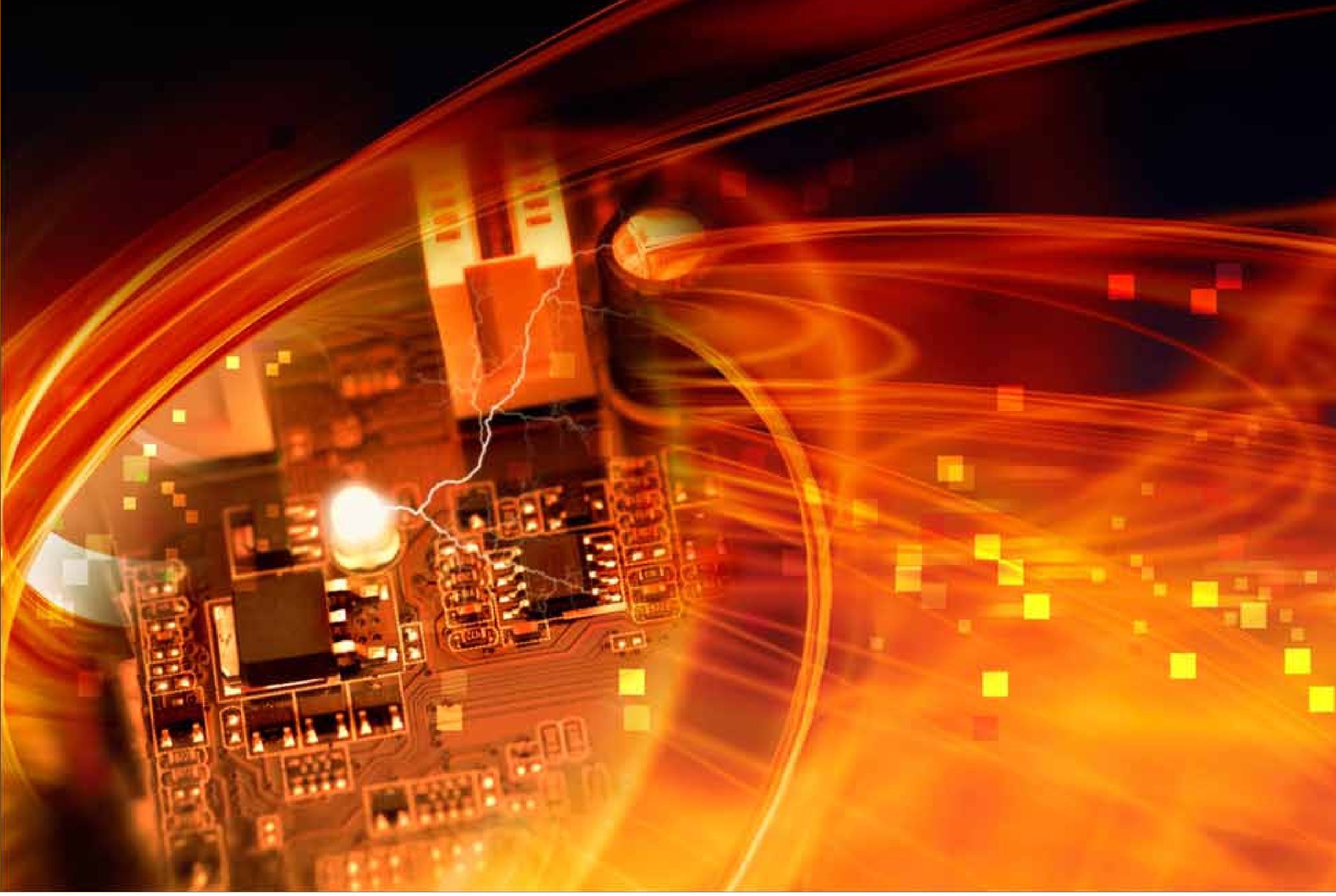

The Optical World

ITU-T Technology Watch Report

June 2011

The use of optical technologies in computing is very promising indeed for the future. It will help to support the bandwidth requirements of next-generation networks, cloud computing and the expansion of the Internet. Major breakthroughs are expected in the areas of optical networking, silicon photonics, nanotechnologies and non-linear optics which could lead to major changes in the way computers, networks and data centres are designed. This ITU-T Technology Watch Report provides an overview of the optical world and surveys standards and ongoing research that will lead to a new generation of Internet and computing devices.

ITU

The rapid change of the telecommunication/information and communication technologies (ICT) environment requires related technology foresight and immediate action in order to propose possible ITU-T standardization activities as early as possible.

ITU-T Technology Watch surveys the ICT landscape to capture new topics for standardization activities. Technology Watch Reports assess new technologies with regard to existing standards inside and outside ITU-T and their likely impact on future standardization.

Acknowledgements

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Please send your feedback and comments to tsbtechwatch@itu.int.

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The Optical World

I. Introduction

Optics is the science of light and has a very long history. In the modern world of telecommunication and information and communication technologies (ICT), the term "photonics" is sometimes used for the application of optical technology, such as lasers and optical fibre, in electronics.

In the past, high costs have prevented optical components from finding their way into computers. But as optical technology matures, prices drop and the limits of miniaturization appear to have been reached, the computer industry is re-evaluating the situation and incorporating optical alternatives into computer systems. The use of all types of optical equipment in communication networks and computers, because they consume less power, is seen as a major saving on operational costs for service providers, while at the same time helping to reduce the carbon footprint of telecommunication. The gradual incorporation of optical technology into the world of traditional electronics is paving the way for the era of the optical world.

Today, the most widely used optical technology is optical fibre for high-speed interconnections, such as in server racks, connecting offices, buildings, metropolitan networks, and even continents via submarine cables. Optical technology is also employed in CD-ROM drives, laser printers, and most photocopiers and scanners. However, none of these devices is fully optical; all rely to some extent on conventional electronic circuits and components.

The above-mentioned technologies represent entry paths for optical components into other areas of the ICT universe. This report will focus primarily on the use of optical technology in data communication devices, and this is what is referred to whenever the term "optical computing" is used. The term "photonics" is taken to cover all applications of light technology, from the ultraviolet part of the spectrum, through the visible, to the near-, mid- and far-infrared (See Figure 1).

Photonics is increasingly being used in data communication because it provides more ultra-high-capacity and speed in storage, communication and computation. Without optical technologies and optical networking related standards, the Internet as we know it today would not be feasible. Optical technologies have been the driving force behind the bandwidth growth of the Internet and enabled the emergence of bandwidth hungry applications for video and new business models such as YouTube which allows users to share video clips.

