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Review

Future Scenarios for Software-Defined Metro and Access Networks and Software-Defined Photonics

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Abstract: In recent years, architectures, devices, and components in telecommunication networks have been challenged by evolutionary and revolutionary factors which are drastically changing the traffic features. Most of these changes imply the need for major re-configurability and programmability not only in data-centers and core networks, but also in the metro-access segment. In a wide variety of contexts, this necessity has been addressed by the proposed introduction of the innovative paradigm of software-defined networks (SDNs). Several solutions inspired by the SDN model have been recently proposed also for metro and access networks, where the adoption of a new generation of software-defined reconfigurable integrated photonic devices is highly desirable. In this paper, we review the possible future application scenarios for software-defined metro and access networks and software-defined photonics (SDP), on the base of analytics, statistics, and surveys. This work describes the reasons underpinning the presented radical change of paradigm and summarizes the most significant solutions proposed in literature, with a specific emphasis to physical-layer reconfigurable networks and a focus on both architectures and devices.

Keywords: software-defined networking; SDN; metro-access networks; software-defined photonics

1. Introduction

"Prediction is very difficult, especially about the future." This sentence, commonly attributed to Niels Bohr, is very well suited to the telecommunication context of the next years which will experience a deep and rapid mutation due to the social, economic, and technological implications of Internet growth. One of the most probable forecasts is the starring role which will be played by the reconfigurable and programmable approach enabled by the SDN paradigm.

1.1. SDN Overview

The SDN model is based on the complete decoupling between the data plane, i.e., the part of the network deputy for traffic packet forwarding, and a centralized programmable control plane, in order to enable the abstraction of network resources to develop new applications and services [1]. The first definition of the SDN architecture has been provided by the Open Networking Forum (ONF), a group of network operators, service providers, and vendors. The ONF SDN architecture is constituted by three separated layers: the Infrastructure Layer, i.e., the network elements for packet switching and forwarding; the Control Layer, i.e., the network intelligence controlling the network elements; and the Application Layer, i.e., the apps for service provisioning. In the ONF version of SDN, the centralized controller uses an open interface—the OpenFlow protocol—to communicate with the network elements. Although the SDN field is quite recent, it is growing at a very fast pace. The original idea has gained a considerable interest across both academia and industry. According to the original definition, an SDN solution should be characterized by five fundamental characteristics: plane separation, simplified devices, centralized control, network automation and virtualization, and openness [2]. Nevertheless, a wide variety of proposals have been advanced in order to simplify the network management and enable innovation through network programmability. The main idea is to allow developers to manage network resources with the same flexibility as they already do with storage and computing resources [3].

It is worth noting that the idea of re-configurable and programmable networks has been around for many years: in 1995 the Open Signaling (OPENSIG) working group proposed open, programmable network interfaces and led to the specification of the General Switch Management Protocol (GSMP) by IETF. In the middle of the 1990s, the Active Networking Initiative proposed user-programmable switches and capsules, i.e., program fragments in user messages to configure routers. In the same period, the Devolved Control of ATM Networks (DCAN) project aimed to provide scalable control and management of ATM networks. In 2004, the 4D project advocated a clean slate design that emphasized separation between the routing decision logic and the protocols for network elements interaction. In 2006 the SANE/Ethane project recommended a centralized controller to manage policy and security in a network [3].

Nowadays, the major transformation introduced by the SDN in the communication industry is going to be enforced by the synergy with the adoption of another important trend, the Network Functions Virtualization (NFV). According to the NFV approach, the network elements become software applications, called virtual network functions (VNFs), dynamically instantiated by the network operator on a commodity-off-the-shelf (COTS) infrastructure. The combination of SDN/NFV technologies will enable the so-called 'network slicing', i.e., a dynamic composition of parallel elementary logic functions instantiated, like building blocks, by the network operator in order to provide or configure new or preexisting services [4]. Therefore, the 'softwarization' of the network resources will be an overall systemic transformation which is already steering the evolution not only of networks but also of future terminals and service platforms [5]. Then, among cloud computing architectures, the Network as a Service (NaaS) paradigm will take a great benefit by SDN deployment.

SDN allows the optimal use of existing links using traffic engineering and centralized, network-wide awareness of the network state. This implies an efficient use of network bandwidth and the possibility to respond immediately and with minimal service interruptions to changes in requirements related to customer needs, service contract upgrades and downgrades, or failures and network impairments. In other words, SDN will enable the dynamical changes of paths to higher-bandwidth and lower-latency paths and traffic prioritization [2]. Network services will be provisioned as easily as web services. As the operating systems of personal computers provide a programming abstraction of the underlying hardware, the future network operating systems (NOSs) will be developed to provide a centralized network abstraction of the underlying network elements with an intuitive interface and the perception of seemingly infinite network resources for the users [6].

1.2. SDN-Induced Market Place Evolution

It can be easily predicted that the revolution introduced by the SDN reconfigurable approach will have a strong impact on the business models of network operators and on the whole telecommunication ecosystem. On the other hand, the market place evolution will drive SDN technological development as well. For instance, since bandwidth demand is growing and providing more bandwidth is not free, the actual flat rate charging regimes, where revenues and usage of network resources are decoupled (the users buy a bundle of capacity and services and their use of the network does not affect how much they pay), will no longer be economically sustainable. Bandwidth on demand (BoD) business models will become a necessity for network operators. Furthermore, network operators will need to transform their production chain in order to be competitive with Google, Amazon, Facebook, and the other over-the-top (OTT) players which can deliver high flexibility, agility, and highest availability. Deutsche Telekom, for instance, will find its strategy also on SDN-inspired real-time network and service management to become a software-defined operator [7]. A new global capacity marketplace, where capacity can be bought and sold in near-real-time [6], can be envisioned. In this scenario, network operators, which are typically global in scope, will open their NOS interfaces to third parties (developers, smaller companies, etc.) in a logic of competitive collaboration. Therefore, in order to reduce time-to-market and to satisfy the predominant upfront demand, a new global social-economic order will born, where digital services will be offered globally and tailored and delivered locally [6].

