Trends and Challenges in Optical Packet Networking: The Network Layer Perspective

(Invited Paper)

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Abstract—The immense growth of the Internet which is accompanied by the emergence of new communication technologies, applications, and devices, results in the evolution from voice-centric toward data-centric optical networks. In this paper we overview some of the trends in optical packet networking and identify several related research problems. Our particular focus is on the network layer aspects of future optical networks.

I. INTRODUCTION

During the past couple of years, optical networking has undergone tremendous changes which have been governed by developments of networking capabilities and emerging applications. This evolution can be translated to denser WDM transmission systems (i.e., 80–160 wavelengths per fiber) operating at higher line rates (e.g., 10/40/100 Gbit/s) with coarser granularities at switching level (optical circuit/burst/packet switching, OCS/OBS/OPS) [1], as well as the emerging of new technologies such as Optical Orthogonal Frequency Division Multiplexing (O-OFDM). At the same time, we observe the integration of diverse network technologies (wireless and wired networks) and disparate communication paradigms (mobile and fixed communications), as well as the convergence of different applications and services (data and multimedia) within a unified Internet Protocol (IP) packet-oriented network infrastructure. The observed trends are accompanied by rapid development of wired and wireless access technologies (FTTx, WiFi, WiMAX, LTE) as well as new applications (grid, P2P, gaming, 3DTV) which results in a tremendous increase of network traffic generated by users and network devices. All these factors have an impact on the requirements put on optical networking both in the backbone, where the aggregated traffic is transported, and in the access, where different communication technologies meet together. These requirements concern, among others, large transmission capacities, low costs, quality guarantees, energy efficiency, high granularity, dynamic resource reservation, flexible network reconfiguration, and interoperability with diverse network technologies.

The purpose of this paper is to overview current trends in optical networking and identify some research challenges that have to be addressed in order to enable future progress in development of next-generation packet-oriented optical networks. Our particular interest is in the network layer aspects.

The reminder of this paper is organized as follows. In Section II we focus on next-generation optical transport networks (OTN). In Section III we address the issue of fiber-wireless (FiWi) convergence in access networks. In Section IV we discuss two new challenges in optical networking, namely, the physical layer impairment-aware network design and the energy efficiency. Finally, in Section V we conclude our discussion.

II. NEXT-GENERATION OPTICAL TRANSPORT NETWORKS

The main role of future optical networks is to provide a transport infrastructure for legacy and new IP services. Nowadays, transport networks are based mainly on static point-to-point and ring connections, and they involve an excessive protocol stack (IP/ATM/SDH). The role of optics in communication networks is limited to the realization of transmission functions only, mainly due to still costly all-optical devices (tunable lasers, wavelength converters, fast switching elements, etc.) and the lack of viable technologies (optical RAM). Nonetheless, anticipating future advances in the optical technologies, the next generation optical transport networks are expected to perform either some or all the switching and control functions in the optical domain.

In this Section, we discuss several architectural and technological choices for next-generation packet-oriented OTNs and we present some commonly accepted solutions.

A. Architectural and Technological Choices

1) Communication Modes: The fact that the Internet is a connectionless packet-based network is the main driver in the development of data-centric OTNs. There are two candidate operational models considered by the research community for future data-centric OTNs, namely, the circuit switching (CS) model and the packet/burst switching (PS/BS) model. CS networks are connection-oriented and, in particular, the transmission of data packets through the network is realized on pre-established circuits. On the contrary, in PS/BS networks the data stream consists of statistically multiplexed packets, or bursts of packets, which belong to different connections and share common transmission link resources.

2) Frequency Division Multiplexing Technologies: At present, the most advanced technology that can deal with the huge capacity requirements of OTNs is the Dense WDM (DWDM) technology. DWDM transmission systems multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths (colors) of laser light to carry different signals.
Recently, the concept of Optical Orthogonal Frequency Division Multiplexing (O-OFDM) emerged [2]. The key idea behind O-OFDM is to split a high-rate data-stream into a number of low-rate data-streams that are transmitted simultaneously over a number of subcarriers.

In light of the emerging demand for 100 Gb/s and higher data rates in future optical transport systems, optical OFDM is considered to be a promising enabling technology. In contrast with DWDM systems, OFDM introduces significantly higher spectrum-efficiency.

