Flexible, Dynamic and Efficient Optical Transport Networks in Support of Emerging Services and Applications

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Abstract. *Recent developments in cloud computing, consumer devices and wireless networks as well as the growing importance of machine-to-machine communication set very high requirements on transport networks. Consequently, optical networks of the future will need to become more dynamic, flexible, adaptable and energy efficient. We review enabling technologies and approaches for future optical networks able to meet the high requirements of future applications in an efficient manner.*

1. Introduction

Various current and emerging applications set very high requirements on optical transport networks. Some examples are scientific, special purpose applications, which require extremely high data-rate streams over longer time period, and applications for education and remote learning requiring high data-rate streams over medium time period. Some other applications such as online gaming demand high data-rate streams over short time period and low latency, while process control and automation require low bandwidth and are extremely sensitive to latency and data consistency. Additionally, we can expect an introduction of a number of new applications, whose demands are still unknown. Thus, future optical systems and networks will need to optimally provide very high capacities on demand in a flexible, efficient and virtualized manner, in order to efficiently support all existing, emerging and future applications.

Two important milestones towards future high-capacity, ubiquitous, flexible and energy efficient optical networks are fast and efficient provisioning of high data rate optical paths and development of advanced network elements and concepts. Also a seamless interoperability and interaction between optical communication systems and other parts of the network is continuously gaining in importance. As an example, optical access networks will play an important role in providing 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 development of advanced optical interconnects for data centers will pave the way for high-performance optical clouds [Aleksic and Miladinovic 2014]. Besides providing high performance, the use of advanced optical communication systems can also lead to improved energy efficiency. The potential for the energy efficiency improvement can be maximized by using advanced optical components and systems in an adequate way on one hand and optimizing the network concept on the other. Here, we will also briefly address selected approaches for improving energy efficiency.

2. Evolution of Optical Communication Networks

When looking back into the past, we can see that several generations of optical communication networks have emerged. The first generation includes plesiochronous digital hierarchy (PDH), fibre channel (FC) and first implementations of the optical Ethernet. Those networks were based on point-to-point optical links and applied bit-wise multiplexing at data rates up to slightly more than 100 Mbit/s. The representatives of the second generation are synchronous optical networks (SONET/SDH) with mainly ring topology, supporting automatic protection switching, byte-wise multiplexing and data rates up to 2.5 Gbit/s. The third generation networks already used wavelength-division multiplexing (WDM) and meshed topology with data rates up to 40 Gbit/s. State-of-the-art optical networks make use of optical transport networks (OTN) and optical data unit (ODU) switching at data rates up to 100 Gbit/s, but still rely on the fixed wavelength grid and traditional network management. Future optical networks, which we refer here as the fifth-generation (5G) optical transport networks, are expected to provide high flexibility and elasticity while making use of network function virtualization (NFV) and software-defined networking (SDN) to optimally support a number of different applications such as cloud computing, machine-to-machine communication and 5G backhaul. They will make use of software-controllable, high-speed optical components that work on a flexible wavelength grid and use adaptive modulation and multiplexing formats [Aleksic 2015].

3. Enabling Technologies

The first step towards flexible optical networks is the introduction of flexible wavelength grid and the use of adaptive modulation and multiplexing, which will enable dynamic and on-demand provisioning of optical paths and a more efficient use of the available spectrum. One of the most important components in this context is the tunable, bandwidth-variable and software controllable transceiver. However, an increase in the modulation level, and thus a higher spectral efficiency cases a reduction of the achievable transmission distance, which has an influence on routing and resource assignment algorithms. Additionally, network nodes on the path must also be able to switch channels and data streams in an elastic and adaptive manner. Recently, optical transmission experiments with huge capacity have been demonstrated. For this purpose, complex systems using advanced multilevel modulation formats and multiplexing techniques while utilizing amplitude, phase, frequency, time, polarization and space have been built. Capacities of more than 100 Tbit/s over single-mode, single-core fibers and 1 Pbit/s using space division multiplexing (SDM) over few-mode, multi-mode or multi-core fibers and have been demonstrated in the laboratory. But before systems providing such extremely high capacity can be deployed in practical networks, a number of important questions have to be answered.

