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Advances in local area optical data communication systems

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Abstract

This paper reviews optical fibre technology for local area optical communications systems. Technologies used in local systems include single and multimode fibre, single and multimode lasers, optical modulators, photodetectors, wavelength division multiplexing, multilevel modulation formats, electronic packet switching, electronic equalization and error correction. These methods have enabled the local area optical link data rate to increase from 0.1 Gb/s in 1990 to nearly a Tb/s in 2019. The challenges to increasing link data rates further, whilst reducing the transmitted power per bit, at reduced cost are discussed. Potential technical solutions and newly proposed methods which might address these challenges are highlighted.

Keywords: CWDM, data communications, DFB, direct detection, Ethernet, Fibre Channel, InfiniBand, integrated photonics, intensity modulation, local area network, optical communications, optical modulators, pulse amplitude modulation, parallel optics, silicon photonics, VCSEL

Introduction

During the past 30 years, the growth in data transmitted over communications networks has been dramatic. This is reflected by the trend in the specified maximum link data rates of local and storage area networking standards. Taking the Ethernet standard as an example of a communications standard[1], over the past 30 years the specified link data rate has increased by nearly five orders of magnitude as follows: 10 Mb/s in 1990, 100 Mb/s in 1995, 1 Gb/s in 1998, 10 Gb/s in 2002, 100 Gb/s in 2010, 400 Gb/s in 2017. Astonishing as this growth is, it has not kept pace with the growth demanded by networking equipment manufacturers as they attempt to satisfy the data communication demands of their customers.

The near exponential growth in communications capacity, previously discussed in terms of local area systems, is also evident in the history of capacity per single fibre for installed trans-oceanic optical links. This is illustrated by figure 1.

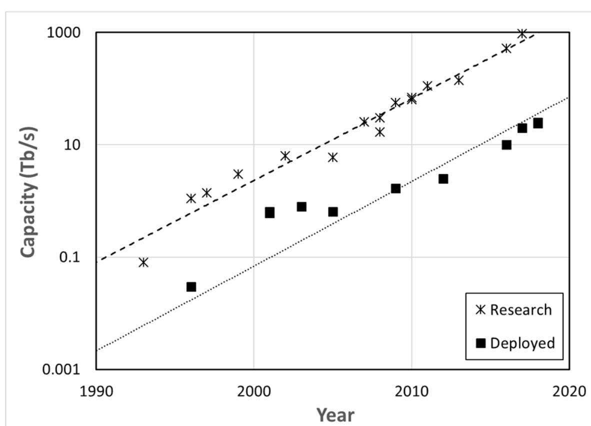

Figure 1. Illustrative trend for the capacity of a single fibre for trans-oceanic links over the past 30 years. Research([2]-[17]), Deployed: TAT-9, TAT-12/13, VSNL Transatlantic, FLAG, Apollo, SE-ME-WE-4, Hibernia, Faster, Marea 2017, Pacific Light.

During the past 30 years, the telecommunications industry has gone through a series of very successful technology developments, some important ones being:

- Multimode fibre (MMF)
- Single-mode fibre (SMF)
- Multimode Light Emitting Diodes (LEDs)
- Multimode and single-mode lasers
- Light modulators
- Transmission via optical intensity modulation
- Transmission via optical coherent modulation
- Wavelength Division Multiplexing (WDM)
- Optical amplification
- Error correction methods

Today's state-of-the-art long distance, optically amplified links, use single-mode fibre, dense wavelength division multiplexing (DWDM), optically coherent transmission, complex modulation formats, electronic dispersion compensation and error correction methods[18][19].

The resulting availability of relatively cheap high data rate links within enterprises and over the fixed broadband or mobile networks has enabled new applications such as: email, distributed computing, the web, interactive mapping services, on line banking, social networking, music and video streaming, Video-On-Demand (VOD), video conferencing, cloud storage and computing. It is expected that new data communication intensive applications will continue to be developed.

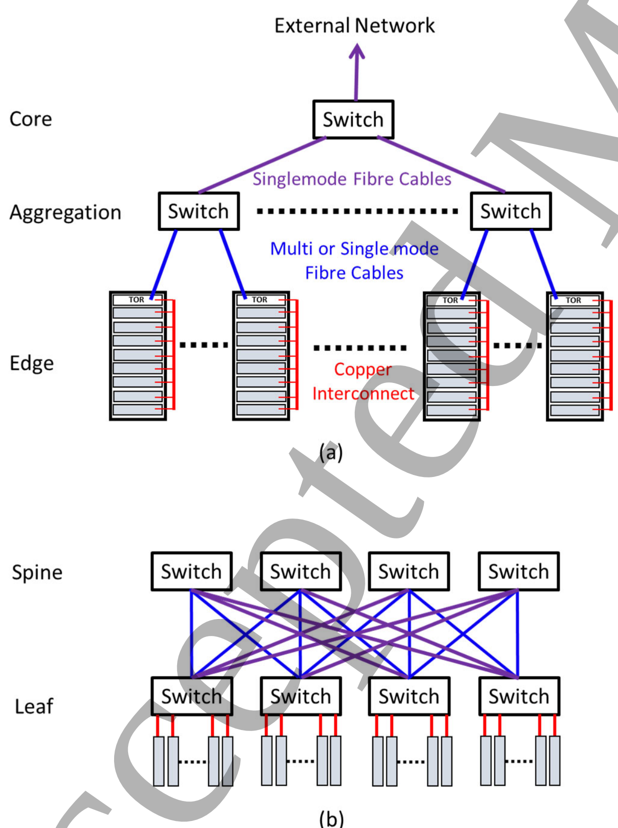

Figure 2. Simplified diagrams of the basic fat tree and leaf and spine network architectures.

To support these applications hyperscale data centres, have been deployed[20][21][22]. Much of the communications technology used within these data centres is derived from technology originally developed for Local Area and Storage Area Networks (LANs & SANs). Data centres are massive parallel computing infrastructures consisting of groups of interconnected servers, as conceptually illustrated by figure 2. Figure 2a illustrates the basic fat tree architecture commonly used in early data centres[23]. The servers within a rack are typically connected to a Top-Of-Rack (TOR) electronic packet switch by short copper cables or a copper backplane. The TOR switches are connected to a set of aggregation switches which in turn connect to core switches that also communicate with the external network. The various switches would typically be Ethernet local area network (LAN) switches[24]. The physical links between the various switches may use multimode or single mode optical fibre.

Today variations of the leaf and spine architecture[21][25], a basic form of which is illustrated in Figure 2b, are preferred over the basic fat tree. The leaf switches gather the traffic from the end nodes and are fully interconnected to the spine switches. More complicated multi-dimensional architectures are also in use[26][27]. The mesh-based networks have been introduced to provide more consistent performance in terms of parameters like bandwidth, delay and latency. They can also enable more economic scalability.

Memory storage portions of a data centre would use similar network architectures but may use other switch based technologies such as Fibre Channel[28] or InfiniBand[29] to form a Storage Area Network (SAN).

Figure 3, which is loosely based on the TIA-942 Data Centre Cabling Standard[30], illustrates the link lengths required within data centres that use structured cabling. It also indicates the positions of the various patch panels for

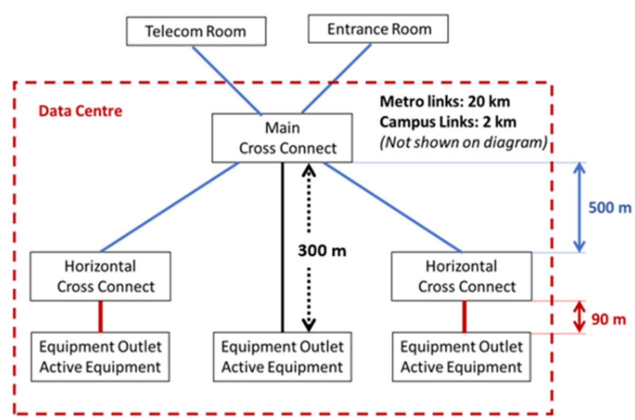

Figure 3. Maximum link lengths when structured cabling is used.

interconnecting the various fibres (cross connects) of the fibre cabling. Link lengths for campus (building-to-building) and metropolitan links are also stated in the figure. Within data centres important distances are 100 m, 300 m and 500 m. The first two lengths may be served by multimode or single mode fibre. However, longer lengths are typically serviced by single-mode fibre.

Whilst we have emphasized hyperscale data centres it should be recognized that smaller scale data centres employed by enterprises would have a similar structure. They would simply be more modest in terms of the number of links and amount of equipment used. At the other extreme, hyperscale supercomputing systems would also use similar technology but would likely require more, possibly even higher bandwidth links, directly between processors and/or memory rather than simply between servers and network attached storage.

The "Cloud" is made up of data centres distributed throughout the world[31]. Buildings housing the data centres could be located within a single campus, or they could be at separate sites within a metropolitan area[24], or they could be located across a country or even the world. To provide the various "Cloud" services these separate data centres need to be interconnected with high data rate links. For this reason Data Centre Interconnect (DCI), which emerged over the last decade or so, is one of the fastest growing network market segments[32]. Essentially, DCI fulfils a role similar to long haul telecommunications.

Data centres located within a campus or metropolitan area can usually be connected via SMF links of less than about 20 km (see figure 3). However, more widely separated data centres may require longer link lengths[24] and may require optical amplification of the optical signals every 40 km to 80 km. Inter-continentally connected data centres require total interconnection link lengths of many thousands of km – again these would include optical amplification every 100 km or so. Both types of optically amplified, long distance link use technology originally developed for telecommunications. To enable long distance DCI, it is now common for technology companies such as Google, Facebook and Microsoft to fund or partly fund transcontinental and transoceanic optical fibre links.

In this paper we will review optical fibre technology for local area optical communications systems. We assume that the term local area system includes LANs, SANs, data centres and supercomputing systems. We will focus on the optical technologies used within data centres which enable link lengths up to a maximum of 2 km. These short links are the most numerous within the network and are a vital part of the Internet. Finally, due to their ubiquity, they must have a very low cost and a low power dissipation.

This paper will not consider local access networks, Passive Optical Networks, home networks, industrial or automotive networks.

The optical technologies developed for local area optical systems were initially based on technology originally developed for telecommunications. For long distance telecommunications links, it is extremely expensive and difficult to install new cables and the required in-line equipment (e.g. optical amplifiers, optical filters). Therefore, for telecoms, it is imperative to use as much of the bandwidth of each available optical fibre as possible.

However, data communications require many input/output (I/O) ports. Ideally, the ports would operate at the maximum serial data rate supported by the attached equipment. This means that the optical links attached to the ports should operate at the serial data rate of the I/O port. Due to limitations in the bandwidth of the optical and electrical components, this may not be possible. Therefore, it has become common to use parallel fibres or sets of widely separated wavelengths to create higher data rate links. For local systems, the use of parallel fibres can be justified since it is less difficult and much less expensive to install new cable and equipment within a local system when compared with a long-distance telecommunications system.

The different requirements and boundary conditions of local area systems has meant that the optical technology used for local systems has diverged from that of traditional telecommunications. Some examples of the divergence, which are often due to cost, size and power consumption limitations, are

- LANs use both multimode and single-mode fibre rather than just singlemode fibre.
- Multiple cables per link are available.
- New cables can relatively easily be installed.
- Due to the limited space for equipment racks, the data rate density per faceplate area (of a switch or rack) is much more important than achieving the capacity of a single MMF or SMF.
- Due to the limited power allocated on a per equipment rack basis, the power dissipation of LAN optics and associated electrical processing must be kept very low.
- Optical transmitters must operate over a wide temperature range rather than being temperature controlled.
- Intensity rather than optical coherent modulation is prevalent.
- Coarse Wavelength Division Multiplexing (CWDM) rather than DWDM is prevalent.
- Optical amplification is uncommon.
- The latency of the optical link must be minimized.

Due to these differences designers of local area systems place much more emphasis on parameters such as low cost, small physical size, minimum total power dissipation, the ability to manufacture in large unit numbers and interoperation between different vendors equipment, when compared with the designers of telecoms systems.

Modulation, Detection and Multiplexing

In this section methods to transmit, detect and multiplex optical signals will be conceptually introduced. It will become clear that the highest capacity optical links utilise all five orthogonal dimensions of an optical wave: colour, polarisation, phase, amplitude and spatial propagation mode.

Intensity Modulation

Intensity modulation of an optical wave is usually considered the most straightforward method of optical modulation. The intensity of the optical source could be modulated by changing a modulating signal, usually an electric current or voltage, which "drives" the source. This is termed direct modulation. Alternatively, an additional optical element which changes its light transmission in response to a drive signal could be used to modulate the intensity. Since the modulator is external to the optical source, this is called external modulation.

Coherent Modulation

Coherent modulation refers to the situation were the some or all of parameters defining the optical wave of the optical source are modulated. For monochromatic sources, the available optical wave properties are polarisation, amplitude and phase. Like intensity modulation, coherent modulation could be achieved by direct modulation of the source, though this will be normally accompanied by amplitude modulation. However, it is more common for external modulation to be used.

Direct Detection

When the optical receiver is designed to output a signal in response to the received optical intensity, the optical signal is said to have been directly detected. The output of a direct detection receiver may be designed to be linear with respect to optical intensity. However, the output is non-linear with respect to the electric field amplitude of the received optical wave. This is because optical intensity is proportional to the square of the optical electric field amplitude. Optical receivers which utilize direct detection of intensity only are the simplest form of receiver. For that reason and the associated low manufacturing cost, they have become the dominant optical receiver type used for local area systems.

It is possible to design direct detection receivers to recover some or all of the properties of the optical wave[33][34]. Such receivers are more complicated compared to ones based on basic direct detection, especially in terms of the required optical and electrical signal processing. However, they may be viewed as simpler than receivers based on coherent detection, i.e. they may require fewer optical components, photodiodes etc., and so are an active research topic. An advantage of such receivers over basic direct detection of intensity is that electronic digital signal processing can be used to compensate for the optical filtering, dispersion and polarisation rotation of the fibre link. At high data rates, greater than 50 Gb/s per wavelength or so, such receivers might become important for data centre interconnection in the metropolitan area network (MAN) or the wide area network (WAN) [34][35].

Coherent Detection

Optical receivers which interferometrically recover some or all the properties of the optical wave are called coherent receivers. This method of optical detection is usually termed coherent detection. Modern coherent receivers digitize the received signals using high sampling rate analog-to-digital-converters (ADC). For this reason, they are normally referred to as digital coherent receivers[18]. If the complete optical field is sampled and digitized, then digital signal processing (DSP) and adaptive equalisation methods can be used to compensate for the optical filtering, dispersion and polarisation rotation of the fibre link.

Multiplexing Methods

As previously mentioned, there are five physical optical wave parameters that can be used to combine or multiplex optical signals: colour, polarisation, phase, amplitude and spatial propagation mode or direction.

Wavelength Division Multiplexing (WDM) is the general name for combining channels having different optical colour. If the spectral separation between channels of different colour is relatively large, then the separation and channel width are stated in units of wavelength. In this case the term Coarse Wavelength Division Multiplexing (CWDM) is commonly used. If the separation and channel width are narrow, then units of frequency are also commonly stated and the term Dense Wavelength Division Multiplexing (DWDM) is used.

Each WDM channel can support two orthogonal polarisations. In modern high capacity coherent transmission systems, each polarization is used to carry a separate data signal. For each optical polarisation a further two orthogonal channels can be formed by using quadrature sine and cosine waves. The amplitude of the quadrature phased sine and cosine waves could then be amplitude modulated to impose data waveforms.

Whilst, not an optical property, time is also used to multiplex the data signals. A common method is to use a pulse shape which is maximum at the sampling time for the desired symbol and zero at all other symbol sampling times. On each quadrature channel, a series of amplitude symbol levels could then be used to represent various data symbols. If this method is used, then it is called Quadrature Amplitude Modulation (QAM). QAM is just one example of many methods that could be used to multiplex data onto the channel. For example, the amplitude could be kept constant whilst the phase or polarisation is modulated. Essiambre et al[36] includes clear constellation diagrams of many optical modulation formats. Also, rather than modulating time domain pulses, Orthogonal Frequency Division Multiplexing (OFDM)[37][38] may be used to impose data onto the WDM carrier wave.

Space Division Multiplexing (SDM) is the name given to the use of parallel spatial channels to multiplex optical data. It is generally applied to the situation were specialty fibres having many embedded, weakly coupled, single mode cores or many strongly coupled SMF or MMF cores or large core, few mode, fibres are used to create parallel optical communication paths[39].

If weakly coupled SMF cores are used, then to first order, each core behaves like a SMF and the capacity is increased by the number of SMF cores. At the other extreme if large core, few mode, MMF is used, then each mode of the fibre could be used to create a communication channel and the capacity is increased by the number of modes. Due to mode coupling effects, few mode MMF requires multiple-input multiple-output (MIMO) digital signal processing methods to recover the data from the various modes[40].

In the literature, SDM has sometimes been used for the case were the parallel optical channels have been created using ribbon cable consisting of parallel fibres[18]. However, in this paper, we will use the term parallel optics for that case. The term SDM will be reserved for the case where the spatial channels are formed within a single fibre structure by separate cores or modes of the fibre.

Channel Capacity Considerations

For an ideal linear channel corrupted by additive white Gaussian noise, Shannon[41] proved that the maximum channel capacity, C, in units of bits per second, is given by:

$$C = W \cdot \log_2(1 + \Lambda) \quad (1)$$

where, W, is the bandwidth of the channel and Λ is the signal to noise ratio at the receiver. The most simplistic definition of an ideal channel assumes that the response of the channel is constant over the bandwidth W, the signal power is confined to the channel and the noise power spectral density is constant. Obviously, if K independent ideal channels are used to form a communications link, then the total link capacity is simply K times C.

A direct method for creating independent channels is to simply provide a set of K parallel optical fibre links, see Figure 4a. Alternatively, SDM within a single fibre structure could be used to create the parallel channels. Additionally, on a per

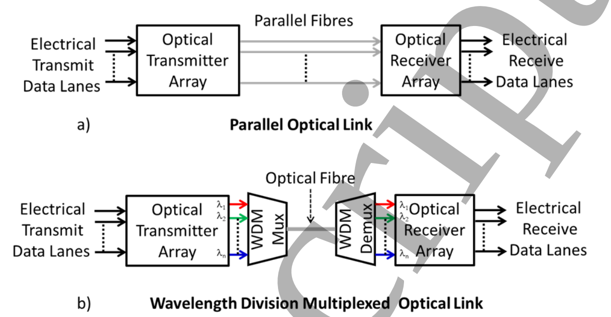

Figure 4. Common optical methods for increasing the aggregate capacity of an optical link for local area networks.

optical wavelength basis, the optical polarization and the optical phase provide four additional degrees of freedom which can be exploited to create four independent communication channels. Therefore, if N separate wavelength channels are used, the total maximum capacity, due to the parallel fibres and separate wavelengths, would be 4 K N C. That value should be considered an ideal upper limit on the capacity.

At high data rates, for lengths of single mode fibre greater than a few tens of kilometres, the optical signal creates significant optical distortions and noise due to non-linear optical effects. It has been shown that these non-linear effects reduce the channel capacity to a value commonly called the Non-linear Shannon Limit (NSL)[36]. However, there is still some debate as to whether the NSL is a true limit. This is because, at least in principle, some of the non-linear distortion can be corrected. The NSL for a single, single-mode fibre is on the order of 100 Tb/s[36][39].

The highest capacity long distance telecommunications-based optical communications links use DWDM, both optical polarizations and the two optical phases with digital coherent receivers. Using these methods, the NSL of a single-mode optical fibre has been approached experimentally[42][43].

If SDM via multimode fibre is used, each mode of the fibre could theoretically create an independent transmission channel. By spreading the optical power over a larger core area, the use of multimode fibre also reduces the strength of the non-linear optical effects which further increases the total capacity. Thus, the use of multimode fibres which support a few modes has become an active area of investigation[39]. Fibres supporting a few modes are preferable since the smaller number of modes simplifies the detection and processing of the signals carried by each mode.

It has been shown that the capacity of optical links, using direct detection, can approach that of ones using coherent detection[44]. To achieve this level of performance, it is assumed that, to reject out of signal band noise, the received optical signal is filtered with an optical band-pass filter; the optical signal is then square law detected (directly detected) by a single photodiode per polarization. The photodiodes and subsequent electronics are assumed to have electrical bandwidth of at least twice the bandwidth of the transmitted data signal. The high bandwidth of the photodiodes and electronics is required due to the frequency doubling property of direct detection. By collecting and processing all the frequency doubled received signal, almost all the information, including the optical phase terms, contained in the complex electric field of the optical signal can be recovered. Therefore, the capacity is decreased by a relatively small amount when compared with coherent detection. To achieve these results, the transmitter must have similar optical signal fidelity to that of a coherent transmitter. Kramers-Kronig receivers[33] are an implementation of direct detection that can achieve this level of performance.

In the previous discussion, it was implicitly assumed that the optical transmitter had high enough signal quality that both the amplitude and the phase of the optical signal could be modulated. For cost, complexity and power dissipation reasons, the optical transmitters used for current local area systems do not have such fidelity. Instead the intensity of the optical signal is modulated. Also, currently, the optical polarization degree of freedom is not used. Furthermore, most high data rate, optical links use photodiodes and receive electronics having bandwidth less than the transmitted electrical signal bandwidth. Therefore, since the four orthogonal dimensions due to optical polarization and optical phase are not utilized, today's optical links for the local area, based on intensity modulation with direct detection (IM-DD), have a maximum capacity of approximately one quarter that of the coherent and the optimum direct detection schemes discussed in the previous sections. However, since local area links need only operate at the maximum data rate of the communication ports to which they attach, this large reduction in capacity of the individual optical links is not a limiting issue.