B. OTN Architectures

1) Wavelength-Routed OCS Networks: Taking into account the current status of optical technologies the short-term OTNs will apply the CS model in DWDM networks, resulting in the so called wavelength-routed optical circuit switching (WR-OCS) network. The transmission of data packets through the WR-OCS network is realized on pre-established optical circuits called the lightpaths. In WR-OCS, each lightpath is identified with a physical route, i.e., a subset of network links, and the DWDM wavelength channels assigned in consecutive links. The establishment of lightpaths in the network is performed by OCS nodes, also called the optical cross-connects (OXC). The switching capability of OXCs can be achieved by means of commercially available technologies such as, for instance, micro-electro-mechanical (MEMS) elements. The relatively long switching times of MEMS are sufficient for rather slow OCS operation.

The switching granularity of the OXC is a wavelength. It means that no further aggregation and drop of data is possible before the lightpath reaches its destination. In order to allow the transmission of data packets between nodes that do not have direct lightpath connections, electronic routers are used on top of the OXC nodes. In such a multi-layer architecture, electronic routers serve both as network ingress/egress nodes and traffic aggregators. They route packets over existing lightpath connections and intermediate routers towards their destination. It is worth noting that the packets undergo optical–electronic–optical (OEO) conversion every time they come across a router.

The cost of electronic devices, their high energy consumption, the heat dissipation and device dimensioning issues are the main drawbacks of the OCS-based packet transport networks.

From the network-layer perspective, the design of packet-oriented WR transport networks requires dedicated models and algorithms so that to take into account the multi-layer network architecture, which consists of the optical network layer and the electronic router network layer. Efficient methods for the cross-layer optimization in network planning, routing, resilience, etc. are up-to-date research problems.

2) Wavelength-Routed OBS/OPS Networks: OBS and OPS technologies have arisen as an alternative to the OCS network model. The principal objective of OBS/OPS is the provisioning of sub-wavelength switching granularity in the optical domain so that the wavelength resources could be used temporarily and shared between different connections. With respect to DWDM-based OCS networks, where wavelength resources are limited, this feature allows to increase the network scalability as well as its adaptability to the bursty characteristics of IP traffic.

In OBS/OPS, the data packets from the client networks are assembled into optical bursts/packets at the edge of the network and send towards their destination on wavelength channels. The bursts/packets are switched over the network by means of intermediate optical switching nodes and they remain in the optical domain all the way. In order to perform selective switching of arriving bursts/packets, the intermediate nodes have access to the control information that is generated and carried with the bursts/packets. The control information is separated from the user data either in time (OPS) or in space (OBS). A dynamic character of OBS/OPS requires fast switching elements. Thanks to the aggregation of a number of data packets into the burst in OBS, this requirement is slightly relaxed with respect to OPS. Indeed, in OPS the length of the optical packet is considered to correspond to the length of the electronic data packet.

In the perspective of network optimization the implementation of burst/packet switching techniques directly in the transport network will bring more statistical sharing of physical resources and will reduce the connection costs. Besides, there is no need for the energy-consuming electronic routers and expensive OEO conversion in the network.

Nowadays, the main challenge for OBS/OPS networks is the lack of low-cost all-optical processing devices. For this very reason, OBS/OPS is considered as a long-term solution for OTNs. Apart from technological difficulties, OBS/OPS needs a special treatment so that to solve problems typical of data-centric networks. The problem of routing with quality of service (QoS) guarantees [3] and the development of control plane protocols [4] are, among other things, key designing issues in OBS/OPS networks. Besides, for network planning and routing purposes, new modeling approaches are required to take into account the wavelength-continuity constraints in OBS networks. So far, models based on the Erlang B loss formula have been considered under rather ideal assumption of full-wavelength conversion capability in switching nodes [5]. For our recent, more complete surveys on the QoS and routing methods, the reader is referred to [6] and [7].

3) O-OFDM Networks: O-OFDM is identified as a promising solution due to its intrinsic characteristics of spectrum efficiency and scalability achieved by means of flexible bandwidth provisioning [8]. Due to the finer granularity of an OFDM-based network compared to a traditional WDM network just enough bandwidth can be allocated to a given traffic demand. In this context, O-OFDM enables a new network architecture, where any two nodes can be connected with the amount of bandwidth required, either providing a sub-wavelength service or super-channel connectivity.