1.3. Application of the SDN Model to Optical Networks

All the above considerations demonstrate the considerable changes that the SDN concept is introducing in the technical and economic outlook of telecommunications networks. Nevertheless, while the SDN concept has been adopted inside data centers in the past five years, the SDN implementations in the context of wide area networks (WANs) are still rare: the most notable ones are the two intercontinental backbone networks interconnecting Google's data centers, even if it can be argued that Google's backbone does not have the complexity of a public Internet network operator [8]. Anyway, a great research effort is being invested to develop solutions for optical networks based on the SDN paradigm and to standardize its application. The ONF has a working group dedicated to SDN applications for optical transport networks (OTNs): the fact that such networks transmit data over lightwave-based channels lends itself naturally to the SDN concept of a flow [2]. According to the ONF vision, transport SDN (T-SDN) extends OpenFlow to support Layer 0 and Layer 1 networks, allowing logically centralized control for some critical operations, administration, and maintenance (OAM) capabilities, i.e., provisioning, recovery, performance monitoring, and network inventory. Some of the T-SDN use cases considered by the ONF group include BoD services and photonic enterprise networks [9].

The above-described context depicts a really dynamic scenario where the SDN technology promises to dramatically simplify network management and enable innovation and evolution, also in the field of optical WANs. However, the SDN concept is still in an early stage of penetrating metro and access segments. In the next paragraphs, the possibility of extending SDN to optical metro and access networks is explored. Firstly, the main technical driving forces and the main recent proposals are analyzed and the evolution required for photonic components and devices is then examined. Finally, the architectural solutions for reconfigurable and programmable metro and access networks are reviewed.

2. Reasons for Software Defined Metro and Access Networks

In this work the term 'software-defined metro and access networks' refers to metro and access networks whose management is inspired to the principles of SDN, even if they are not fully compliant to the ONF standards and definitions. In our acceptation, software-defined metro and access networks have two main features, i.e., programmability and re-configurability (or flexibility). The programmability expected of software-defined metro and access networks fundamentally requires automation, abstraction of the underlying network resources, and intuitive high level service configuration. The re-configurability (or flexibility) of software-defined metro and access networks implies the capability of these networks to adapt dynamically to their operational situation in order to fulfill dynamical requirements of capacity, security, and quality of service with rapidity and efficiency. The main reasons for software-defined metro and access networks are sketched in Figure 1.

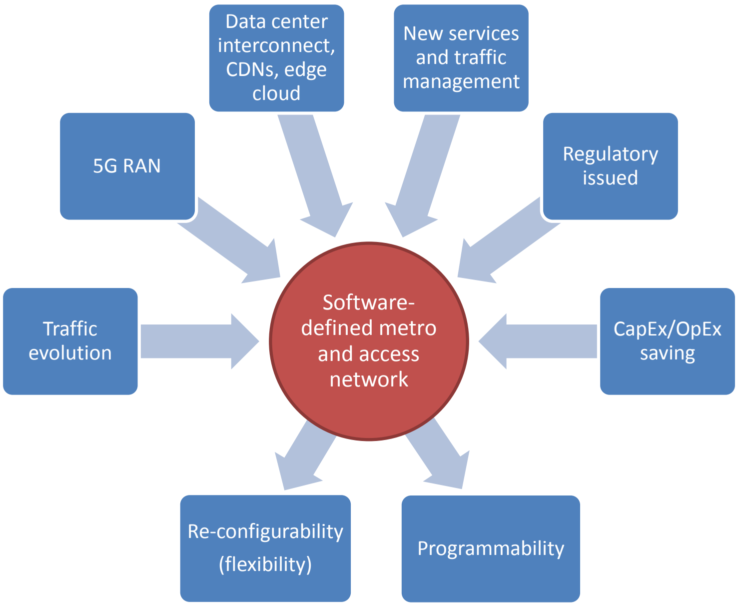

Figure 1. Main reasons for software-defined metro and access networks.

2.1. *Metro and Access Network Traffic Evolution*

In order to evaluate the need for reconfigurable and programmable metro and access networks, it is necessary to analyze how the traffic typologies and distribution are changing, especially in the edge network segments.

First of all, it is worth noting that the growth of bandwidth hungry services (e.g., ultra-high definition 4K video), made available by the optical access network deployed in recent years, is driving the explosion of traffic in the access segment according to the well-known Nielsen's law (high-end user's connection speed grows by 50% per year) [10]. For example, near-term pressures for capacity scaling include: 4G LTE-Advanced mobile networks that drive backhaul capacity from Mb/s to Gb/s and even 10-Gb/s channels; fixed access speeds moving from Mb/s to Gb/s with G.fast access networks and to 10-Gb/s and higher with time- and wavelength-division multiplexed passive optical networks (TWDM-PONs); data-center-interconnect demands moving to 10-Gb/s [11]. Figure 2 shows an increased forecast for 100 Gb/s or higher channels in the metro portion of the network [12].

