Invited paper

100/1000 Gbit/s Ethernet and beyond

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Abstract—100 Gbit/s Ethernet is foreseen in metro and access by 2014, while 1 Tbit/s Ethernet is forecasted for trunk links before 1020. This paper reviews the advantages and constraints of the optical networking and discusses how they meet the 100 Gbit/s Ethernet needs.

***Keywords*— converged networks, dense wavelength division multiplexing, high-speed Ethernet, optical networking, transparent optical networks.**

1. Introduction

Ethernet, being originally a computer networking protocol, nowadays is able to unify long distance, metro and access networking into a single network of the future [1]. The deployment of fibre-to-the-home (FTTH) in access observed in Japan, Korea, US and Europe will assure a broad bandwidth for the user at an affordable cost [2].

The previous decade has upgraded optical fibre transmission with the transparency of the links and with a possibility of long distance dense wavelength division multiplexing (DWDM) transmission with hundreds or thousands of independent transmission channels within a single fibre. However, while DWDM network application for voice and data transmission is already in a mature and highly sophisticated stage, novel kinds of traffic and services can be allocated to optical systems, and attempts to develop hybrid architectures for circuit and packet switched networks were reported recently [3]. Fixed and mobile communications will continue to converge coming years.

The next generation networking (NGN) initiative has been recently adopted by the International Telecommunication Union (ITU) as a goal to be achieved during study period 2005–2008 [4]. It is generally recognized that the Internet will support the majority of services offered by NGN both in access and in backbone, however a careful selection and separation of the services in the network is a necessary condition to assure the quality of service (QoS) and security. Consequently, the concept of NGN assumes the connectionless traffic be used for any kind of services even those that traditionally have been realized as a circuit switched connection traffic provided the average packet networks characteristics allow for satisfactory level of quality of service.

In parallel to classical point-to-point circuit switched connections, Internet traffic and packet services are globally and increasingly used for a variety of services. It is generally but apparently erroneously accepted that the packet traffic should replace the circuit-switched traffic everywhere, provided QoS and security issues are resolved satisfactorily. In fact that is criticized in this paper, and an optimal hybrid solution satisfying the needs and constraints of both real-time and packet services is proposed here. Indeed, the Internet as being based on a "best-effort" principle and carrying traffic of statistic nature is inherently vulnerable as QoS and security is concerned. The golden age of the Internet when it was a network connecting exclusive scientific community has passed for ever. Now everybody can access the Internet, and obviously not honest people also. In contrary, mass attacks towards the global Internet network or towards dedicated important targets seem to be inevitable in not a distant future.

The expansion of Internet traffic worldwide forces the global communication community to shift from classical circuit switched connection oriented networks to modern packet switched, connectionless transmission of data, with a strong interest in guarantees of the network reliability and availability as well as the security of the information and of the infrastructure, generalized mobility, etc. This revolutionary change is reflected in the International Telecommunication Union policy on the next generation networks. Consequently, NGN are expected to be deployed widely starting from the ITU study period 2005–2008, and this will be continued under the network of the future under the study period 2009–2012.

Consequently, communication networks target to transmit a variety of services. Those are not only classical voice telephony and facsimile transmission, but also the Internet traffic, data transmission, radio and digital television broadcasting (IPTV). Consequently, a variety of transmission media are used in access as metal and fibre cables, and microwave, millimeter wave, and optical free space communication links. However, owing to top performance of contemporary optical fibres there is a tendency to deploy fibres as far close to the end user as possible [5]. Thus fibres are used not only for digital voice or Internet traffic transmission, but also for expanding radio-over-fibre transmission applications that exploit the optical carrier wave amplitude modulation with a microwave carrier [6], [7], including analogue cable television transmission.

A question arises: why higher speed Ethernet? Fundamental bottlenecks are happening everywhere. Increased number of users together with increased access rates and methods and increased services results in explosion of bandwidth demand. Computing speed and system throughput doubles approximately every two years.

Networking is driven by the aggregation of data from multiple computing platforms. As the number of computing platforms grows fast, this results in a multiplicative effect on networking [8].

