

Evolution of Optical Fiber Technologies

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Abstract

This paper describes evolution of optical fiber technologies to meet high capacity demands

Keywords

Optical Networks, Optical Fibers, Capacity



History of Optical Fiber Development

Developments in Optical fiber communication technologies date back to 1960s at a time when glass fibers and lasers were invented. Initially, the fiber attenuation was extremely high (> 1000 dB/km) but was dramatically improved to 20 dB/km by Corning Glass Works in 1970. In early 1980's, InGaAsP lasers were developed for data transmission, emitting light at 1300 nm where the fiber loss was below 1 dB/km. The maximum transmission speed demonstrated was 44.7 Mb/s up to a 23.3 km and 274 Mb/s over 7.5 km without repeaters [1] in graded index multimode fibers. The transmission distance was mainly limited by dispersion in multi-mode fibers. In 1981, the single mode fibers were developed for long distance transmission. The signal transmission at bit rate of 154 Mb/s over 58 km fiber was demonstrated in 1983 [2]. Later, the single mode InGaAsP semiconductor lasers operating at wavelength of 1550 nm were developed which helped extend the repeater spacing to 130 km with a bit rate of 2 Gb/s [3] due to lower fiber attenuation at 1550 nm. At present, commercially deployed systems operate at bit rates of 100 Gb/s over transmission distance exceeding 1000 km.

From a fiber evolution perspective, single mode G.652 fiber was developed and optimised for operation at 1310 nm wavelength. However, due to lower Rayleigh scattering at higher wavelengths and invention of Erbium doped fiber amplifiers operating at 1550 nm, the transmission spectrum in long distance and metro-city networks moved to 1550 nm. As bit rate-rates increased to 10 Gb/s to meet capacity demand, chromatic dispersion (CD) started becoming a serious problem. To solve dispersion issue, G.653 fibers were introduced which has a negligible dispersion at 1550 nm. This approach worked well for single channel transmission, however with the advent of multi-channel wavelength division multiplexed (WDM) system, this fiber suffered from nonlinear effects due to Four wave mixing (FWM). Therefore, the non-zero dispersion shifted fiber (NZDSF, G.655) was introduced which had a small dispersion coefficient at 1550 nm wavelength. However for WDM systems spaced at 50/100 GHz channel spacing, other nonlinear effect such as cross phase modulation (XPM) started limiting the signal transmission performance. As a result, G.656 fiber with relatively higher dispersion than G.655 was introduced. As data rates continued increasing to 40 and 100 Gb/s, Coherent modulation and demodulation technologies were introduced, which along with digital signal processing made electronic compensation of CD possible. This led to a resurgence of G.652 fibertypes which are now the dominant fibertypes deployed in long haul and metro-city networks. As the bit-rate of backbone networks increased, access networks started developing to ensure superior end to end transmission performance. Further, access networks started pushing into the last mile connectivity space, to optically connect businesses and homes resulting in Fiber to the Home (FTTH) networks. In the FTTH application space, the bend-insensitive fibers (G.657) were developed to reduce the macro-bending loss that inevitably happens due to tight fiber bends needed in homes and enterprises, due to limited physical space. This family of G.657 fibers was categorised by its macro-bend performance at different bend diameters. Going forward, it is anticipated that network growth needs would keep pushing the fiber manufacturers to develop small diameter fibers, with lower attenuation and macro-bending losses, allowing transmission of high bit-rate signals with minimum signal distortion.



Capacity Growth in Optical Networks

The Internet traffic is continuously growing due to demand for bandwidth consuming services, high performance tele-computing, mobile broadband access for smart portable devices and high definition television applications. According to Cisco VNI global traffic forecast [4], the annual global IP traffic in 2016 can reach at avolume of 1.3 zettabytes (ZB) - (a zettabyte is equal to a sextillion bytes, or a trillion gigabytes). It has been projected that the overall IP traffic will grow at a compound annual growth rate (CAGR) of 29% from 2011 to 2016. The monthly growth of wireless and mobile traffic in relation to traffic from wired devices is shown in Figure 1 which shows significant growth in mobile data traffic. This mobile data traffic is generally back-hauled using optical networks, which would mean a healthy demand for optical fiber and cable.