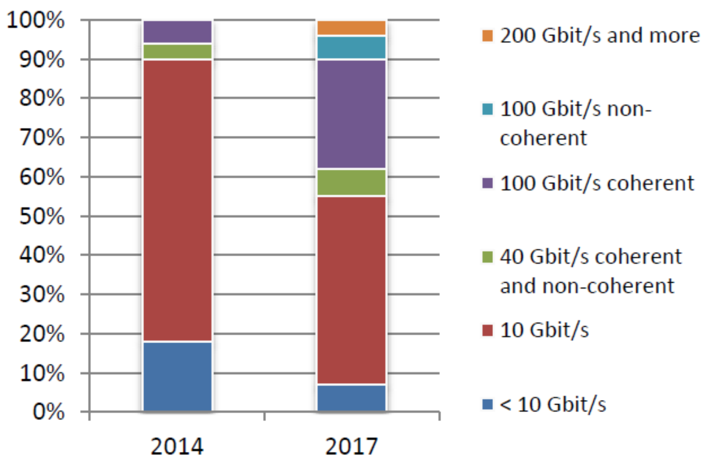

Figure 2. Evolution towards higher capacity channels in the metro network [12].

Simultaneously, in addition to traffic growth, the dramatic increase of new generation mobile networks and cloud-computing traffic is causing traffic patterns to become ever more dynamic and unpredictable [9]. The traffic related to cloud-based services is extremely time-varying. On the other hand, mobility traffic is highly volatile. Just to describe an exemplary scenario, the daily traffic pattern in a big city can be so considered: during the morning, an high traffic peak can be imagined in business quartiers and industrial areas; then, the 'traffic storm' would shift to commercial centers and free-time zones (public parks, sport facilities, etc.); in the evening, bandwidth demand would increase in residential areas. In addition to this, the emerging trend of Internet of Things (IoT) is changing where and how bandwidth is being consumed: on one hand, IoT is causing a significant change in the traffic characteristics with the proliferation of 'short-burst' type communications [6]; on the other hand, the number of connected devices will exponentially grow as the fully-digital connected homes will become an everyday reality.

To support this highly dynamic environment and to avoid congestion phenomena due to tremendous traffic growth, reconfigurable capabilities are required to metro and access optical networks according to different service requirements in terms of downstream and upstream bandwidth and latency [10]. Programmability is necessary as well to manage connectivity services in real-time through a high-level intent-based orchestration covering potentially multiple network domains.

2.2. 5G Radio Access Network

Another important reason for adoption of the SDN model in the metro and access segments is related to the development of the 5G radio access network (RAN). 5G is the next generation cellular system currently in an embryonic state. Its main requirements are an increased capacity (up to 600 Mb/s peak data rate), a reduced latency (optimized to 1 ms) and a higher connection density (~2000 active users per km^2) [13]. In addition to the growth of traffic which will be necessary to be carried by metro and access optical network, 5G RAN will have a deep impact on the architecture of the access segment itself, offering the opportunity to embrace SDN and NFV. In fact, the objectives of 5G can be achieved only by exploiting advanced radio access technologies (such as small cells, co-ordinated multi-point, massive multiple-input multiple-output, beamforming, and carrier aggregation), which will need to be supported by novel reconfigurable optical networks interconnecting the RAN nodes among themselves and with the core network [14].

Densifying macro cells and adding small cells will make topology and traffic distribution of the mobile backhaul (MBH) networks more complex. Dense wavelength-division multiplexing (DWDM) could be the candidate technology for future passive optical networks (PONs), since high-capacity point-to-point logical connections can be provided for backhaul links. Moreover, 5G is also expected to dramatically change the fronthaul network segment, i.e., a RAN where the remote radio unit (RRU), co-located with the antenna, is split from the base band unit (BBU) communicating with the RRU through the common packet radio interface (CPRI). Mobile fronthaul (MFH) networks could also take advantage from DWDM-PONs. A convergence of fronthaul and backhaul in a unified network segment will also be possible, referred to as Xhaul [14].

The centralization of the BBUs, called centralized-RAN (C-RAN), is considered one of the most relevant evolutional trends to support 5G solutions. The main advantage of C-RAN is the possibility of implementing coordination features among BBUs to mitigate radio interference, especially in small-cell deployments where user equipment (UE) is often within reach of a number of BBUs [15]. The control plane centralization promoted by the SDN paradigm will facilitate not only the required architectural agility needed in C-RAN solutions, but also the provision of fast re-configurability and high capacity on-demand for certain locations [16]. In an extreme implementation, C-RANs could evolve toward cloud based infrastructures (Cloud RANs) and Virtualized RANs (V-RANs), where BBUs can be activated in general purpose servers following the concept of NFV and network slicing [14]. Several possible solutions to implement software-defined metro and access network fulfilling 5G RAN requirements are described in the Section 5.3.

2.3. Data Centers Interconnect and Edge Cloud

Simultaneously with diffusion of broadband access services, the metro traffic is expected to grow in the coming years even at a faster and faster pace driven by IP video and cloud services. In other words, since client-server applications require ever more frequently access to distributed databases intercommunicating one to each other, the 'horizontal' (or east-west) traffic between servers is progressively increasing together with the traditional 'vertical' (or north-south) traffic between client and server. According to a Bell Labs study, data center traffic will have increased more than 440% from 2012 by 2017 and total metro traffic will have increased 560% during the same time period, i.e., about two times faster than the backbone traffic [17], as shown in Figure 3a. Moreover, according to Cisco forecasts, metro traffic will represent the 66% of total IP traffic by 2019 [18], as shown in Figure 3b.

