments showing maximum transmission capacity over a single fiber vs. the year of the research results.

interference are important. To mitigate the reduced receiver power at higher bit rates, research focused on moving to the lowest-loss wavelength window around 1.55 μm. Unfortunately, for the standard single-mode fiber then available, chromatic dispersion at 1.55 μm was significant. For systems that employed directly modulated lasers that exhibit wavelength "chirp" during the change from the "on" to "off" state, that dispersion caused problematic pulse spreading interference.

Three technology advances were instrumental in strongly mitigating these limitations to enable increased TDM rates. To avoid chromatic dispersion, it was essential that the semiconductor laser operating at 1.5 μm be truly single frequency. That capability was provided by the distributed feedback (DFB) laser, which could also be directly modulated to provide information encoding. In addition, as TDM rates increased, external optical waveguide modulators that provided high-speed optical information encoding without the "chirping" effects proved to be essential for data rates above several gigabits per second.

Finally, high-gain, high-bandwidth avalanche photodiodes (APDs) to provide reasonable optical to electrical conversion efficiency were also needed for high-speed TDM systems. The combination of single-frequency lasers operating at 1.5 μm, signal encoding with external interferometer waveguide modulators, and detection with APDs resulted in record transmission experiments (2–16 Gb/s over 100-km spans) in the early 1990s that led to commercially deployed 10 Gb/s systems in the late 1990s.

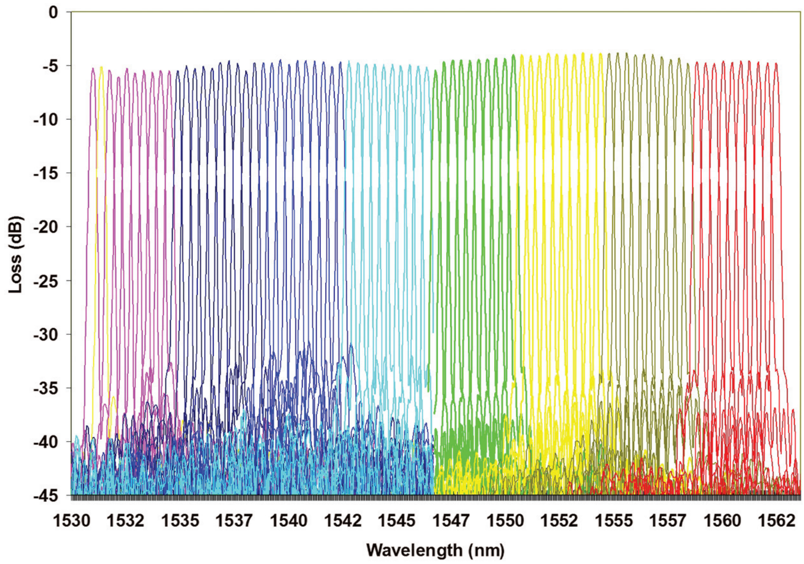
Wavelength division multiplexed (WDM) transmission systems employ multiple wavelengths, each separately encoded with information that is passively multiplexed together onto a single single-mode fiber, transmitted over some distance, and then wavelength demultiplexed into separate channels whose information is detected and received. While such systems had been proposed earlier, they had not initially gained popularity because of the need for a regenerator for each wavelength at repeater sites. Compared with increasing capacity via TDM, the approach did not scale capacity as cost effectively as TDM.

The fiber amplifier totally changed the value proposition of WDM systems. While not a pulse regenerator, the optical amplifier provides relatively low-noise 20–30-dB amplification—sufficient to compensate for transmission loss over 50–100 km of low loss fiber. Most importantly, the optical amplifier can simultaneously amplify multiple wavelengths, each carrying a high-capacity TDM signal. Notably, there is no mixing of signals, and amplification can be achieved for signals with arbitrarily high information rates. Both erbium-doped and Raman-based fiber amplifiers have been developed, with the former being the commercial workhorse. The erbium-doped fiber amplifier gain peaks at about 1.55 μm—well aligned to the fiber loss minimum.