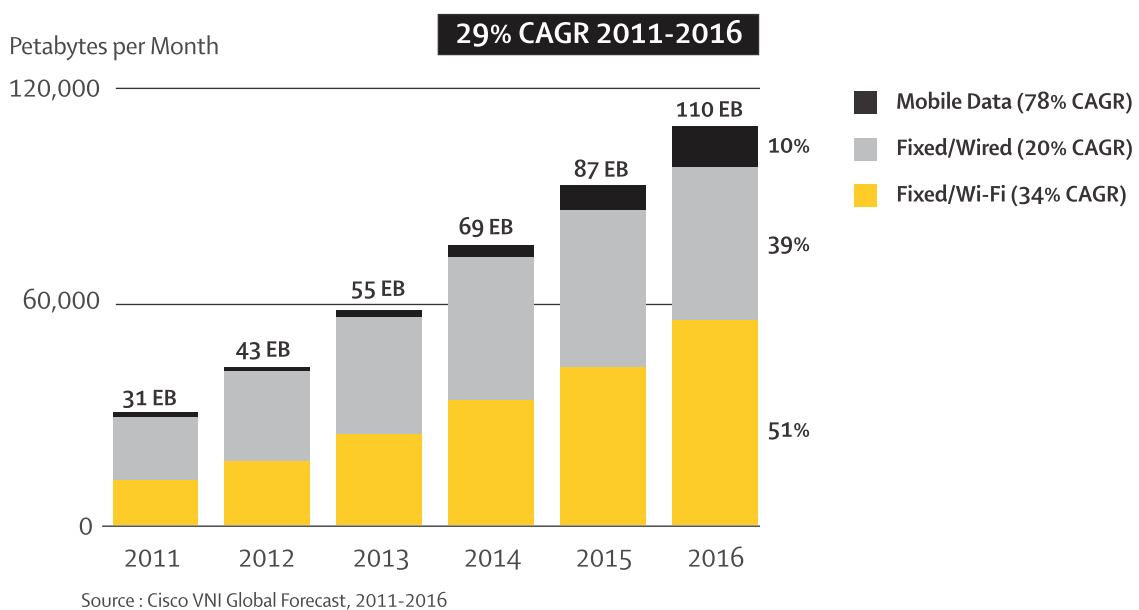


Figure 1: Global IP traffic per month, Wired and wireless, [EB: Exabyte: 1000x petabytes]

Developments in Optical Transmission Technologies

ITU-T G.694.1 standards introduced multiple channel WDM transport networks at 50 GHz channel spacing. Commercially deployed systems following those standards generally operated at data rates of 2.5 - 10 Gb/s with non-return-to-zero (NRZ) signal modulation format. Rapid technology progression in the last ten years has resulted in the ability to encode more bits per symbol within limited spectral width, coherent detection based on digital signal processing and utilising high coding gain forward error correction (FEC). 100 Gb/s transmission system utilising DP-QPSK format with a spectral efficiency of 2 b/s/Hz has been recommended by Optical Internetworking Forum (OIF) for deployments in the commercial core/metro networks and such systems have indeed been deployed worldwide. Laboratory investigations are ongoing to increase channel capacity beyond 100 Gb/s over a single fiber using higher order modulation



formats. However, transmission distance can be limited by system penalties induced by the requirement of high optical signal-to-noise ratio (OSNR). For example, a 400 Gb/s system utilising DP-16QAM would require a 10 dB higher OSNR as compared to a 100 Gb/s DP-QPSK even with optimal digital coherent detection which would result in a 10x reduction in transmission distance. In real systems, the requirement for high OSNR cannot be met by simply launching more optical power into the fiber, since the maximum allowable signal power in a fiber is limited by fiber nonlinear effects. Additionally, higher order m-QAM signals are more susceptible to nonlinear phase noise and distortion further limiting the transmission distance. Although some improvements in total throughput without significantly increasing OSNR requirements can be achieved by putting together multiple wavelength channels spaced at the baud rate without having guard bands between channels (super-channels), we are fundamentally at a point where a step change in optical fiber technology is needed to meet future capacity demands.

Deployment of fiber types in optical networks

An optical network enables the data transmission at high bit rate from source to destination over long distances without optical-to-electronic format conversion. An architectural overview of optical transport networks is shown in Figure 2. The core or backbone network has a meshed interconnection between switches/routers in the network. These switches and routers are located at very long distances from each other (~ 500 km). The Metro networks extend the connectivity from the core network to the edge and provide aggregation for a wide range of end user services within cities (~100 km). In core and metro network system, the signals are transmitted over different WDM channels around 1550 nm. In core and metro-city networks, the dominant fiber types deployed are G.652.D and G.655 with G.652.D being the more dominant of the two. A small number of networks also have G.653 and G.656 types of fibers. In the access network region, Passive Optical Networks (PONs) are emerging as the solution for the “last mile” connectivity and can support high speed broadband access within a transmission distance of < 20km. PON architectures are now adopted for wide-scale deployments in Asia, Europe and North America due to inherent advantages of low forward and return losses in the network components with high optical power handling capability.