ITU-T standards in optical transport networks have played an leading role in transforming the Internet's bandwidth capabilities. This work is led by ITU-T Study Group 15, which has developed a set of international standards (or Recommendations) that defines the existing optical transport network (OTN) framework, and is currently developing future technologies such as gigabit-capable and 10-gigabit-capable passive optical networks (GPON and XGPON) to satisfy the unprecedented bandwidth requirements that will soon be demanded by service providers and consumers.

This report surveys the developments and challenges ahead for optical communication and computing, and identifies optical related standardization activities.

II. Why optical technology?

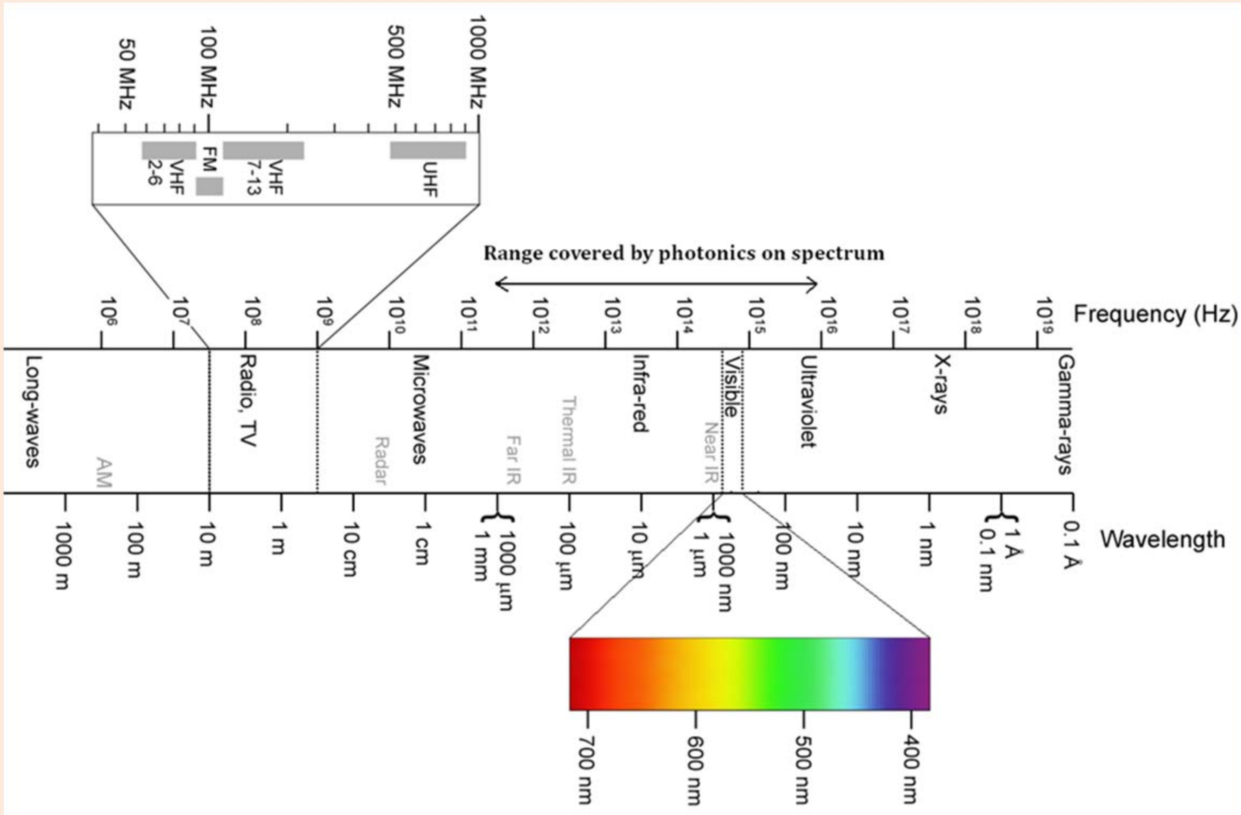
Optical technology is viewed by industry experts as the most feasible means of solving the bandwidth limitation of electronics. It has the ability to deliver higher speeds that can enhance processing power and data transmission rate compared to current silicon chips – and all while consuming less power.

Using optical technology in data communication has other desirable advantages over electronic circuits, in that it is immune to electromagnetic interference and free from electrical short circuits. Photons have low-loss transmission and provide large bandwidth, offering multiplexing capacity for communicating several channels simultaneously without interference. The difference in speed between electrons and photons means that data traveling through an electronic network will be measured in megabits per second (Mbit/s) compared to terabits per second (Tbit/s) in photonic networks. The power requirement for an electronic switching component is about one microwatt, whereas the same power requirement for a photonic switching component is measured in nanowatts. Compared with magnetic materials, optical materials are compact, much lighter and cheaper to manufacture and possess much higher storage capacity.

Furthermore, optical parallel data processing is faster and less expensive than when it is implemented with electronic devices. Thus, optical computing systems could offer significantly higher computational speeds for parallel data processing than the currently fastest electronic systems.

The recent revival of optical computing technology is due to an ever-increasing need for computational speed, coupled with the rapid increase in global demand for Internet access, television and video services, and next-generation broadband. Indeed, service providers in the telecommunication sector have transformed their offerings into a new business model for triple-play services (combining voice, data and video) that rely on sufficient bandwidth to carry large amounts of data. As telecommunication networks expand on a global scale, it can be observed that optical communication will continue to be a strategic enabler for next-generation Internet services.

Figure 1: Range covered by photonics on electromagnetic spectrum



Source: Wikimedia Commons, http://en.wikipedia.org/wiki/File:Electromagnetic-Spectrum.png

III. Optical communication networks and devices

In this report, optical communication is used taken to mean devices that transmit data by sending pulses of light through an optical fibre. The light forms an electromagnetic carrier wave that is modulated to carry information. First developed in the 1970s, fibre-optic communication systems have revolutionized the telecommunication industry and have played a major role in the advent of the information age. Because of its advantages over electrical transmission, optical fibre is rapidly replacing copper wire in core networks in the developed world and is key for developing countries in bridging the digital divide.

Traditionally, optical devices include items such as polarizers, waveplates, reflectors, filters, and lenses. However, when we consider the concept of communication in optical devices, the scope widens to encompass beam-splitters, phototransistors, laser diodes and more, including:

- light emitters and receivers;
- linear image sensors;
- optoelectronic devices; and
- photodetectors.