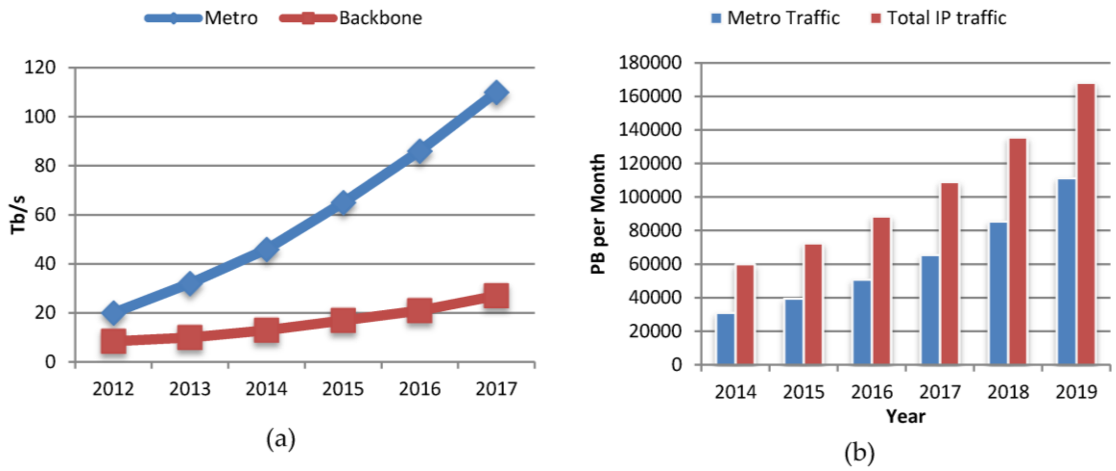

Figure 3. (**a**) Traffic growth in metro and backbone networks. (**b**) Metro and IP traffic growth.

It is also worth noting that, by 2017, 75% of total metro traffic will be terminated within the metro network [17]. This is also due to the increasingly significant role of content delivery networks (CDNs), i.e., distributed networks of proxy servers in data centers for caching content closer to the end user within the metro network. The diffusion of CDNs is contextualized in the so-called 'edge cloud' trend (i.e., small, highly-distributed data centers) which can be implemented by telecommunication operators through a strategy that will move the data center to the central office (CO), i.e., central office re-architected as a datacenter (CORD). The main goals of CORD strategy is to make the COs integral parts of the cloud strategies and to enable them to support new networking services. Other side goals are the optimization for east-west traffic and the commoditization of connectivity to the access network (in coherence with the SDN principles) [5]. The maximum distance between the edge cloud and the end users will be approximately 20 to 40 km according to latency requirements, possibly through a fully passive network without locally powered repeaters or amplifiers [6]. Moreover, processing of data in an edge cloud will be the key also to meet the new real-time latency requirements of the IoT [6].

All the technological trends described above will result in a traffic tremendous growth in metro networks which are already under pressure and will risk to become the bottleneck of the entire telecommunication system. In order to mitigate this risk, the adoption of innovative reconfigurable SDN-based converged metro-access networks will allow an optimization in traffic management to avoid congestion.

2.4. Benefits for Users and Regulatory Issues

Programmable access network will enable a large variety of control functionalities, such as traffic management (tunneling and virtual LAN), access nodes configuration, and diagnostics and troubleshooting. For example, dynamic spectrum management can minimize the interferences among very high-speed digital subscriber lines (VDSLs) in fiber to the cabinet (FTTC) architecture, with further improvements in addition to the benefits of vectoring techniques [19]. Different classes of service and end-to-end traffic engineering can be actuated in order to guarantee pre-determined round-trip delay for mission-critical applications requiring high interactivity [10].

Moreover, programmable capabilities in the access network can automate monitoring, fault, and performance management operations [19]. Programmable access networks and virtualized customer premised equipment (CPE) could empower customers for a profitable collaboration with their service providers for an improved quality of experience (QoE). For example, through a user-friendly application installed on the CPE, first the user can choose the services needed and configure their quality, secondly he/she can be informed of quality of service (QoS) in real-time and then can tune the quality in order to achieve a better adaptation to his/her expectations. In such a scenario, the user can control downstream and upstream bandwidth in real-time and prioritize traffic typologies for the different devices in the same LAN according to his/her needs [10].

Obviously, the adoption of SDN/NFV approach in metro and access network and the commercial proposals for users must be compliant to regulatory dictates which are evolving to follow technological development. The European Commission (EC), for instance, has performed a public consultation in 2015 [20] to study the potential impacts of SDN and NFV on access-services demand. Most of the subject involved in the consultation (52% of the answerers) agree that the on-going virtualization of network infrastructures will have an impact on the future demand for wholesale access products, but not in the short term (more than 10 years needed according to the 55% of the answerers), as shown in Figure 4.