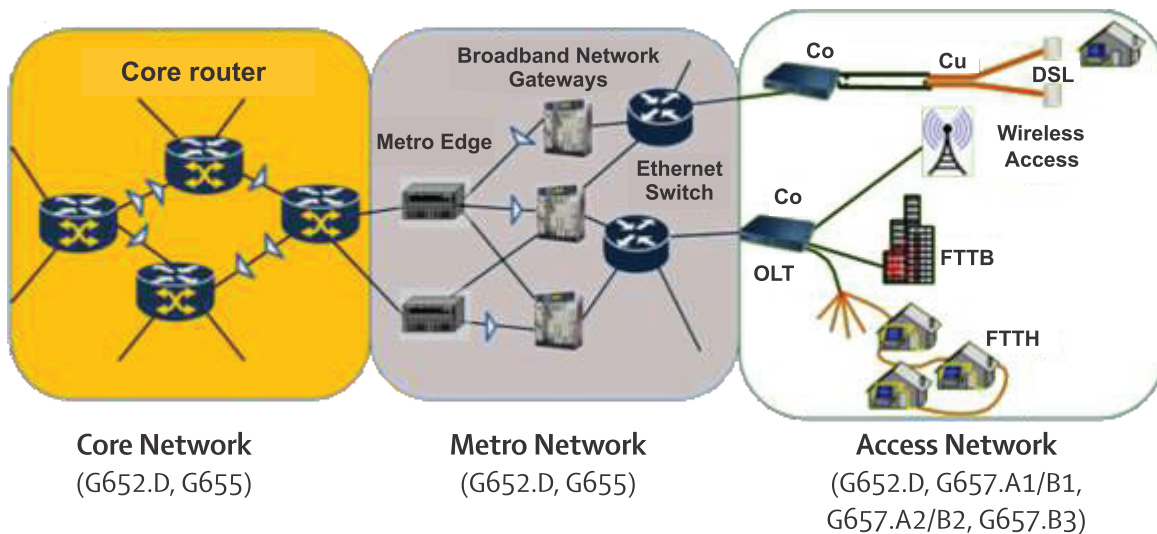


Figure 2: The optical fiber network architecture

There are two main types of PON technologies deployed in the access network. They are EPON (Ethernet Passive Optical Network) and GPON (Gigabit Passive Optical Network). EPON is one implementation of Ethernet in the access network. The optical fiber access systems referred as fiber-to-the-x (FTTx) is a point-to-multipoint fiber connection to the 'home', 'curb', 'building', etc., depending on depth of deployment of field fiber. Moreover, the optical line terminal (OLT) at the service provider's central office acts as an active remote distribution node through a passive optical splitters to serve multiple optical network units (ONUs), typically 16 -128. In a fiber-to-the-home (FTTH) system, the optical fiber is connected to household users. In addition, the ONU can easily be bridged to a customer premises device using different access technologies such as Ethernet over twisted pair, DSL or wireless backhaul. The deployment of ITU-T G.984-GPON can support transmission at bit rate of 2.488 Gb/s at wavelength of 1490 nm for downstream and 1.244 Gb/s at wavelength of 1310 nm for upstream. The GPON can also be used in rural areas to support high speed access connectivity which are normally underserved by broadband access.

In PON systems, G.652.D fibers are normally used as a feeder fiber between OLT and the distribution points. However, signal transmission performance can be severely impacted by large macro-bending loss introduced in the link due to tight fiber bends ex.; sharp street-bends, extreme indoor tight bends during the fiber deployments. G.657A1/B1 and G.657A2/B2 fibers offers reduced macro-bend loss than G.652.D and are preferred in the distribution part of the network. For the extreme tight bend scenarios that may occur during deployment of fiber along walls till access point inside rooms/house G.657B3 fibers have been developed with significantly enhanced macro-bend performance. A judicious choice of these bend-insensitive fibers is needed to meet the power budget requirements on FTTX networks and provide safety margins for unexpected deployment conditions. The recommended macro-bend loss for different G.657 fibertypes is summarised in Table 1 [5].



		ITU-T G.657.A1/B1		ITU-T G.657.A2/B2			ITU-T G.657.B3		
Bend Radius (mm)		15	10	15	10	7.5	10	7.5	5
Number of Turns		10	1	10	1	1	1	1	1
Macro-bend	Max at 1550nm	0.25	0.75	0.03	0.1	0.5	0.03	0.08	0.15
loss (dB)	Max at 1550nm	1.0	1.5	0.1	0.2	1.0	0.1	0.25	0.45

Table 1: Recommended macro-bend values for G657 fiber types

Future Fiber Design Trends

In order to meet capacity crunch in existing fibers, there have been several advances to increase capacities over single mode fibers in commercial communication systems. Moreover, space division multiplexing (SDM) has been investigated recently that increases the data carrying capacity of single fibers [6]. The development of future generation fibers can be categorised as follows:

- 1. Larger Core Area:** The optical fiber nonlinearities can be significantly reduced by increasing the effective mode field area. This can allow system designers to increase launch power of WDM signals increasing OSNR and thus either allowing for more transmission distance or higher bit-rate signals or both.
- 2. Lower Fiber Attenuation:** Lower fiber attenuation can lead to higher OSNR in optically amplified systems facilitating higher bit rate communications. It can also allow longer repeater spacing or higher system margin..
- 3. Multi Core Fiber:** The information carrying capacity in single fiber can be dramatically increased by having more single modes cores with a common clad region. In the multi-core fiber, the data transmission capacity increases directly proportional to number of fiber cores.
- 4. Few Mode Fibers:** In few mode fibers, a few modes can be excited and the transmission capacity in a single core fiber can be increased. However, such systems can support only a limited transmission distance due to intermodal dispersion and crosstalk.
- 5. Multi-core-Few Mode Fibers:** By combing multi-core and few-mode fibers, one can dramatically increase capacity in a single fiber (ex. 1 petabit/s) [7]. These fibers will be suitable in future access networks.



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