The main advantages of using optical technologies in communication systems are that the high frequency of the optical carrier enables significantly more information to be transmitted over a single channel than is possible with a conventional radio or microwave system. Optical components are much smaller and lighter, with the additional benefit of consuming less power. Since energy conservation is gaining increasing interest nowadays, the energy-saving characteristics of optical technologies represent huge opportunities for reducing the carbon footprint of ICTs.

The communication process using optical fibre involves the following basic steps (shown in Figure 2):

- creating and encoding the optical signal involves the use of a transmitter – lasers and light-emitting diodes (LEDs) are generally used for this purpose;
- transmitting the signal along the fibre;
- ensuring that the signal does not become too distorted or weak, hence the use of amplifiers; and
- receiving the optical signal and converting it into an electrical signal using an optical receiver.

Figure 2: Basic steps in optical communication

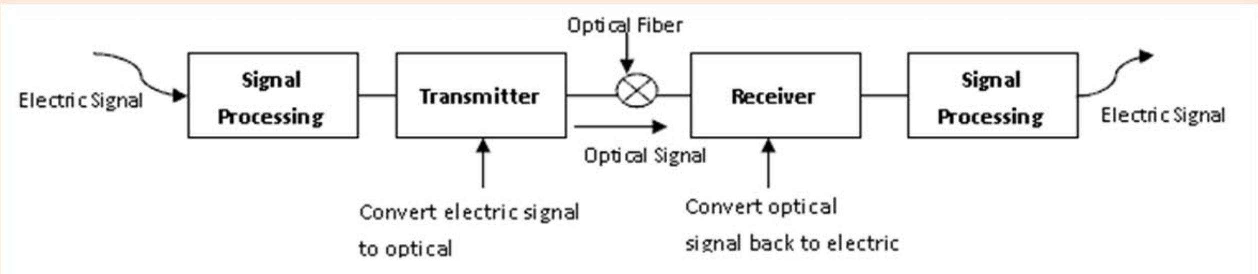
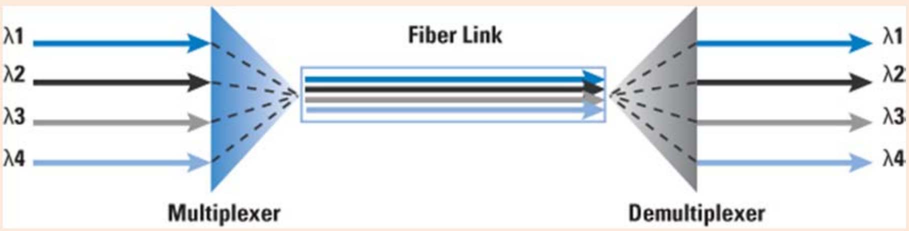


Figure 3: Wavelength Division Multiplexing (WDM), functional model



Source: http://www.cisco.com/web/about/ac123/ac147/archived_issues/ipj_11-3/113_gmpls.html

Wavelength division multiplexing (WDM) can optimize the potential high bandwidth of optical fibres by enabling several distinct data signals to share a single fibre, provided that they have different wavelengths. Multiple wavelengths are therefore multiplexed into a single optical fibre and multiple light-path data are transmitted [1] (See Figure 3).

Current communication networks using optical fibre still need to convert the electrical signal into an optical one for transmission, and then back into electrical form at the receiving end. Thus, the potential bandwidth of optical fibres is not being fully exploited. Therefore, future research and standardization work will be focused on developing purely optical devices for communication networks.

IV. Standardization activities

This section mainly looks at current and future standardization activities in the following areas:

1. optical transport network;
2. optical switching and optical cross-connect;
3. automated switching optical network architecture;
4. passive optical network;
5. optical Internet exchange;
6. visible light communication;
7. optical data transfer inside the computer; and
8. all-optical computer.

4.1 Optical Transport Network (OTN)

Synchronous optical networking (SONET) was adopted as the backbone of most fibre-optic telecommunication networks in the late 1990s. SONET was originally designed for optical interfaces that used a single wavelength per fibre. As fibre-optic technology has advanced, it has become more economical to transmit multiple SONET signals over the same fibre using WDM instead of going to a higher rate SONET signal. In 2003, ITU-T Study Group 15 defined a transport network that was optimized for cost-effective transparent transport of a variety of client signals over WDM networks. The optical transport network (OTN) architecture is specified in Recommendation ITU-T G.872 and the frame format and payload mappings are specified in Recommendation ITU-T G.709 for carrying SONET, Ethernet and storage area network (SAN) signals in a much more cost-effective manner than was possible over SONET networks.

Using OTN, multiple networks and services such as legacy SONET, Ethernet, storage protocols and video can all be combined onto a common infrastructure. Most importantly, unlike SONET, OTN is the only transport layer in the industry that can carry a full 10/40/100 Gbit/s Ethernet signal from IP/Ethernet switches and routers at full bandwidth. With the rapid migration to IP/Ethernet-based infrastructure, OTN becomes the transport layer of choice for network operators.

OTN is composed of a set of optical network elements connected by optical fibre links. It is able to provide functionality of transport, multiplexing, routing, management, supervision and survivability of optical channels carrying client signals.[1] The OTN framework is based on a set of Recommendations with ITU-T G.709 at the heart. An OTN is sometimes also referred to as an all-optical network (AON), where optical connections known as light paths are used for data transmission.[2]

Recommendation ITU-T G.709 "*Interfaces for the Optical Transport Network (OTN)*" describes a means of communicating data over an optical network, as well as requirements in the areas of optical transport hier-

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[1] See Optical Transport Networks & Technologies Standardization Work Plan at http://www.itu.int/oth/T0901000001/en

[2] See http://www.buzzle.com/articles/wavelength-service-in-optical-transport-networks.html

archy (OTH), functionality of the overhead in support of multi-wavelength optical networks, frame structures, bit rates and formats for mapping client signals. It is a standardized method for transparent transport of services over optical wavelengths in dense wavelength division multiplexing (DWDM) systems.

In June 2010, ITU announced that it had agreed on updates to OTN standards, including ITU-T G.709. The revisions provide mapping of a recently launched next-generation high-rate Ethernet standard from the Institute of Electrical and Electronics Engineers (IEEE) into the OTN.