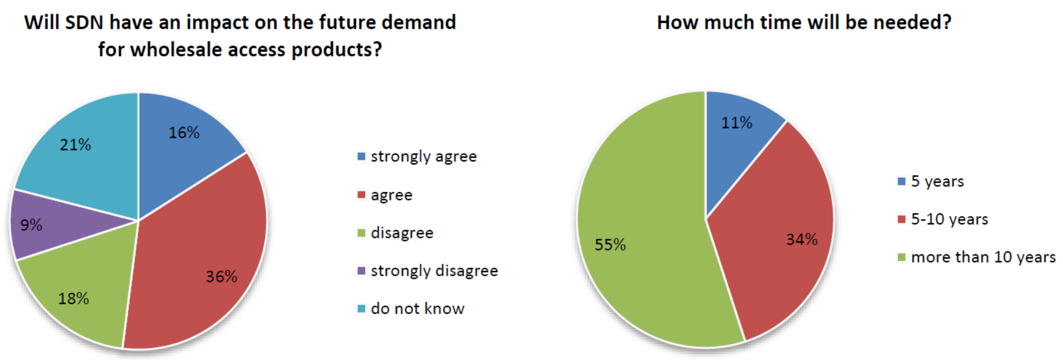

Figure 4. Results of the 2015 EC public consultation on SND/NFV impacts on access services.

It is possible that the adoption of the SDN paradigm in the access networks will contribute to a deregulation of wholesale service provisioning. In 2016, the Body of European Regulators for Electronic Communications (BEREC) has organized a public expert workshop on "Regulatory implications of SDN and NFV". In summary, the following highlights on fixed access networks emerged: SDN and NFV will probably provide alternative network operators with more control over the network of the incumbent; SDN and NFV will enable new type of services that may also be offered by new parties; it is too early to make definitive statements about the impact on access regulation [21]. Finally, according to a WIK-Consult forecast study on behalf of the EC, in the short term, SDN and NFV will give alternative network operators a higher degree of flexibility, but where these solutions can be a substitute for access to passive infrastructure is still uncertain [22].

2.5. Cost Savings

In order to be implemented, each technological solution needs to be economically attractive. In other words, the benefits introduced have to be compared with the cost of the technology needed to provide it. This is also true for telecommunication networks and, in particular, for metro and access networks, where network costs have to be amortized over a fewer number of users. Of course, deploying software-defined metro and access networks requires significant investments for the telecom industry which will generate a return in the following years thanks to the incomes allowed by benefits of re-configurability and programmability, as described in the previous paragraphs. In addition to this, the break-even point of these investments will be decreased by the cost reduction: the application of SDN offers significant reductions in capital expenditures (CapEx) and operational expenditures (OpEx), and minimizes a network total cost of ownership (TCO). It has been estimated that, for a high-scale tunable IP/optical network with 10× traffic growth over five years, the TCO savings will be approximately 70% per-unit capacity (e.g., per gigabit), where over 40% of the benefit arises from SDN automation and network optimization [6]. By analogy, TCO savings can be guessed for software-defined metro and access segments.

OpEx savings can be achieved since programmability enables efficient sharing of resources also in the metro and access segments. Re-configurability enables provisioning of resources on-the-fly, facilitating the dynamic service creation, and enhanced programmability can make such procedures even more efficient [15]. Also, CapEx savings can be achieved since an SDN-based approach allows the optimal use of existing network resources and scalability (the capacity allocated to a service can be scaled up or down easily). These features defer costly network upgrades and future investments.

3. Solutions for Software Defined Metro and Access Networks

In this paragraph a comprehensive survey about the most important solutions for SDN-based metro and access networks is provided. As sketched in Figure 5, the survey is organized into two main categories: proposals focused on higher-layer re-configurability and proposals focused on physical layer re-configurability. Some of the proposals described take their origin from the official SDN definition by ONF, other proposals aim to allow dynamic re-configurability and/or programmability, although they are not directly referred to the original SDN concept.

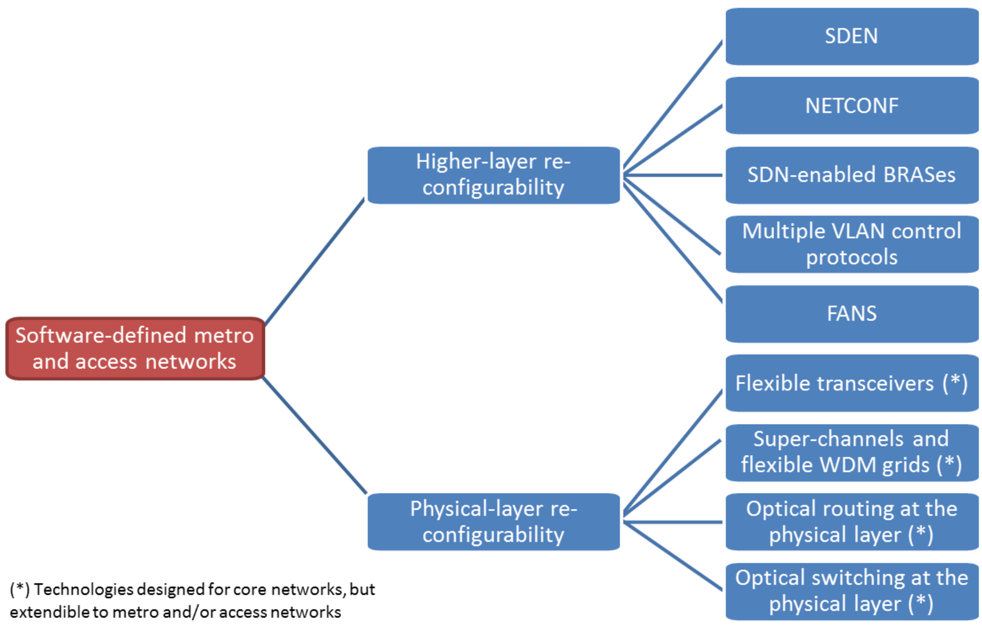

Figure 5. Main solutions for software-defined metro and access networks.