Besides the fiber amplifier, the other key enabling technologies for WDM transmission systems are the wavelength multiplexing and demultiplexing devices and single-mode lasers whose wavelength can be precisely matched to the mux/demux wavelength response. For large wavelength counts, waveguide grating routers based on silica waveguide technology are typically employed. Figure 2 shows the 80-wavelength output from an early silica-based arrayed waveguide router. High-power (~100-mW output power) semiconductor pump lasers are required. Fiber amplified transmission systems are essentially analog systems where amplifier noise from each repeater accumulates, as does dispersive and nonlinear pulse spreading. Careful dispersion management is very important. Zero-chirp optical modulators are especially important for signal encoding to leverage the cost effectiveness of the amplifier over longer distances without electrical regenerators.

The first WDM commercial systems, deployed in terrestrial long-haul applications in the mid-1990s, employed eight wavelengths at 2.5 Gb/s, a tenfold improvement over the single-channel systems

Fig. 2. Measured wavelength response of a silica waveguide based grating router 80-wavelength channel multiplexer/demultiplexer with 50 GHz channel spacing.



previously available. As multiplexing devices and amplifier performance was improved, the number of wavelengths was soon doubled and then quadrupled. In the research lab, work focused on WDM for higher TDM rates, 10 Gb/s and beyond.

The first WDM systems were deployed over existing "standard" single-mode fiber. However, to reduce the phase-matched nonlinear mixing effect of fiber at its zero-dispersion wavelength, so called "non-zero-dispersion shifted" fibers were developed. Such fibers could be used as the transmission fiber or in the repeater site as a "dispersion compensating fiber" to undo dispersion accumulation. In this case the transmission fiber has sufficient dispersion over the transmission distance to avoid four-wave mixing but produces pulse spreading that is undone by the compensating fiber.

Undersea lightwave systems were an important driver and early adopter of fiber amplified WDM transmission systems that were especially attractive because they avoid undersea high-speed electronics, which reduced the lead time for reliability testing. In addition, properly designed WDM transmission systems offered the potential for future capacity growth by increasing the wavelength bit rate or the number of wavelengths. The first such system, a transatlantic system, included 16 wavelengths at 2.5 Gb/s each with repeater spacing of 100 km.

In research labs around the world, as multiplexing devices and amplifier performance were improved and techniques to mitigate dispersive and nonlinear transmission impairments developed, single-fiber transmission capacity results were improved, sometimes quite dramatically, every year. These extraordinary "hero" transmission systems experiments became the highlight of the post-deadline session of The Optical Society (OSA, and IEEE Photonics and Communications) sponsored Optical Fiber Conference (OFC) each year. Increased capacity in transmission systems experimental results over the years (Fig. 1) were achieved by increasing the per wavelength bit rate from 2.5 Gb/s to 10 Gb/s to 40 Gb/s to 100 Gb/s. Key issues that needed to be addressed included demonstrating high-speed electronics, modulators, and receivers at the higher rates; mitigating nonlinear fiber; and managing dispersive effects. Total capacity was also increased by increasing the number of wavelengths. This was achieved either by increasing the bandwidth of the amplifier or by finding ways to reduce the wavelength spacing without reducing the information rate/wavelength, resulting in improved spectral efficiency.

The adoption of WDM transmission led to wavelength-based reconfigurable optical networks that provide wavelength-level, cost-effective network bandwidth management. That evolution is shown schematically in Fig. 3. Initially WDM was employed over linear links where all wavelengths were aggregated onto the fiber at one node and carried with periodic amplification to an end node. However, in real networks, especially as the distance achievable without electronic regeneration has been increased, the sources and destinations of traffic require off and on ramps for traffic entering between