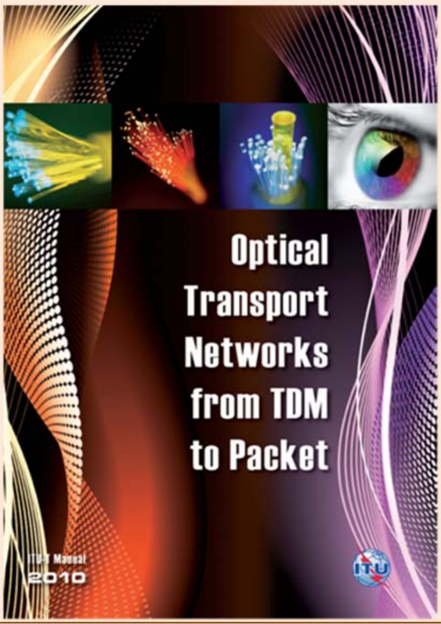
Collaboration between ITU-T Study Group 15 and the IEEE P802.3ba 40 Gbit/s and 100 Gbit/s Ethernet Task Force ensured that these new Ethernet rates are transportable over optical transport networks.[3] A manual on OTN highlights the applications of ITU-T Recommendations in this field (see Box 1).

Optical communication systems reaching terabit speeds could become the norm in the future. A major breakthrough in terms of data transfer speed in optical communications was announced, in the May 2011 issue of the Nature Photonics journal[4], when researchers at Karlsruhe Institute of Technology established a record by transmitting 26 Tbit/s using a single laser. A fast Fourier transform was used to decode more than 300 distinct colors of light in a single laser beam with very short pulses. Optical communications at terabit speed would be highly beneficial to bandwidth hungry applications such as cloud computing, 3D high definition TV (HDTV) and virtual reality. The breakthrough could pave the way for future standardization work in this area.

4.2 Optical switching and optical cross-connect

In order to implement the all-optical network, a number of optical devices are required. Two of them are optical switches and optical cross-connects, which are very important in enabling a truly optical backbone. In an optical switch, both the input/output (I/O) modules and the backplane are optical. An optical switch enables signals in optical fibres to be selectively switched from one optical circuit to another. These switches use the concept of combining optical add/drop multiplexing and optical cross-connect between two main transmission lines in order to implement the wavelength routing operation.

Box 1: ITU-T manual: Optical Transport Networks – from TDM to Packet



The ITU-T manual "Optical Transport Networks: from TDM to Packet" was launched in February 2011. It is based mainly on the standards issued by ITU-T on optical transport networks, and covers synchronous digital hierarchy (SDH), optical transport network (OTN) and Ethernet over transport (EoT) Recommendations, which are currently used in telecommunication networks. Each chapter is dedicated to a specific aspect, such as architecture, multiplexing hierarchy, protection and synchronization. The overall aim is to give a non-expert reader background information that is useful for understanding the context of the Recommendations and their main content. The manual provides, at a glance, descriptions of the most important issues associated with implementing OTN structures, with a focus on how ITU-T Recommendations address these challenges. It offers practical help and guidance to operators, suppliers and management in planning and implementing OTN, which will continue to grow in importance as fundamental infrastructure for the modern world.

The manual is available at http://www.itu.int/publ/T-HDB-IMPL.08-2010/en.

3 See ITU Newslog (21 June 2010) at http://www.itu.int/ITU-T/newslog/Optical+Network+Standard+Mapped+To+New+Ethernet+Spec.aspx

4 See Nature Photonics Journal: http://www.nature.com/nphoton/journal/v5/n6/full/nphoton.2011.74.html

An optical cross-connect (OXC) is used by telecommunication carriers to switch high-speed optical signals in a fibre-optic network. Core optical networks consist of OXCs and fibre links interconnecting OXCs. Examples of OXCs include optical add drop multiplexers (OADM), photonics cross-connects (PXC), and reconfigurable optical add/drop multiplexers (ROADM). Each OXC can route an input wavelength to an output wavelength. Thus, an optical connection can be established between edge nodes.

ROADMs are being implemented to provide automated provisioning in modern multichannel fibre-optic networks. They reduce costs, speed up provisioning time, and eliminate human error from manual reconfiguration. Essentially, this type of multiplexer has the ability to control the direction and focus of both infrared and visible light emissions within a range of different wavelengths. The technology of ROADM makes it unnecessary to convert these emissions into electrical signals that must be converted back into their original form at the point of termination.[5]

The primary benefit of all-optical devices may be their greater scalability compared with optical-electrical-optical (OEO) ones. In an OEO switch, the I/O modules are optical, but receivers convert photons into electrons for their journey over the electronic backplane. At the output module, the electrons are converted back into photons.

All future optical switch and OXC designs, however, are focused on AONs, where the user's data travel entirely in the optical domain. In order to achieve this, there is a need to evolve to transparent optical networks where there is no OEO conversion at the router level. The elimination of OEO conversion in AONs will allow for very high transmission rates.

AONs can further be categorized as wavelength-routed networks (WRNs), optical burst switched networks (OBSNs), or optical packet-switched networks (OPSNs). The emergence of multi-degree ROADMs (MD-ROADMs) that can add, drop and pass through a large number of wavelengths in different directions, with the possibility of dynamic reconfiguration, is important for the development of AONs. ITU-T Study Group 15 is developing international standards (known as "Recommendations") to define the characteristics of such MD-ROADMs (ITU-T G.rmon), as well as to define a "degradation function" of the optical network elements (DWDM line segment, PXC, OADM, etc.) between two OEO conversion points (ITU-T G.680).

4.3 Automatically switched optical network (ASON) architecture

According to the annual Cisco Visual Networking Index[6], the estimated global Internet Protocol (IP) traffic was estimated at 176 exabytes (x10^{18}) in 2009 and is projected to increase more than fourfold to reach 767 exabytes by 2014. This growth will be driven mainly by video, due to improvements in bandwidth capacity and the increasing popularity of high-definition and 3D television.

Backbone networks must preserve quality of service amidst this ever-expanding growth of broadband Internet traffic and bandwidth-hungry IP devices and applications. In view of this, the need for network flexibility for AONs has given rise to the emergence of the automatically switched optical network (ASON). Its purpose is to automate resource and connection management within the network to preserve quality of service.

Therefore, future optical backbone networks should be capable of:

- controlling and managing multiple layers;
- coping with unexpected situations quickly;
- applying the operator policies;
- providing rate- and format-free flexibility; and
- providing on-demand services.

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5 See "What is ROADM?" at http://www.wisegeek.com/what-is-roadm.htm

6 See http://newsroom.cisco.com/dlls/2010/prod_060210.html and http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360_ns827_Networking_Solutions_White_Paper.html

The main issue in the area of standardization for ASON has been the optical control plane. Optical control plane standards can provide two benefits:

- automated optical networks can be built with devices from a mixture of vendors;
- all devices will need to conform to a set of minimum requirements to ensure interoperability.