3.1. Higher Layer Re-Configurability

The first proposal to introduce the ONF SDN paradigm in the access segment, called software-defined edge network (SDEN), has been advanced by Parol and Pawlowski in 2013 and then developed by Amokrane et al. in 2014 [23]. The purpose of that work is to extend OpenFlow protocol to gigabit-capable PONs (GPONs) through two main features: the flow mapping at the GEM ports, i.e., the logical connection between optical network unit (ONU) and optical line terminal (OLT) in the GPON standard, each of them characterized by a specific class of service and a unique ID; the standard interface between the SDN controller and the OLTs through application program interfaces (APIs). In fact, the conventional PON management system allows manual configurations of the network by the administrator user, e.g., for the definition of the service profiles or the PON port attributes. SDEN approach, instead, allows real-time PON control by acting on SDEN agents, software modules placed on OLTs, through API [23].

A software defined access optical network (SDAON) architecture based on OpenFlow-enabled passive optical network has been proposed also by Yang et al. [24] in order to ensure remote unified control and service-aware flow scheduling. Their proposal can enhance the resource utilization and QoS guarantee and reduce the OpEx by remote interaction and operation.

Another method to allow programmability is to use the network configuration protocol (NETCONF), developed and standardized by the IETF in 2006. This protocol enables service orchestration for the IP layer through remote procedure calls and notifications to configure the network elements whose states, configurations, and parameter values are described through a data modeling language called YANG. NETCONF is gaining a growing industry acceptance and in the next years it is expected to enable end-to-end programmability through a description not only of network elements but also of links, adaptations, connections, communication paths, and bindings [6].

A recent proposal by Ruckert et al. [25] in order to flexibly support advanced services, is based on SDN-enabled home gateways and SDN-enabled broadband remote access servers (BRASes). In actual network architectures, the BRAS—also called the broadband network gateway (BNG)—is the single aggregation point which is connected to the home gateways through a metro network using a point-to-point protocol in order to establish a session. The innovative proposal consists in a network composed of SDN-enabled home gateways, BRASes and OpenFlow switches in the metro network, under the supervision of a centralized SDN controller which manipulates traffic flows according to the operator needs and policies and frees the BRAS from many of the typical functions, such as policy enforcement and traffic monitoring. This solution enables flexible and granular control over traffic flows throughout the network, with the ability to implement QoS and traffic policies right at the edge of the network, without requiring a single aggregation point for policy enforcement [25].

Specific SDN solutions for optical access networks have been recently proposed by Dai and Dai [26]. This work takes its origin from an approach similar to the one described by Ruckert et al. [25]: the control plane of the core network, based on multi-protocol label switching (MPLS), can be extended to the edge router—e.g., the BNG—using SDN concepts. In order to separate control and data planes inside the optical access networks, multiple virtual local area network (VLAN) control protocols are proposed to be used as the Ethernet control plane protocols in active optical networks. In this way, a centralized SDN controller can extend its control to both MPLS control plane for core optical networks and Ethernet control plane in optical access networks. The proposal is applicable also to PONs considering the passive network as a N + 1 ports distributed Ethernet switch: one port for OLT, N ports for ONUs [26]. On the other hand, Dai and Dai consider the proposal by Woesner and Fritzsche problematic for an OpenFlow controller to replace Dynamic Bandwidth Allocation (DBA) in GPON [27].

The idea of replacing DBA with a software-defined approach has been recently re-proposed by Li et al. [28] for Ethernet PON (EPON), i.e., the IEEE standard equivalent to GPON. Their proposal takes origin from the assumption that there is no single DBA algorithm able to fulfill different requirements, especially in the highly dynamic case described in the Section 2.1. While DBA algorithms are hard-coded in specific hardware, reprogrammable DBA module based on SDN can reduce traffic delay and increase throughput with better support to differentiated QoS [28].

Fixed access network sharing (FANS) is a re-configurable architectural approach, proposed by Cornaglia et al. [29] with the purpose of sharing access network resources between an infrastructure network provider (INP) and virtual network operators (VNOs), in order to allow fast and flexible service creation for the INP and better control and monitoring for the VNOs. According to this proposal, the physical access network is sliced into multiple virtual area networks. Two possible implementations of FANS have been presented: (i) a centralized management system, under the INP control, performing centralized functions and providing automated data from network elements to VNOs; (ii) a high-level abstraction layer based on an NFV which orchestrates virtual access nodes (vANs). Each vAN could manage interfaces belonging to different physical nodes by using a mapping between physical ports and virtual ports (INP port mapper).

3.2. Physical Layer Re-Configurability

In the last decade, a wide spectrum of proposals has been advanced to implement network re-configurability at the physical layer (or photonic layer). Most of them have been advanced firstly for core networks but can be applied to metro and access segments as well, provided that technologies for access and metro networks should have low cost and complexity. In fact, in recent years these technological solutions have been quite widely debated for the application in core networks but, in the opinion of the authors, they will be the enabling technologies for the application of the SDN principles at the physical layer in the metro and/or access segments as well. Therefore, we can currently define them as technologies designed for the core networks, but extendible to metro and/or access networks, even if this is still an open research area. Great advances are desirable in this field in order to design low power, high-speed, and small area footprint and compact solutions, which would be suitable for metro and/or access applications, which represent very cost-sensitive contexts. In addition to this, in most cases, these solutions have been already proposed for metro and/or access networks very recently, even if their concept is still in an embryonic stage and their application in these contexts is not yet commercially available or still very rare.