Intensity Modulation with Direct Detection for LANs

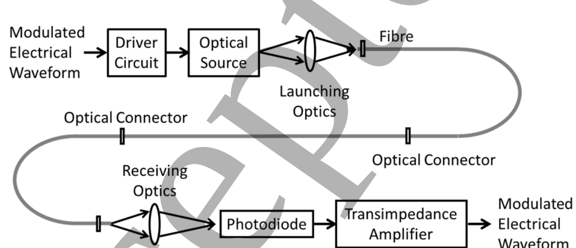

Figure 5. Simplified optical link based on intensity modulation and direct detection of the intensity.

Today, local area optical links utilize intensity modulation with direct detection (IM-DD). Figure 5 illustrates the components used to form a single channel optical link based

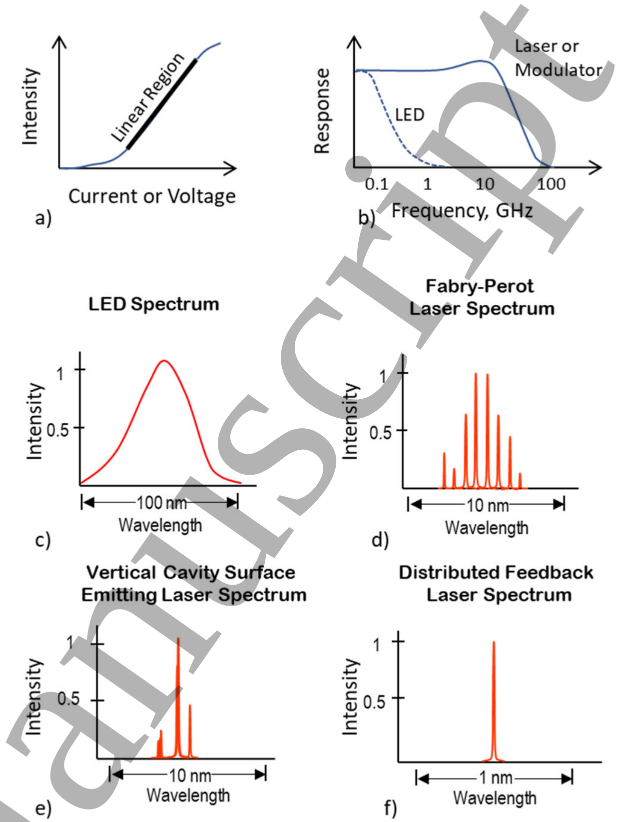

Figure 6. Illustrative graphs of some important characteristics of optical sources used for local systems.

on IM-DD. The data to be transmitted is converted to an electronic waveform which either directly modulates the bias current or voltage of the optical source or is used to modulate an optical modulator which modulates the output intensity of the optical source. The modulated light intensity is then collected and focused into an optical fibre. The optical fibre could support only one transverse optical mode or it may support multiple transverse modes. If single mode fibre (SMF) is used, it would be glass fibre, having a core diameter of approximately 10 µm. If multimode fibre (MMF) is used, it would be glass fibre, having a core diameter of 50 or 62.5 µm (denoted as 50MMFand 62MMF). These MMFs typically support hundreds of optical modes. Optical connectors are also included in the optical link. The link connectors introduce attenuation, reflections and, in the multimode case, mode mixing and modal noise. The term modal noise refers to noise caused by the interference of the optical modes at connectors and the optical receiver. At the receiver, the light is collected and focused onto a photodiode, typically the photocurrent is amplified using a low noise transimpedance amplifier (TIA) and the modulated electrical waveform is recovered. The photodiode is typically a PIN diode. The use of avalanche photodiodes is rare due to the requirement to provide higher voltages, the extra circuit complexity and at high data rates relatively low avalanche gain. Although not shown on the diagram, the data would be recovered from the received electrical waveform.

Figure 6 illustrates some important characteristics of various optical sources used for local systems. As shown by figure 6a, the optical intensity is modulated in response to the modulated current or voltage. Figure 6b indicates the electrical frequency response of the various sources. Typically, the modulation current required by LEDs would be ~ 100s mA; for edge emitting lasers it would be ~ 10s mA; whilst for surface emitting lasers it would be ~ mAs. The total modulation bandwidth available would be ~ 100s MHz for LEDs and up to ~ 30 GHz for the state-of-the-art commercial directly modulated lasers or optical modulators. The optical receivers could also have an electrical bandwidth up to about 30 GHz. To reduce component cost and noise, the modulation bandwidth of the optical devices is typically limited to approximately half the data rate for two level modulation, less if multilevel modulation is used.

Figures 6c – f illustrate the optical emission spectra of the various sources. In optical fibre links, the received pulse duration is broadened, compared with the transmitted pulse duration, due to chromatic and modal dispersion. The chromatic dispersion can be reduced by using an optical source with a narrow optical emission spectrum. For this reason, high data rate optical links use laser sources with narrow optical spectral width.

For MMF links, to first order, the dispersion caused by excitation of the various fibre modes, called modal dispersion, is a property of the MMF. The bandwidth of an MMF is reduced by modal dispersion.

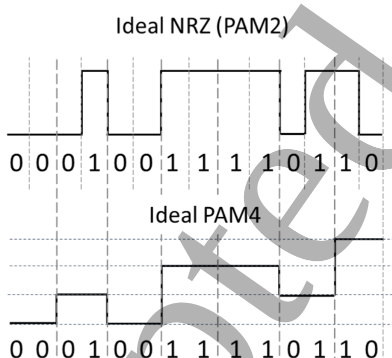

Figure 7. Idealized NRZ and PAM-4

Until recently, most optical links, for local systems, have used two level modulation. However, to support twice the data rate without increasing the required modulation bandwidth, pulse amplitude modulation with four levels (PAM4) has become common. Multilevel modulation has had to be introduced because the modulation bandwidth of available optical transmitters and receivers have not increased sufficiently to support data rates above about 40 Gb/s with two level modulation. Figure 7 illustrates idealized versions of the common forms of two and four level modulation. The diagram shows that one bit and two bits are transmitted by Non-Return-to-Zero (NRZ) and PAM4 modulation formats respectively. Since the pulse duration for PAM4 is twice that of NRZ, half the bandwidth of NRZ is required by PAM4. However, since the maximum separation between the extreme levels must usually be kept the same, PAM4 has less separation between its levels compared with NRZ. This makes it more vulnerable to noise.

For PAM4, the most common errors are due to noise causing the detected level to be a nearest neighbour level compared with the transmitted level. Therefore, it is common to use Gray coding[45] which assigns the two data bits to levels so that common errors change only one of the two data bits.

If the required data rate is higher than can be supported by an individual optical link, parallel transmission methods must be used. Figure 4 illustrates the two parallel optical transmission methods most commonly used within the local area.

Early History of Optics for Local Networking

The period from the late 1980s until the early 2000s was seminal for local area networking and associated optics. At the beginning of that period, data communications and data networking were very young. The number of connected nodes was small but explosive growth was predicted. Academic and industrial researchers knew that much had to be explored and learned. Many of the fundamental methods and techniques now incorporated in the optics and associated standards for the local area were first explored and developed during this exciting time of creative, sometimes chaotic, competition and research. Whilst many names and details of the innovators, companies and network technologies of that period may have been forgotten, we will discover that their best innovations live on in today's local systems. This is because they were incorporated into the surviving technologies and standards. During the past twenty years, these methods have continued

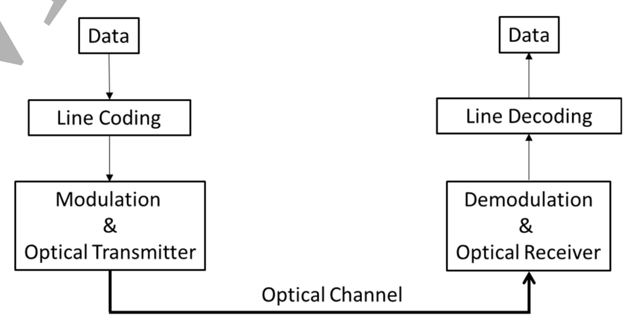

Figure 8. Key functions of an optical link for the local area during the period of late 1980s to early 2000s.

to be adapted, refined and improved to meet the need for higher data rate optical links.

Ethernet & Token Ring

In the late 1980s, two of the most widely deployed local area networking technologies were Ethernet and Token Ring. Ethernet first became an IEEE 802.3 standard in 1985[46]. This standardized version of Ethernet used a coaxial cable bus and the famous Carrier Sense Multiple Access with Collision Detection (CSMA CD) shared media access protocol. However, it was not until the standardization of 10BASE-T[47] in 1990, which used a centralized network concentrator and star wired twisted pair telephone cables, that Ethernet became widely adopted.

Similarly, Token Ring became an IEEE standard in 1985 (IEEE 802.5)[48]. It connected network nodes in a ring topology using IBM type 1 shielded twisted pair (STP) copper cabling and used a token passing protocol for media access control. During this time period, the data rates for Ethernet and Token Ring were 10 Mb/s and (4 Mb/s or 16 Mb/s), respectively. By the early 1990s, both networks were widely deployed in business, university and government LANs with a world-wide combined installed base of many 10s of millions of nodes.

FDDI & CDDI

During the mid-1980s, it became clear that the copper-based LANs would need some form of higher data rate optical interconnect to enable multiple LANs to be interconnected over a wider area. The Fiber Distributed Data Interface (FDDI) was developed to fulfil this need[49][50]. FDDI used a dual counter rotating ring topology. It also used a token passing protocol like Token Ring but modified to be more efficient.

Initially, FDDI used multimode fibre, light emitting diode (LED) based transmitters and PIN-photodiode based receivers. This enabled link lengths of up to 2 km when the optical wavelength range of 1270 to 1330 nm was used. Later, FDDI incorporated single mode fibre and Fabry-Perot (FP) laser-based transmitters[51] to enable much longer link lengths of up to about 50 km between nodes.

At a high architectural level, figure 8 illustrates the key functions of optical links for LANs applicable from the late 1980s up until the early 2000s. In that time period, the optical output power of the optical transmitters, sensitivity of receivers and their bandwidth was enough to enable reliable transmission using two level NRZ modulation without recourse to equalization or error correction coding. Since the optical components had enough modulation bandwidth, line coding was used to ease the recovery of the data and a bit clock at the receiver and to also allow AC coupling of the electronics.

During the early 1990s, the developers of the FDDI standard realized that for it to become a commercial success, it would also need to address the local area with a copper cable variant for deployment to the desktop. This resulted in the influential FDDI Twisted Pair Physical Media Dependent (FDDI TP-PMD) specification of 1995[52], sometimes called Copper Distributed Data Interface[50]. Ultimately, FDDI was superseded by 100 Mb/s Ethernet, 100BASE-T called "Fast Ethernet", of IEEE 802.3[53]. However, at the physical layer, the Fast Ethernet standard incorporated or referenced most of the innovations developed by FDDI. These innovations included:

- MMF with 62.5 µm core diameter – now commonly called FDDI grade fibre[50] or OM1[54] MMF
- Line coding via a block code (4B5B/NRZI)[50]:
  - to reduce the power transmitted at zero frequency
  - to enable control and data words to be easily and reliably detected
- Data Scrambling to reduce electromagnetic interference (EMI)

Whilst details of the method used for scrambling the bits of the transmitted symbol stream is different between CDDI (stream-cypher) and Fast Ethernet (self-synchronous scrambler), importantly, it was recognized that error detection need not be impeded by scrambling. This taught LAN standards developers that line codes including scrambling could safely be incorporated into future higher data rate local area systems.

Whilst FDDI was being developed, it was recognized that even higher data rate local area systems were required. Therefore, in the late 1980s and early 1990s much effort was expended developing technologies suitable for Gigabit per second data rates over optical fibre.

ESCON

One of the first major deployments of optical fibre technology for computer-based data communications was made by IBM with the introduction of the Enterprise System Connection (ESCON) Architecture in 1990[55]. ESCON used bi-directional, point-to-point channels and had a maximum link rate of 200 Mbit/s. An unrepeated distance of 3 km was specified with 62MMF and light emitting diode-based transceivers. Fabry-Perot (FP) laser-based transceivers were used to support a maximum unrepeated distance of 20 km. Both transceiver types operated near wavelengths of 1300 nm.

For the serial fibre optic links, the IBM 8B10B block code[56] with NRZ modulation was used. When compared with the 4B5B/NRZI coding scheme used by FDDI, the 8B10B code greatly reduced the transmitted low frequency spectral components. That property was very helpful, especially when laser-based transmitters were used. The

8B10B coding reduced potential thermal issues due to the low frequency content, limited baseline wander, helped reduce the optical coherence length of the laser and generally enabled a higher signal-to-noise-ratio. The 8B10B code also had many other good features such as simple delineation of control sequences, data words, packets/frames and extensive native error detection capabilities. It could also be implemented very efficiently into hardware.

HIPPI Serial

During the late 1980s it was recognized that there was a growing need for Gb/s interconnects between computers. This was especially true for users of supercomputers, mainframes or applications dealing with very large data sets such as computer visualization or nuclear physics experiments at places such as CERN. To meet this need, the High Performance Parallel Interface (HIPPI) was specified[57][58][59]. Networks of equipment and computers could be formed by using HIPPI switches. HIPPI was specifically designed for supercomputers and many of the features developed for HIPPI have since been integrated into InfiniBand[60].

However, because HIPPI used cables of 50 copper twisted pairs, it could support a maximum length of 25 metres only. That was a serious limitation. Therefore, during 1991, a fibre optic extender, Serial-HIPPI[61][62], was specified. The initial specification supported a 10 km maximum link length via single-mode fibre with Fabry-Perot laser transmitters operating near wavelengths of 1300 nm and PIN-TIA based optical receivers. By adopting methods then under development by Fibre Channel, later versions supported 0.5 km of 50MMF via short wavelength laser-based transmitters[63].

An important aspect of Serial HIPPI was its use of the G-Link chipset[64], developed by Hewlett-Packard. It used a novel and flexible line coding method called Conditional Inversion with Master Transition (CIMT)[65]. The code accommodated various word lengths which was very different to the block coding methods prevalent at the time. Four code bits were added to each input data word. To reduce the low frequency content of the serially transmitted data stream, the bits of the resulting code word were then directly transmitted or inverted before transmission. To enable fast, simple framing and to aid clock recovery, the four added code bits were specified to ensure that a master transition always occurred between bits 2 and 3 of each code word. The coding method was an important precursor to the line code that would eventually be developed for 10 Gigabit Ethernet.

Fibre Channel

Fibre Channel began in the late 1980s. As will be discussed, researchers from IBM made many important contributions to the early development of Fibre Channel. In large part this was because they had gained experience of optical fibre technology through the commercialization of the IBM Enterprise System Connection (ESCON) technology, as well as, optical bus extenders that were developed for the IBM AS400 minicomputers. It soon became clear that data rates greater than the 200 Mb/s of ESCON were required. Eventually, higher data rates of 266 Mb/s, 531 Mb/s and 1063 Mb/s were settled on. It also seemed evident that if low cost laser-based transmitters could be developed, then these would enable more robust optical links compared with those based on LED transmitters. This was based on the observation that lasers could provide better optical beam quality, faster optically modulated signals and higher optical power for less drive current.

Now, it should be remembered that in the early to mid-1980s, there simply were no lost cost lasers suitable for data communications. Commercially, it was highly desirable for laser-based transmitters to operate on the MMF already installed for FDDI and ESCON. But, the use of MMF and lasers raised huge concerns regarding the interference of the light from the modes of the fibre which caused a type of noise called modal noise[66][67]. The issue of modal noise was largely solved by a set of innovative, visionary scientists and engineers at IBM who investigated low cost laser sources for data transmission on MMF. They identified that lasers similar to those developed for Compact Disc (CD) players could be used for high data transmission rates, even over MMF[68]. At data rates of 266 Mb/s and 531 Mb/s, they proved that CD lasers, of the self-pulsating type, had very low optical coherence[69]. That meant modal noise was not an issue. In addition, they showed that CD lasers of the self-relaxation-oscillation type could be modulated at gigabit per second data rates[70][71].

Notably, it was also shown that whilst the self-relaxation-oscillation lasers had higher optical coherence than the self-pulsating CD lasers, the coherence was low enough to enable MMF applications[72]. Importantly, methods that enabled CD lasers having very long Mean-Time-To-Failure (MTTF) to be selected for use as optical data transmitters were developed.

Early in the standardization of Fibre Channel, it was decided that a serial rather than a parallel optical bus interface would be developed. Also, it was decided that IBM's 8B/10B block coding with NRZ modulation be adopted. The first draft of the Fibre Channel standard was published during 1989. In October 1994 the Fibre Channel physical and signalling interface standard, FC-PH, was approved as ANSI standard X3.230-1994[73]. The initial Fibre Channel standard specified four data rates:

- 100 Megabytes per second (Mbytes/s), which after the framing overhead and 8B10B coding translated to 1062.5 Megabaud
- 50 Mbytes/s or 531.25 Megabaud
- 25 Mbytes/s or 265.625 Megabaud

- 12.5 Mbytes/s or 132.812 Megabaud

The initial Fibre Channel specification provided a maximum link data rate of about one gigabit per second with full duplex transmission between ports using separate transmit and receive fibres. The standard included specifications for short copper cable-based links at the same data rates. Multimode fibre links at data rates from 266 Mb/s to 1063 Mb/s were supported with specifications suitable for short wavelength (770 to 860 nm) CD laser-based transceivers. 50MMF was the preferred MMF type and with it the maximum supported link lengths were 2 km, 1 km and 0.5 km at 266 Mb/s, 531 Mb/s and 1063 Mb/s. Long wavelength (near 1300 nm) laser-based transceivers could support 10 km at all data rates via SMF.

ATM Forum

Asynchronous Transfer Mode (ATM) is a method for providing a connection orientated transfer of a continuous stream of short cells of data between equipment connected to ATM switches. ATM was originally developed by the telecommunications industry as part of the Broadband Integrated Services Digital Network (B-ISDN)[74]. ATM uses asynchronous time-division multiplexing and encodes data into small, fixed-size, 53-byte cells rather than the variable-sized packets and frames used by the Internet Protocol (IP) and LANs such as Ethernet. It was envisioned that ATM would provide a universal networking technology to support all traffic types for data communications in the LAN, WAN and traditional telecommunications.

The ATM Forum was founded in 1991 with an objective to accelerate the use of ATM products and services through rapid development of interoperability specifications. When research on ATM began, FDDI at 100 Mb/s was the fastest LAN technology in widespread use. To rapidly achieve a higher data rate for LAN applications quickly ATM took advantage of the then newly developed and cost-effective Fibre Channel physical layer chipsets for 155.52 Mb/s fibre optic links. It also released specifications for copper twisted pair-based links at data rates of 25.6 Mb/s[75], 55.84 Mb/s[76] and 155 Mb/s[77]. In the WAN, ATM-SONET interfaces at 155 Mb/s and 622 Mb/s via single-mode fibre were commonly used as the interface between backbone routers. Note: SONET refers to the Synchronous Optical Network[78].

However, in 1994-1995, Fast Ethernet appeared, and then around 1997, Gigabit Ethernet and Packet-Over-SONET (POS) were released. Initially, compared with IP router technology, ATM had many advantages, but the rapid improvement of IP routers soon mitigated the advantages[79]. During 2005, the ATM Forum merged with groups promoting other technologies, and eventually became the Broadband Forum. By then, various manufacturers began to stop support for ATM LAN-based products. From that time on switched Ethernet and IP became the basis of local area networking and with the addition of routing technologies, like Multiprotocol Label Switching (MPLS), the basis of the MAN and WAN as well.

VCSELs for Data Communications

The first view of Vertical Cavity Surface Emitting Lasers (VCSELs) becoming ready for commercial applications was provided by the ATM Forum debates during 1994 and 1995[71][80][81][82][83]. VCSELs lasing near wavelengths of 850 nm, 980 nm, and 1300 nm were discussed. Hewlett-Packard (HP) demonstrated that VCSELs operating at 980 nm were extremely reliable, relatively simple to manufacture and could support building backbone link lengths (550 m) at Gb/s data rates with both 62MMF and 50MMF. However, in the compromises that must be made in the standards arena, the 980-nm VCSEL proposal for Gb/s ATM links was rejected. An important reason for the rejection of the proposal was the existence of the low cost 780 nm, Fabry-Perot, edge emitting, (CD) laser diode transmitters and associated Fibre Channel specifications. The resulting ATM optical specification for 622 Mb/s using MMF[84] was written to include both the existing 780-nm Fabry-Perot edge emitting laser diodes (CD lasers) and the emergent 850-nm VCSELs. However, link lengths of 550 m on 62 MMF could not be supported with those wavelengths.

As a result of the ATM-Forum decision, Hewlett-Packard and other companies, paused commercial development of 980 nm VCSELs and switched to the development of 850 nm VCSELs. For those companies, that was a bitter pill, but it was accepted as part of what happens during technology standardization and they simply redoubled their efforts to regain a competitive position with 850 nm VCSELs.