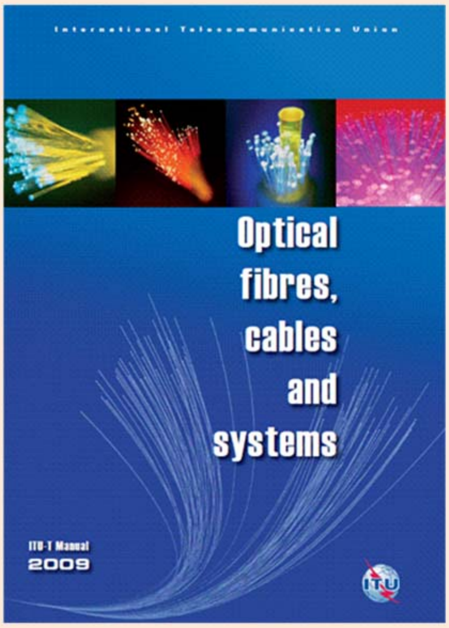
These benefits will reduce the cost of deploying and operating optical networks for the consumers of optical switches: the operators and service providers. The work to define the standards for the optical control plane is being investigated by international standards bodies, including ITU-T, which is working on ASON architecture.

Controlling quality of service is one of the essential elements for managed IP networks. ITU-T has recently achieved significant results in standardizing the operations, administration and maintenance (OAM) functionality for Ethernet networks in cooperation with IEEE. Several standardization organizations have considered extensions of OAM functionality in Ethernet networks and protection techniques. The concept of operation and maintenance in Ethernet OAM lies at the core of IP packet transmission platforms and is an essential technology for next-generation networks. ITU-T has published a manual which highlights ITU-T Recommendations in this field (see Box 2).

4.4 Passive optical network (PON)

A passive optical network (PON) extends from an operator's central facility into individual homes, apartment buildings and businesses. PONs can be deployed in a fibre-to-the-home (FTTH) architecture or in fibre-to-the-building (FTTB), fibre-to-the-curb (FTTC) or fibre-to-the-cabinet (FTTCab) architecture, depending on local demands.[7]

Box 2: ITU-T manual: Optical Fibres, cables and systems



The first ITU-T Handbook related to optical fibres, "Optical Fibres for Telecommunications" was published in 1984, and several others have been produced over the years keeping pace with developments in the field. The latest manual was published in 2009, with the title "Optical fibres, cables and systems."

ITU-T has been active in the standardization of optical communication technology and the techniques for its optimal application within networks from the infancy of this industry. The manual attempts to aggregate all of the available information on ITU-T's work. It is intended as a guide for technologists, middle-level management and regulators, to assist in the practical installation of optical fibre-based systems.

Throughout the discussion of practical issues associated with the application of this technology, the explanations focus on how ITU-T Recommendations address them. The manual can be downloaded free of charge at: http://www.itu.int/pub/T-HDB-OUT.10-2009-1/en.

Under the *Bridging the Standardization Gap* initiative, ITU-T conducts tutorials for developing countries based on the manual, to provide an in-depth insight into application of ITU-T Recommendations in this field.

7 See ITU-T manual: Optical fibres, cables and systems at http://www.itu.int/pub/T-HDB-OUT.10-2009-1/en

In order to reduce the need for separate fibres for the two directions of transmission, PON systems can take advantage of the WDM signal multiplexing technique, where downstream and upstream channels are transmitted at different wavelengths. Compared with point-to-point architectures, a PON configuration reduces the required amount of fibre and equipment at the central facility. The traffic is encrypted to prevent eavesdropping.

One common application of PON has been in providing broadband Internet access to homes for applications such as IP television (IPTV), where it is a serious competitor with digital subscriber line (DSL) technology. FTTH allows for much greater bandwidth, which is essential for broadband triple-play services. However, it also requires the installation of new transmission, wiring and receiving infrastructure.

PONs use passive optical components such as optical fibres, directional couplers, star couplers, splitters, passive routers and filters. Since PONs are used for communication over short distances, usually less than 60 km, optical signals do not require amplification. They consume less power because they do not use active components that require electricity to operate.

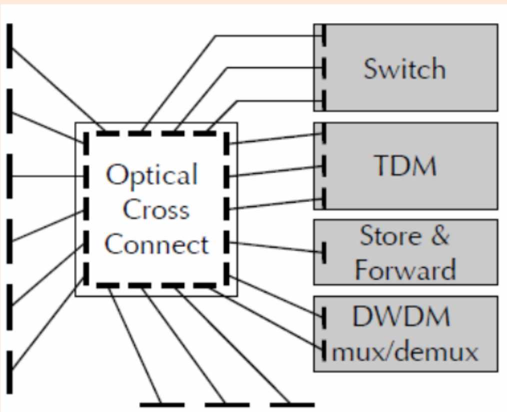
The advantage of PONs is that they offer high reliability and high bandwidth at low cost. Some Gigabit-capable PON (GPON) products already include a the power-saving mode which reduces up to 95% of the optical network unit (ONU) power consumption during power outages and standby periods [9]. Recommendations ITU-T G.983.2 and G.984.4 describe the process for shedding power in the user-network interface (UNI), which connects the ONU to user equipment, by turning it off when not in use.

4.5 Optical exchange

Peering of regular Internet traffic has led to switching-based Internet exchanges [2]. Optical exchanges on the other hand will not require switching technology at peering locations. With the fall in cost of optical devices, they could become viable as components in Internet exchange points. An optical exchange is a peering location that allows traffic to pass from one provider to another in a connection-oriented manner [2].

An example is NetherLight[8] in Amsterdam, which is based on SONET/SDH cross-connect and gigabit Ethernet switching facilities for high performance access to connected networks (see Figure 4).

Figure 4: Schematic diagram of an optical exchange



Source: http://www.glif.is/publications/papers/20041029KdL_OpticalExchanges.pdf

8 See ITU-T Technology Watch Report: "The Future Internet" at http://www.itu.int/oth/T230100000A/en

The NetherLight Exchange Point is part of the Global Lambda Integrated Facility (GLIF) network. GLIF is an international organization that promotes optical networking using lambda switching, which can switch individual wavelengths of light onto separate paths for specific routing of information. The GLIF network is based around a number of lambda networks contributed by GLIF participants who own or lease them. These are interconnected through a series of exchange points known as GOLEs (GLIF Open Lightpath Exchanges). GLIF takes advantage of the cost and capacity advantages of optical multiplexing, in order to build powerful distributed systems at various sites around the globe.[9] GLIF uses optical multiplexing capabilities to provide the bandwidth needed for scientific research and collaboration on a global scale. Some sites which form part of the GLIF network are CERNLight (Geneva), UKLight (London), MoscowLight (Moscow), StarLight (Chicago) and TaiwanLight (Taipei).