First, the existing transceivers and nodes have to be replaced, which will cause a high implementation cost. Therefore, the cost of these components and systems should be comparable with that of already deployed ones. Additionally, in order to take the advantage of SDN over multicore fibers, these fibers have to be widely deployed, which is related to very high installation costs. Second, energy consumption of new systems should be kept low in order to reduce the OPEX of network providers. Third, a very important question is how much dynamics the optical network, or even more important the network operators, can tolerate. Optical networks have been built and used for decades as very static structures. Finally, due to the increased dynamics and changing conditions on transmission paths, constrained-based routing and resource assignment algorithms are required. It is very probable that bandwidth-variable optical transceivers will operate on a flexible-wavelength grid. However, the parameters to be changed and their ranges are still not defined. In order to reduce the complexity of the entire system and to define an efficient architecture, one needs to identify and determine minimum requirements on bandwidth-variable transceivers. This can help keeping not only complexity but also cost and power consumption at the lowest possible level. For this purpose, one can try to achieve a trade-off between the complexity of the implementation in electrical and optical domains and to realize format-flexible digital signal processing (DSP) in a resource-efficient manner. With the current technology, it could be already possible to control a number of parameters by software. The selection of parameters to be controlled and the means how to control those parameters must be carefully defined and standardized. All stakeholders including component and system vendors, network operators, service operators and application developers should be actively involved in the standardization process in order to obtain a practical and widely acceptable standard. Additional to capacity and flexibility the energy consumption should be considered. As we already know, optical transmission systems inherently provide high energy efficiency. As regarding switching technologies, optical circuit switch elements based on optical beam steering can potentially reduce the energy consumption per bit by a factor of 100 comparing to electronic buffered packet switches [Fiorani et al. 2013]. However, an increase in system's complexity usually leads to a significant reduction of the achievable energy savings. For example, a large optical packet switch with similar size and complexity as an electronic packet switch would consume similar energy as its electronic counterpart. A large optical circuit switch still consumes less energy than an electronic switch, but the savings are reduced by increased complexity to a factor of 10 instead of 100 [Fiorani et al. 2013].

A network concept that efficiently combines different switching paradigms can lead to a large improvement in energy efficiency. Also achieving a trade-off between the implementation in the optical and the electronic domain is important. Finally, architecture on demand that provides adaptability on traffic changes can lead to energy savings, but also to an improved scalability, upgradability and reliability. An example of such a network concept is the so called hybrid optical switching (HOS), which has the potential to reduce the energy consumption by up to 88% in comparison to a pure electronic packet switched network. The price that we have to pay is a small penalty in throughput of 2 % at very high loads of more than 90% [Fiorani et al. 2013]. Flexibility and adaptability is equally important to be provided at the transmission and switching levels. In on-demand node architectures, a slow optical switch can be used as an optical backplane in order to interconnect various electronic and optical modules such as filters, switches, amplifiers and transponders and to provide re-configurability within the range of several hundreds of milliseconds. By carefully designing and implementing the architecture an improved scalability, energy efficiency and resilience can be achieved through switching on and off modules and ports as well as providing redundant modules and interconnections. The modular architecture and software controllability could enable a straightforward and efficient implementation of NFV and SDN.

Optical access networks have been considered as a promising technology for the fronthaul and backhaul of 5G wireless networks and beyond. This is because no one of the conventional methods for providing backhaul to radio base stations are capable of providing high data rate links in the order of several Gbit/s, which will be required for connecting 5G wireless access networks to core networks. Since optical fiber-based transmission can provide several orders of magnitude higher capacities over long distances, it is considered as a best suited candidate for a future-proof wireless backhaul. However, optical cables are not always available and the installation of new cables is costly and even not possible in some cases. Therefore, a combination of optical access with high-speed radio links such as millimeter waves seems to be most suitable option of the future wireless backhaul.

Not only the wireless backhaul, but also providing a high-speed fixed internet access is an important task. We have been witnesses of extending the reach of optical access and an integration of access and metropolitan network areas. Next generation passive optical networks (PONs), i.e. NG-PON3 will be able to provide integration of different data types and services and provision of high bandwidth to a large number of users and over distances of up to 100 km or even 200 km. Within the integrated access and metro network, advanced technologies such as multilevel modulation and multiplexing formats, tunable sources and receivers as well as flexible grid, SDN and NFV can be applied on the links connecting the aggregation and core nodes, while in the last few hundreds of meters, heterogeneous and low-cost technologies can coexist. This would enable an easy migration path. Important steps here are ensuring compatibility, coexistence and interoperability between different access technologies.

4. Summary and Conclusions

Next generation, i.e., the fifth-generation (5G) optical transport networks are expected to be able to optimally support current developments in cloud computing, wireless networks, consumer devices and machine-to-machine communication. An important step towards 5G optical transport networks is a fast and efficient provisioning of high data rate optical paths. To achieve this goal, practical high-speed, flexible, bandwidth-variable and software-controllable optical components and systems as well as advanced network concepts are needed. Additional standardization is required for optical software-defined networking (O-SDN) to become reality. Optical access technologies in combination with high-speed radio links (e.g. E-band) and microwave links where applicable seem to be the most suitable option for implementing high-capacity and future-proof backhaul for 5G wireless networks and beyond.

5. References

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