Four main trends can be outlined: flexible transceivers; flexible WDM grids and super-channels; optical routing at the physical layer; and optical switching at the physical layer [10]. In Table 1, these technological trends and solutions are outlined with reference to several recent proposals which will be detailed in the following paragraphs. The table explicitly reports whether the specific proposals refer to the metro segment or to the access segment.

Table 1. Technologies designed for the core networks and extendible to metro and/or access networks.

Technological Trends	Technological Solutions	References for Application in Metro/Access Segments
Flexible transceivers	Flexible modulations and distance-adaptive transceivers	Metro: [30]
		Access: [31–33]
Super-channels and flexible WDM grids	Flexible grid	Access: [34,35]
		Metro: [30,35]
	Spatial super-channels	Access: [36]
Optical routing at the physical layer	Flow routing	Access: [37–39]
	ROADM	Metro: [40–47]
		Access: [41]
Optical switching at the physical layer	OPS, OLS, OBS	Metro: [48–51]
		Access: [49,52]
	Flexible modulations and distance-adaptive transceivers	Metro: [30]
		Access: [31–33]

All these trends and solutions would enable re-configurability and programmability in metro and access segments, allowing these networks to address the challenges raised in the Section 2.

In this paragraph, only the trends are described, since several examples of their building blocks are reviewed in the next paragraph.

3.2.1. Flexible Transceivers

In this context, flexible transceivers are reconfigurable transmitters and receivers installed on OLTs and ONUs. Their parameters should be varied in real-time: bitrate, launch power, modulation format and order, coding technique, optical carrier wavelength, forward error correction (FEC) payload ratio, multiplexing scheme, and number of subcarriers [10]. In order to realize flexible transceivers, it is necessary to work on laser sources, external optical modulators, driver electronic circuits, and digital signal processing (DSP) techniques.

Flexible transceivers, also called software-defined transceivers (SDTs), offer flexibility, increased resilience to channel impairments, and an upgrade path for future transmission systems, as they allow data rate adaptation and channel bandwidths allocation on the fly. Being more mature in recent years, they are now going to be used in long-haul optical communications but they are expected to have great importance also in future re-configurable access networks [53].

Vacondio et al. [31] have demonstrated that software-defined coherent transponders, which digitally processes the burst transmissions according to the distance of a user from the OLT, can double the average transmission capacity per user.

Choi et al. [54] have developed flexible bandwidth variable transceivers (BVTs). The transmitters are composed by a tunable laser diode and a combination of dual-drive Mach-Zehnder modulator (MZM) and dual-parallel MZM with electrical binary drive signals and a polarization-division-multiplexing (PDM) synthesizer. They are capable of dynamically changing the symbol rate and the modulation format among binary phase-shift-keying (BPSK), quadrature phase-shift-keying (QPSK), 8-ary quadrature amplitude modulation (8QAM), and 16-ary quadrature amplitude modulation (16QAM). The receivers are based on a coherent detection scheme dual-polarization 90° optical hybrid followed by four balanced photodetectors (BPDs) and analog-to-digital converters (ADCs). They are capable not only of detecting the optical signal with any modulation format/rate, but also to send the bit error ratio (BER) information to an OpenFlow controller to automatically change the network parameters.

Several DSP-enabled flexible transceivers for optical access network have been proposed by Zhou et al. [32] in synergy with OLT side access network resource virtualization and software-defined programmable network functions and resource scheduling. One of them uses QPSK, 16QAM, 32QAM, or 64QAM modulations for achieving different optical power budgets of 36, 32, 30, or 28 dB, respectively [32].

Iiyama et al. [55] have proposed and demonstrated BVTs for PONs. If compared to the previous proposal by Choi et al. and Zhou et al., the approach is obviously simpler: the available modulation schemes are only on-off keying (OOK) and quadrature amplitude modulation (QAM), which are simultaneously sent from the OLT and filtered by the ONUs.

A recent detailed analysis about the feasibility of elastic transceivers in optical metro rings also in terms of spectrum occupation has been carried on by Rottondi et al. [33]. In particular, the impact of grid flexibility and of the usage of distance-adaptive modulation techniques is analyzed and significant gains in terms of spectral occupation and number of transceivers have been demonstrated.

Other proposals aim to obtain increased flexibility by replacing single-carrier with multi-carrier multiplexing schemes, e.g., orthogonal frequency division multiplexing (OFDM) and Nyquist frequency division multiplexing (NFDM), where optical sub-carriers can be dynamically allocated and eventually grouped together in super-channels [53–56].

3.2.2. Super-Channels and Flexible WDM Grids

Super-channels can be defined as a group of separated signals which are digitally combined to create an aggregate channel of a higher data rate. This approach is originated from the need of overcoming the limitation of DSP techniques in the elaboration of higher-order modulation schemes, which become increasingly sophisticated in order to maximize the total throughput of the optical transport system. Two main categories of super-channels have been proposed: spatial super-channels and spectral super-channels (sketched in Figure 6a). Spatial super-channels are a form of space-division multiplexing (SDM), since multiple spatial paths are used in parallel. They could be distinct light paths belonging to multiple parallel physical fibers, multi-core fibers, or different optical modes inside a multimode fiber. Spectral super-channels use multiple parallel sub-carriers (at different frequencies or wavelengths) with lower-order modulation to achieve a more efficient use of the spectrum [6].