Dawn of Switched Ethernet LANs

In November 1992, a higher-speed study group of the IEEE 802.3 committee was formed to develop 100-Mbit/s Ethernet. This culminated in July 1995 when the IEEE ratified two new 100-Mbit/s standards that used Ethernet frames: IEEE 802.3u (Fast Ethernet) and IEEE 802.12 (100VG-AnyLAN). These new 100-Mbit/s standards were designed to provide an upgrade path for the many tens of millions of 10BASE-T and Token Ring users worldwide. Both standards supported commonly installed copper twisted pair and MMF cabling, as well as existing network management and application software. To support MMF both simply referenced the FDDI MMF LED-based specifications which enabled 2 km link lengths on 62 MMF.

The availability of these relatively cheap, mainly twisted pair-based, 100 Mb/s LANs accelerated the need for higher data rate building backbone and campus multimode and single-mode fibre optic links.

Significantly, during the development of the 100 Mb/s standards, Ethernet frame switching, using full duplex links, gained momentum as a method for increasing network capacity. The wider data communications networking community realised that the future of LANs, SANs and likely WANs would to be based on the Internet Protocol supported by packet switching using full duplex links.

Gigabit Ethernet

Gigabit Ethernet was a catalyst which brought together and forced optical data communications experts to address many unresolved technical issues regarding the specification of robust, very high volume, economic, optical links. This resulted in specifications and test methods that have been adopted and adapted by almost all optical data communications standards ever since.

During 1996, a crescendo of activity began on the development of Gigabit Ethernet. The starting points were the ATM Forum specifications for 622 Mb/s[84], the Fibre Channel standard operating at 1.0625 GBaud[73] and the Serial-HIPPI (1.2 GBaud) specifications. The great commercial success of Gigabit Ethernet is due, in large part, to the fact that many of the key technical contributors to Gigabit Ethernet had deep experience of those preceding foundational standards.

Gigabit Ethernet brought to the forefront some remaining unresolved technical challenges previously identified during the ATM Forum 622 Mb/s debates:

- how to support 2 km campus backbone links?
- how to allocate an optical power penalty for modal noise?
- the need for robust transmission methods for 550 m backbone links using installed 62MMF?

Whilst the new higher bandwidth, at short wavelengths, 50MMF was aggressively being installed, most of the building backbone links in the U.S. and Europe were still using 62MMF. Ensuring 550 m links could be supported on the installed 62MMF was critical to the early adoption and commercial success of Gigabit Ethernet.

Since the installed base of building-to-building campus links was quite small, it was viewed that installation of single-mode fibre would be acceptable for campus links. However, an unresolved technical issue regarding single-mode fibre links was how to treat the optical power penalties due to the laser mode partitioning, mode partition noise, of Fabry-Perot lasers. Based on experience gained from the telecommunications industry[85], Serial-HIPPI[86] and Fibre Channel, specifications enabling the use of long wavelength Fabry-Perot laser diodes operating near 1310 nm were developed[87]. Conservatively, a worst-case link length of at least 5 km was specified, well beyond the 2 km needed for the campus building-to-building backbone.

Regarding multimode fibre, another unresolved issue was the method for the allocation of modal noise penalties. The Gigabit Ethernet committee and other fibre optic standards groups jointly studied modal noise. Those studies concluded with an agreed allocation for modal noise within the optical link power budget. Test methods were also developed to enable modal noise penalties to be measured[88].

A much more difficult issue was how to support 550 m on installed 62MMF. Initially, it was assumed that by restricting the number of multimode fibre modes excited by the short wavelength lasers the effective modal bandwidth (EFBW) of an MMF link could be increased sufficiently to support the 550 m link length. Surprisingly (at the time), in many cases this turned out not to be true. The cause was quickly identified as being due to small perturbations in the graded refractive index profile of the MMF, primarily near the centre and edge of the core. With laser-based transmitters, which naturally excite far fewer modes of the MMF compared with LEDs, the perturbations caused large variations in the time of flight between the excited modes of the MMF. The reduction in the effective modal bandwidth was the result of the relatively large differential mode delay (DMD) of the received optical signal when restricted launch and lasers were used. This meant that, with the then preferred short wavelength laser transmitters, only the new 50MMF, championed by Fibre Channel, could support 550 m.

Fortunately, it had recently been discovered that offset single-mode fibre launches into the multimode fibre using 1310 nm lasers could support 550 m, on both 62MMF and 50MMF[89]. In the Gigabit Ethernet standard, offset launch was enabled by the specification of singlemode-to-multimode fibre, offset launch patch cords[87] for 50 MMF and 62 MMF. This meant that single-mode transmitters could simply be connected to the patch cord and then to the MMF. Obviously, this meant that the optical receivers used for the single-mode links must have photodiodes and optics large enough to collect all the light from the MMF and not just from a single-mode fibre.

Even after these changes, it was judged that the worst case received signal was worse than normally accepted (up until that time). For this reason, a new stressed optical receiver sensitivity (SRS) test method and specification was developed[87]. This ensured the specified minimum error rate would be achieved even with the specified poorest received optical signal. Additionally, to further reduce noise and jitter, a test was developed to ensure the electrical bandwidth of the optical receiver was not more than 1.2 x (inverse symbol periods)[87].

Importantly, and for the first time, a specification to ensure the light launched was launched into the desired region of the core of the MMF was developed. "Launch Conditioning" as it became known, was further studied and refined by the Telecommunications Industry Association FO-2.2

subcommittee and launch conditioning is now universally required for laser based MMF transceivers/transmitters.

Other key technologies, at networking layers above the optics, loosely associated with Gigabit Ethernet, were Link Aggregation and VLAN (Virtual LAN) tagging[90]. Link Aggregation enabled groups of links to be treated as a single logical, higher data rate, link. It also enabled redundant links to be created for increased reliability.

The Emergence of Parallel Optics

Optical signal processing and optical interconnects were extensively investigated during the 1980s. As that decade grew to a close, it was clear that parallel optical interconnects should be energy efficient compared with electrical interconnects for system board-to-board, rack-to-rack and for local area networks[91][92]. The first parallel optical link demonstrations used 1x12 monolithic LED and PIN diode arrays[93][94], multifibre array connectors and a few hundred meters of fibre ribbon cable to achieve aggregates data rates of a few Gb/s[95][96]. Whilst these proved the concept, it was realized that inefficient LED-based parallel optics and the immaturity of the ribbon fibre and array connectors would not enable commercial links. However, by the end of the 1980s, the emergence of very low threshold lasers and particularly VCSELs reinvigorated the field[97][98].

The realization that it was beneficial to use large area, multi-transverse mode, VCSELs with MMF was an important advance. The benefits included decreased current density within the active region of the VCSEL leading to increased reliability. By exciting more multimode fibre modes, the large area VCSELs also increased resilience to modal noise[82][83]. They also promised to be simpler to manufacture and test. However, some research remained focused on the use of single transverse mode edge emitting lasers for both MMF and SMF[99]. This was advantageous as at aggregate data rates of 100 Gb/s, or more, longer reach SMF parallel optics, has recently become vital.

Regarding the VCSEL-MMF-based parallel optical links, in the early to mid-1990s, collaborative research projects were established[100][101][102][103][104][105][106]. The various projects were extremely successful. They established prototypes which included most of the important sub-components and techniques required to commercialize the technology. The main application targets for the parallel optical links were optical interconnects within supercomputers, telecommunications switching systems and data communication routing systems. Links lengths on the order of a 100 m or less were acceptable for these applications. This meant that MMF could be used, which relaxed optical alignment tolerances, further simplifying the manufacturing of transceivers and connectors.

Parallel optical links gained commercial success in the period after 2000. Initially, they were used in proprietary systems. Later, various standards and trade associations, most notably the InfiniBand Trade Association (IBTA) and the Optical Internetworking Forum (OIF), developed specifications which enabled them to be more widely adopted.

Pluggable Optics Modules

During the 1990s, it became clear that local area equipment (switches, servers, adaptor cards etc.) would require both electrical and optical ports. However, it was very difficult to predict the correct mix of port type. Additionally, the optics was expensive and, compared with the electronics, it was relatively unreliable. Therefore, the ability to “hot swap” the optics was deemed extremely important. The computer and data communications industry responded to this challenge by inventing pluggable optical transceivers[107].

The first widely adopted pluggable optical module was the Gigabit Interface Converter (GBIC)[108] which was first proposed during 1995. GBIC was widely used for Gigabit Ethernet and Gigabit Fibre Channel. However, as the number of ports on equipment increased a smaller module was required and GBIC was eventually replaced by the small form factor pluggable (SFP) module[109]. The early GBIC and SFP pluggable modules were a vital enabling innovation. It is now clear that optics for the local area would have been much less successful without this development.

Over the past 25 years, as the data rate increased, pluggable optics modules have been developed for each new rate. Typically, a relatively large module is defined to cope with the likely high-power dissipation of early products. However, as technology matures, later versions use a smaller form factor pluggable format which, as with the GBIC-to-SFP migration, enables equipment to have higher port density.

Optics for Local Networking: 2000 - 2020

By the beginning of the new millennium most of the electronic, mechanical, optical and manufacturing methods required for optics for local area networking had been developed. These methods, with incremental improvements, would serve until the present day. Only the best methods and techniques of the explorations of the previous 15 years of hectic research, standardization, commercialization and competition survived. Gigabit Ethernet was becoming a major success, parallel optics was finding applications within high-performance computing (HPC), telecom systems and IP routers. The full breadth of the wisdom, gained from those previous years, were brought into focus by 10Gigabit Ethernet and the associated efforts within Fibre Channel, the OIF and InfiniBand.

10Gigabit Ethernet

During 1999, as soon as Gigabit Ethernet was completed, an IEEE 802.3 standard group began the development of

10Gigabit Ethernet. From the experience of Gigabit Ethernet, it was clear that 10 Gigabit Ethernet would be based on packet switches interconnected by full duplex 10 Gb/s links. For local systems, serial transmission at the desired data rate is always preferable. At that time, 10 Gb/s serial links based on SMF and scrambled NRZ were becoming common in telecommunications. Unfortunately, it was soon recognized that, due to cost, power dissipation and complexity, the serial transmission technology was not yet suitable for local area systems. Some form of parallel transmission via parallel optical fibres or multiple wavelengths would be required for early adopters. The specification of serial 10 Gb/s optical links on MMF and SMF was still viewed as vital. Interestingly, although not the focus of this paper, the telecommunications community recognized that Ethernet was becoming important for Wide Area Networking (WAN) and so they insisted that a WAN physical layer also be specified.

Emergence of CWDM

Coarse Wavelength Division Multiplexing (CWDM) near wavelengths of 1310 nm was selected as the parallel transmission method[110]. Two optical fibres were used to form the duplex link, one for transmission and the other for reception of the CWDM signals. Four wavelengths having a separation of 24.5 nm were defined. Distributed Feedback lasers (DFBs) were used, although it was hoped that eventually long wavelength, single mode, VCSELs could also be used. The use of wavelengths near 1310 nm enabled both installed MMF links of at least 300 m in length and SMF links of at least 10 km in length to be supported. In contrast to the then common practice for Dense Wavelength Division Multiplexing (DWDM) of stabilizing the laser wavelengths by temperature control of the lasers, the CWDM method enabled the transmitters to be non-temperature controlled. By removing the need for Peltier coolers this saved ~1 watt of power dissipation per optical transceiver.

For each of the four wavelengths, Non-Return-to-Zero (NRZ) modulation of the 8B10B encoded data was used. Front panel, pluggable optics modules, with the four NRZ/8B10B electrical input/output lanes and corresponding optical lanes were developed.

The importance of CWDM for LANs was quickly recognized by the telecommunications community and a set of CWDM wavelengths were added to the ITU-T wavelength grid[111]. In order to maximize the number CWDM wavelengths, the ITU-T grid was separated by 20 nm rather than the 24.5 nm of the first CWDM-based Ethernet standard.

New Multimode Fibre For 10 Gb/s Serial Transmission

To enable serial transmission using VCSELs lasing near wavelengths of 860 nm, the industry developed laser grade multimode fibre[112][113][114]. The objectives for the new multimode fibre were to enable 10 Gb/s serial transmission over a length of at least 300 m. Gigabit Ethernet taught that the specification of any new multimode fibre must include optical launch conditioning and a limit on the maximum amount of differential modal delay (DMD). The new laser grade multimode fibre achieved these goals by introducing new specifications as follows.

1) The flux of light launched into the core of the fibre as a function of radius, Encircled Flux (EF)[113][115][116]

2) The maximum differential mode delay[113][117] as a function of the position of radius within the core.

These new specifications ensured that the effective modal bandwidth (EFMBW)[118] was at least 6.7 GHz over 300 m which achieved the desired goals.

10 Gb/s VCSELs, DFBs and associated challenges

In the early years of the new millennium, when 10Gigabit Ethernet was being drafted, VCSELs for data transmission were still embryonic. Commercially, data rates of a few gigabits per second were the state-of-the-art. The first generation of VCSELs were based on ion implantation and gain guiding as mode control mechanisms[119][120]. To achieve higher data rates, improved guiding methods were required. Quite quickly, the industry focused on index guiding based on oxidation methods, so called oxide confined VCSELs[121][122][123]. Rapidly many examples of 10 Gb/s oxide confined VCSELs were reported[123][124][125][126].

For SMF applications at 10 Gb/s for ~ 10 km link lengths, non-temperature controlled, DFB lasers, operating near wavelengths of 1310 nm were also rapidly developed[127][128][129][130].

Optical Modulation Amplitude

In order to have good waveform quality, the extinction ratio (ratio of the high light level to the low light level) of the output optical intensity from the high speed VCSELs needed to be relatively low, approaching 2:1 or 3 dB optical. It became clear that directly modulated, non-temperature controlled, DFB lasers, exhibited the same issue. Initially, this was perceived as a problem because telecommunications and even Gigabit Ethernet required extinction ratios of at least 10:1. This was because low extinction ratios meant that a significant portion of the light output was not modulated and could be considered wasted optical power. Especially when the optical budget was performed based on the available average optical power, as was then common practice.

However, a few innovative developers notably advocated for the optical power budget to be defined for only modulated optical signals[131]. They argued that whilst the non-modulated optical power was wasted, so long as the optical transmitter could produce enough modulated optical power, then the low extinction ratio was not of real concern. To enable this form of budgeting, they proposed the Optical Modulation Amplitude (OMA)[132] [133] be used as the measure of optical power. The OMA was defined as the difference between the high-power level and the low power level between a relatively long series of transmitted "One" and "Zero" bits.

OMA is now a common specification parameter for optical power and optical power budgeting for links in local area systems. Whilst OMA was developed at a time when two level modulation was exclusively used, it has since been adapted for use with four level pulse amplitude modulation (PAM4) now common at per optical lane data rates > 40 Gb/s[134].

Scrambler based line coding: 64b66b

In the early 2000s, the newly developed 10 Gb/s VCSELs and DFB lasers did not have enough bandwidth for the 8B10B code per Gigabit Ethernet and Fibre Channel. It was also postulated that the bandwidth of lasers would not quickly improve. Therefore, line codes requiring much less overhead than the 20% required for 8B10B were sought.

Eventually, the 64b66b line code which required an overhead of 3.125% was proposed by a team from Hewlett-Packard[135]. Whilst not compatible with it, 64b66b was similar in spirit to the SONET line code which was then widely used by telecommunications. However, 64b66b was simpler to implement, requiring much less on chip memory and significantly for local networking, it enabled much lower latency.

As with G-Link (used for Serial HIPPI), the code featured code words which included two initial bits for synchronization transitions. The phase of the synchronisation bits could be used indicate normal data or control words. Unlike G-Link, rather than inverting the payload of the code words as was required to reduce low frequency content, the payload was pseudo randomized using a long self-synchronous scrambler. This reduced radio frequency emissions by smoothing the RF spectrum of the encoded modulated signal. How to safely combine scrambling with line coding for physical layers for LANs, without compromising error detection, had been solved by CDDI, 100VG-AnyLan and Fast Ethernet. Due to the synchronization bits, the maximum run length was guaranteed to be less than 64 enabling straightforward clock and data recovery (CDR), with acceptably small levels of low frequency components at the optical receiver to allow AC coupled electronics.

64b66b is now embedded within the physical layer of almost all high data rate local area links. However, as will be discussed later, if error correction is required, the 66b stream is compressed, forward error correction encoded and NRZ or PAM4 modulated as required for the optical link. At the receiver, the signal is demodulated, corrected and de-transcoded back to the 66b stream for communication within the electrical chip/switch/system.

Adaptive Electronic Dispersion Compensation For MMF

In the second phase of 10 Gigabit Ethernet standards development, to increase port density and to reduce cost, a serial 10 Gb/s solution for non-laser grade multimode fibre was developed: 10GBASE-LRM[136]. To support both old installed FDDI grade multimode fibre and new grades of multimode fibre, lasers operating near wavelengths of 1310 nm were specified. Due to the very low bandwidth of the old multimode fibre, with NRZ modulation format, a transmission length of about 80 m, rather than the required 300 m, could be supported. Clearly a new modulation format or a powerful equalization method was required. Initially, both PAM4 and NRZ modulation with receiver-based electronic equalization were considered. Since it was compatible with the already specified NRZ-based transmit electronics, electronic equalization of the 10 Gb/s, NRZ signal was selected.

A reference equalization architecture, based on tapped delay line equalization, was developed[137]. By tapped delay line, we mean that the signal passes through a delay line and a portion of the signal is periodically bled-off (tapped). Two sets of delay line were used, a so-called Feedforward Equalizer (FFE) and a so-called Decision Feedback Equalizer (DFE).

Feedforward tapped delay line equalizers can reshape the received signal by forming a weighted linear combination of delayed versions of the input waveform. For LRM, the delay between the taps of the FFE was assumed to be half the NRZ symbol period. At the data sampling times, over a certain range of distortion, the equalized output can be made approximately equal to the transmitted symbol as seen without the distortion. However, a linear combination of the noise is also formed which will have its high frequency components boosted causing enhancement of the noise and reduced signal to noise ratio.

A decision feedback tapped delay line avoids some of the noise enhancement as follows: Assuming past symbols have been correctly detected then, at the symbol decision times, the distortion due to them can be cancelled. Since the signal to be subtracted is electronically synthesised in the receiver, it can have very high signal fidelity and there is no noise enhancement. However, an FFE section is required, as some of the distortion is due to symbols not yet detected and so there will still be some noise enhancement.

One complication is that the distortion of the multimode fibre link is unknown to the receiver. Also, the distortion changes slowly with time. These issues can be resolved by using adaptive methods to track the distortion and set the weighting function for the linear combination of the FFE and DFE canceller signals appropriately.

10GBASE-LRM[136] was the first standardized electronic equalization specification for optical links within LANs.

Electronic equalization has since become a well understood and widely accepted building block used within various sections of high data rate optical links.

Parallel Optical Lanes Augmented by Signal Processing

The demand for higher data rate links simply outstripped the increase in the available bandwidth of practical optical transmitters and receivers. Therefore, as will be discussed in the next few sections, almost all higher data rate links have had to use some combination of parallel transmission and signal processing methods. The common signal processing methods used are per lane clock recovery, electronic equalization, error correction and recently, multilevel modulation. It is unlikely that this situation will change unless timely increases in the bandwidth of optical active and electronic components are made. Take directly modulated lasers as an example, Figure 9 indicates the recent trend in the modulation bandwidth. Increasingly, this will become a problem as the multiplexing of the data to parallel optical lanes will eventually cause unacceptable increases in the number of active optical components, power, size and the number of cables. If timely increases in the bandwidth of the optical transmitter, optical receiver and associated electronics cannot be achieved, then some form of large-scale integration of optical components will be required.

It is sometimes suggested that the adoption of optical coherent detection may be a fundamental solution. This seems unlikely as, even with coherent detection, the optical device bandwidth is similarly restricted and so parallel channels are still required. This is not to say that coherent detection will not prove useful. It should also be remembered that coherent detection is not easily made compatible with MMF links.

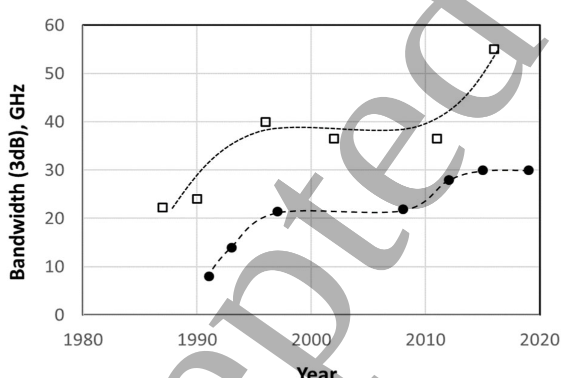

Figure 9. Trend in modulation bandwidth for long wavelength edge emitting lasers (squares) [138] to [143] and vertical cavity emitting lasers with wavelength near 850 nm (circles)[144] to [150] also see [151].

In the "Challenges for the Future" section, later in this paper, we will adopt a more optimistic view than that implied by this section.

40 Gigabit Ethernet

Whilst an NRZ-based, serial 40 Gb/s optical link was specified for up to 2 km of SMF[152], for lower cost MMF and longer SMF links, parallel transmission methods proved more practical[153][154]. These parallel links used four optical lanes per direction (four wavelengths for SMF and four fibres for MMF) to form a duplex 40 Gigabit Ethernet link. Since the data rate per optical lane was 10 Gb/s on a per lane basis with appropriate minor adaptations, the 10Gigabit Ethernet specification methods could be reused. The SMF links used CWDM near wavelengths of 1310 nm and the ITU-T grid with 20 nm spacing between the four wavelengths. This meant non-cooled transmitters could be used, saving cost, complexity and power.

