Towards Fifth-Generation (5G) Optical Transport Networks

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ABSTRACT
Currently, optical communication systems and networks undergo a radical change from traditional static architectures to more dynamic, flexible, adaptive and energy efficient concepts. In this paper, we briefly review emerging technologies and approaches for future optical networks that will be able to meet the high requirements of current and emerging applications. Such high-capacity, ubiquitous, flexible and energy efficient optical networks are referred here to as fifth-generation (5G) optical transport networks.
Keywords: network technologies and concepts, optical transport networks, software-defined networking.

1. INTRODUCTION

During the last two decades, optical transport networks have continuously made progress with respect to link capacity, network topology and functionality. A view on historical development of optical transport networks is graphically depicted in Figure 1.

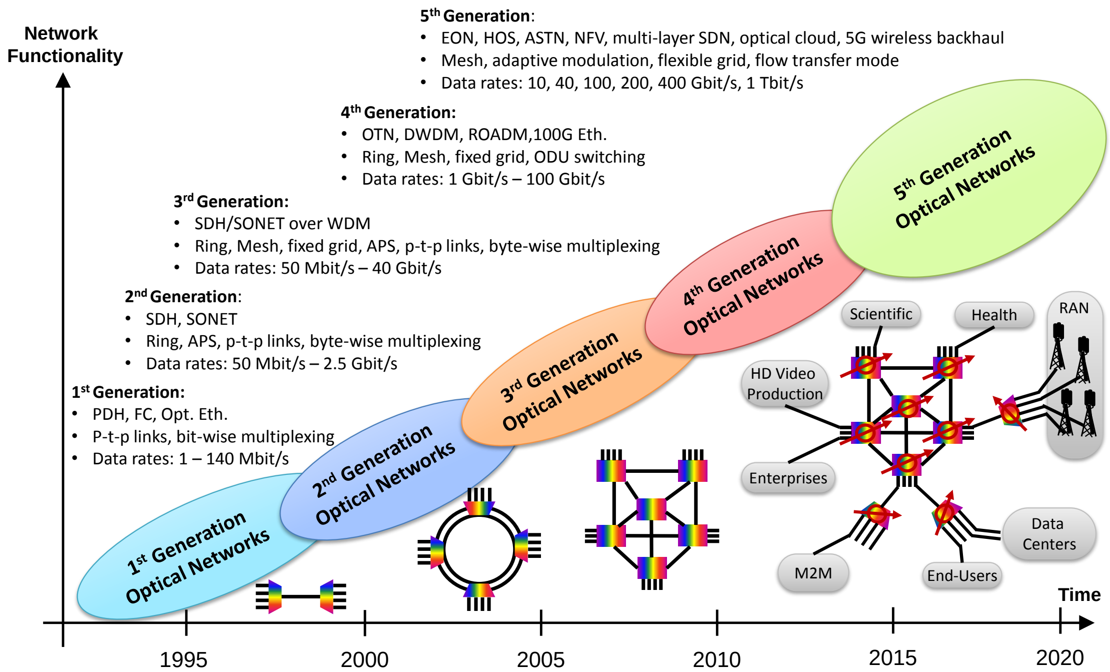

Figure 1. Evolution of optical transport networks. PDH: Plesiochronous Digital Hierarchy, SDH: Synchronous Digital Hierarchy, FC: Fibre Channel, SONET: Synchronous Optical Network, APS: Automatic Protection Switching, EON: Elastic Optical Network, ASON: Automatically Switched Optical Network,M2M: Machine-to-Machine Communication, HOS: Hybrid Optical Switching, RAN: Radio Access Network OTN: Optical Transport Network, ROADM; Reconfigurable Optical Add/Drop Multiplexer, SDN: Software-Defined Networking, NFV: Network Function Virtualization