The Automated GOLE Pilot is a project initiated by the GLIF community to create an infrastructure of multiple GOLEs that allow automated user agents to request VLAN connections from a terminus at any one of the GOLEs, across the multi-domain GOLE fabric, to another edge terminus likewise attached to some other GOLE (see Figure 5 for sites in the automated GOLE pilot).[10]

Optical exchanges could represent a new area of research for packet-based optical networks that could provide the backbone for grid computing.

4.6 Visible light communication (VLC)

White light-emitting diodes (LEDs) are well known for their energy saving properties and long life. However, white LEDs also have the potential of being used as an indoor optical wireless broadband communication system. VLC using LEDs is emerging as a key technology for ubiquitous communication systems, because LEDs have the advantages of fast switching, long life expectancy, relatively low cost, and safety for the human body. This is an emerging area of research that is attracting attention.

Currently, WiFi is the technology which is used in most wireless networks in homes and businesses. WiFi is a radio frequency-based technology and its bandwidth is limited. On the other hand, visible-frequency wireless does not have the bandwidth limitation problem. The signal would be generated in a room by slightly flickering all the lights in unison. People would not notice this, because the rate of modulation would be millions of times faster than a human eye can see. Since visible light cannot penetrate walls like radio, there would be no interference from stray signals and reduced opportunity for outside hackers, thus making the system more secure. In January 2010, Siemens researchers, in collaboration with the Heinrich Hertz Institute in Berlin, achieved a wireless data transfer rate of up to 500 Mbit/s using white LED light.[11]

Research has shown that infrared light could also be used in visible light communication. The Infrared Data Association (IrDA) has been developing technical standards for infrared wireless communication and has recently announced the GigaIR standard for very short range line-of-sight infrared communication links operating at 1 Gbit/s. Speeds of more than 1 Gbit/s have been obtained with infrared light, according to research carried out by Penn State University.[12]

The Visible Light Communication Consortium (VLCC) and IEEE 802.15 Task Group 7 have been quite active in standardization work related to VLC.[13]

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9 See http://www.glif.is/resources/

10 See http://www.glif.is/meetings/2011/winter/poster/AutoGOLE-handout-20110217-v5.pdf

11 See http://www.siemens.com/innovation/en/news_events/ct_pressreleases/e_research_news/2010/e_22_resnews_1002_1.htm

12 See http://www.sciencedaily.com/releases/2010/01/100127211857.htm

13 See http://www.vlcc.net/?ml_lang=en and http://www.ieee802.org/15/pub/TG7.html

Figure 5: Sites in the Automated GOLE Pilot Project

Source: *http://www.glif.is/meetings/2011/winter/poster/AutoGOLE-handout-20110217-v5.pdf*

Major applications for visible light communication would be in private networks, home networks, sports broadcasts, live television interviews, and in optical beacons for collection of information in real time. Other major applications could include use in restricted areas where secure access is important, projection of high definition images, and in aircraft and medical facilities as the optical system will not interfere with the radio used for aircraft navigation or with medical systems. Visible light communication could also be considered in global location positioning, where it could be used in intelligent transport systems.

4.7 Optical data transfer inside the computer

So far, optical technology has been confined mostly to telecommunication networks and the cabling in data centres. However, progress in computer technology is becoming heavily reliant on ultra-fast data transfer between and within microchips. This is an emerging area of technology in which optical interconnects are being applied.

4.7.1 Thunderbolt

New data transfer technology based on optical fibres will lead to dramatic advances in the performance and design of computers. An example is Thunderbolt (originally codenamed Light Peak), a technology that has been developed by Intel to give ordinary personal computers the ability to connect with other devices using high-speed fibre-optic cables at 10 Gbit/s – twenty times faster than a standard, copper-based USB 2.0 cable [6]. This means the cable could drive a high-definition (HD) display or transfer an HD movie in seconds.

Thunderbolt technology enables engineers to [6]:

- Design standalone performance expansion technologies commonly used in desktops and workstations, using existing native device drivers and interconnected by a single cable.
- Introduce thinner and lighter laptops, expandable through Thunderbolt technology and its miniature connector designed for mobile applications, without sacrificing I/O performance.

- Extend to reach other I/O technologies by using adapters that use widely available PCI Express controllers. It is simple to create gigabit Ethernet, FireWire or eSATA adapters using existing PCI Express device drivers.

Thunderbolt has been implemented in 2011 in the new line of Apple's MacBook Pro laptops.

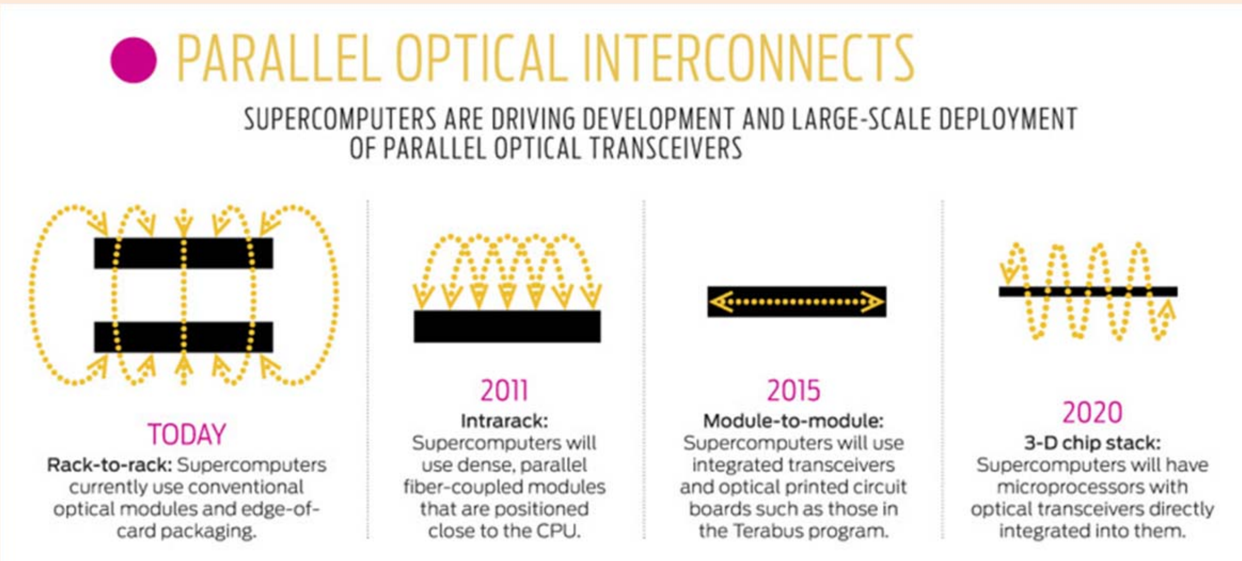
4.7.2 Silicon photonics

At present, the use of multi-core central processing units (CPUs) is expanding as one way of controlling power consumption while maintaining the trend toward high-performance electronic circuits. In a multi-core scheme, a large number of signals must be transmitted at high speed, but when metallic wiring is used, limitations arise due to signal delays and increases in power consumption. To overcome these limitations, researchers are investigating optical interconnection technology for the CPU based on wavelength division multiplexing by applying miniaturization and optical/electronic integration.