2. The 100 Gbit/s Ethernet Challenges

Ethernet is now widely adopted for communications in local area networks (LANs) and in metropolitan area networks (MANs). The Ethernet is facing the next evolutionary step towards 100 Gbit/s Ethernet (100GbE) [8]. As Ethernet becomes more prevalent, the issues related to the software, electronics, and optoelectronics need to be addressed. This becomes more evident for 100GbE, since that technology does not simply refer to high bit rate transmission at 100 Gbit/s, but also relates to switching, packet processing, and queuing and traffic management at 100 Gbit/s line rate. This is in parallel with a remarkable progress in transmission as 10 Gbit/s and recently 40 Gbit/s systems have become commercially deployed standards in optical networking, and multiplying the total aggregate capacity by an use of DWDM technology and transmitting simultaneously several wavelength channels. This has faced problems in view of fibre impairments, one of the most serious ones being fibre polarization mode dispersion (PMD). In particular, care has to be taken to minimize PMD coefficient when manufacturing the fibres and cables. As communication system throughput doubles roughly every 2 years, this implies the following network throughput roadmap [9]: 10 Gbit/s in 2007, 40 Gbit/s in 2011, 100 Gbit/s in 2014, 160 Gbit/s in 2015?, 640 Gbit/s in 2019?

It should be noted that industry experts claim a standard for 1 Tbit/s Ethernet will be needed by 2012 [10]! The IEEE Higher Speed Study Group (HSSG) objectives are:

- Support full-duplex operation only.
- Preserve the 802.3/Ethernet frame format utilizing the 802.3 MAC (media access control).
- Preserve minimum and maximum frame size of current 802.3 standard.
- Support a bit error rate (BER) better than or equal to 10^{-12} at the MAC/PLS (physical layer signalling) service interface.
- Support a MAC data rate of 40 Gbit/s.
- Provide physical layer specifications which support 40 Gbit/s operation over:
  - at least 100 m on OM3 multi-mode fibre (MMF) (i.e., 850 nm laser optimized),
  - at least 10 m over a copper cable assembly,
  - at least 1 m over a backplane.
- Support a MAC data rate of 100 Gbit/s.
- Provide physical layer specifications which support 100 Gbit/s operation over:
  - at least 40 km on single mode fibre (SMF),
  - at least 10 km on SMF,
  - at least 100 m on OM3 MMF,
  - at least 10 m over a copper cable assembly.
- Prior experience scaling IEEE 802.3 and contributions to the study group indicates:
  - 40 Gbit/s Ethernet will provide approximately the same cost balance between the LAN and the attached stations as 10 Gbit/s Ethernet,
  - the cost distribution between routers, switches, and the infrastructure remains acceptably balanced for 100 Gbit/s Ethernet.
- Given the topologies of the networks and intended applications, early deployment will be driven by key aggregation and high-bandwidth interconnect points. This is unlike the higher volume end system application typical for 10/100/1000 Mbit/s Ethernet, and as such, the initial volumes for 100 Gbit/s Ethernet are anticipated to be more modest than the lower speeds. This does not imply a reduction in the need or value of 100 Gbit/s Ethernet to address the stated applications.

Concerning compatibility the following actions have been performed:

- The IEEE 802 defines a family of standards. All standards shall be in conformance with the IEEE 802.1 *Architecture*, *Management*, and *Interworking* documents as follows: 802. *Overview* and *Architecture*, 802.1D, 802.1Q, and parts of 802.1f. If any of variances in conformance emerge, they shall be thoroughly disclosed and reviewed with 802. Each standard in the IEEE 802 family of standards shall include a definition of managed objects that are compatible with systems management standards. As an amendment to IEEE 802.3, the proposed project will remain in conformance with the IEEE 802 *Overview* and *Architecture* as well as the bridging standards IEEE 802.1D and IEEE 802.1Q.
- As an amendment to IEEE 802.3, the proposed project will follow the existing format and structure of IEEE 802.3 MIB (management information base) definitions providing a protocol independent specification of managed objects (IEEE 802.1F).
- The proposed amendment will conform to the full-duplex operating mode of the IEEE 802.3 MAC.
- As it was the case in previous IEEE 802.3 amendments, new physical layers specific to either 40 Gbit/s or 100 Gbit/s operation will be defined.

