Terabit Optical Ethernet and Enabling Integration Technologies

Daniel J. Blumenthal
Terabit Optical Ethernet Center (TOEC), Department of ECE, University of California at Santa Barbara
danb@ece.ucsb.edu

Abstract: The potential evolution to Terabit Ethernet transmission and network systems will be discussed. Evolution directions and applications drivers as well as transmission, switching and routing technology and photonic integration will be covered.

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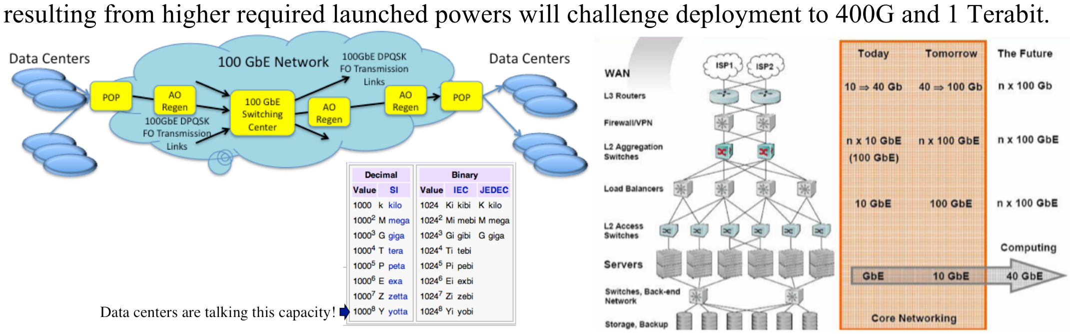
1. Introduction

Today's communications and data networks are pushing capacities that will drive the 40Gpbs and 100Gps Ethernet markets to be ubiquitous. Ethernet has become the de facto standard for all future applications including voice, video, data storage, and more recently cloud computing, data centers, and large scale high bandwidth FTTH deployment. At one extreme, pervasive applications like the Intel fiber to the chip for PC applications standard will drive fiber to the laptop with 100Gbps Ethernet and beyond [1]. At the other extreme large-scale applications like cloud computing will push unheard of boundaries for computing and communications requirements as evidenced by projections that cloud computing will exceed YottaBytes in 5-10 years. Ethernet is the most widely installed LAN and DC technology and is becoming pervasive in the Enterprise, WAN and LH transport, reducing costs of transport protocols like SONET. The explosive growth number of low bandwidth IP connected edge devices coupled with new anticipated growth in high definition TV and cloud computing/distributed data centers will continue to drive bandwidth requirements past today's 100GbE.

Ethernet was originally developed from Aloha-Net as a random media access network protocol designed to run with many users asynchronously accessing the same network. For Ethernet data rates lower than 10Gbps, the protocol is designed to run asynchronous using techniques like collision detection and avoidance to handle the random media access. However, as Ethernet become more pervasive (over alternative protocols like ATM) and evolved to a high-speed transport protocol at 10-Gigabit per second and beyond, media access with collision detection was set aside, and only the low cost transport features remained in the protocols to reduce the cost of transport over more traditional SONET protocols [2]. As a transport protocol, framing was introduced into originally variable sized asynchronous packet communications in order to facilitate transmission requirements over fiber media. The 10Gbps Ethernet approach was extended to 100GbE [5]. At these faster data rates new modulation techniques were employed to overcome fiber transmission impairments for medium to long haul distances.

The 100G standardization has ranged from 10x10Gbps and 4x25Gpbs to serial 100Gbps depending on the application, with the serial standard just finalized and designed to be carried over a standardized optical transport channel. As discussed in [2], [5] and [3], the first 100GE standards were in place for short range applications like data centers and LAN Ethernet Transport, utilizing current 10GbE technology with 10 wavelengths or four wavelengths with 25-Gb/s technology. Operation at 1300 enables a migration to 100GbE and 400GbE using 16 x 25Gbps with the potential for evolution to 40Gbps external modulated laser designs. Near term barriers to operating at 400Gbps using 4x100Gbps for DC and LAN applications will most likely occur due to cost of 100GE. For longer reach applications, the lower dispersion tolerance of 100G transmission over 25G transmission [3] and nonlinear distortion resulting from higher required launched powers will challenge deployment to 400G and 1 Terabit.



(a) (b)

Figure 1.

2. New Applications Drivers

The drive to 1TbE will most likely come initially from new data intensive applications like data centers [9], communications between data centers [8] or new high volume high data rate applications like video distribution [7][4]. Increases in IP traffic growth due in particular to consumer demand for services like video are projected to increase by a factor of 5-fold by 2013 [7]. As shown in Figure 2a, today's 100GbE links will be used to interconnect data centers with 100GbE used mostly as a transmission technology. However interconnected data centers will be required to support cloud computing environments and new global data center applications. New functions at 100GbE like line regeneration and higher bandwidth Ethernet switching and routing will be required in the near term with link data rates growing to 400G and beyond. Figure 2b shows the traditional data center communications, computation and storage hierarchy and Ethernet growth to higher multiples of 100GbE.