Additionally, around the time 40/100 Gigabit Ethernet was being developed, methods for aggregating links at the physical layer were developed[155]. Also, as part of 40/100Gigabit Ethernet, a new method for distributing the data to be transmitted to multiple electrical and optical lanes was provided[156]. A benefit of the parallel transmission and data distribution methods was that rather than always being used as a 40 Gb/s duplex link, the four duplex 10 Gb/s lanes could be broken out, via special optical cable splitters and a data distribution mode of the switching equipment, to become separate 10Gigabit Ethernet links. This configuration increased the port density of switches used primarily for 10Gigbit Ethernet applications. The breakout ability has become a popular feature of parallel transmission. This is

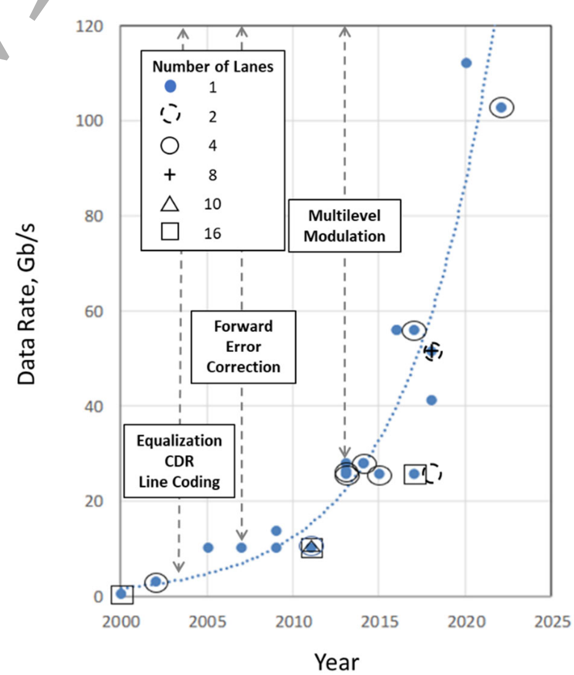

Figure 10. Trend of per lane data rate for copper interconnects, the number of lanes is also stated.

because the various servers at the lowest tier of the network typically operate at a lower serial data rate compared with the inter-switch links.

16/32/128 GFC: The Optical Signal Integrity Crunch

By 2010, the slow increase of the bandwidth of optical transmitters and optical receivers caused problems for the specification 16 Gigabit Fibre Channel. With NRZ modulation, the slow rise time of the transmitters meant that the received signal had a small separation between the high and low optical levels, especially for signals including high frequency content, …01010…, for example. To ensure enough signal integrity, closely coupled clock and data recovery (CDR) circuits had to be included, usually within the optical transceiver. A few years later, during the development of 32 Gigabit Fibre Channel. It became clear that, with NRZ modulation format, forward error correction (FEC) would also be required. This was due to insufficient bandwidth and signal to noise ratio of the then available optical components.

Ethernet had previously adopted FEC codes for Ethernet over the electrical backplane of switches and for copper cables using both NRZ and PAM4 modulation formats[157]. Figure 10 illustrates the approximately exponential increase (trend line on graph) in per PCB trace or cable data rate of the electrical channel for both Ethernet and Fibre Channel. The figure also indicates when various signal-integrity methods had to be adopted e.g. closely coupled CDRs, equalization, FEC, PAM4. For the electrical channels, the adoption of PAM and the various signal integrity methods was guided by well-known theory regarding modulation and coding for linear channels[158]. Figure 11 illustrates the key functional blocks of the multilane electrical links. The application of these methods to optical channels of local area networks had also previously been investigated[159]. Fibre Channel adopted the Ethernet FEC scheme for NRZ modulation to enable its 32GFC optical specification to be completed. The FEC and associated methods will be discussed in more detail in later sections of this paper.

Interestingly, the adoption of the FEC was initially resisted because the encoding and particularly the decoding adds latency and power dissipation. Whilst the FEC code added a small amount of latency and power, it was still believed that even this could cause issues for applications such as HPC and high frequency trading. Nevertheless, the FEC was adopted.

For 128 GFC, a parallel optical link using four MMFs per direction was developed. Each lane of the link essentially reused the specifications for 32GFC.

It should be noted that some proprietary and standards-based systems, notably InfiniBand, may leave out the FEC. This can most simply be supported by using shorter optical links or optical active cables (OAC). Optical active cables have pluggable optical transceivers permanently connected at each end of the cable. Since the optical signal is never exposed proprietary methods can be used to improve signal quality. Also, the loss due to in-line optical connectors is eliminated. The improved optical signal quality can be used to provide lower error rates, removing the need for FEC, or lower cost or lower power dissipation or a mix of these attributes.

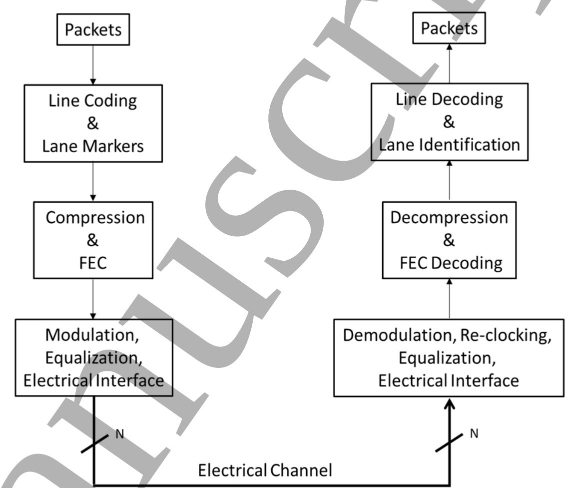

Figure 11. Key functions of an FEC protected multilane copper interconnect.

InfiniBand

An early adopter of parallel optical technology was InfiniBand[60]. InfiniBand is an industry-standard specification, initiated around 2001, by the InfiniBand Trade Association (IBTA). It defines an input/output architecture for high-performance computing (HPC) that enables high-throughput and very low latency. It is used to interconnect servers, switching equipment, storage, and embedded systems. Increasingly, it is also being used within large data centres and by nuclear research centres that must deal with massive amounts of data, such as CERN.

InfiniBand uses point-to-point connections with data rates up to 600 Gbps[160]. It achieves these high link data rates by using parallel transmission via multiple, parallel copper cables or optical fibres. InfiniBand defines the data rate for a single serial duplex link which can then be aggregated in groups of 4, 8 or 12 to achieve correspondingly higher link data rates. To maintain pace with the increasing demands of HPC applications and user demand, as with Ethernet and Fibre Channel, the InfiniBand data rate has increased by a factor of two about every three years. Not surprisingly, the underlying encoding and modulation schemes have followed the same trend, at roughly the same pace, as Ethernet and Fibre Channel: 8B10B, 64b66b, NRZ, PAM4. However, as has already been mentioned, to reduce latency, error correction at the optical link level tends not to be used.

100 Gigabit Ethernet

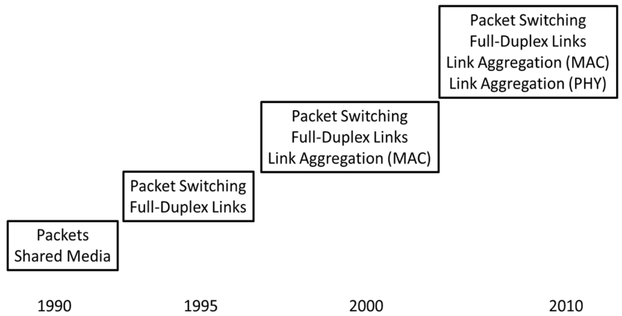

Figure 12. Development of packet switching supported by full duplex and aggregated links.

At the inception of 100Gigabit Ethernet, from a high-level point of view, it was clear that high data rate local networks would be based on packet switching, using full duplex transmission, with link aggregation. A simplified view of the history of this development, for Ethernet, is shown in figure 12. Other local systems followed similar trends.

To support 100 Gb/s, full duplex, Ethernet links, on SMF, four wavelengths per direction and DWDM were used. The data rate per optical lane was 25 Gb/s and NRZ modulation format was specified. The four wavelengths, near 1310 nm, were placed on the ITU-T Grid with 800 GHz (~ 4.5 nm)

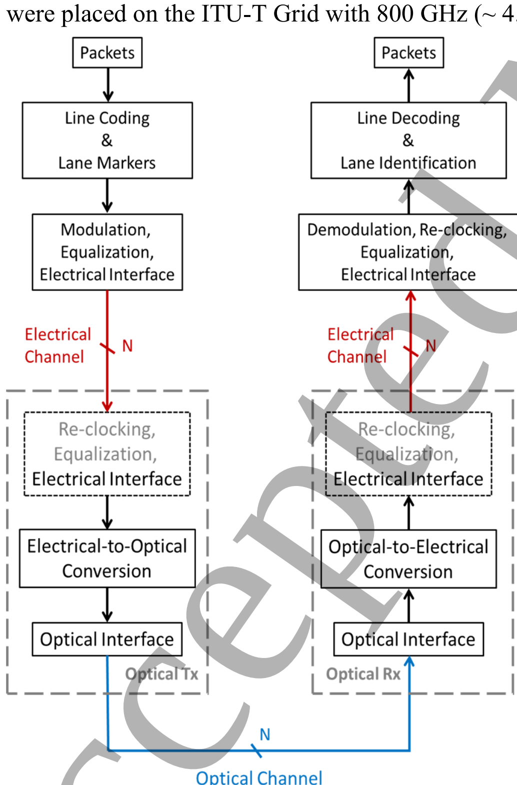

Figure 13. Key functions of an optical link when the modulated signal quality is poor but FEC is not required.

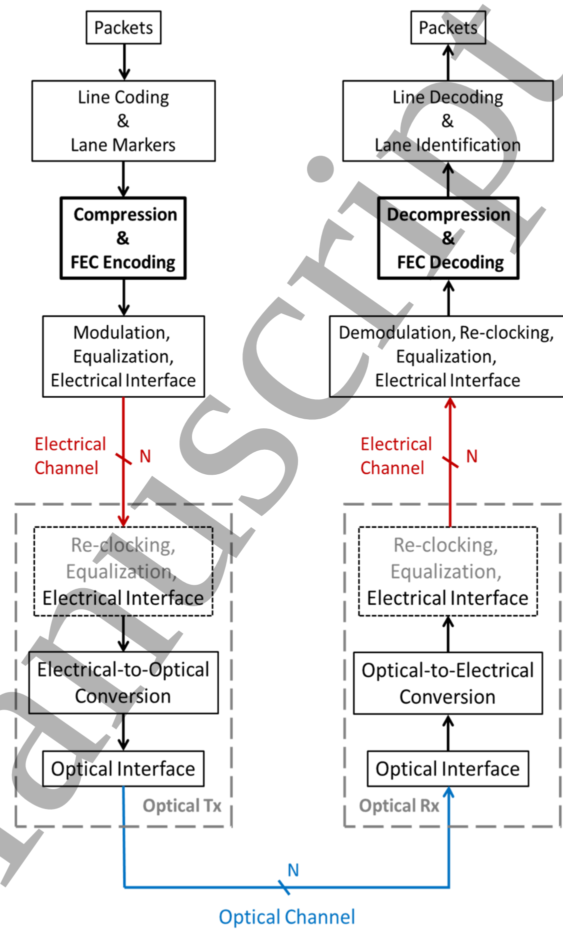

Figure 14. Key functions for an FEC protected optical link.

separation. This meant that the transmitter had to be temperature controlled. With these choices, 10 km and, with higher transmit power and receiver sensitivity, 40 km of SMF could be supported. The signal quality was such that FEC was not required for these WDM-based specifications[161].

For MMF, initially ten optical fibres per direction were used[153]. Each MMF essentially reused the specifications for a serial 10 Gb/s, short wavelength, VCSEL-based link. Whilst this might seem an excessive number of optical links, the ability to disaggregate the link into ten individual 10 Gb/s links meant that, for switches supporting mainly 10 Gb/s clients, significantly higher port density could be provided at the faceplate of the switch. Also, these ten wide links did not require FEC and could support 300 m link lengths. Figure 13 illustrates the case when FEC is not required. Typically, the per lane optics simply provided electrical-to-optical-to-electrical conversion. If long electrical channels are used, electronic equalization and re-clocking functions within the optics module may be required.

Eventually, there was a need for a four optical lanes per direction, MMF solution with a data rate per lane of 25

Gb/s[162]. Due to the lack of bandwidth of the optical components and the higher levels of noise, forward error correction (FEC) was required for this link.

Forward Error Correction For Local Area Optical Links

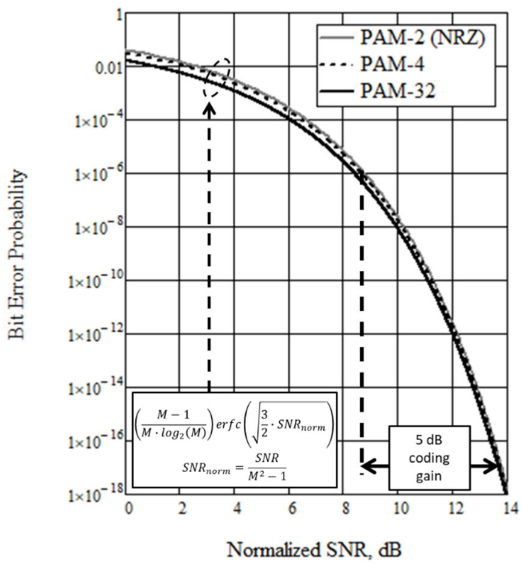

Figure 15. Illustration of FEC coding gain.

For optical links, the FEC methods that had previously been developed to support 100 Gb/s Ethernet on copper-based, electrical channels were adopted. Two versions of FEC were developed for the copper case, one to support NRZ modulation and another for PAM4 modulation. The four lane MMF optical links use NRZ modulation.

As illustrated in Figure 14 the 66b data stream is first compressed by transcoding with a 256b257b code. The compression removes redundancy by deleting the two synchronization bits of the 66b words. Then new synchronization bits, at a lower bit density, are re-inserted. The periodic lane markers, that were inserted into the 66b data stream, to enable lane identification at the receiver, are deleted and replaced by new makers. The method of deletion and insertion of the lane markers does not increase the data rate. This means that the aggregate output rate of the 256b257b transcoder is simply (257/256) x 100 Gb/s where the 100 Gb/s is the data rate of the ethernet MAC.

The transcoded data is then processed by a Reed Solomon (RS) encoder which, when the optical modulation format is NRZ, is RS(528,514)[157]. One reason the RS FEC was selected is due to its low latency, about 100 ns, at 100 Gb/s. The resulting aggregate symbol rate due to all four lanes after trans and FEC encoding is (257/256) x (528/514) x 100 Gb/s = 103.125 Gb/s, the same as the non-FEC protected 64b66b encoded 100 Gb/s input data rate.

The coding gain of the RS(528,514) FEC is approximately 5 dB. To be conservative, the coding gain includes the effect of correlated error bursts. Error bursts might, for example, be generated by some forms of equalization. Coding gain is defined as the reduction in the received electrical signal-to-noise ratio that can be sustained, at the decision point of the optical receiver, whilst still achieving a given target error probability at the FEC output. Figure 15 illustrates the concept of coding gain and indicates that 5 dB of coding gain can reduce the probability of error from ~ 10^{-6} to ~10^{-17}. The figure also includes curves for the approximate probability of a bit error as a function of the normalized signal-to-noise ratio for various PAM-M formats, M being the number of levels. The curves follow approximately the same trajectory, indicating that a given coding gain can achieve similar improvement in error performance for all formats. The various equations and definition of the normalized signal-to-noise-ratio, SNR_{norm}, are stated on the diagram.

On reception the RS decoder corrects the errors, then, inverse transcoding and lane marker reinsertion are performed to recover the transmitted 66b data stream on each output electrical lane. Figure 14 illustrates the insertion of the optical transmit functions, optical channel and optical receive functions into the electrical channel of figure 11.

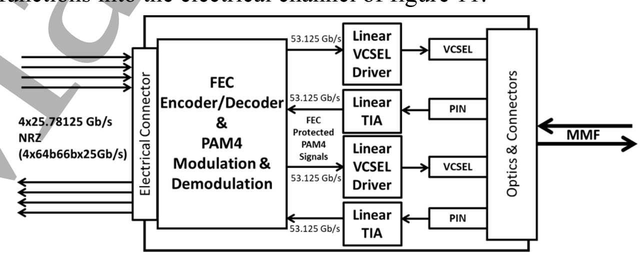

Figure 16. Illustration of case where the number of electrical and optical lanes and the electrical and optical modulation formats are different. The FEC function is within the optics module.

In some cases, illustrated in figure 16, the optics uses fewer optical than electrical lanes. The case shown is were four electrical lanes at 25 Gb/s are converted to two 50 Gb/s PAM4 modulated optical lanes. In this case, the electrical links would likely be designed to be high quality so that transcoding and FEC are not required. However, the PAM4 optical link would need FEC protection and so the transcoding and FEC functions would be moved to be within the optics module.

For 100Gigabit Ethernet, the FEC for PAM4 is RS(544,144)[157]. As was discussed previously, the PAM4 symbols would be Gray coded[45] so that single bit errors are most likely. The transcoding method is common between the NRZ and PAM schemes. The higher overhead of the FEC for PAM4 results in a slight increase in the net coding gain to ~5.4 dB. However, longer error bursts are protected, which is important for the poorest copper-based channels for which the FEC scheme was designed. Due to the increased FEC overhead, the resulting FEC protected PAM4 symbol rate is 3% higher compared with simply PAM4 modulating the original, non-transcoded and non-FEC coded, 66b stream. Hence the data rate carried by the FEC protected lanes is 53.125 Gb/s and the PAM4 symbol rate is 26.5625 GSymbols/s.

200 and 400 Gigabit Ethernet

By 2018 Ethernet developed CWDM, LAN DWDM and parallel optics-based specifications for SMF links at aggregate data rates of 200 and 400 Gb/s. The WDM based links use multiple, FEC protected, PAM4 lanes: 4 lanes for 200 Gb/s and 8 lanes for 400 Gb/s.

To provide a lower cost option for data centres, parallel optical SMF links were specified to support 500 m links with four, FEC protected, transmit and receive lanes (8 fibres). Both the 200 Gb/s[163] and 400 Gb/s[164][165] parallel optics-based links used four FEC protected PAM4 lanes. This means that the 400 Gb/s link uses PAM4 to transmit 100 Gb/s per lane. This is possible because single mode modulators, either III-V or Silicon Photonics based, can have large bandwidths. Recent research papers have reported modulator bandwidths as high as 100 GHz[166][167].

A major technical issue that had to be resolved for the SMF PAM4 links was how to control and allocate the optical power penalty due to multipath reflections between the optical connectors of the link[168][169][170][171]. This was resolved by providing guidance on the allowable reflection per connector as a function of the number of connectors within a link[171][163][164][165].

Duplex Fibre 25, 50 & 100 Gigabit Optical links

Typically, equipment at the lowest tier of a network operates a lower port data rate than the links between the ports of the packet switches that form the network. Therefore, single lane optical specifications for full duplex (one transmit and one receive fibre), 25 Gb/s, 50 Gb/s and 100 Gb/s data rates have been standardized[172]. At 25 Gb/s, NRZ modulation is used. For the MMF case, typically, FEC is also required. For the 50 Gb/s and 100 Gb/s cases PAM4 modulation and FEC is used for both SMF and MMF links.

At present, commercial VCSEL-based optical links can support up to 50 Gb/s per lane with PAM4 modulation. To support 100 Gb/s MMF duplex fibre links, various proprietary methods have been developed: 4 wavelength, VCSEL-based, CWDM using four 25 Gb/s NRZ based lanes[173][174] and CWDM bidirectional transmission using two lanes of FEC protected, 50 Gb/s, PAM4 modulated lanes[175][176].