- By utilizing the existing IEEE 802.3 MAC protocol, this proposed amendment will maintain maximum compatibility with the installed base of Ethernet nodes.
- Bandwidth requirements for computing and networking applications are growing at different rates. These applications have different cost/performance requirements, which necessitates two distinct data rates, 40 Gbit/s and 100 Gbit/s.
- Substantially different from other IEEE 802 standards.
- One unique solution per problem (not two solutions to a problem).
- Easy for the document reader to select the relevant specification.

The technical feasibility of 100GbE has been already proven, as well as its confidence in reliability. The principle of scaling the IEEE 802.3 MAC to higher speeds has been already established within IEEE 802.3. Systems with an aggregate bandwidth of greater than or equal to 100 Gbit/s have been demonstrated and deployed in operational environment. The 100GbE project will build on the array of Ethernet component and system design experience, and the broad knowledge base of Ethernet network operation. Moreover, the experience gained in the deployment of 10 Gbit/s Ethernet might be exploited. For instance, parallel transmission techniques allow reuse of 10 Gbit/s technology and testing.

Economic feasibility study includes: known cost factors, reliable data, reasonable cost for performance, and consideration of installation costs [8]. Moreover, the costs of components and systems are defined. For the network aggregation market and core networking applications, the optimized rate offering the best balance of performance and cost is 100 Gbit/s.

3. Transparent Optical Transmission

Here we discuss the optical transparency and its fundamental limitations due to physical constraints as dispersion, polarization mode dispersion, and fibre nonlinearities, and we evaluate the achievable network performance [11].

Erbium-doped fibre amplifiers (EDFA) are nowadays widely exploited in optical transmission links, and their use results in the optical transparency of those links and networks. We understand transparency here as the feature allowing for the optical signal at the output of a link be proportional to the signal at the input. Thus the transparency is an analogue feature of a link.

The notion of transparency has already been applied also for metallic cable based electrical links: those links are so called transparent if the output signal is proportional to the signal at the input. Transparency in optical domain has also its common sense: the medium is transparent if the light goes through. The advent of erbium-doped fibre amplifiers resulted in transparency of optical link, thus in a possibility of wavelength division multiplexing (WDM) transmission.

Wavelength division multiplexing technology is one of the most promising and cost effective ways to increase optical link total throughput. In a WDM system many information channels are transmitted through one fibre using different optical wavelengths modulated by independent data streams. This method is analogous to frequency division multiplexing (FDM) which is widely exploited in other communication systems, especially in radio broadcasting. Using WDM we can easily increase the capacity of already existing fibre links that is particularly significant in the areas where placing new cables is impossible or too expensive. WDM is a technique compatible with the idea of all-optical networks, where one can create transparent optical paths connecting successive network nodes by switching optical channels organized at the different wavelengths.

Unfortunately, in real systems one is faced to the lack of the ideal transparency rather than to the transparency itself. Namely, the signal quality suffers from physical limitations of the fibre, which are the attenuation, chromatic dispersion, and nonlinear distortion. An ideal transparency is not realizable in an optical network, since even an ideal glass fibre exhibits attenuation, chromatic dispersion of the first and higher orders, and glass optical nonlinearities. Moreover, in real fibres polarization mode dispersion results from random local lack of circular symmetry of the fibre due to technology imperfections and local stresses caused by cable layout. Those analogue features of a fibre result in distortion, crosstalk, and noise of the transmitted optical signal. The term PMD is used both in the general sense of two polarization modes having different group velocities, and in the specific sense of the expected value of differential group delay $<\delta\tau>$ between two orthogonally polarized modes. PMD causes the spreading of a pulse in the time domain and it is actually the main transmission distance-limiting factor in 40 Gbit/s systems and above, and as such it became recently a subject of intense research both for fibre optimization and characterization as well [12].

Chromatic dispersion is an inherent feature of an optical link that severely limits the transmission distance of high bit rate data streams. Although dispersion compensating fibres (DCF) are commonly used in order to cope with the chromatic dispersion, they have a substantial drawback as they introduce additional power losses. Another way to combat dispersion effects is to use chirped fibre Bragg gratings as dispersion compensators. The transmission performance of a system with chirped Bragg gratings has been proven to be significantly superior to that of an equivalent DCF module [13].