O-OFDM is still at an early stage of development and its application in optical transport networks is unlikely in the near future. Besides technological challenges, new research problems arise in the network layer. Indeed, the flexible...
bandwidth allocation of O-OFDM-based networks introduces new constraints in network design [9]. In fact, since bandwidth allocation is not fixed but can vary, traditional RWA algorithms of WDM networks are not applicable anymore. As a consequence, a problem of Routing and Spectrum Allocation have to be addressed [9].

III. COVERGENT FIBER-WIRELESS (FiWi) NETWORKS

The integration of wired and wireless networks has recently gained considerable research interest. The Fiber-Wireless (FiWi) architectures [10] are very attractive since they combine the best attributes of both worlds. The optical networks offer almost limitless amount of bandwidth and wireless networks provide ubiquitous access and support for user mobility. Among promising scenarios of FiWi integration we can discern:

- Wireless-Optical Broadband Access Network (WOBAN) [11][12],
- Radio over Fibre (RoF) [13],
- Free-Space Optics (FSO) [14].

Below we address the first two scenarios. Both are dedicated for the deployment in access networks.

A. Wireless-Optical Broadband Access Network (WOBAN)

The idea behind WOBAN is to run fiber as far as possible from the telecom central office (CO) toward the end-user and then to provide wireless access. This concept is very attractive since in some situations it may be costly to connect the end user to the CO with the fiber and, at the same time, it may be impossible to provide wireless access from the CO because of limited spectrum. Consequently, the WOBAN network architecture consists of an optical backhaul, such as e.g., a passive optical network (PON), and wireless access in its front end (e.g., WiFi or WiMAX). The communication in the network is achieved by means of optical line terminals (OLT) and optical network units (ONU), in the backhaul part of the network, and wireless gateways and wireless routers, in the wireless part of the network. The wireless gateways serve as an interface with the backhaul network. The wireless routers provide end-user connectivity and may form a multi-hop wireless mesh network (WMN) that further increases the coverage of the network.

An interesting engineering design and optimization problem is how far the fiber should penetrate before wireless takes over [15]. Other challenges concern the problem of routing and network resilience [11].

B. Radio over Fibre (RoF)

RoF networks allow an optical link to transmit a modulated radio frequency (RF) signal, by these means, moving the processing functionalities to the Central Station (CS) and reducing the radio Access Point (AP) complexity. In some deployment scenarios, such as e.g. indoor picocellular access networks, hundreds of antennas need to be supported and the RoF approach can result in a simplified overall system design due to the aggregation of RF signal generation and network management at a central location [16].

As more applications spring up, overcrowding and interference at high end of the microwave region pushes operating frequencies toward millimeter-wave (mm-wave) band, such as 60 GHz. Higher frequency operation provides larger instantaneous bandwidth for greater transfer of information with reduced dimensions for antennas and other components. As a consequence, at the front end of the RoF network, mm-waves are potentially useful RF resources to cope with Gb/s data transmission [16]. It is worth noting that 60 GHz millimeter waves are highly attenuated in the air (approx. 10 dB/km) and, therefore, are useful only in the short distance communication. Thanks to the extremely low attenuation in fibres, below 0.2 dB/km around 1550 nm wavelength, the RoF transmission will extend significantly the reach and utility of mm-wave band systems.

A passive optical network (PON) is a short-term candidate for the optical back end of the RoF network. The wavelength division multiplexed PON (WDM-PON) is considered to be the next evolutionary solution which increases system capacity and scalability as well as it improves network security [17]. The introduction of wavelength routing capabilities [18] will allow the reconfgurable DWDM-RoF networks to accommodate a huge number of APs with a flexible allocation of resources according to trafic demands and the movement of nomadic users.

Among research topics related to RoF networks is the problem of the impairments in RoF transmission, which occur in an optical link in a mm-wave band, e.g. for 60 GHz carrier frequency [19]. From the network design perspective, an exemplary problem is the resource allocation problem in reconfgurable DWDM-RoF networks [20] under dynamic scenarios with mobile and temporally active users.