Silicon photonics [7] is an emerging area, and involves integrating optical and electronic circuits on silicon. It is one area of research that promises to produce optoelectronic devices in large numbers. The low cost of silicon and its high availability make it the material of choice for optoelectronic devices. It presents tremendous opportunities for both optical communication and for data transfer in computers in the future. Silicon photonics can be applied in optical interconnects and in optical routers.

In August 2010, Intel announced the first complete photonic communication system developed from components fully integrated into silicon chips.[14] Silicon photonic chips could replace the electronic components between a computer memory and processor, for instance. This allows for the processor and memory to be further apart, which is not possible with copper wiring, and could change the way computer systems, laptops and data centres are designed. For example, in laptops, the memory could be located in the display. The breakthrough could pave the way for communication speeds of up to 1 Tbit/s. Locating the processor further from the memory could also reduce power consumption for the cooling system, as optical communication requires less power. For data centres this would imply higher processing power at lower costs.

Figure 6: Parallel optical interconnects



Source: IEEE Spectrum: Get on the Optical Bus (September 2010), at http://spectrum.ieee.org/semiconductors/optoelectronics/get-on-the-optical-bus/. Illustration by McKibillo.

[14] See http://www.technologyreview.com/computing/25924/

The main challenge for silicon photonics is growing the laser on a silicon chip, because silicon is a poor laser material. In February 2011, however, researchers at the University of California announced that they had overcome this problem by taking advantage of the properties of nanostructures and by carefully controlling the growth process.[15] This is the first time that researchers have grown lasers from high-performance materials directly on silicon. The breakthrough could facilitate the process of growing nanolasers directly on silicon, thus paving the way for integrating optical components on silicon chips.

In December 2010, IBM announced the development of a new chip technology: CMOS Integrated silicon nanophotonics.[16] This is expected to enable the creation of a terabit-per-second class of single-chip transceivers that can increase the number of interconnects within a computer system by hundreds of millions. IBM is expecting the new technology to enable a ten-fold improvement in integration density, combining electrical and optical devices on the same piece of silicon. Moreover, since it can be produced on a standard CMOS chip manufacturing line, IBM can produce single-chip optical communication transceivers without needing the special tools of other approaches. According to IBM, the technology makes it feasible to build single-chip transceivers with an area as small as 4×4 mm^2 that can receive and transmit over one terabit (one trillion bits) per second[15].

4.7.3 Optical Bus

Similarly, IBM announced in 2010 that it has successfully developed an optical data bus on a printed circuit board that uses optical links for data transfer between the processor and other external components such as memory and input/output ports. By avoiding the signal-loss and cross-talk problems associated with copper, an optical bus would make supercomputers much faster. IBM is planning to use the optical bus in supercomputers for optical data transfer between printed circuit boards.

In 2004, the fastest machines were the NEC Earth Simulator and IBM's initial Blue Gene L, performing around 36 trillion floating-point operations per second, or teraflops, and all the connections were electrical [8]. In 2008, IBM's Roadrunner became the first to achieve a quadrillion (a thousand million million) such operations per second, which is known as a petaflop (Pflop). The Roadrunner comprised some 40,000 optical links [8]. Supercomputer processing speeds have been increasing tenfold every four years. So if the trend continues, it can be expected that 10-Pflop, 100-Pflop, and 1000-Pflop (exaflop) systems will emerge in 2012, 2016, and 2020, respectively. Figure 6 shows the possible evolution for parallel optical interconnects in order to maintain the performance trend of supercomputers.

IBM is thus conducting research aimed at developing parallel optical interconnects, referred to as optochips, which will enable ultra-fast data transfer between the components on the printed circuit board. The optochips are transceivers that convert the signal from electrical to optical and back again. The optochips can be mass produced as they incorporate CMOS electronics, optoelectronic devices, and microchip packaging techniques that are already in use today. IBM is expecting that within five years the optochips would find their way in the supercomputer, replacing copper wiring as the connection between processors and memory.

4.8 *All-optical computer*

Other research projects take a non-traditional approach, attempting to develop entirely new methods of computing that are not physically possible with electronics.[17] Light can be used to transmit, record and process information. Optical information processing is based on the idea of using all the properties of speed and parallelism of photons in order to process the information at high data rates. The information is in the form of an optical signal. The inherent parallel processing is often cited as one of the key advantages of op-

15 See http://www.technologyreview.com/computing/32324/

16 See http://www.zurich.ibm.com/news/10/nanophotonics.html

17 See http://en.wikipedia.org/wiki/Optical_computing

tical processing, compared to electronic processing using computers that are mostly serial. Therefore, optical technology has an important potential for processing a large amount of data in real time [5].

The main building block of computers is the electronic transistor. In order to build an optical computer, the equivalent optical transistor is required. The biggest challenge in optical computing is that, over short distances, the energy consumed by photons in information processing and transmission is greater than using electrons.

Although the building blocks of the processor (such as all-optical logic gates, optical switches, optical memory and optical interconnections) have been produced in research laboratories, there is no optical transistor equivalent. The main reason has been the difficulty of integrating a large number of all-optical logic gates, as most of the non-linear mechanisms in these optical switches need high optical power fed into the system in order to function, which is not currently feasible for short distances. Non-linear optical technology will play an important role in enabling the development of the all-optical transistor equivalent.

Silicon nanowires are another emerging field of research for the all-optical transistor. A nanowire is a nanostructure with a diameter of around 1 nm. They can guide light like optical fibres but, since they are thinner, the electromagnetic field produced in them by light is more powerful, which allows amplification of the light signal. This positions nanowires as a more promising medium to get light to interact with matter.