An important milestone towards fifth-generation (5G) optical transport networks is a fast and efficient provisioning of high data rate optical paths, which can be made possible by developing and optimally utilizing flexible, bandwidth-variable and software-controllable optical components and systems as well as by using advanced network concepts such as elastic optical networking (EON) and hybrid optical switching (HOS). Also seamless interoperability between optical communication systems and other parts of the network is continuously gaining in importance. As an example, optical access networks are able to provide a high-capacity and future-proof backhaul for 5G wireless networks. Additionally, introduction of the network function virtualization (NFV) concept and software-defined networking (SDN) in the optical domain and the development of advanced optical interconnects for data centres will pave the way for high-performance optical clouds. Recent efforts and achievements in several research areas have smoothed the way towards 5G optical transport networks, especially through:

- Increasing capacity, performance, flexibility and energy efficiency
- Defining, standardizing and implementing optical SDN (multilayer SDN)
- Adapting optical technologies to optimally support cloud computing
- Extending the reach of optical access networks and integrating metro and access areas
- Developing strategies for optical wireless backhaul in support of 5G wireless networks
- Improving security by introducing physical layer security in a combined approach with cryptography

In the following, we briefly outline enabling technologies for 5G optical networks and recent efforts in the above-mentioned fields without any claim to completeness.

2. ENABLING TECHNOLOGIES FOR 5G OPTICAL TRANSPORT NETWORKS

There has been recently a lot of research effort put into developing new components and methods for increasing capacity and performance of optical transmission systems and networks, while making the optical infrastructure more flexible and energy efficient [1-11].

2.1 High-capacity optical links

The capacity limit of optical transmission systems has already approached close to the Shannon limit thanks to using and optimally combining different multiplexing formats such as wavelength-division (WDM), time-division (OTDM), space-division (SDM) and polarization-division (PDM) multiplexing together with advanced multilevel modulation formats that exploit intensity and phase modulation of the optical carrier [3,4]. Recently, transmission of 101.7 Tbit/s with a spectral efficiency as high as 11 bit/sec/Hz over 3x35 km of standard single mode fibre (SSMF) has been successfully demonstrated [10]. Aggregate data rates in the range of Pbit/s are possible by exploiting SDM in specially designed multicore fibres [11].

2.2 Bandwidth-variable and software-controllable optical transceivers

Bandwidth-variable and software-controllable optical transceivers are considered to be a key enabling component for 5G optical transport networks. BVTs should operate on flexible-wavelength grid with 12.5 GHz spectral separation and 6.25 GHz granularity for centre frequencies and be able to accommodate traffic needs by flexibly varying bit rate, reach and spectral efficiency. New-generation optical coherent transceivers with digital signal processing already provide a high level of adaptability to support trade-offs between bit-rate, spectral efficiency and reach. They can provide different modulation formats such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) together with forward error correction (FEC) [12]. The migration scenarios towards fully flexible and elastic optical networks will be influenced by the capabilities and the cost of BVTs, which in turn largely depends on the choice of architecture and required features.

In the literature [4,6,13], several approaches for a flexible variation of the three key parameters of a transceiver (bit rate, reach and spectral efficiency) have been proposed such as (i) to adapt the size *m* of the modulation alphabet and apply time-domain interleaving of symbols belonging to different sizes *m* (time-domain hybrid QAM), (ii) to adjust the forward-error correction (FEC) code rate and the size of the modulation alphabet and (iii) to use alternative modulation formats in four-dimensional (4D) signal space. Achieving a trade-off between complexity of the implementation in electrical and optical domains and realizing format-flexible digital signal processing (DSP) in a resource-efficient manner are expected to become the key design challenges.