Nonlinear impairments result directly from the optical nonlinearity of silica glass used as the row material for communication fibres. Modern high-speed DWDM systems are typically built of several transmission spans, each consisting of an erbium-doped fibre amplifier, a single-mode fibre transmission section, and the dispersion compensation section (typically a piece of dispersion compensating fibre or a chirped fibre-Bragg grating). Such cascaded configuration leads to accumulation of the products of nonlinear optical interactions. That in turn results in increase of the optical interchannel crosstalk and degrades the temporal and spectral characteristics of the signal, including the decrease of signal-to-noise ratio (SNR). Consequently, in real transmission links strong limitations for number of channels, channel spacing, bit rate and distance occur due to nonlinear interactions [14].

The most characteristic and essential problem for multichannel optical systems is interchannel crosstalk [15]. In WDM systems the interchannel crosstalk is caused by nonlinear interplay between many different spectral components of the aggregate optical signal. The nonlinear optical phenomena involved are self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). In spite of the intrinsically small values of the nonlinearity coefficients in fused silica, the nonlinear effects in silica glass fibres can be observed even at low power levels because of very large interaction distances. This is possible because of important characteristics of single-mode fibres, a very small optical beam spot size, and extremely low attenuation.

Major problem of the network upgrade is to know to what extent the already existing infrastructure can be modernized. As a consequence, the network designers should know the limitations for number of channels, maximum transmission speed, as well as the distance between EDFAs. Those system parameters are determined by fibre attenuation, dispersion, and the optical noise level which results from the nonlinear optical phenomena in the silica fibre itself. The transmission system working on higher average optical power is more susceptible to signal distortion caused by nonlinear optical phenomena. Similarly, that problem occurs in multichannel systems because more channels mean higher total optical power in fibre. Signals co-propagating in neighbouring channels strongly interact producing unpredictable noises and decreasing signal-to-noise ratio for signals in different channels. Those phenomena are to be carefully investigated, especially in the case of utilizing new fibre types with decreased dispersion.

The transparent analogue nature of modern fibre communication systems provides a potential to modulate and detect the optical wave power with microwave or millimeter-wave envelope. Broadband wireless signal might be transmitted as an optical wave properly modulated in an analogue way. This works very well in a DWDM network with EDFA. In modern DWDM optical networks, one has to distinguish the physical network infrastructure (fibres and cables) from the virtual infrastructure (wavelengths). A question arises: do we really need separate networks for different services? Or separate fibres in a single network? Why do not use separate wavelengths for that?

An alternative approach to avoid the development of ultra-fast electronic circuits is to use advanced modulation formats that achieve 100 Gbit/s information rate while allowing lower transmission rates. In such a case, the implementation will require components operating around 50 GHz and since electronic circuitry for 40 Gbits/s is already commercially available, there will be an easier migration to the development of say 50 Gbit/s capable silicon components.

Finally, for short reach interfaces there have been a number of implementations that provide 10 or 12 parallel 10 Gbit/s lanes for a total aggregate bit rate of 100 Gbit/s or 120 Gbit/s. Such solutions are being currently under discussion in IEEE's HSSG.

There have been a number of efforts to achieve higher data rates in optical communication systems. In the Information Society Technologies (IST) projects FASHION and TOPRATE have been shown that data rates of 160 Gbit/s can be transmitted using optical time division multiplexing (OTDM). Further IST projects address IP-based optical networks and develop concepts for optical packet switched networks, e.g., IST-LASAGNE and IST-IP NOBEL. In optical packet networks, the next logical step after 10GbE is 100GbE. In this regard another IST project is HECTO working on the development of photonic components, transmitter and receiver, for high-performance and high-speed but cost-efficient communication systems. Applications are time division multiplexed optical systems with up to 160 Gbit/s and optical packet networks based on serial 100GbE signals requiring about 110 Gbit/s. The focus of these projects has been in the optical domain rather than realization of cost-efficient components.

The next step in order to increase data rates and speed of the services is the introduction of services based on 100GbE. But 100 Gbit/s transmission is standing on the very beginning and the worldwide level of knowledge and know-how in the field of 100 Gbit/s is still low. A lot of research activities have to be done until the first test links can be prepared for commercial and field exploitation. First of all integrated circuits are necessary which enable transmission equipment, like, e.g., transceivers to provide this high-speed data signal with an adapted modulation technique. To make the technology suitable for exploitation basic physical effects must be investigated in order to use them for a future technology or to minimize or overcome them if they contribute impairments. Only then all the processes for the production of necessary components can be controlled with the desired and necessary reliability. Other challenges like the cost reduction of the components, the reduction of the operational expenses of the network operators and the minimization of the energy consumptions are also a big challenge and subject of research.