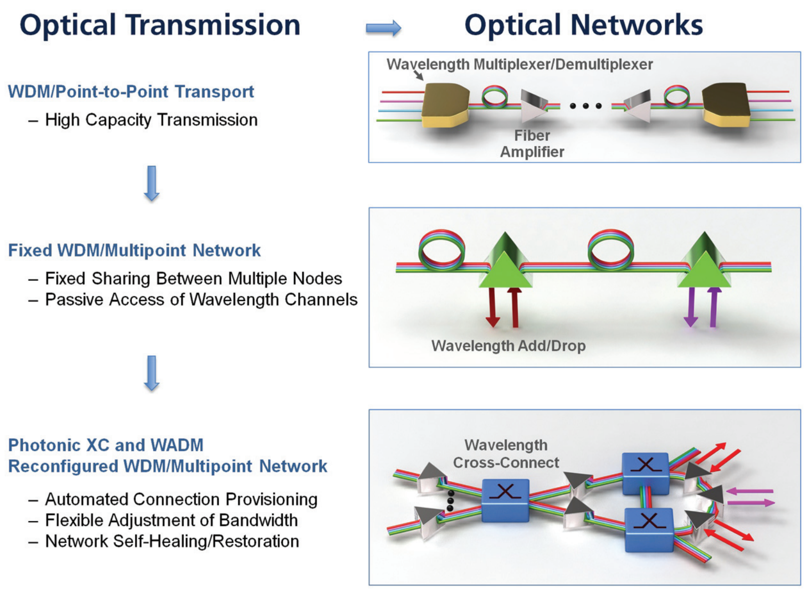


Fig. 3. Evolution of reconfigurable, wavelength routed optical networks employing reconfigurable optical add/drops (ROADMs) and optical cross-connects.

large metropolitan areas. Optical wavelength add/drop multiplexers provide those high-capacity on/off ramps with a full wavelength of capacity and allow all other wavelengths to pass through the node benefiting from the amplification. While initially these were fixed in number and which wavelengths were added/dropped, these modules are now fully remotely reconfigurable with respect to both the number of channels and which wavelengths are added/dropped.

Networks are not linear but are meshed to enhance resilience to equipment failures and fiber cuts. They require branching points where several fiber routes coming into a major metropolitan area connect to several exiting routes and also drop/add wavelengths at the node. In this case optical switch modules, referred to as optical cross-connects, which, in a wavelength-selective manner connect wavelength channels from one input fiber route to a particular output route, are employed.

Automated, reconfigurable optical switch cross-connects have become essential elements in today's WDM optical networks to effectively manage bandwidth capacity as demands increase and change. The enabling technologies for reconfigurable wavelength add/drop multiplexers and cross-connects are electrically controlled optical switches, either broadband or wavelength selective, together with components known as wavelength multiplexers/demultiplexers. A variety of technologies have been used for optical switch fabrics, including micro-mechanical (MEM), liquid crystal, and thermo-optical waveguide switches. Integrated modules that include wavelength demultiplex/demultiplex (demux/mux) together with optical space switches are also commercially available. Commercial wavelength reconfigurable optical networks have been widely deployed at both national and metropolitan levels. Integration, both monolithic and hybrid, has been important to cost effectively achieve the functional complexity required for modern optical networks.

An important advantage of optical networks is the potential to upgrade the bit rate per wavelength without the need to deploy new optical networking elements. The inherent bit rate independence of optical amplifiers (other than the possible need for higher pump power), optical switch fabrics, and mux/demux elements has allowed carriers to upgrade properly designed reconfigurable optical networks, initially operating at 10 Gb/s, to 40 Gb/s and 100 Gb/s by changing out only the ingress transmitters and egress receivers—a significant advantage of optical networks. Express wavelengths can now be carried cross continent without going through costly electronic regenerators, while along the way traffic can be optically dropped and added to fully utilize the high-bandwidth-fiber pipe.

At the time of this writing, commercial reconfigurable optical networks available and deployed for national and metro applications have capacities of ~10 Tb/s (100 wavelengths at 100 Gb/s) with fully reconfigurable wavelength add/drop capability. Transoceanic commercial systems are operating at capacities of ~4 Tb/s.