400Gigabit Ethernet for Multimode Fibre

Two link types have been standardized for 400Gigabit Ethernet over multimode fibre: Firstly, an eight MMF per

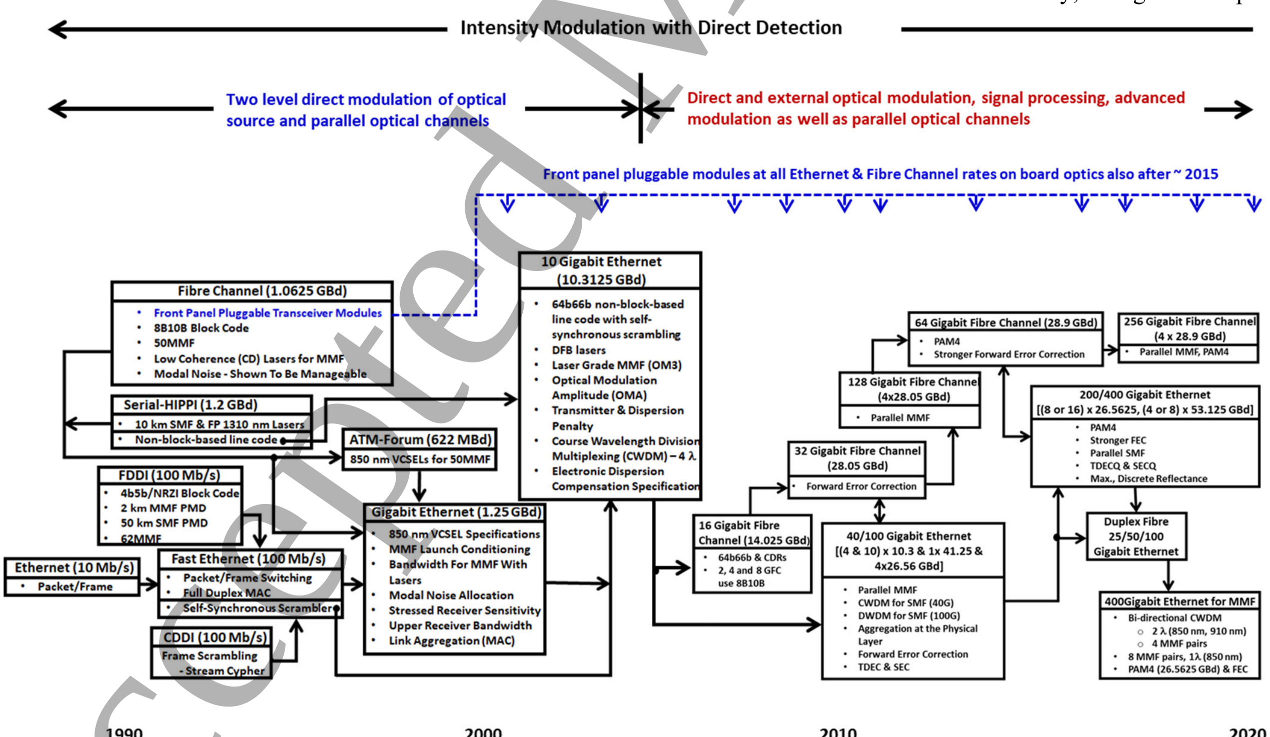

Figure 17: Illustration of historic development and linkages of key aspects of optical fibre-based Ethernet and Fibre Channel

direction parallel optics link and secondly a four MMF per direction, bidirectional, two wavelengths, CWDM based specification. Both use short wavelength VCSELs[177]. The centre wavelengths for the CWDM case are 850 nm and 910 nm. The bidirectional case is interesting as it combines parallel optical fibres, bidirectional transmission and CWDM. Both link types use the FEC protected PAM4 transmission methods already discussed to achieve a per lane data rate of 50 Gb/s.

Recently, a new wideband multimode fibre, called OM5, was standardized[178][179][180]. The new fibre has been specified for CWDM applications in the wavelength range of approximately 840 nm to 960 nm. With OM5, the supported link length will be 150 m compared with 100 m with OM4.

Discussion of Historic Trends

The progress in optical communications for local area systems over the time period from 1985 to 2020 has been reviewed. The focus has been on what was successfully commercialized and standardized within IEEE 802, ANSI, INCITS, OIF and InfiniBand. It is sometimes difficult to grasp the various interactions that occurred during the development of the technology and standards. Therefore, in this section, a series of diagrams and graphs which may aid visualization of the various interactions are presented.

The historical development in terms of data rate for Fibre Channel and Ethernet is summarized by Figure 17. The

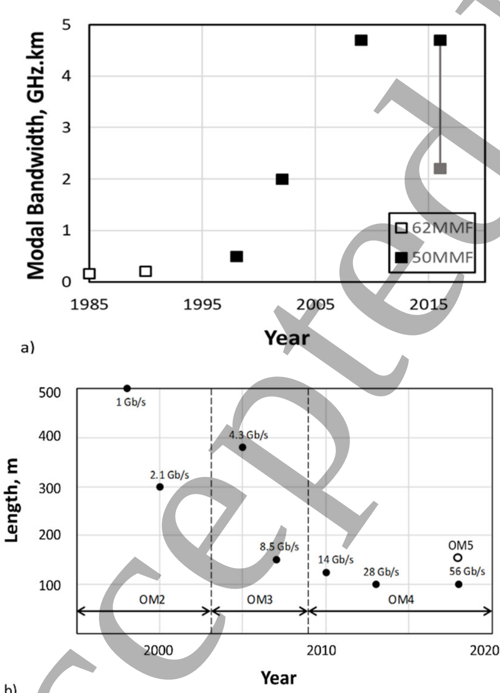

Figure 18. Illustration of the development graded index multimode fibre for LANs: a) indicates the increase in minimum bandwidth and b) gives examples of the minimum link length

diagram is based on a review of the various standards specifications and from the experience of the authors as contributors to the various standards groups. Obviously, other authors may have decided to highlight different features.

The focus of figure 17 is on the contribution to the optical links for local systems. Important contributions from FDDI, Serial-HiPPI, CDDI and the ATM forum have been represented. The various blocks in the diagram attempt to indicate some key technical contributions and learnings, discussed previously in this paper, that fed into the development of the next data rate, many of which are still important today.

For example, the initial Fibre Channel development for up to ~ 1 Gb/s was vital in that it seeded and nurtured the concept of front panel pluggable optics. Pluggable optical modules, and more recently, active optical cables have been developed and, used at every data rate ever since, as represented by the dotted arrows on the diagram. Fibre Channel also embraced the 8B10B line code that fed into the ATM Form, Gigabit Ethernet, 10Gigabit Ethernet and, not shown on diagram, Infiniband.

Fibre Channel also championed 50 μm core multimode fibre (50MMF) and the use of lasers with low optical coherence (CD lasers). It demonstrated that modal noise could be tolerated and managed in MMF links. This learning was passed on to the ATM Forum and Gigabit Ethernet which

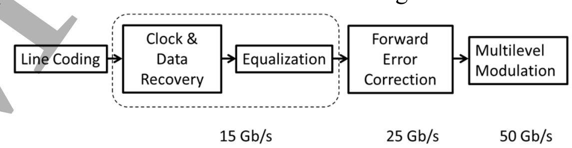

Figure 19. High level view of the signal processing functions for local area fibre optic links as a function of lane data rate.

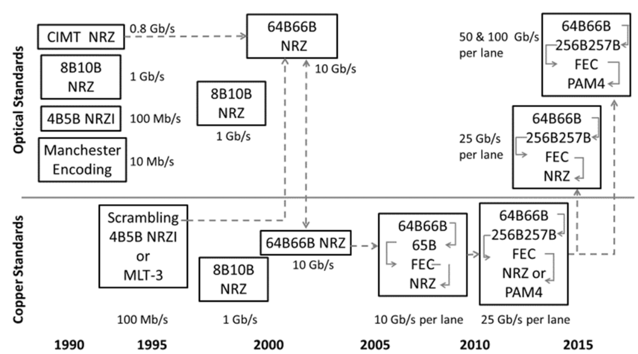

Figure 20. Historical progress of line coding, modulation format and FEC for local area fibre optic links with key linkages shown (dotted arrows).

became champions for VCSELs and multimode fibre.

Within Gigabit Ethernet, many of the methods for developing robust optical power budgets[181], specifications and test methods (e.g.: Vertical Eye Closure Penalty (VECP),

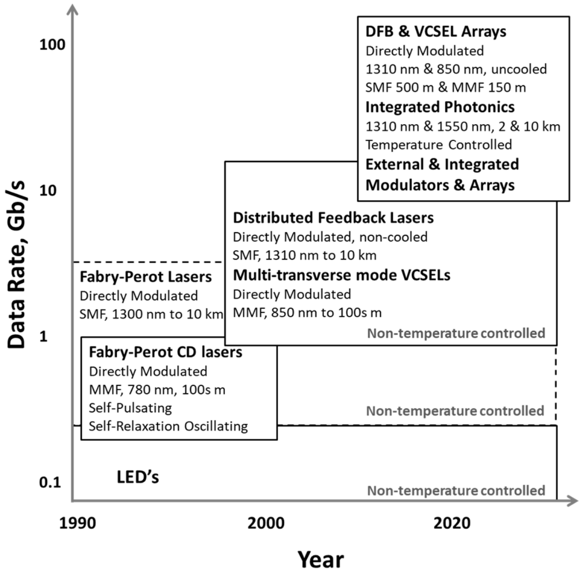

Figure 21. Historic progression in type of optical source used for local area fibre optic links as a function of aggregate link data rate.

Stressed Receiver Sensitivity (SRS), Upper 3 dB Receiver Bandwidth) were developed[88]. To enable consistent bandwidth performance, Gigabit Ethernet also taught the importance of controlling or "conditioning" how the light is launched into a multimode fibre[89]: learning which fed into the development of various generations of laser grade multimode fibre by the TIA and ISO/IEC which led to the commercialization of OM3, OM4 and OM5 multimode fibres.

By understanding how to allocate a power penalty for mode partition noise, Serial-HiPPI taught how Fabry Perot lasers operating near wavelengths of 1310 nm, with standard single mode fibre, could be used for Gigabit links of up to 10 km in length. This knowledge was applied to Fibre channel and Gigabit Ethernet.

Additionally, Ethernet, Fast Ethernet and Gigabit Ethernet, in competition with ATM, confirmed that local systems would be based on the Internet Protocol, full duplex links and packet switching. In the same time period, Ethernet adopted link aggregation enabling higher bandwidth and redundant links.

Also, the combination of learnings regarding novel line coding and data scrambling from Serial-HiPPI, FDDI, CDDI and Fast Ethernet prepared the way for acceptance by 10Gigabit Ethernet of the then novel, but seminal, 64b66b coding scheme[135].

This understanding and knowledge came together in 10Gigabit Ethernet which embraced parallel transmission methods to enable early market adoption. Coarse Wavelength Division Multiplexing (CWDM)[182][183][184] was a major achievement enabling the support of 300 m links on both 50MMF & 62MMF and 10 km links on SMF[185]. It also seeded the ITU-T CWDM grid[111].

However, for local systems, 10Gigabit Ethernet also championed and developed 10 Gb/s serial transmission methods for 10 km links and 300 m MMF VCSEL-based links. By embracing the use of Optical Modulation Amplitude (OMA)[131][132][133] from Fibre Channel, it enabled the specification of links based on non-temperature-controlled DFB lasers (at long wavelengths) and VCSELs (at short wavelengths). It's adoption and support of the then new laser grade (OM3) MMF[113], which many experts from 10Gigabit Ethernet, led by the TIA FO 2.2 committee, helped to create, enabled low cost 10 Gb/s MMF links[114]. Also, the standardization of electronic equalization for MMF optical links made it simpler for future standards to include embedded equalization methods[186].

Whilst, in many respects, great progress was made in terms of manufacturability and reliability of the optical components,

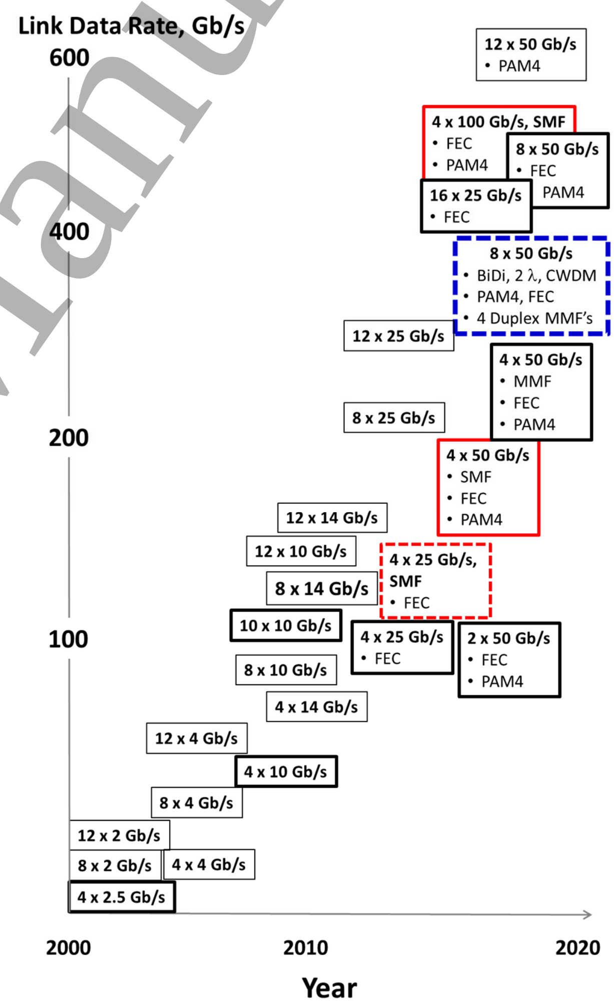

Figure 22. Illustration of the historic trend in aggregate link data rate, number and type of fibres, over the past 20 years for parallel optical links. Thin boxes InfiniBand, bold and dashed boxes Ethernet specifications.

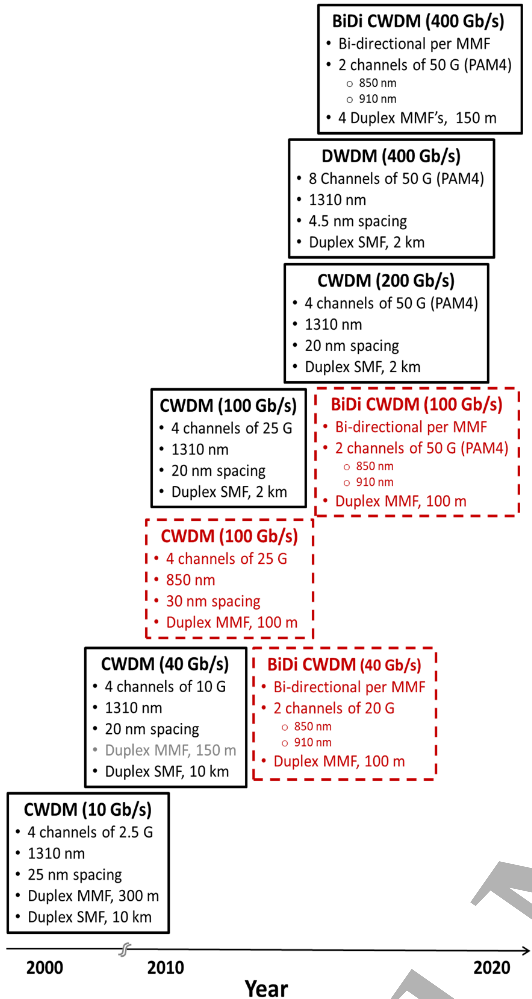

Figure 23. Illustrative development of WDM based links for local area systems during the past 20 years.

the period after 10Gigabit Ethernet seems to be one of consolidation rather than of breakthroughs. The fundamental bottleneck has been the slow progress in the increase of bandwidth of the optical transmitter and receiver as illustrated by figure 9.

Proprietary HPC systems, the OIF and InfiniBand championed parallel optical links[187][188] to enable higher aggregate bandwidth, a method only later embraced by Ethernet and Fibre Channel.

The minimum specified modal bandwidth of the various types of laser grade MMF, developed during the period 2000 to 2020, are shown in Figure 18. The figure also shows how the link distance for fibres, with the minimum bandwidth, has decreased over time. The new generations of MMF have ensured that at least a 100 m link length can always be supported.

The response of the Ethernet and Fibre Channel technical community to this lack of bandwidth was to fall back on their well-trodden path; for bandwidth constrained channels that do not have multiple severe dips within the channel frequency response, of PAM-M with equalization and error correction[158]. Whilst, many other modulation schemes were studied for the local area optical links[189][190][191][192][193], PAM4 was shown to be sufficient[194][195][196][197][198]. Its selection also enabled a wealth of experience and specifications, from within the copper transmission standards working groups, to be reused. At a high level, the application of the various electrical signal processing methods versus optical lane data rate is illustrated in Figure 19. Figure 20 outlines the development of line coding, modulation format, FEC and some of the important interactions from 1990 to 2020. These methods enabled single wavelength, single lane, data rates of 50 Gb/s via PAM4 with VCSELs for MMF and 100 Gb/s via PAM4 with optical modulators for SMF.

To enable duplex links having aggregate data rates approaching 0.5 Tb/s, all of the parallel optical methods developed over the past 30 years (WDM, parallel fibres, bi-directional transmission) have been standardized and deployed. Figure 21 illustrates the progression of the type of optical sources that have been used versus the data rate over the past 30 years.

Figure 22 shows the progress in aggregate data rate for MMF and, more recently, SMF parallel optical links from 2000 to 2020. The number of lanes and per lane data rate are stated on the graph. On the graph, the boxes with thin borders represent InfiniBand links and the bold and dashed bordered boxes are Ethernet link rates. If no fibre type is stated within the box, then the type of fibre is MMF. Figure 23 depicts some key developments between 2000 and 2020 regarding CWDM-based local area links for Ethernet. The dashed boxes represent non-standardized solutions. Duplex fibre is used for most of the links. However, the 400 Gb/s, bidirectional, CWDM case uses multiple duplex MMF cables and is a hybrid parallel optics and CWDM solution.

Energy and Price Per Gb/s

Table 1: Simplified metrics for optical interconnects

Lane Data Rate, Gb/s	Local Area or Rack to Rack Maximum Energy per Bit, pJ	PCB or Chip Maximum Energy per Bit, pJ	Maximum Price per Gb/s, $
25	100	10	5
50	50	5	0.5
100	20	2	0.25

Targets for the energy and the price per transmitted bit for optical links within data centres and supercomputing systems have been suggested[199][200][201]. The definition of the metrics by various authors is not always clearly aligned. However, for the purposes of our review, we give a simplified summary of our interpretation of the metrics. Until recently, the metrics listed in Table 1 under the heading "Local Area or Rack to Rack" have been sufficient to enable both data centre and HPC applications. However, the next generation of Exascale supercomputers require metrics similar to those listed for under "PCB or Chip" optical interconnects[202].

In this section we will assume the targets apply to a unidirectional point-to-point link. We will consider three types of optical link as follows:

1. A link with a pluggable optical transmitter and a pluggable optical receiver which do not include retiming or SERDES circuits.
2. A link with a pluggable optical transmitter and a pluggable optical receiver which include retiming or SERDES circuits.
3. A link formed by an optical transmitter and a transmit SERDES within a multichip module (MCM) and an optical receiver and a receive SERDES within another MCM.

In the first two cases, the transmitting and receiving ports of the electrical switch, would also include a transmit and receive SERDES function respectively. Therefore, for the first two cases, the power dissipation of a port SERDES must be added when estimating the power dissipation for a unidirectional link. In the third case it is assumed that the SERDES in the MCMs are the SERDES of the switch ports.

These link scenarios are consistent with those used by Ghiasi[203] and Stone[204]. By combining the information stated in the two publications, the energy per transmitted bit due to the SERDES for the three link cases and for lane data rates of 10 Gb/s, 25 Gb/s and 50 Gb/s can be estimated. For the pluggable optics cases, SERDES with FEC are assumed. The 100 Gb/s estimates are not directly based on the information within the two papers, rather they are predictions based on the trend from 10 Gb/s to 50 Gb/s. The results are plotted on figure 24.

Stone assumed full SERDES with FEC for both the switch ports and the optics module. Ghiasi assumed that if the optics module could use re-timers, rather than full SERDES, then the energy per bit for the links involving pluggable optics would be reduced by about 25% compared with using full SERDES. This indicates that power savings of between 25% and 50% are possible with non-retimed optics which seems to have recently been confirmed[205].

The power estimates for the SERDES appropriate for MCM plotted on figure 24 seem reasonably consistent with more recent publications[206][207]. The estimates for the

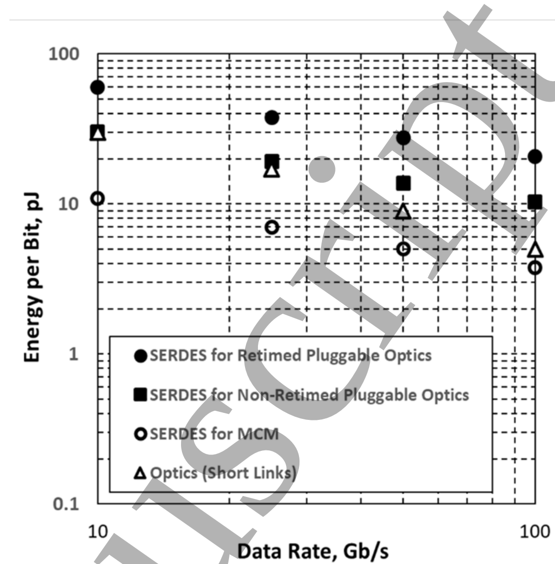

Figure 24: Estimated energy per bit as a function of lane rate for various SERDES types based on[203] and [204] and illustrative energy per bit for the optics for a short reach optical link.

MCM SERDES do not include an allocation for FEC and so represent a near lower bound.

In the marketplace, the progression from 10 Gb/s per lane to 100 Gb/s per lane took place from around 2010 to 2019. During that period, the feature size of the CMOS process used for the switch and SERDES has steadily reduced from 40 nm to 28 nm to 16 nm and, lately, to 7 nm.

The power dissipation due the electrical packet switching operation is not included in the calculation of the power dissipation for the point-to-point optical links. Rumley[202] has suggested that the energy per bit, due to the electrical packet switching, is on the order of 30 pJ per bit for 100 Gb/s switch ports.