In February 2011, researchers at Harvard University announced that they had been able to build a programmable array of nanowires that have up to eight distinct logic gates, referred to as a logic tile.[18] Multiple logic tiles could be connected to perform more complex logic functions. The transistor was made from nanowires comprised of a germanium core (10 nm wide) surrounded by silicon (2 nm thick). CMOS transistors require about eight times more space than a nanowire transistor and researchers predict that they could reach their limit at 16 nm. The nanowire requires less power than CMOS (1 nW per element compared to 10-100 nW) and will enable many more transistors to be placed in the same area. However, nanowire is not expected to replace CMOS because it operates at between 10-100 megahertz (MHz) instead of at the gigahertz (GHz) of CMOS.

Because of their low power consumption and size, nanowires are expected to be used in areas such as implantable medical monitors that must be small and where fast processing is not needed. The use of nanowires in building the all-optical transistor is still at an experimental stage, however, and more innovations are expected in this field in future.

As well as work on optical communication, the research on developing the all-optical computer is a multidisciplinary arena and involves new topics such as biophotonics, nanophotonics, femtosecond nonlinear optical technology, materials science and nanotechnologies. A new paradigm is needed for packaging all-optical components that is different from what is being done currently. Until this process is standardized so that the optical transistor equivalent can be packaged and mass produced, then the optical computer will continue to remain a dream.

4.9 Challenges ahead

Optical network architectures not only provide transmission capacities to higher transport levels, such as inter-router connectivity in an IP-centric infrastructure, but also provide the intelligence required for efficient routing and fast failure recovery in core networks. This is possible due to the emergence of optical network elements that have the intelligence required to efficiently manage such networks. The work is in the early stages and needs to be further expanded over the coming years.

18 See http://spectrum.ieee.org/semiconductors/processors/harvard-team-makes-programmable-logic-from-nanowires

New optical devices such as DWDM multiplexers, ADMs and OXCs are making possible an intelligent all-optical core where packets are routed through the network without leaving the optical domain. This is the beginning of an all-optical core Internet.

At the same time, it is worth noting that all-optical components could have vulnerabilities of a different nature than their optoelectrical counterparts. Therefore, one area of future standardization work would be to develop security schemes for AON to prevent or detect direct attacks on the physical infrastructure.

The key to achieving desirable speeds and quality of service in these networks is to keep the signal in optical form in order to avoid the overhead of conversion to and from the electrical form. In such an all-optical OXC it would be possible to carry signals of any format and with a wide range of bit rates (at least from about 10 Mbit/s to more than 10 Gbit/s). These transparent OXCs would be the next development of the photonic layer, offering carriers more dynamic and flexible options in building network topologies with enhanced performance and scalability [1]. The development of large, flexible and transparent OXCs, would be enabled by a new generation of optical components such as optical amplifiers, tunable lasers and wavelength filters, which eliminate the need for optoelectronic transponders.

Similarly, as optical devices become more and more commonplace in the Internet and corporate networks, security solutions will need to evolve into the optical domain to keep communication secure and to keep up with the fast data transmission rates.

Already, research is being undertaken for the development of an optical firewall named WISDOM. The WISDOM firewall acts as a kind of primary, high-speed filter that routes suspect packets to electronic processes for further analysis [4]. It is able to carry out optical packet recognition, inspection and manipulation of data streams, incorporating features of parity checking, flag status and header recognition [4]. And, because there is no optical equivalent of electronic memory, the entire process has to be carried out instantly. In future, we may see an entire new generation of all-optical devices such as firewalls and intrusion prevention systems.

V. Conclusion

As has been outlined in this report, the main areas for future work on optical communication can be summarized as follows:

- Evolution of bandwidth capability of optical network components to achieve terabit speeds.
- Standards for all-optical devices such as DWDM multiplexers, ADM and OXC, which are essential components of an intelligent all-optical core router for the Internet where packets are routed through the network without leaving the optical domain.
- Security schemes to protect against attacks targeting all-optical devices in a fully optical communication system or computer.
- Visible light communication systems for indoor networks and global location positioning.
- New ways for packaging optical devices to standardize the development of an all-optical transistor that can be mass-produced.

Standardization work in ITU is already well engaged on the evolution towards an all optical core network for Internet and other telecommunications services. In order to provide more visibility to the work being done in field of optical networking in ITU it is suggested that a workshop be held with the objective of showcasing the developments made and future evolution of the optical network. The all-optical network could be the focus of a future Technology Watch Report where the standardization work in the field of optical networking could be investigated. The potential applications for visible light communication systems could also be investigated further.

The concept of the energy-efficient optical network would require further study as it will contribute to reducing the carbon footprint of ICT and protect the environment. Methodologies and techniques for measuring the energy efficiency of optical network designs would need to be investigated and metrics proposed for measuring their energy consumption. New concepts, such as energy-aware routing (green routing) and energy-aware traffic grooming, will represent a paradigm shift in the way network design, traffic engineering and network engineering have been carried on so far.

Similarly, all-optical computers would need further study as this is a completely new field that will be reaching maturity over the next five years or so. Some of the topics that could be investigated under this area are: the architecture of the all-optical computer, chip-to-chip communication, mechanisms for protecting optical devices against external attacks and optical equivalents of core security devices such as firewalls.

Glossary of acronyms

ADM	Add/Drop Multiplexer
ASON	Automated Switching Optical Network (architecture)
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
FTTB	Fibre-to-the-Building
FTTC	Fibre-to-the-Curb
FTTCab	Fibre-to-the-Cabinet
FTTH	Fibre-to-the-Home
GLIF	Global Lambda Integrated Facility
GMPLS	Generalized Multi-Protocol Label Switching
GPON	Gigabit-capable Passive Optical Network
ICT	Information and Communication Technology
IETF	Internet Engineering Task Force
LED	Light-Emitting Diode
MD-ROADM	Multi-Degree Reconfigurable Optical Add/Drop Multiplexer
MPLS	Multi-Protocol Label Switching
NGN	Next-Generation Network
OADM	Optical Add/Drop Multiplexer
OAM	Operations, Administration and Maintenance
OBSN	Optical Burst Switched Network
OEO	Optical-Electrical-Optical
ONU	Optical Network Unit
OPSN	Optical Packet-Switched Network
OTN	Optical Transport Network
O/E	Optical/Electrical
OXC	Optical Cross-Connect
PON	Passive Optical Network
PXC	Photonics Cross-Connect
ROADM	Reconfigurable Optical Add/Drop Multiplexer
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Networking
TDM	Time-Division Multiplexing
VLC	Visible Light Communication
WDM	Wavelength Division Multiplexing
WRN	Wavelength-Routed Network

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