The ubiquitous deployment of broadband wireless systems together with massive sharing of consumer produced video and growing demand to access "cloud" based computational services continues to drive bandwidth demand at 25%–40% per year. There is every indication that demand will continue to grow at ~10× over the next ten years. Given the state of current commercial systems, this suggests the need for 1 Pb/s systems in the next 8–10 years. Commercially, the next targeted bit rate is likely to be 400 Gb/s followed by 1 Tb/s. To achieve higher speeds requires continued advancement in high-speed electronics, photo detectors, modulators, and integration. It also requires the ability to launch higher optical power while mitigating nonlinear effects. The number of wavelength channels is limited by the required bandwidth per channel and the total transmission bandwidth limited by the amplifier. Optimizing system spectral efficiency is essential. Achieving long-distance transmission without regeneration is also important for cost-effective networks.

To achieve higher effective per wavelength channel capacity while limiting speed requirement, research has focused on advanced coding techniques that use both amplitude and phase information as offered by coherent detection. By employing coherent techniques it is also possible to apply polarization multiplexing to effectively double channel capacity. Coherent techniques also allow the use of electronics to mitigate deleterious transmission impairments. These modulation formats, including quadrature phase-shifted keying (QPSK) and quadrature amplitude modulation (QAM), require the use of high-speed digital signal processors to convert the input signal information into the coded amplitude and phase-modulation signals to drive complex nested optical amplitude and phase modulators to encode the optical signal. As an example, with polarization multiplexing and 64-QAM (64 symbols per bit), one can transmit at an effective rate of 320 Gb/s with electronics, modulator, and receiver operating at only 80 Gbaud/s. The benefits come with transmission trade-offs as well as the complexity of high-speed digital signal processors. There has been substantial research progress in this area over the last five years as reflected in the systems results of Fig. 1.

Within the past several years, concern has been growing that keeping up with bandwidth demand will require another major technological leap—an additional dimension of multiplexing. The proposed dimension is to use space division as implemented either via multiple cores in a fiber or multi-modes of a single-core fiber. For the system to be cost effective compared to simply building parallel fiber optic systems, it likely will be necessary to also demonstrate optical amplifiers, at least, to act upon multiple spatial modes simultaneously. Integration is likely to be essential.

Because of limited space we have focused here on long-haul and metro optical communication networks. However, leveraging the technologies outlined here, there has been tremendous progress in optical access systems as well. Fiber optic technology has been used to feed coaxial cable systems, allowing increased reach and per user capacity. There is also increasing deployment of fiber-to-the-home systems, especially using TDM-based passive optical network (PON) technology. Recently, combined WDM and TDM PON technologies have been deployed to provide per home/business capacities of 1 Gb/s.

In addition, optical technology to provide intrabuilding interconnection in data centers is a growing application that will become even more critical as cloud services evolve. Distances are relatively short, and low cost is especially important. Optical and opto-electronic integration, either hybrid or monolithic, will be essential. The role of optical switching in data centers is being explored.

Throughout this history of incredible progress, OSA has played a critically important role in fostering and nurturing the continuous discovery, invention, and demonstration of optical components and systems that have been key to the dramatic progress of this field. OFC, a premier global conference on optical communications, was first held (as the Topical Meeting on Optical Fiber Transmission) in 1975 in Williamsburg, Virginia. OFC/NFOEC 2013 had more than 12,000 attendees from all over the world. The OFC post-deadline sessions are standing-room only events where researchers around the globe present their latest breakthrough results.

OSA has also nurtured newly emerging technologies in their formative stages, including fiber amplifiers, reconfigurable optical networks, and fiber to the home through highly focused topical meetings that offer ample opportunity for discussion and debate. The *Journal of Lightwave Technology*, co-sponsored by OSA and IEEE, has been a key journal for sharing and archiving advances in the field. Many of the members of the optical communication field have played leadership roles in OSA as well.

Acknowledgements

In this short historic overview, scope and space have not allowed proper citations [2]. My thanks to the large global community—many of whom are members of OSA—who have contributed to the extraordinary progress in optical networks described here.

References

1. Adapted from R. W. Tkach, “Scaling optical communications for the next decade and beyond,” Bell Labs Tech. J. **14**, 3–9 (2010).
2. Suggested further reading for recent overview and update: Special issue on the Evolution of Optical Networks, Proc. IEEE **100**(5) (2012).