For illustrative purposes, representative estimates for the energy per bit for the optics (combination of the optical transmitter and the optical receiver) are also plotted on Figure 24. The energies per bit for the optics, at 10 Gb/s and 25 Gb/s lane data rates, were estimated from product data sheets for VCSEL, parallel optics, products[208][209]. The estimates assumed non-retimed optics. However, the optical modules included electrical interfaces and some management functions. Therefore, the power estimate can be expected to be larger than the combination of the optical transmitter and the optical receiver alone. For example, various research implementations of VCSEL-based optics have achieved an energy per bit of ~ 5 pJ for lane rates in the range from 10 Gb/s to 28 Gb/s. At 25 Gb/s silicon photonics based optics have been implemented with a total energy per bit in the range 2 pJ to 25 pJ[205][210]. Although, in general, these figures do not include the power dissipation due to the laser and so, as was pointed out by Mahgerefteh et al.[211], a few pJ per bit may need to be added. Therefore, both VCSEL and Silicon

Photonic optics implementations should be able to be implemented for 17 pJ, per figure 24, or less.

At 50 Gb/s lane rates, various VCSEL and Silicon Photonics based optical implementations have been reported with energy per bit in the range 2 pJ to 25 pJ[210][211][212]. For Figure 24, we have used a value of 9 pJ for the optics since this seems representative of the optics used within recent 50 Gb/s per lane VCSEL based products[176].

The energy per bit of 5 pJ, at a lane rate of 100 Gb/s, was based on a continuation of the trend from 25 Gb/s to 50 Gb/s. However, recent publications seem to indicate that this energy per bit value should be possible[213][214].

The total energy per bit for the various cases are found by adding the value for the optics to the value for the relevant SERDES case. Comparing our estimated values to the targets of Table 1, we find that for short reach links, pluggable, retimed, optics, can meet the targets for "Local Area or Rack-to-Rack" for lane data rates up to about 50 Gb/s. To meet the target for the 100 Gb/s lane rate, the energy per bit would need to be reduced by about 20%. Given the previous discussion regarding the use of re-timers rather than full SERDES for the optics module, such a reduction seems possible. Non-retimed, pluggable, optics or MCM based links can meet the target energy per bit values of the "Local Area or Rack-to-Rack" column with significant margins.

However, none of the link cases can meet the suggested energy per bit targets of the "PCB or Chip" column. This likely indicates, as pointed out by Rumley[202], that current optical solutions will not meet the energy per bit targets required by Exascale HPC systems.

Regarding the price targets of Table 1, it has been documented that parallel optics-based solutions reduced the price per bit from ~20$ per Gb/s in 2000 to ~1$ per Gb/s in 2014[215]. Pluggable optics, for Ethernet and Fibre Channel, remained more expensive at ~10$ per Gb/s in 2010 but is projected to reach ~1$ per Gb/s in the early 2020s[211][216]. Currently, no solutions are expected to reach the target of 0.25 $ per Gb/s soon.

The targets in Table 1 are suggestions, not specifications. The inability to meet them does not mean links of that type would be unsuccessful in the market. However, difficulty meeting the targets indicates potential problems that should be addressed.

Challenges for the Future

The Ethernet roadmap[217] suggests 800 Gb/s and 1.6 Tb/s Ethernet will be required by about 2025. Initially, the roadmap implies the optical links for those Ethernet rates would be implemented using aggregated lanes operating at 50 Gb/s or 100 Gb/s. Not surprisingly, the roadmaps for Fibre Channel[218] and InfiniBand[160] make similar predictions.

It should be recognized that the roadmaps are an expression of what is believed to be required. They not are not a statement of what is known to be definitively possible. They are targets that technologists should aim to fulfil. In that spirit, for the rest of this section, we will adopt an optimistic view of what might be technically possible in order to meet the challenges set by the various roadmaps.

As we have already discussed, by using intensity modulation and direct detection (IM/DD) with PAM4, Ethernet has already specified operation at 100 Gb/s per lane for some link distances with SMF. Eight and sixteen, 100 Gb/s lanes, via parallel fibres or a set of wavelengths would then enable 800 Gb/s and 1.6 Tb/s Ethernet for the early market.

At a serial lane data rate of 100 Gb/s and for SMF links of up to 2 km, various investigations have shown that intensity modulation in conjunction with PAM4 modulation is a good choice[171][197][219][221][222]. However, for these short reach links, intensity modulation, in conjunction with NRZ modulation, could enable less circuit complexity and lower power dissipation. Recently, an experimental demonstration of an integrated silicon photonics, NRZ-based, 100 Gb/s link was reported[221]. Since a high bandwidth Transimpedance Amplifier (TIA) was not available, the demonstration used optical pre-amplification. The authors have since reported progress on an integrated, fully differential, Si BiCMOS, TIA-based, optical receiver design that enabled 90 Gb/s with NRZ modulation[213][221]. In addition, various standards groups are in the process of defining serial 100 Gb/s electrical interfaces, including the copper PCB and cable channels[223][224]. Regarding multimode fibre (MMF) and VCSEL-based transmitters, recent papers have shown that with IM/DD and PAM4 modulation, 100 Gb/s per lane could be supported[225][226][228]. As it might be difficult to achieve enough bandwidth to enable 100 Gb/s NRZ via direct modulation, VCSELs with integrated modulators are being investigated[228]. Therefore, it seems likely that by 2025, for both MMF and SMF, all link lengths could support a per lane data rate of 100 Gb/s using PAM4. Furthermore, some cases might be able to use NRZ modulation to reduce the power and complexity.

Eventually, to reduce power dissipation and cost, a route to lower lane counts will be required. A simplistic way to predict the required future serial lane rates for LANs is to extrapolate from the current trend. Figure 10 plotted the historical, standardized, electrical, serial lane, rates, along with a fitted exponential trend. Extrapolation of the trend indicates that serial lane data rates of 200 Gb/s, 400 Gb/s, 800 Gb/s and 1.6 Tb/s would be required by about 2024, 2028, 2032 and 2036, respectively. This is in reasonable agreement with industry roadmaps[160][217][218] and a recent review of fibre-optics for telecommunications and networking [18]. Obviously, by aggregating 2, 4, 10 or 16 lanes, even higher link data rates could be supported.

Assuming Moore's Law continues then the electrical switch chip capacity will increase exponentially. If the chip area and number of I/O pads remains constant, then the required serial data rate will follow the trend stated in the roadmaps. This should not be surprising as it is the underlying basis of the various roadmaps. The switch chip can make use of the exponentially increasing number of transistors to support the increasing capacity without excessive increases in the clock rate of the internal logic. However, once data must be transmitted by a port of the switch chip, then it must be multiplexed to the appropriate higher lane rate. Therefore, a high data rate SERDES function will be required for each port of the chip.

Ideally, to reduce power and circuit complexity, the electrical lane rate would be supported by NRZ modulation. Obviously, the transistors of the SERDES, which are likely to be on some form of Si BiCMOS process, must have enough bandwidth to support the serial rate. The unity gain frequency of Si BiCMOS is somewhere in the range of 300 to 500 MHz (in 2019) and it is predicted that, at most, it might be increased to near 1 THz[229]. For the transmitter to operate properly, the transistors within its circuits must also have gain. Unfortunately, this implies that Si BiCMOS supports NRZ at rates much less than 1 Tb/s. Winzer et al.[18] suggested that CMOS ASICs could support symbol rates of 50 GBaud, 120 GBaud and 300 GBaud by 2017, 2027 and 2037, respectively. Note: Baud equals the symbols per second. Therefore, even in the long term, it seems that at the I/O pads of a switch chip, serial data rates above 300 Gb/s will likely have to be supported by some form of multilevel modulation.

Assuming the extrapolated serial data rates, the symbol rates assumed by Winzer et al. and no increase in the number of I/O pads, then Table 2 indicates the minimum required link bandwidths and PAM formats. Due to the likely lag in the bandwidth of the optical link, it would appear that the serial rates could be achieved with PAM4 but with a four-year delay compared with the desired dates. If the desired dates must be met, then PAM with many levels would be required. However, that would significantly decrease signal integrity and increase the complexity and power dissipation of the SERDES. Whilst other multilevel modulation schemes might be considered they would still impose a significant increase in power

Table 2: Possible future rates, bandwidths and PAM formats

Parameter	Year				Units
	2024	2028	2032	2036	
Serial Rate Lane	200	400	800	1600	Gb/s
Predicted Achieveable Symbol Rate	85	120	210	300	GBaud
Minimum Required Link Bandwidth	42.5	60	105	150	GHz
Minimum PAM Format	PAM6	PAM12	PAM16	PAM42	N/A
Minimum PAM Format With Twice The Number Of I/O Pads	PAM4	PAM4	PAM4	PAM8	N/A

dissipation. Also, since electrical interconnects do not have orthogonal dimensions for modulation, such as the optical polarization and the optical phase of optical links, only an increase in the number of I/O pads beyond that used today could reduce the required number of levels per I/O pad. Increasing the number of I/O pads and associated balls of the ball grid array package has been avoided due to cost[203]. Additionally, the switch chip area is already at the maximum supported by CMOS processes[230].

The use of multiple I/O pads, to support higher rates, might be beneficial for schemes that modulate the optical polarization and optical phase of the transmitter. This is because an optical modulator is required for each orthogonal optical dimension to be modulated. Methods for reducing the cost and power dissipation of optical coherent technology to make it suitable for local communications are being investigated[231]. Also, various direct detection schemes, which may be simpler to implement than the fully coherent schemes, are also being investigated[34]. Therefore, whilst an electrical link using multiple I/O pads might not strictly be considered a serial link, multi-dimensional optical modulation schemes would encode the information onto a single laser wavelength. At the receiver, multiple photodiodes and electronic receiver processing chains would be required[34].

The electrical signal must be transmitted to and from the switch chip I/O port to electrical interface of the optical transmitter and receiver. However, the use of traditional PCB electrical traces will become extremely difficult for symbol rates above 100 GBaud. Short chip-to-chip and coaxial copper cabling for longer links might be possible. For this reason, it is believed that the optics will need to be placed very close to the switch ASIC, possibly within a multichip module[232][233]. This creates opportunities to integrate the optics with the switch ASIC[234]. The placement of the optical transceivers on the PCB or in a package with the ASIC chip is referred to as onboard or embedded optics. Embedded optics removes the electrical bandwidth bottleneck between the optical transceivers I/O and the ASIC I/O lanes. As was discussed previously, embedded optics can also significantly reduce the power dissipation, for example by elimination of retiming circuits[204]. Recent publications regarding HPC, data centre systems and the announcement of the first co-packaged optics-ethernet-switch indicate that this is an active and very important future trend[205][235][236].

However, since integrated photonics may have feature sizes that would be wasteful of silicon chip area[237] or may have been fabricated in a different semiconductor material, the optics might need to be mounted directly on the switch ASIC[237] via some form of 3D integration.

Table 2 indicates the extrapolated minimum required link bandwidth as a function of time. The bandwidth of the concatenation of the optical transmitter, optical fibre and optical receiver must be at least equal to the minimum link bandwidth.

The modulation bandwidth of the optical transmitter will be a function of technology. In the near term, up until 2025 say, directly modulated lasers will likely have bandwidths less than about 60 GHz[143]. Optimistically, in the longer term, the bandwidth might be postulated to have increased to about 100 GHz[151]. Similarly, optical modulators for optical communications, have been reported to have modulation bandwidths of about 100 GHz. Modulators for use in radar and radio over fibre applications already have reported broadband modulation bandwidths of around 500 GHz [238]. Conservatively, it seems reasonable to postulate that modulators for optical communications could have a modulation bandwidth of around 200 GHz by 2036.

For singlemode fibre, optical communications and RF over fibre applications, photodiodes having bandwidths of many hundreds of GHz are already possible[238][239]. However, the high bandwidth photodiodes have small detection areas and so they are not suitable for MMF applications.

Given we have assumed that the symbol rate of CMOS will progress per Table 2, it seems reasonable to assume that integrated transimpedance amplifiers and the following electrical signal processing circuits will also be able to operate at the projected symbol rates.

With regards to per lane bandwidth, at least to first order, for the short link lengths of interest in this review, SMF will either not be the limiting factor or its effect could likely be compensated for by various equalization methods[240]. However, at lane rates above about 100 Gb/s, the bandwidth of MMF will likely become a limiting factor and methods for mitigating it may need to be explored. Otherwise, the MMF link length will fall below todays 100 m length.

Whilst very significant technical challenges remain to be solved, there seem to be potential technical paths that could enable the projected serial rates to be supported.

Conclusion

The development of optical fibre technology for local area communications systems over the past 30 years has been reviewed. The focus was on what was successfully commercialized and standardized within IEEE 802, ANSI, INCITS, OIF and InfiniBand. Some history of how the internet protocol and packet switching grew to dominate over shared media access methods like the Fibre Distributed Data Interface and connection-oriented methods such as Asynchronous Transfer Mode was reviewed. Whilst Ethernet, Fibre Channel and InfiniBand came to be dominant, important technology developments and learnings from competing technologies and standards were adopted and adapted by them. The process of adaptation was enabled by the willingness of the various technical contributors and competing organisations to collaborate in support of the success of the various standards bodies, associated research and commercial deployment.

The communications capacity of local systems has experienced near exponential growth and the growth is projected to continue over the coming decade. However, we discovered that the growth rate of capacity associated optical technologies for local systems are lagging the desired growth. In large part, this is due the ability of the CMOS semiconductor industry to enable faster design cycles and higher growth rates than can be achieved by the optical technology industry.

As data rates increased from 0.1 Gb/s in 1990 to nearly a Tb/s in 2019, various optical and electronic methods have had to be developed. These technologies include single and multimode fibre, single and multimode lasers, optical modulators, photodetectors, parallel fibre links, wavelength division multiplexing, integrated optics, multilevel modulation, electronic equalization and error correction. Even with the increasing complexity of the electronics required for optical links, the energy per transmitted bit has been decreasing and has largely met the targets for local systems and rack-to-rack communications. However, there is a large gap with respect to the targets for on PCB, on chip and especially for future high-performance computing systems. It is still not clear how that gap can be closed.

Front panel, pluggable, optics modules were a vital innovation which enabled different link types to be flexibly and economically supported. This was especially true in the early development of optical technology when the innovation also helped manage the higher failure rate of optics compared with electronics. It seems clear that front-panel pluggable optics will continue to be important even at higher data rates. However, some future systems require significantly lower power dissipation than can be supported with pluggable optics. To enable those systems, a higher level of integration between optics and electronics will be required.

The current price per transmitted bit, ~ 1$ per Gb/s, is well matched with the needs of short reach local communication systems. However, it is still not sufficiently low to enable the next generation of Exascale high-performance computing systems or on PCB or on chip networks.

The serial lane rate has already reached 100 Gb/s and is expected to increase by factors of two about every four years. The projected increase in the per I/O symbol rate of CMOS processes are projected to be much less than the increase in required serial lane rate. A key challenge will be to ensure the optical components have enough bandwidth to enable this progression in serial lane rates. For example, due to the likely lag in the bandwidth of the optical link, the serial lane rates could be achieved with PAM4 but with a four-year delay compared with the desired dates.

If the desired dates must be achieved, then PAM with many more levels or an equivalent complex modulation scheme would be required. That might make it difficult to maintain signal integrity and low power dissipation. Alternatively, if the number of I/O chip ports is doubled then PAM4 could likely be supported at each port. The aggregation of two ports would then enable the desired serial link data rate. Whilst this is not a lane, the data rate could be imprinted onto a single laser wavelength by using an optical property with two orthogonal dimensions, optical polarization for example.

In conclusion, for the foreseeable future, whilst there are many challenges to be overcome, it appears that it should be possible to meet the needs for higher data rate, optical local area, systems. However, it is less clear how to satisfy the needs of high-performance computing systems or how to enable on PCB or on chip optical networks.

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References

[1] IEEE 802.3-2018 IEEE Standard for Ethernet
[2] Chraplyvy A R, Gnauck A H, Tkach R W, and Derosier R M 1993 8 × 10 Gb/s transmission through 280 km of dispersion-managed fiber *IEEE Photon. Technol. Lett.* **5** 10 1233 1235
[3] H. Onaka et al 1996 1.1 Tb/s WDM transmission over a 150 km 1.3 μm zero-dispersion single-mode fiber *Optical Fiber Communication Conference* 2 PD19
[4] Kawanichi S et al 1.4 Tbit/s (200 Gbit/s x 7 ch) 50 km optical transmission experiment *Electron. Lett.* **33** 20 1716 1717
[5] Kawanichi S et al., 1999 3 Tbit/s (160 Gbit/s x 19 ch) optical TDM and WDM transmission experiment *Electron. Lett.* **35** 10 826 827
[6] G. Charlet et al. 2002 6.4Tb/s (159 × 42.7Gb/s) Capacity Over 21 × 100 km Using Bandwidth-Limited Phase-Shaped Binary Transmission *28TH European Conference on Optical Communication Copenhagen*
[7] Charlet G Corbel E Lazaro J Klekamp A Dischler R Tran P Idler W Mardoyan H Konczykowska A Jorge F and Bigo S 2005 WDM Transmission at 6-Tbit/s Capacity Over Transatlantic Distance, Using 42.7-Gb/s Differential Phase-Shift Keying Without Pulse Carver *J. Lightwave Technol.* **23** 104 107
[8] Gnauck A H, Charlet G, Tran P, Winzer P, J Doerr C R, Centanni J C, Burrows E C, Kawanishi T, Sakamoto T and Higuma K 2007 25.6-Tb/s C+L-Band Transmission of Polarization-Multiplexed RZ-DQPSK Signals *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference* PDP19
[9] Freund R et al 2008 30 Gbit/s RZ-8-PSK Transmission over 2800 km Standard Single Mode Fibre without Inline Dispersion Compensation *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference* OSA Technical Digest OMI5
[10] Yu J. et al 2008 17 Tb/s (161x114Gb/s) PolMux-RZ-8PSK Transmission over 662 km of Ultra-Low Loss Fiber using C-Band EDFA Amplification and Digital Coherent Detection *Proceedings of European Conference on Optical Communication* Th.3.E.2
[11] Gnauck A H Winzer P J Doerr C R and Buhl L L 2009 10 x 112-Gb/s PDM 16-QAM Transmission over 630 km of Fiber with 6.2-b/s/Hz Spectral Efficiency *Optical Fiber Communication Conference and National Fiber Optic Engineers Conference* Technical PDPB8
[12] Sano A. et al. 2010 69.1-Tb/s (432 × 171-Gb/s) C- and Extended L-band Transmission over 240 km using PDM-16-QAM Modulation and Digital Coherent Detection *National Fiber Optic Engineers Conference* PDPB7
[13] Zhou X et al. 2010 64-Tb/s (640x107-Gb/s) PDM-36QAM Transmission over 320km using both Pre- and Post-Transmission Digital Equalization *National Fiber Optic Engineers Conference* PDPB9
[14] Zhu B, Taunay T F, Fishteyn M, Liu X, Chandrasekhar S, Yan M F, Fini J M, Monberg E M and Dimarcello F V 2011 112-Tb/s Space-Division Multiplexed DWDM transmission with 14-b/s/Hz Aggregate Spectral Efficiency over a 76.8-km Seven-Core Fiber *Opt. Express* **19** 16665 16671
[15] Igarashi K, Tsuritani T, Morita I, Tsuchida Y, Maeda K, Tadakuma M, Saito T, Watanabe K, Imamura K, Sugizaki R, and Suzuki M 2013 1.03-Exabit/s×km Super-Nyquist-WDM Transmission over 7,326-km Seven-Core Fiber *Proceedings of European Conference on Optical Communication* PD3.E.3
[16] A. Turukhin et al. 2016 Demonstration of 0.52 Pb/s Potential Transmission Capacity over 8,830 km using Multicore Fiber *Proceedings of European Conference on Optical Communications* Tu1.D.3
[17] Mizuno T, Shibahara K, Kobayashi T and Miyamoto Y 2017 High-capacity Dense Space Division Multiplexed Multicore Fiber Transmission *Proc. of OSA Advanced Photonics Congress* New Orleans LA USA paper NeTu2B.3 https://doi.org/10.1364/NETWORKS.2017.NeTu2B.3
[18] Winzer P J, Neilson D T, and Chraplyvy A R, 2018 Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited] *Opt. Express* **26** 18 24190 24239
[19] Agrell E, Alvarado A and Kschischang F R 2016 Implications of Information Theory in Optical Fibre Communications *Phil. Trans. R. Soc. A* **374:** 20140438 http://dx.doi.org/10.1098/rsta.2014.0438
[20] Singh Arjun et al 2015 Jupiter Rising: A Decade of Clos Topologies and Centralized Control in Google's Datacenter Network *Proceedings of the 2015 ACM Conference on Special Interest Group on Data Communication* 183-197
[21] Farrington N and Andreyev A 2013 Facebook’s Data Center Network Architecture *Optical Interconnects Conference (Santa Fe, NM) 49 50 doi: 10.1109/OIC.2013.6552917*
[22] Morgan T P 2016 A Rare Tour of Microsofts’ Hyperscale Datacenters *The Next Platform* https://www.nextplatform.com/2016/09/26/rare-tour-microsofts-hyperscale-datacenters
[23] Al-Fares M Loukissas A and Vahdat A 2008 A scalable, commodity data center network architecture *ACM SIGCOMM Computer Communication Review 38 63 74*