IV. NEW CHALLENGES IN OPTICAL NETWORKING

A. Physical Layer Impairment-Aware Network Design

Optical network architectures are evolving from traditional opaque networks, in which optical signal undergoes an OEO regeneration, toward all-optical (i.e., transparent) networks. The lack of practical all-optical regeneration gives rise to the so called semi-transparent network architectures, in which a set of sparsely but strategically placed OEO regenerators is used to maintain the acceptable level of signal quality.

In this context, the common problem in optical networks is the problem of Routing and Wavelength Assignment (RWA). So far, in the literature the assumption was that the optical layer is a perfect transmission medium and therefore all outcomes of a RWA algorithm are considered valid and feasible. The reality is that the actual performance of the system may be unacceptable for some RWAs due to the optical signal degradation, which is particularly harmful in high-rate and long-distance transmission systems. Indeed, as optical signals traverse the optical fiber links and also propagate through passive and/or active optical components, they encounter many impairments that affect the signal intensity level, as well as...
its temporal, spectral and polarization properties. For this reason the incorporation of physical layer impairments (PLI) in (semi-)transparent optical network planning and operations has recently received increasing attention from the research community [21].

The problems that still require effective solutions are the PLI-aware RWA (PLI-RWA) problem and the Regeneration Placement (RP) problem. Both PLI-RWA and RP are NP-complete problems [22][23], i.e., there is no algorithm known to solve them efficiently (in polynomial time). Most of the solutions proposed in the literature to address these problems employ analytical PLI estimation models and use heuristic algorithms. The few works that are based on network optimization methods make use of PLI models that estimate only static impairments, which do not involve actual network state information. A particularly challenging problem is the modelling of dynamic PLIs and their incorporation into efficient design methods.

Although the PLI-aware methods presented in the literature focus mainly on OCS networks, still there are issues specific to OBS/OPS, such as short connection holding times and the effect of optical signal dispersion on the transmission offset time, which require dedicated solutions. Some RP algorithms incorporating a static PLI model have been proposed in [24]. Similarly as in OCS, in OBS there is need for the development of computationally efficient and applicable for the optimization purposes the analytical models of dynamic PLIs.

B. Energy Efficiency and Awareness

One of the most important problems facing our civilization nowadays is the problem of increasing (exponentially) energy consumption and the associated problem of carbon dioxide emission. Consequently, many activities are carried out all around the world aiming both at the reduction of energy consumption and the replacement of existing energy sources with renewable ones. Among these activities, there are new initiatives, such as the Green Touch started by scientists of Alcatel-Lucent Bell Labs and the Green Communications initiated by ITU, which aim at the development of the energy efficient communication devices and networks.

New energy efficient technologies and techniques should aim at the reduction of energy consumption in the network but without negative impact on its performance. An important concept concerns the energy-awareness in the network and it characterizes a technology that adjusts its behaviour or performance according to the energy sources (either renewable or fossil) which supply the network and its components.

In the context of optical networking, it is expected that energy-efficiency and energy-awareness might be achieved through dedicated energy-driven design solutions and optimization schemes. [9]. One of the possible solutions is the reduction of the use of electronic routers in the network by keeping the traffic in the optical domain as far as possible. Indeed, optical devices are characterized by much smaller energy consumption per bit than electronic devices and, therefore, minimizing the number of potential IP hops can bring significant power savings. To this aim, the traffic might bypass intermediate IP routers by means of direct lightpath connections [25]. Also, putting underutilized network components in low-energy consumption modes and re-routing the traffic over already awaken devices might help to save power in the network [26].

V. Conclusions

The main purpose of this paper was to overview current trends in optical networking taking into account the emergence of new communication technologies and applications. In the next future, we should observe further development of the WR-OCS networks, however, new technologies, such as e.g. O-OFDM, sound very promising and they may attract research interests as well. The OBS/OPS technology is still immature and further advances in the development of inexpensive and functional devices is required. Among new challenges we can mention the development of integrated optical-wireless network technologies enabling ubiquitous access and high bandwidth available for end users. Another problem concerns network modelling and design methods incorporating, among others, the impact of physical layer impairments on the signal degradation, so that to support efficient network operation and provide quality guarantees. Last but not least is the issue of energy efficiency and awareness which requires dedicated technologies and techniques and which introduces new objectives and constraints on the optical network design problem.

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