Furthermore, since it appears to be very challenging to build 100 Gbit/s transmission link with non-return-to-zero (NRZ) serial modulation of data at such ultra-high rates using current technology (due to the lack of suitable modulators, drivers, amplifiers, etc.), alternative electronic modulation formats could be explored as possible candidates for data multiplexing up to 100 Gbit/s, providing lower symbol rates, more easily handled by available components. Moreover, also parallel transmission approaches can be considered, although this brings along its share of problems, e.g., ensuring equal signal transit times through multiple paths in the cable or printed circuit board (PCB) being subject to bending, temperature variations and other factors expected during installation and operation, plus potentially lower reliability due to multiple interconnections and higher number of components. For network interface, parallel optical transmission schemes are not compatible with current 1GbE and 10GbE standards using single fibre per transmission direction in the network interface and shall be avoided. Use of parallel signal paths inside the 100GbE module and towards the backplane is free of such restrictions and can be considered. A possible solution for 100GbE modulation format can be a pure multi-level amplitude modulation, offering the advantage of lower clock frequency and required signal bandwidth of critical components, e.g., modulators. On the other hand, the robustness of multi-level modulation scheme against such common impairments in the transmission path as optical amplifier noise and fibre dispersion must be carefully analyzed.

The existing 802.3 protocol has to be extended to the operating speed of 40 Gbit/s and 100 Gbit/s in order to provide a significant increase in bandwidth while maintaining maximum compatibility with the installed base of 802.3 interfaces, previous investment in research and development, and principles of network operation and management. The joint IEEE & ITU work has been accelerated recently and a standard for 40/100GbE is expected in 2010 [16]. Nevertheless, advanced optical fibre infrastructure allows for realization of a ultra-high speed Ethernet, and a pioneering attempt towards a successful 100GbE link has been recently achieved in Japan [17].

4. Conclusions and Future Directions

Optical networks consisting of standard single-mode fibres are in principle suitable for transportation of data rates up to 100 Gbit/s and more, are to be widely deployed both in long distance and in metro/access. Physical limitations laid by the fibres themselves require new technologies to overcome these constraints. Noise accumulation, chromatic dispersion, polarization mode dispersion and nonlinear effects limit data rate and maximum transmission distance. Highly stable 100 Gbit/s Ethernet transmission over different distances through the network would require pushing state of the art in the limits towards optimization and development of new technologies and components for transmitters and receivers.

Therefore it is necessary to provide a solution for applications that have been demonstrated to need bandwidth beyond the existing capabilities. These include IPTV, downloading/uploading of large files at short time, Internet exchanges, high performance computing and video-on-demand (VoD) delivery. High bandwidth applications, such as video on demand and high performance computing justify the need for a 100 Gbit/s Ethernet. Indeed, even a personal computer will surpass 10 GHz computation speed in few years.

Bandwidth requirements for computing and core networking applications are growing at different rates, which necessitates the definition of two distinct data rates for the next generation of Ethernet networks in order to address these applications: servers, high performance computing clusters, storage area networks and network attached storage all currently make use of 1GbE and 10GbE, with significant growth of 10GbE in '07 and '08. The I/O bandwidth projections for server and computing applications indicate that there will be a significant market potential for a 40 Gbit/s Ethernet interface.

Dense wavelength division multiplexing technology allows to accommodate the high-speed Ethernet traffic with classical voice and emerging packet networks in a single access infrastructure, therefore reducing the costs of the 100GbE introduction.

Finally, we have to abandon the usual question "what in the hell will people do with the 100GbE access?" Twenty years ago, when the optical fibres were revolutionising long distance communications, conservative people asked "do we really need millions of phone calls at the same time?" In 1829 conservative people asked looking at George Stephenson's "Rocket" "do we really need 13 tons of coal travelling with a speed of 12 miles per hour?" One can multiply such sort of questions: "Do we really need to fly at the 36 000 feet attitude?", "What we have to do in the space?" The experience says the opening of new opportunities results in a prompt exploitation and novel applications.

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