[24] Filer M Booth B and Bragg D 2018 The Role of Standards for Cloud-Scale Data Centers *Optical Fiber Communications Conference and Exposition* W4I.6 1-3
[25] Greenberg A et al 2009 VL2: A scalable and flexible data center network *In Proc. ACM SIGCOMM Computer Communication Review pp. 51 62*
[26] Andreyev A 2014 Introducing data center fabric, the next-generation Facebook data center network https://engineering.fb.com/production-engineering/introducing-data-center-fabric-the-next-generation-facebook-data-center-network/
[27] Andreyev A Wang X Eckert A 2019 Reinventing Facebook's data center network https://engineering.fb.com/data-center-engineering/f16-minipack/
[28] https://fibrechannel.org/
[29] https://www.infinibandta.org/
[30] Telecommunications Infrastructure Standard for Data Centers 2017 TIA-942 Revision B
[31] Hecht J 2016 The Bandwidth Bottleneck Nature 536 139 142
[32] Hessong D Whitehurst D 2018 Growth in the Data Center Interconnect Segment *Lightwave* https://www.lightwaveonline.com/network-design/packet-transport/article/16676100/growth-in-the-data-center-interconnect-segment
[33] Mecozzi A Antonelli C Shtaif M Chen X Chandrasekhar S and P Winzer P 2018 The Kramers–Kronig Receiver *Proc. Opt. Fiber Comm. Conf., Mar. 2018, Paper Tu2D.1.* doi:10.1364/OFC.2018.Tu2D.1
[34] Morsy-Osman M and Plant D 2018 A Comparative Study of Technology Options for Next Generation Intra- and Inter-datacenter Interconnects *Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2018) paper W4E.1*
[35] Chagnon M 2019 Optical Communications for Short Reach *J. Lightwave Technol.* **37** 8 1779 1797
[36] Essiambre R J Kramer G Winzer P J Foschini G J and Goebel B 2010 Capacity Limits of Optical Fiber Networks J. Lightwave Technol. 28 4 662 701
[37] Armstrong J 2009 OFDM for Optical Communications *J. Lightwave Technol.* **27** 3 189 204
[38] Haunstein H Mayrock M 2010 OFDM spectral efficiency limits from fiber and system non-linearities *in Proc. Opt. Fiber Commun. Conf., 2010, Paper OThM7*
[39] Takayuki Mizuno and Yutaka Miyamoto 2017 High-Capacity Dense Space Division Multiplexing Transmission Optical Fiber Technology 35 108-117 https://doi.org/10.1016/j.yofte.2016.09.015
[40] Weng, Yi et al 2019 Recent Advances in DSP Techniques for Mode Division Multiplexing Optical Networks with MIMO Equalization: A Review Appl. Sci. **2019** 9,1178
[41] Shannon C E 1948 A Mathematical Theory of Communication *Bell Syst. Tech. J.* **27** 379 423 and 623 656
[42] Qian D, Huang M, Ip E, Huang Y, Shao Y, Hu J and Wang T 2011 101.7-Tb/s (370 x 294-Gb/s) PDM-128QAM-OFDM Transmission over 3 55-km SSMF using Pilot-Based Phase Noise Mitigation *Proceedings of OFC/NFOEC* Postdeadline paper PDPB5
[43] Sano A, Kobayashi T, Yamanaka S, Matsuura A, Kawakami H, Miyamoto Y, Ishihara K and Masuda H 2012 102.3-Tb/s (224 x 548-Gb/s) C- and Extended L-band all-Raman Transmission Over 240 km using PDM-64QAM Single Carrier FDM with Digital Pilot Tone *Proceedings of OFC/NFOEC* Postdeadline paper PDP5C.3.
[44] Mecozzi A and Shtaif M Information 2018 Capacity of Direct Detection Optical Transmission *Systems J. Lightwave Technol.* **36** 3 689 6942 https://doi.org/10.1109/JLT.2017.2777188
[45] Gray F 1953 Pulse Code Communication United States Patent 2632058
[46] IEEE Std 802.3-1985, Original 10 Mb/s standard, MAC, PLS, AUI, 10BASE5
[47] IEEE Std 802.3i-1990 (Clauses 13 and 14), 10 Mb/s UTP MAU, 10 BASE-T
[48] IEEE 802.5-1985 *Token Ring Access Method and Physical Layer Specifications*
[49] ISO/IEC 9314-3:1990 Information processing systems—Fibre Distributed Data Interface (FDDI)—Part 3: Physical Layer Medium Dependent (PMD)
[50] Jain R 1994 FDDI Handbook (New Jersey: Prentice Hall)
[51] Roucher E Y 1988 Singlemode Fiber Distributed Data Interface (FDDI) *Proc. SPIE* **0991** 56 60
[52] ANSI X3.263-1995 Fibre Distributed Data Interface (FDDI) – Token Ring Twisted Pair Physical Layer Medium Dependent (TP-PMD)
[53] IEEE Std 802.3u-1995 (Clauses 21–30) Type 100BASE-T MAC parameters, Physical Layer, MAUs, and Repeater for 100 Mb/s Operation
[54] ISO/IEC 11801 2017 Information technology — Generic cabling for customer premises — Part 1: General Requirements
[55] Elliot J C and Sachs M W 1992 The IBM Enterprise Systems Connection (ESCON) Architecture *IBM J. Res Dev.* **36** 4 577 591 doi: 10.1147/rd.364.0577
[56] Widmer A X and Franaszek P A 1983 A DC-Balanced, Partitioned-Block, 8b/10b Transmission Code *IBM J. Res Dev.* **27** 440 451
[57] ANSI X3.183-1991 High-Performance Parallel Interface-Mechanical, Electrical, and Signalling Protocol Specification (HIPPI-PH)
[58] Tolmie D E 1994 High-Performance Parallel Interface (HIPPI) *Tantawy A.N. (eds) High Performance Networks. The Springer International Series in Engineering and Computer Science* **237** Springer, Boston, MA https://doi.org/10.1007/978-1-4615-3194-4_6
[59] Anguelov T Burckhart D Mclaren R A van der Bij H C van Praag A Bovier J Cristien P Haben M Jovanovic P Kenyon I Staley R Cunningham D Watson G Green B and Strong J 1991 HIPPI Developments for CERN experiments *IEEE Nuclear Science Symposium and Nuclear Imaging Conference* **2** 778 782
[60] https://www.infinibandta.org
[61] Tolmie D and Halvorson M 1992 HIPPI/Serial-HIPPI *COMPCON Spring 1992* (*San Francisco CA USA*) 222 228 doi: 10.1109/CMPCON.1992.186715

[62] Yen C Walker R McFarland W Cunningham D Kwan G and Hornak T 1992 Serial Extension for 800/1600 Mb/s Computer Interconnect *SUPERCOMM/ICC '92 Discovering a New World of Communications* **2** 981 984

[63] ISO/IEC 11518-9:1999 Information Technology -- High-Performance Parallel Interface -- Part 9: Serial Specification (HIPPI-Serial)

[64] Walker R C Hornak T Yen C Doernberg J and Springer K H 1991 A 1.5 Gb/s Link Interface Chipset for Computer Data Transmission *J. Sel. Areas Comm.* **9** 698 703

[65] Crandall D et al. 1991 DC -Free Line Code for Arbitary Data Transmission U.S. Patent 5022051

[66] Epworth R E 1978 The Phenomenon of Modal Noise in Analogue and Digital Optical Fibre Systems *Proc. of 4th European Conference on Optical Communications* (Sept. 1978 Genoa, Italy) 492 501

[67] Epworth R E 1981 Modal Noise, Causes and Cures *Laser Focus* 109 115

[68] Soderstrom R L, Block T R, Karst D L and Lu T 1988 CD Laser As A Fiber Optic Source For Computer Data Links *Proc. SPIE 0991, Fiber Optic Datacom and Computer Networks* 179 182

[69] Soderstrom R L, Block T R, Karst D L and Lu T 1991 Optical Data Link Using a CD Laser *Proc. SPIE 1577, High-Speed Fiber Networks and Channels* 163 173

[70] Soderstrom R L, Baumgartner S J, Beukema B L, Block, T R and Karst D L 1993 CD Laser Optical Links for Workstations and Midrange Computers *Proceedings of 43rd Electronic Components & Technology Conference* (Buena Vista Palace, Orlando, FL., 1-4. June 1993) 505-509

[71] Soderstrom R, Jackson K and Kuchta D 1995 New 850 nm VCSELs and CD-type Lasers Provide Interoperable Low Cost Data Links Conference Proceedings *LEOS '95. IEEE Lasers and Electro-Optics Society 1995 8th Annual Meeting* (San Francisco, CA, USA) **1** 236-237 doi: 10.1109/LEOS.1995.484849

[72] Bates R J S, Kuchta D M and Jackson K P 1995 Improved Multimode Fiber Link BER Calculations due to Modal Noise and Non Self-Pulsating Laser Diodes *Opt Quant Electron* **27** 203 224

[73] Fibre Channel—Physical and Signaling Interface (FC-PH), X3.230-1994, Rev. 4.3, American National Standards Institute.

[74] Delisle D and Pelamougues A 1991 A Guide to Data Communications: B-ISDN and How It Works *IEEE Spectr* **28** 8 39 42 doi: 10.1109/6.83489

[75] af-phy-0040.000: Physical Interference Specification for 25.6 Mb/s over Twisted Pair 1995 *The ATM Forum Technical Committee* https://www.broadband-forum.org/download/af-phy-0040.000.pdf

[76] Im G Harman D B Huang G Mandzik A V Nguyen M and Werner J J 1995 51.84 Mb/s 16-CAP ATM LAN Standard *IEEE J Sel Area Comm* **13** 4 620 632 doi:10.1109/49.382153

[77] af-phy-0015.000: ATM Physical Medium Dependent Interface Specification for 155 Mb/s over Twisted Pair Cable 1995 *The ATM Forum Technical Committee* https://www.broadband-forum.org/download/af-phy-0015.000.pdf

[78] ANSI T1.105-1991 Telecommunications - Digital Hierarchy - Optical Interface Rates and Formats Specifications (SONET)

[79] Kalmanek C 2002 A Retrospective View of ATM *ACM SIGCOMM Computer Communications Review* **32** 5 13 19

[80] Joiner S 1997 Vertical Cavity Lasers for Datalinks (Invited) *The Digest of the LEOS Summer Topical Meetings* 57 58

[81] Cunnigham D G Hanson D C Nowell M C and Joiner S C 1997 Developing Leading-Edge Fiber-Optics Network Link Standards Hewlett-Packard Journal **48** 5 62 73

[82] Hahn K H, Tan M R, Houng Y M and Wang S Y 1993 Large-Area Multitransverse-Mode VCSELs for Modal Noise Reduction in Multimode Fiber Systems Electron. Lett. **29** 16 1482 1484

[83] Kuchta D M and Mahon C J 1994 Mode Selective Loss Penalties in VCSEL Optical Fiber Transmission Links *IEEE Photon. Technol. Lett.* **6** 2 288 290 doi: 10.1109/68.275453

[84] af-phy-0046.000: 622.08 Mbps Physical Layer Specification 1996 *The ATM Forum Technical Committee* https://www.broadband-forum.org/technical/download/af-phy-0046.000.pdf

[85] Agrawal G P, Anthony P J and Shen T M 1988 Dispersion Penalty for 1.3 µm Lightwave Systems with Multimode Semiconductor Lasers *J. Lightwave Technol.* **6** 5 620 625

[86] Methley S Cunningham D and Kallimani K 1993 Limitations in Gigabit Optical Data Communication System Performance due to Uncooled 1300 nm Fabry-Perot Laser Source Instability *Conference on Lasers and Electro-Optics Technical Digest (Optical Society of America)* **10** CWJ107

[87] IEEE Std 802.3z-1998 Clause 38 Physical Medium Dependent (PMD) sublayer and baseband medium, type 1000BASE-LX (long wavelength laser) and 1000BASE-SX (short wavelength laser)

[88] Cunningham D G and Lane W G 1999 *Gigabit Ethernet Networking* Indianapolis Macmillan Technical Publishing

[89] Raddatz L White I H Cunningham D G and Nowell M C 1997 Increasing the Bandwidth-Distance Product of Multimode Fiber using Offset Launch *Electron. Lett.* **33** 232 233

[90] IEEE 802.1Q-2018 - IEEE Standard for Local and Metropolitan Area Networks—Bridges and Bridged Networks

[91] Goodman J E Leonberger F J Kung Sun-Yuan and Athale R. A 1984 Optical Interconnections for VLSI Systems *Proc. IEEE* **72** 7 850 866

[92] Tsang D Z 1990 Optical Interconnects in Digital Systems – Status and Prospects *Opt. Photon. News* **1** 10 23-29

[93] Deimel P et al. 1985 Individually Addressable Monolithic 1 × 12 Light-Emitting Diode Array *J. Lightwave Technol.* **3** 5 988 991

[94] Ota Y et al. 1987 Twelve-channel individually addressable InGaAs/InP p-i-n Photodiode and InGaAsP/InP LED Arrays in a Compact Package J. *Lightwave Technol.* **5** 8 1118 1122

[95] Ota Y and Swartz R G 1991 Multichannel Parallel Data Link for Optical Communication *IEEE LTS* **2** 2 24 32

[96] Nagahori T et al. 1990 150-Mbit/s/ch 12-Channel Optical Parallel Transmission using an LED and PD Array *Optical Fiber Communication* THC3

[97] Lau K L Derry P L and Yariv A 1988 Ultimate Limit in Low Threshold Quantum Well GaAlAs Semiconductor Lasers *Appl. Phys. Lett.* **52** 88 90 DOI: 10.1063/1.99042

[98] Jewell J L Scherer A McCall S L Lee Y H Walker S Harbison J P and Florezi L T 1989 Low Threshold Electrically Pumped Vertical Cavity Surface Emitting Moicrolasers *Electron. Lett.* **25** 1123-1124

[99] Takai A Kato T Yamashita S Hanatani S Motegi Y Ito K Abe H and Kodera H 1994 200-Mb/s/ch 100-m Optical Subsystem Interconnections Using 8-Channel 1.3 um Laser Diode Arrays and Single-Mode Fiber Arrays *J. Lightw Tech.* **12** 260 270

[100] Wong Y M Muehlner D J Faudskar C C Buchholz D B Fishteyn M Brandner J L and Parzygnat W J 1995 Technology Development of a High Density 32 Channel 16 Gbit/s Optical Data Link for Optical Interconnect Applications for the Optoelectronics Technology Consortium (OETC) *J. Lightw Tech.* **13** 995 1016

[101] Ishak W S Hahn K H Booth B L Mueller E H Levi A F J and Craig R R 1995 Optical interconnects: the parallel optical link organization (POLO) approach *Proc. SPIE **2400** Optoelectronic Interconnects III* 214 doi:10.1117/12.206311

[102] Crow J D et al 1996 The Jitney Parallel Optical Interconnect *Proceedings 46th Electronic Components and Technology Conference* 292

[103] Liu Y S et al 1996 Polymer Optical Interconnect technology (POINT) *Proc. IEEE's Electronic Components and Technology Conference (ECTC'96)* 308

[104] Schwartz D B et al. 1996 A low-cost high-performance optical interconnect *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part B* **19** 3 532 539

[105] Norton L J et al. 1997 OPTOBUS I: A Production Parallel Fiber Optical Interconnect", *Proc. 47th Electronic Components and Technology Conference* 204-209

[106] Rosenberg P Giboney K Yuen A Strazincky J Haritos D Buckman L Schneider R Corzine S Kiamilev F and Dolfi D 1999 The PONI-I parallel-optical link *Proc. 49th Electronic Components Conference* 763 769

[107] Lavoie R 2012 The Evolution of the Pluggable Module Broadcast Engineering Magazine

[108] SFF-8053 GBIC (Gigabit Interface Converter) 5.5 https://www.snia.org/technology-communities/sff/specifications

[109] INF-8074 SFP (Small Formfactor Pluggable) Tansceiver 1.0 https://www.snia.org/technology-communities/sff/specifications

[110] IEEE P802.3ae 10Gb/s Ethernet Task Force 2000 Blue Book http://www.ieee802.org/3/ae/public/blue_book.pdf

[111] ITU-T Recommendation G.694.2: Spectral Grids for WDM Applications: CWDM Wavelength Grid

[112] Schlager J Hackert M P Pepeljugoski P and Gwinn J 2003 Measurements for Enhanced Bandwidth Performance Over 62.5 µm Multimode Fiber in Short-Wavelength Local Area Networks *J. Lightw. Technol.,* **21** 1276 1285

[113] Pepeljugoski P Hackert M Abbott J S Swanson S Golowich S Ritger J Kolesar J P Chen C and Schlager J 2003 Development of Laser System Specification for Optimized 50-µm Multimode Fiber for Multigigabit Short-Wavelength LANs *J. Lightw. Technol.,* **21** 1256 1275

[114] Pepeljugoski P Golowich S E Ritger J Kolesar P and Risteski A 2003 Modeling and Simulation of Next-Generation Multimode Fiber Links *J. Lightw. Technol.* **21** 1242 1255

[115] TIA/EIA-455-203 A FOTP-203 Light Source Encircled Flux Measurement Method

[116] IEC 61280-1-4: 2009 Fibre Optic Communication Subsystem Test Procedures—Part 1-4: General Communication Subsystems—Light Source Encircled Flux Measurement Method

[117] TIA/EIA-455-220 2001 Differential Mode Delay Measurement of Multimode Fiber in the Time Domain

[118] minEMBc per TIA/EIA 455-220A and IEC 60763-1-49

[119] Lei C Hodge L A Dudley J J Keever M K Liang B Bhagat J R and Liao A 1997 High Performance Vertical-Cavity Surface Emitting Lasers for Product Applications *Proc. SPIE Conf. Vertical Cavity Surface-Emitting Lasers (San Jose California USA)* **3003** 28 33 https://doi.org/10.1117/12.271069

[120] Tatum J A Clark A Guenter J K Hawthorne R A and Johnson R H 2000 Commercialization of Honeywell's VCSEL Technology *Vertical-Cavity Surface-Emitting Lasers IV* K.D. Choquette K D Lei C editors *Proceedings of the SPIE (Bellingham WA USA)* **3946** 2 13

[121] Lear K L Choquettee K D Schneider R P Jr. Kolcoyne S P and Geib K M 1995 Selectivity Oxidised Vertical Cavity Surface Emitting Lasers With 50% Power Conversion efficiency *Electron. Lett.* **31** 208 290

[122] Deng H Dudley J J Lim S F Lei C Liang B Tashima M Hodge L A Zhang X Herniman J and Herrick R W 1999 850 nm Oxide VCSEL Development at Hewlett-Packard *Proc. SPIE 3627, Vertical-Cavity Surface-Emitting Lasers III* (29 April) https://doi.org/10.1117/12.347103

[123] Tatum J A and Guenter J K 2003 The VCSELs Are Coming *Vertical-Cavity Surface-Emitting Lasers VII Proc. SPIE* **4994** (17 June 2003); doi: 10.1117/12.475724

[124] Michalzik R Giaretta G Ritger A J and Williams Q L 1999 10 Gb/s VCSEL Based Data Transmission Over 1.6 km of New Generation 850 nm Multimode Fiber *Proc. IEEE LEOS Annu. Meeting, LEOS '99 (San Francisco, CA)* Postdeadline Paper PD1.6

[125] Webster W Penty R V White I H Tan M R T and Corzine S W 2000 Perfomance of 10Gbit/s VCSELs Operating at 85C *Conference on Lasers and Electro-Optics (CLEO)* 201 202

[126] Kicherer M Jager R King R Mederer F Unold H J and Ebeling K J 2000 Single- and Multi-mode VCSELs for 12.5 Gb/s Data Links *Conference Digest. 2000 Conference on Lasers and Electro-Optics Europe Nice* doi: 10.1109/CLEOE.2000.909796

[127] Aoki M et al 2000 85°C - 10Gbit/s Operation of 1.3- µm InGaAlAs MQW-DFB laser *Proc. Eur. Conf. Optical Communication (ECOC)* **1** 123

[128] R. Paoletti et al. 2001 100 ◦C, 10-Gb/s Directly Modulated InGaAsP DFB Lasers for Uncooled Ethernet

Applications *Proc. Eur. Conf. Optical Communication (ECOC)* Amsterdam The Netherlands 84–85

[129] Takemasa K Sugiyama T and Yatagai Y 2003 Development of the 10Gbit/s 1.3 µm AlGaInAs DFB Laser *OKI Technical Review* October Issue 196 **70** 4 96 98

[130] Shirai S Tatsuoka Y Watatani C Ota T Takagi K Aoyagi T and Omura E 2004 120 ◦C Uncooled Operation of Direct Modulated 1.3 µm AlGaInAs–MQWDFB Laser Diodes for 10-Gb/s Telecom Application *Conf. Optical Fiber Communication (OFC)* (*Los Angeles CA)* ThD2

[131] Donhowe M Martin R and Peters F 1999 Specifying Optical Modulation Amplitude instead of Extinction Ratio http://www.ieee802.org/3/10G_study/public/sept99/donhowe_1_0999.pdf

[132] Dudek M 2000 OMA Proposal http://grouper.ieee.org/groups/802/3/ae/public/nov00/dudek_2_1100.pdf

[133] Fröjdh F and Öhlen P 2000 Optical Modulation Amplitude (OMA) Specifications http://www.ieee802.org/3/ae/public/nov00/ohlen_2_1100.pdf

[134] IEEE 802.3 2018 Standard for Ethernet Sub-Clause 121.8.4 Outer Optical Modulation Amplitude (OMAouter)

[135] Walker R C and Dugan R 1999 Low Overhead Coding Proposal for 10Gb/s Serial Links, IEEE 802.3 High Speed Study Group *(Kauai, HI, November 9th-10th*) http://grouper.ieee.org/groups/802/3/10G_study/public/nov99/walker_1_1199.pdf