2.3 Flexible and elastic optical network nodes

Nodes for 5G optical transport networks will need to provide a high level of flexibility in various domains such as wavelength, space and time as well as to support elastic switching over a flexible wavelength grid. Other important requisites are adaptability, scalability and resilience. Thus, there is a need for node architectures that allow flexibility and adaptability through a reconfigurable and on-demand structure [2]. Various components such as flex-grid (FG) wavelength selective switches (WSSs), multiplexers/demultiplexers, optical amplifiers, fast optical and/or electronic switches and transponders can be a part of a flexible architecture that allow different configurations to be created by interconnecting functional components to best cope with changing traffic demands. Additionally, such a modular architecture will enable scalability and an easy extension of the node functionality through adding new functional modules or replacing the old ones in order to optimally support future services. Also redundancy and protection switching can easily be used for critical functions, leading to improved resilience. Inactive modules can be switched off, thereby reducing the energy consumption and increasing energy efficiency.

2.4 Energy-efficient communication systems and networks

Energy efficiency considerations have gained in importance in recent years due to the ever increasing energy consumption of communication infrastructure and thermal issues. Therefore, it is extremely important to carefully address technologies and methods for increasing energy efficiency in 5G networks. Indeed, many recent studies have concentrated on the development and use of energy-efficient data transmission and processing systems, adaptive transmission links and dynamic power management [8,9,14]. Transmission links and line cards that are less utilized can be switched off or put in a sleep mode. It has been shown that significant savings in energy consumed by network infrastructure can be achieved when optimizing both the network concept and the architecture of network elements with regard to energy consumption [9]. Energy-efficient switching technologies and paradigms, power-aware routing and wavelength assignment (RWA) algorithms as well as multilevel traffic engineering and cross-layer optimization are examples of methods that can be applied at system level.

2.5 Multilayer software-defined networking

Already for many years now, multilayer integration has been a wish of networking industry. Since multilayer SDN provides centralized network intelligence, it makes possible to inspect all network layers concurrently to determine a path and transport technology best suited to carry traffic. Even on a single path, a data flow can be transported using different technologies and using different layers. For example, using multilayer SDN, a network can establish a transport path partly over OTN and partly over GMPLS. Additionally, multilayer SDN could monitor and evaluate the performance at each layer and across several network areas and dynamically reroute traffic or add some bandwidth from a lower layer to avoid congestions and find an optimal solution in milliseconds. This can avoid the need for hold-down timers, which are provisioned waiting periods defined and used by upper layers to provide enough time for lower layers to react to failures. Multilayer SDN can open the way for dynamic network optimization as well as for automated congestion control and cost management.

Current SDN implementations focus mainly on Ethernet networks for data centres. It is essential to extend and apply the SDN concept to transport networks on layer 0/1 (e.g. DWDM, OTN, HOS, EON), layer 2 (e.g. Ethernet) and layer 2.5 (e.g. MPLS-TP), where there is currently a lack of standards and products providing automated provisioning across these layers. Modern optical transport networks already provide a relatively high level of flexibility and controllable attributes. Some of the attributes can be controlled by software, so a SDN controller can control them. Many optical transport systems available on the market today implement the path computation element (PCE), which is standardized in IETF RFC 4655 as a control protocol for MPLS and GMPLS networks. PCE engine can be implemented in a SDN controller as a software module to provide path computation across several layers. Topology management and virtual routing modules are also available. However, additional standardization is required to allow the SDN controllers to directly manage optical transmission components such as variable bandwidth transceivers (VBTs) and reconfigurable add/drop multiplexers (ROADMs). Within the network, the available spectrum can be flexibly handled by allocating one, two or more spectral slices to a data flow. Some realizations of ROADMs are very flexible and allow the control of the wavelength (colour), ingress/egress direction and wavelength reuse without restrictions [15,16]. Such ROADMs are called colourless, directionless and contentionless (CDC) add/drop multiplexers. Figure 3 shows examples of components that can be used to implement software defined optical transport networks together with parameters that could potentially be controlled by software.