4. Moving to Terabit Ethernet

True Ethernet is more than just transport, it includes many functions including ***(1) Aggregation, (2) Synchronization, (3) Transmission, (4) Transport, (5) Switching and Forwarding (6) ADC and (7) Electronic Processing***. In LAN and DC environments, even as single channel Ethernet rates climb to 40G per channel, functions 1-7 will be required at wire rates by traditional electronic router chip sets. Power, cost and footprint challenges will continue to emerge as Ethernet functions have to be handled at 40GE, 100GE, 400GE and TbE wire rates and will push the practical limits of systems built on pure electronic solutions. Historical growth of high-end router capacity and the dependence on continued electronics performance to maintain flat system power footprint will drive re-architecting routers and data networks [7]. The system bandwidth of high capacity systems and even edge systems in the data center and external telecommunications infrastructure will rely on continued improvements in electronics in terms of MHz-gate/mW and Mbps/W in order to keep the system power flat while scaling capacity.

Transmission: While parallel transmission will most likely be the near term economic choice for DC and LAN applications, the economics of moving to single carrier/channel 100GbE and beyond in the MAN, WAN and longer distance transmission will continue with increased transmission speed. Historically, we have seen the move to 10GE, 40GE and now 100GE for reasons of more efficient use of wire-speed switching fabrics, better economics for higher speed interfaces and the ability for a single high capacity channel to handle peak bandwidth and lower operations and maintenance costs (OAM) over parallel wavelength or channel transmission Ethernet links [6]. In terms of raw transmission there is a wealth of work underway on Terabit modulation formats, improved spectral efficiency, transmission reach and other issues required for practical Terabit transmission. Since tradeoffs exist between transmission reach vs. spectral efficiency and between modulation symbol-space vs. SNR, it is an open question if single-carrier or multi-carrier systems will be used to transport Terabit Ethernet [16]. Examples of single channel Terabit transmission experiments to date include [11], [12] and [13]. Examples of multi-carrier include OTDM and Superchannels [14]. Pushing for single channel 400G transmission for WAN distances and beyond could be achieved using techniques with 8-b/s/Hz spectral efficiency to 16 b/s/Hz [3]. Recent studies on the Shannon capacity of nonlinear fiber channels estimate the spectral efficiency limit of a polarization-multiplexed 1000-km link of standard fiber to be at ~16 b/s/Hz [24]. At ECOC 2010, Ericsson projected next generation Ethernet to run at 400Gbps PM-16QAM single-carrier in 2015 and 1TB commercial in 2018 commercial with required spectral efficiencies of 8b/Hz. The practical limits of transmission for high spectral efficiency channels include fiber nonlinear distortion of signal constellations [21]. A key function to enable Terabit coherent transmission is the optical coherent 3R regenerator, to overcome the dispersion, nonlinear and ASE induced transmission impairments. Research on 3R all-optical regeneration for coherent systems shows promise for lower cost repeaters with tolerance to nonlinearities, ASE and dispersion is underway and examples of published results include [24], [25], [22], [23].

Another key issue is related to if Terabit Ethernet will remain a framed optical transport protocol or if there are new technology opportunities to move to a media access based protocol so that more of the functions 1-7 can be handled in addition to transport. This could become increasingly important as the power required to switch and regenerate Terabit Ethernet channels could become prohibitively expensive and power hungry if done using traditional lower speed electronic techniques. The architecting of distributed networks for applications like cloud computing could put pressure on having the ability to add/drop and route packets at Terabit rates.

DSPs and ADCs: The edge where electronics is used for converting coherent optical analog signals to electronics signals and for compensation of fiber impairments will hit barriers due to practical in-line Terabit electronics. In order to move to single channel or multi-channel Terabit Ethernet, the amount of ADC and DSP will most likely become prohibitive in cost and power consumption. Among the open issues are optical vs. electrical dispersion compensation and ADC and the electronics bandwidth for high symbol constellations at high modulation rates. For example, the 56G electrical bandwidth for PM 16 QAM, yet will require multi-terabit DSP processing capacity! The impact on high ADC sampling rage > 100Gsps, with the required sampling resolutions have been discussed in a paper on limits and it is likely that current technologies will run out of steam for Terabit Ethernet

[17]. Optical ADC is a potential alternative that can significantly reduce the power requirements for a given bandwidth, bit resolution and dynamic range. Examples include [26] [18], [19] and [20].

Synchronization, Switching, Buffering and Routing: At the higher levels of functions 1-7, optical packet synchronization and buffering for statistical multiplexing/demultiplexing [33][35][36][37][38], switches and add/drop multiplexers that can support Terabit rates [27][28][29][30][31], and edge multiplexers for speeding up lower bit rate packets to Terabit rates [34] will be required if true Terabit Ethernet is to be performed at all levels of the Ethernet hierarchy. To date, many of the experimental implementations have been based on nonlinear fiber effects with some results reported using semiconductor electroabsorption modulators (EAM). Packet routing has been demonstrated out to 160Gbps packets [32], and these techniques are scalable to Terabit rates.

5. Photonic Integration

Key to all aspects of moving to Terabit Ethernet is photonic integrated circuits (PICs). The required stability and performance for high modulation symbol space and high bit rates will inherently depend on PIC technology married with low power electronics and lower power photonics are a potential solution [43]. Terabit coherent transmitters and receivers will require new levels of integration density that go way beyond today's state of the art [39] [40] [41]and will require integration of new ultra low loss waveguides [42] and highly power efficient materials and devices to achieve the performance and density required. PICs that can handle higher level functions like switching, regeneration, add/drop and packet forwarding functions

4. References

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