[136] IEEE Std 802.3aq-2006 Physical Layer and Management Parameters for 10 Gb/s Operation Type 10GBASE-LRM

[137] Swenson N Voois P Lindsay T and Zeng S, 2007 Standards Compliance Testing of Optical Transmitters Using a Software-Based Equalizing Reference Receiver *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference OSA* Technical *Digest* NWC3

[138] Olshansky R Powazinik W Hill P Lanzisera V R B and Lauer R B 1987 InGaAsP Buried Heterostructure Laser with 22 GHz Bandwidth and High Modulation Efficiency *Electron. Lett.* **23** 839 841

[139] Meland E Holmstrom R Schlafer J Lauer R B and Powazinik W 1990 Extremely High-Frequency (24 GHz) InGaAsP Diode Lasers with Excellent Modulation Efficiency *Electron. Lett.* **26** 1827 1829

[140] Weisser S Larkins E Czotscher C K Benz W Daleiden J Esquivias I Fleissner J Ralston J D Romero B Sah R Schonfelder A and Rosenzweig J 1996 Damping-Limited Modulation Bandwidths up to 40 GHz in Undoped Short-Cavity In0.35/Ga0.65/As-GaAs Multiple-Quantum-Well Lasers *IEEE Photon. Technol. Lett.* **8** 608 610

[141] Bach L Kaiser W Reithmaier J P Forchel A Berg T W and Tromborg B 2003 Enhanced Direct-Modulated Bandwidth of 37 GHz by a Multi-Section Laser with a Coupled-Cavity-Injection-Grating Design *Electron. Lett.,* **39** 22 1592 1593

[142] Troppenz U Kreissl J Mohrle M Bornholdt C Rehbein W Sartorius B Woods I M and Schell M 2011 40 Gbit/s Directly Modulated Lasers: Physics and Application *Proceedings of the SPIE* **7953** id. 79530F https://doi.org/10.1117/12.876137

[143] Matsui Y Pham T Ling W A Schatz R Carey G Daghighian H and Sudo Roxlo T C 2016 55-GHz Bandwidth Short-Cavity Distributed Reflector Laser and its Application to 112-Gb/s PAM-4 *Optical Fiber Communication Conference and Exhibition (OFC)* PDP paper Th58.4

[144] Choa F S Lee Y H Koch T L Burrus C A Tell A B Jewell J L and Leibenguth R E 1991 High-Speed Modulation of Vertical Cavity Surface Emitting Lasers *IEEE Photon. Technol. Lett.* **3** 8 697 699 doi: 10.1109/68.84456

[145] Shtengel G Temkin H Brusenbach P Uchida T Kim M Parsons C Quinn W E and Swirhun S E 1993 High-Speed Vertical-Cavity Surface-Emitting Laser *Photon. Technol. Lett.* **5** 1359 1362

[146] Lear K L Hietala V M Hou H Q Ochiai M Banas J J Hammons B E Zolper J and Kilcoyne S P 1997 Small and Large Signal Modulation of 850 nm Oxide-Confined Vertical Cavity Surface Emitting Lasers *Conference on Lasers and Electro- Optics , CLEO '97* (*Baltimore,Maryland)* **11** 193 194 paper CWA2

[147] Westbergh P Gustavsson J S Haglund A Sunnerud H and Larsson A 2008 Large Aperture 850 nm VCSELs Operating at Bit Rates up to 25 Gbit/s *Electron. Lett.* **44** 15 907 908 doi: 10.1049/el:20081475

[148] Westbergh P et al. 2012 High-speed 850 nm VCSELs with 28 GHz Modulation Bandwidth Operating Error-Free up to 44 Gbit/s *Electron. Lett.* **48** 18 1145 1147 doi: 10.1049/el.2012.2525

[149] Haglund E et al. 2015 30 GHz Bandwidth 850 nm VCSEL with sub-100 fJ/bit Energy Dissipation at 25-50 Gbit/s *Electron. Lett.,* **51** 14 1096

[150] Wang H Fu W Qiu J and Feng M 2019 850 nm VCSELs for 50 Gb/s NRZ Error-Free Transmission over 100-Meter OM4 and up to 115 °C Operation *Optical Fiber Communications Conference and Exhibition (OFC)* (San Diego, CA, USA) 1 3

[151] 2018 *Datacenter Connectivity Technologies: Principles and Practice* Delft The Netherlands River Publishers Yasuhiro Matsui Chapter 3 Directly Modulated Laser Technology: Past, Present, and Future

[152] IEEE 802.3-2018 Clause 89 40GBASE-FR

[153] IEEE 802.3-2018 Clause 86 40GBASE-SR4 and 100GBASE-SR10

[154] IEEE 802.3-2018 Clause 87 40GBASE-LR4

[155] Frazier H M 2008 Aggregation at the Physical Layer 2008 *IEEE Commun. Mag.* **46** 2 S12 doi: 10.1109/MCOM.2008.4476164

[156] Gustlin M 2008 An Introduction to CTBI *IEEE Commun. Mag.* **46** 2 S13 doi: 10.1109/MCOM.2008.4476165

[157] Cideciyan R D Gustlin M Li M P Wang J and Wang Z 2013 Next Generation Backplane and Copper Cable Challenges *IEEE Commun. Mag.* **51** 12 130-136 doi: 10.1109/MCOM.2013.6685768

[158] Forney G D and Ungerboeck G 1998 Modulation and Coding for Linear Gaussian Channels *IEEE Transactions on Information Theory* **44** 6 2384 2415 doi: 10.1109/18.720542

[159] K. Azadet et al. 2002 Equalization and FEC Techniques for Optical Transceivers *IEEE J. Solid-State Circuits* **37** 3 317 327 doi: 10.1109/4.987083

[160] https://www.infinibandta.org/infiniband-roadmap/

[161] IEEE 802.3-2018 Clause 88 100GBASE-LR4 and 100GBASE-ER4

[162] IEEE 802.3-2018 Clause 95 100GBASE-SR4

[163] IEEE 802.3-2018 Clause 121 200GBASE-DR4

[164] IEEE 802.3-2018 Clause 124 400GBASE-DR4

[165] IEEE 802.3-2018 Clause 122 200GBASE-FR4 and LR4 400GBASE-FR8 and LR8

[166] Ozolins O et al. 2016 100 GHz EML for High Speed Optical Interconnect Applications *ECOC 2016; 42nd European Conference on Optical Communication*

[167] Weigel P et al., 2018 Bonded Thin Film Lithium Niobate Modulator on a Silicon Photonics Platform Exceeding 100 GHz 3-dB Electrical Modulation Bandwidth *Opt. Express* **26** 23728 23739 https://doi.org/10.1364/OE.26.023728

[168] Bhatt V et al. 2012 PAM MPI – Overview & Recommendations IEEE 802.3 *Next Generation 40Gb/s and 100Gb/s Optical Ethernet Study Group* http://www.ieee802.org/3/100GNGOPTX/public/may12/bhatt_01_0512_optx.pdf

[169] Farhood A et al. 2012 Improved MPI “Upper Bound” Analysis *IEEE P802.3bm 40 Gb/s and 100 Gb/s Fiber Optic Task Force* http://www.ieee802.org/3/bm/public/nov12/farhood_01_1112_optx.pdf

[170] King J 2016 MPI Statistical Model and Results *IEEE P802.3bs 200 GbE & 400 GbE Task Force "SMF" Ad Hoc Area* http://www.ieee802.org/3/bs/public/adhoc/smf/16_01_07/king_01a_0116_smf.pdf

[171] 2018 *Datacenter Connectivity Technologies: Principles and Practice* Delft The Netherlands River Publishers Chan T and Way W Chapter 4: PAM4 Modulation Using Electro-absorption Modulated Lasers

[172] IEEE Std 802.3cd-2018 Amendment 3: Media Access Control Parameters for 50 Gb/s and Physical Layers and Management Parameters for 50 Gb/s, 100 Gb/s, and 200 Gb/s Operation

[173] Lyubomirsky I et al. 2015 100G SWDM4 Transmission Over 300m Wideband MMF *European Conference on Optical Communication (ECOC)* 1 3

[174] Hardy S 2017 SWDM MSA Publish Two Shortwave WDM Standards *Lightwaveonline.com* https://www.lightwaveonline.com/network-design/article/16673359/swdm-msa-publishes-two-shortwave-wdm-standards

[175] Sun Y et al. 2017 High Speed Short Reach Optical Interconnect Over OM4 and OM5 Multimode Optical Fiber *Proceedings of the 66th IWCS Conference, International Wire and Cable Symposium* 791 796

[176] VCSEL PAM4 2x50G BiDi Transceiver for 100 Gigabit Ethernet https://www.foit-foxconn.com/products/optical-transceivers/qsfp28/afbr-89bddz

[177] Sun Y and Lingle R 2018 Technical Feasibility of New 200 Gb/s and 400 Gb/s Links for Data *Centers IEEE Optical Interconnects Conference (OI) (Santa Fe, NM*) 37 38 doi: 10.1109/OIC.2018.8422042

[178] Chen X Bickham S R Abbott J S Coleman J D and Li M J (2018) Multimode Fibers for Data Centers. In: Peng GD. (eds) *Handbook of Optical Fibers*, Springer, Singapore

[179] TIA-492AAAE 2016 Detail Specification for 50-µm Core Diameter/125-µm Cladding Diameter Class 1a Graded-Index Multimode Optical Fibers with Laser-Optimized Bandwidth Characteristics Specified for Wavelength Division Multiplexing *Telecommunications Industry Association*

[180] 2018 *Datacenter Connectivity Technologies: Principles and Practice* Delft The Netherlands River Publishers Sun Y Kamino J Chapter 5: Optical Fiber for Datacenter Connectivity

[181] Nowell M C Cunningham D G Hanson D C and Kazovsky L G 2000 Evaluation of Gb/s Laser Based Fibre LAN Links: Review of the Gigabit Ethernet Model *Opt. Quant. Electron* **32** 169 192

[182] Lemoff B E Buckman L A Schmit A J and Dolfi D W 2000 A Compact, Low-Cost WDM Transceiver for the LAN *Proceedings 50th Electronic Components and Technology Conference* 711 716

[183] Grann E B 2001 Low Cost CWDM Optical Transceivers *Proceedings. 51st Electronic Components and Technology Conference (Cat. No.01CH37220), (Orlando, FL, USA)* 26-29 doi: 10.1109/ECTC.2001.927676

[184] Lemoff B E Ali M E Panotopoulos G Flower G M Madhavan B Levi A F J and Dolfi D W 2004 MAUI: Enabling Fiber-to-the-Processor With Parallel Multiwavelength Optical Interconnects *J. Lightw. Technol.* 22 9 2043 2053

[185] IEEE Std 802.3-2018 Clause 54: Physical Medium Dependent (PMD) sublayer and baseband medium, type 10GBASE-LX4

[186] Ghiasi A and Dudek M 2008 Benefits of EDC and linear receivers for short reach 40/100GE *IEEE Commun. Mag.* **46** 2 S17 S21 doi: 10.1109/MCOM.2008.4473082

[187] Kuchta D Kwark Y Schuster C Baks C Haymea C Schaub J Pepeljugoski P Jewell J Graham L and Kucharski D 2003 120 Gb/s VCSEL Based Parallel Optical Transmitter and Custom 120 Gb/s Testing Station *The 16th Annual Meeting of the IEEE Lasers and Electro-Optics Society* **1** 150 151 doi: 10.1109/LEOS.2003.1251645

[188] Buckman Windover L A Simon J N Rosenau S A Giboney K S Flower G M Mirkarimi L W Grot A Law B Lin C K Tandon A Gruhlke R W Xia H Rankin G Tan M R T and Dolfi D W 2004 Parallel-Optical Interconnects > 100 Gb/s *J. Lightw. Technol.* **22** 2055 2063

[189] Cole C Lyubomirsky I Ghiasi A and Telang 2013 Higher-order modulation for client optics *IEEE Commun. Mag.* **51** 3 50–57

[190] Wei J L Cunningham D G Penty R V and White I H 2013 Study of 100 Gigabit Ethernet using Carrierless Amplitude/Phase Modulation and Optical OFDM *J. Lightw. Technol.,* **31** 9 1367 1373

[191] Olmedo M I et al 2014 Multiband Carrierless Amplitude Phase Modulation for High Capacity Optical Data Links *J. Lightw. Technol.,* **32** 4 798 804

[192] Ingham J D Penty R V and White I H 2013 Orthogonal Multipulse Modulation in Optical Data Communications *Int. Conf. Transport Optical Networks (Cartagena, Spain, 2013)*

[193] Wei J L Cheng Q Penty R V White I H and Cunningham D G 2015 400 Gigabit Ethernet using Advanced Modulation

Formats: Performance, Complexity, and Power Dissipation *IEEE Commun. Mag.* **53** 2 182 189

[194] Pavan S K Lavrencik J and Ralph S E 2014 Experimental Demonstration of 51.56 Git/s PAM-4 at 905 nm and Impact of Level Dependent RIN *European Conference on Optical Communication, (Cannes, France)* 1-3

[195] D'Ambrosia J 2015 Closing Report: IEEE P802.3bs 400GbE Task Force *IEEE 802.3* http://www.ieee802.org/3/bs/public/15_07/0715_bs_close_report.pdf

[196] Nowell M et al 2015 50 Gb/s Ethernet Over a Single Lane and Next Generation 100 Gb/s & 200 Gb/s Ethernet Call For Interest Consensus Presentation *IEEE 802.3* http://www.ieee802.org/3/cfi/1115_1/CFI_01_1115.pdf

[197] Sharif M Perin J K and Kahn J M 2015 Modulation Schemes for Single-Laser 100 Gb/s Links: Single-Carrier *J. Lightw. Technol.* **33** 20 4268 4277 doi: 10.1109/JLT.2015.2470523

[198] Parsons E Sun Y Chang F and Amezcua A 2018 http://www.ieee802.org/3/NGMMF/public/Jan18/parsons_NGMMF_01_jan18.pdf

[199] Benner A 2009 Petascale to Exascal: Optics & Interconnect Roadmap for HPC systems MIT-Microphotonics Cente CTR2 Meeting 2009

[200] Benner A 2012 Optical Interconnect Opportunities in Supercomputers and High End Computing *Optical Fiber Communication Conference* OTu2B.4.

[201] DeCusatis C 2014 Optical Interconnect Networks for Data Communications *J. Lightw. Technol.* **32** 544 552

[202] Rumley S 2017 Optical interconnects for extreme scale computing systems *Parallel Computing* **64** 65 80 https://doi.org/10.1016/j.parco.2017.02.001

[203] Ghiasi A 2015 Large Data Centers Interconnect Bottlenecks Opt. Express 23 2085 2090

[204] Stone R 2017 Use of Embedded Optics to Decrease Power Consumption in IO Dense Systems *Optical Fiber Communication Conference* Th3G.5

[205] Minkenberg C et al. 2018 Reimagining datacenter topologies with integrated silicon photonics IEEE/OSA *J. Opt. Commun. Netw.* **10** 7 126 139 doi: 10.1364/JOCN.10.00B126

[206] Depaoli E et al. 2018 A 4.9pJ/b 16-to-64Gb/s PAM-4 VSR Transceiver in 28nm FDSOI CMOS ISSCC 112 114

[207] Sun P 2018 100G SERDES Power http://www.ieee802.org/3/ck/public/adhoc/aug29_18/sun_3ck_adhoc_01_082918.pdf

[208] AFBR-77D1SZ, AFBR-78D1SZ 10 Gbps/Channel Twelve Channel Parallel Fiber Optics Modules

[209] Mellanox 100Gb/s EDR SR4 QSFP28 MMF Optical Transceiver: MMA1B00-E100

[210] Stojanovic V 2019 Monolithic Silicon-Photonic Platforms in State-of-the-Art CMOS SOI Processes [Invited] *Opt. Express* **26** 10 13106 13120

[211] Mahgerefteh D et al. 2016 Techno-Economic Comparison of Silicon Photonics and Multimode VCSELs *J. Lightw. Technol.* **34** 2 233 242

[212] Ledentsov N Jr. et al. 2019 Energy efficient 850-nm VCSEL based Optical Transmitter and Receiver Link Capable of 56 Gbit/s NRZ Operation *Proc. SPIE 10938, Vertical-Cavity Surface-Emitting Lasers XXIII, 109380J* (1 March 2019)

[213] Lambrecht J et al. 2019 90-Gb/s NRZ Optical Receiver in Silicon Using a Fully Differential Transimpedance Amplifier *J. Lightw. Technol.* **37** 9 1964 1973 doi: 10.1109/JLT.2019.2896757

[214] Verbist J 2019 Real-Time and DSP-Free 128 Gb/s PAM-4 Link Using a Binary Driven Silicon Photonic Transmitter *J. Lightw. Technol.* **37** 274 280

[215] Taubenblatt M 2014 Optics Technology Trends in Data Centers *OFC Market Watch* https://www.ofcconference.org/library/images/ofc/2014/Market%20Watch%20and%20SPS/6-Taubenblatt.pdf

[216] 2019 LightCounting optical transceiver report asks what it will take to put market on track https://www.fibre-systems.com/news/lightcounting-optical-transceiver-report-asks-what-it-will-take-put-market-track

[217] https://ethernetalliance.org/technology/2019-roadmap/

[218] https://fibrechannel.org/the-2019-fibre-channel-roadmap/

[219] Zhong K et al. 2015 Experimental Study of PAM-4, CAP-16, and DMT for 100 Gb/s short Reach Systems

[220] Wei S 2018 Silicon Photonic Modulators for PAM Transmissions J. Opt. 20 083002 (18pp)

[221] Verbist J et al. 2018 Real-Time 100 Gb/s NRZ and EDB Transmission With a GeSi Electroabsorption Modulator for Short-Reach Optical Interconnects J. Lightw. Technol. 36 90-96

[222] Kanazawa S 2016 Transmission of 214-Gbit/s 4-PAM Signal using an Ultra-Broadband Lumped-Electrode EADFB laser module Optical Fiber Communication Conference Postdeadline Papers, OSA Technical Digest (online) paper Th5B.3

[223] https://www.oiforum.com/technical-work/hot-topics/common-electrical-interface-cei-112g-2/

[224] IEEE P802.3ck 100 Gb/s, 200 Gb/s, and 400 Gb/s Electrical Interfaces Task Force http://www.ieee802.org/3/ck/index.html

[225] A. Tatarczak et al. 2017 Reach Extension and Capacity Enhancement of VCSEL-Based Transmission Over Single-Lane MMF Links J. Lightw. Technol. 35 4 565 571 doi: 10.1109/JLT.2016.2615815

[226] Lavrencik J et al. 2018 Scaling VCSEL-MMF Links to 1 Tb/s Using Short Wavelength Division Multiplexing J. Lightw. Technol. 36 8 4138 4145 doi: 10.1109/JLT.2018.2858208

[227] Ralph S and Lavrencik J 2019 High Capacity VCSEL Links Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 1-3

[228] Marigo-Lombart L et al. 2019 High Frequency Operation of an Integrated Electro-Absorption Modulator onto a Vertical-Cavity Surface-Emitting Laser JPhys Photonics 1 02LT01

[229] Bozanic M and Sinha S 2019 Emerging Transistor Technologies Capable of Terahertz Amplification: A Way to Re-Engineer Terahertz Radar Sensors *Sensors 2019*, **19** 11 2454; https://doi.org/10.3390/s19112454

[230] Kalkunte M 2019 Design of a Switch Chip Stanford Guest Lecture Seminar Course: Technologies in Finance: April 8th

http://web.stanford.edu/class/cs349f/slides/StanfordGuestLecture-April-08-2019.pdf

[231] Perin J Shastri A and Kahn J 2017 Design of Low-Power DSP-Free Coherent Receivers for Data Center Links J. Lightw. Technol. 35 21 4650 4662 doi: 10.1109/JLT.2017.2752079

[232] Bogatin E 2016 Optics vs Copper for In-chassis Connections @ 56-112 Gbps: is Copper Still a Viable Solution? *DesignCon 2016*

[233] Maki J 2019 Evolution of Pluggable Optics and What Is Beyond Optical *Fiber Communication Conference (OFC)* paper Th3A.2

[234] Cheng Q et al. 2018 Recent Advances in Optical Technologies for Data Centers: a review *Optica* **5** 1354 1370

[235] Maniotis P Schares L Lee B Taubenblatt M and Kuchta D 2020 Scaling HPC Networks with Co-packaged Optics *in Optical Fiber Communication Conference (OFC) 2020, OSA Technical Digest (Optical Society of America, 2020), paper T3K.7.*

[236] https://newsroom.intel.com/news/intel-demonstrates-industry-first-co-packaged-optics-ethernet-switch/#gs.zn7eqb

[237] Levi A 2018 Silicon Photonics' Last-Meter Problem: Economics and Physics Still Pose Challenges to "Fiber to the Processor" *IEEE Spectr.* **55** 9 8 43 doi: 10.1109/MSPEC.2018.8449048

[238] Burla M et al. 2019 500 GHz Plasmonic Mach-Zehnder Modulator *Conference on Lasers and Electro-Optics, OSA Technical Digest* paper SW3F.7

[239] Zhao Z et al. 2017 High-Speed Photodetectors in Optical Communication System *J. Semicond.* **38** 121001

[240] Zhong K et al. 2018 Digital Signal Processing for Short-Reach Optical Communications: A Review of Current Technologies and Future Trends *J. Lightw. Technol.* **36** 2 377 400 doi: 10.1109/JLT.2018.2793881