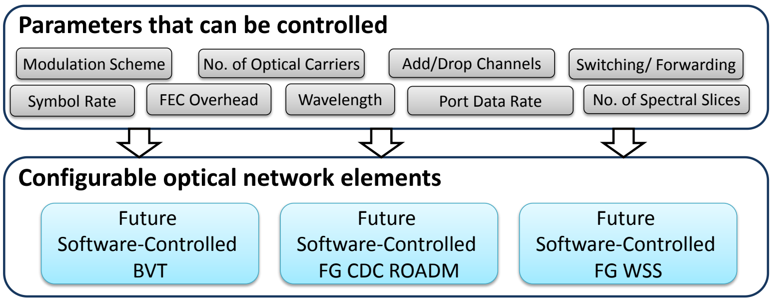

Figure 3. Examples of parameters and network elements that could potentially be software-controlled in optical software-defined networking (SDN). FG: Flex-Grid, CDC: Colourless, Directionless, and Contentionless, ROADM: Reconfigurable Optical Add/Drop Multiplexer, BVT: Bandwidth-Variable Transceiver, WSS: Wavelength Selective Switch

2.6 Optical technologies in support of cloud computing

Multilayer SDN and network function virtualization (NFV) will enable cloud-like virtualization and orchestration of network resources. Both approaches promise cost reduction and a rapid service delivery, i.e., an improved service agility and a revenue growth for network operators. Use cases include the virtualization of mobile networks (base stations, mobile core - EPC, IMS), content delivery networks (CDNs), wired access networks, home/enterprise networks and optical networks. On the one hand, interconnecting large cloud data centres by means of optical technologies seems to be the most promising option because of the high capacity and very low latencies provided by optical networks. In this contest, dynamic provisioning and managing resources in the optical network as well as seamless interoperability with cloud infrastructures and wireless networks is a prerequisite for an optimal support of cloud applications [17-19]. On the other hand, high-performance optical interconnects within data centres have the potential to offer high throughput, low latency and high energy efficiency [19-21].

2.7 Optical/wireless convergence

Optical/wireless convergence has become of particular interest recently because a combined radio wireless and optical wired network has the potential to provide both mobility and high bandwidth in an efficient way. Recent developments of new wireless access technologies such as the Long Term Evolution - Advanced (LTE-Advanced), introduction and a wide use of small base stations (femto and pico), heterogeneous networks (HetNets), and IEEE 802.11ad (WiGig) open new perspectives in providing broadband services and applications to everyone and everywhere, but the instantaneous quality of radio channel varies in time, space and frequency and radio communication is inherently energy inefficient and susceptible to reflections and interference. On the other hand, optical fiber-based networks do not provide mobility, but they are robust, energy efficient, and able to provide both an almost unlimited bandwidth and high availability. Therefore, optical access networks have been considered a promising candidate for a high-capacity and future-proof backhaul to fifth-generation (5G) wireless networks [7,22].

2.8 Physical layer security

Security and privacy are pivotal issues in 5G networks. There are many concerns regarding security of data transmitted and/or stored in the cloud or being exchanged between communicating parties in applications such as smart grids, smart cities, smart buildings, smart manufacturing and intelligent transport systems. In addition to conventional cryptography methods that use public or symmetric keys, physical layer based methods can be applied to increase the security level for critical applications. One example of physical layer security is quantum cryptography, in particular quantum key distribution (QKD), which promises a high level of communication security through utilizing quantum physical properties of optical signals. QKD relies on the principles of quantum physics and does not depend on mathematical or computational assumptions. However, a smooth integration and a wide adoption of QKD systems in telecom networks is an important step towards a practical and economical use of quantum cryptography, which still have remained challenging because of technical and economical obstacles [23-25]. Once QKD becomes a practical solution, QKD secured links and networks will be deployed anywhere, where a high level of security and privacy is required.

3. SUMMARY AND CONCLUSIONS

Future optical transport networks will have to cope with high requirements of future services and applications. They will need to provide a high capacity and reliability, together with increased flexibility, adaptability, energy efficiency and security. This paper presented current trends and briefly outlined the requirements and enabling technologies for fifth generation (5G) optical transport networks.

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