The elastic combination of sub-carriers allows major flexibility in the spectrum management and enables flexible WDM grids (flex-grid), which are already available for core network applications. The advantages are well known and sketched in Figure 6b: if wavelength spacing among optical WDM carriers is not strictly anchored to a fixed grid (e.g., conventional 50 GHz or 100 GHz DWDM grid), the available spectrum for each carrier can be managed dynamically by allocating a minimum required bandwidth. Therefore, spectral efficiency can be optimized and, indirectly, energy efficiency can be enhanced as well; as a consequence, OpEx saving can be pursued. Naturally, the nonlinear dynamics of various high bit-rate super-channel configurations have to be accurately investigated when upgrading the current static network structure to a flex-grid network [57].

While spatial super-channels cannot be considered a viable solution for metro and access networks in the short term (even if some proposals for SDM in the access segment have already been presented [36]), spectral super-channels can be considered a more realistic possibility. In fact, since WDM techniques are expected to be extended also in the domain of access networks (WDM-PONs have been widely proposed in recent years), it can be envisioned that flexible WDM grids will be applied in the edge segment in order to adapt link capacity to the user needs [10] even if, to the best of our knowledge, specific applications of spectral super-channels in metro and access networks have not yet been proposed.

On the other hand, the application of flex-grid in optical ring metro networks, in combination with distance-adaptive optical coherent transceivers, have been discussed and analyzed by Rottondi et al. [30], with a detailed formalization of the routing, modulation level, and spectrum assignment (RMLSA) optimization problem. In the access segment, an optical network paradigm achieving low latency, high throughput, and energy efficiency, based also on the concepts of software defined networks and a flexible grid, has been proposed by Forzati and Gavler [34].

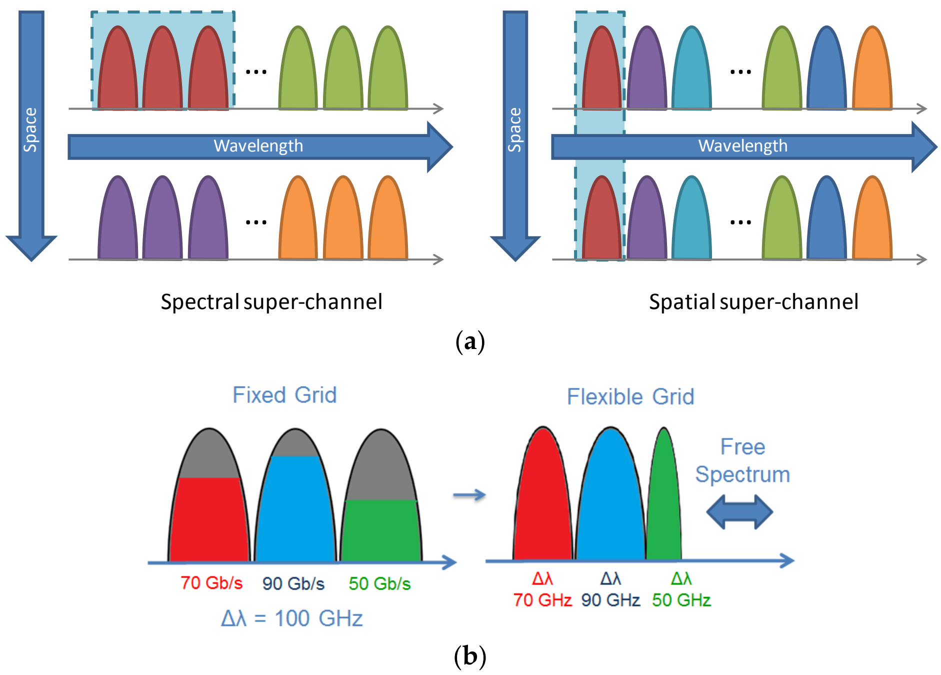

Figure 6. (**a**) Comparison of spatial and spectral super-channels. (**b**) Schematic representation of the advantages of flexible grids in terms of spectral efficiency.

Oliveira et al. [58] have proposed the use of flexible grids in a reconfigurable flexible optical network (RFON) and have demonstrated that concept on a test-bed constituted by four nodes equipped with wavelength selective switches (WSSs), optical amplifiers, and a system for supervision and monitoring of optical channels. Cvjectic et al. [35] have proposed the use of flexible grids in an access network based on OpenFlow protocol.

3.2.3. Optical Routing at the Physical Layer

The evolutionary traffic trends described in the Section 2.1 will drive greater need to route wavelengths optically between service endpoints in the metro and access segments, too. Efficiency, cost-effectiveness, scalability, and re-configurability will be the key requirements for wavelength routers: on-the-fly wavelength add-drop capacity and addition of more 'degrees', i.e., fiber directions, should be enabled by new types of equipment [11]. A recent survey of network providers indicates that the highest-ranking technologies required for metro networks are lower-cost 100 Gbit/s hardware (identical to long-haul form factor, but with reduced performance), pluggable C form-factor pluggable (CFP)-based 100 Gbit/s coherent module, flexible grid, and reconfigurable optical add-drop multiplexers (ROADMs), flexible coherent operation [12], as shown in Figure 7.

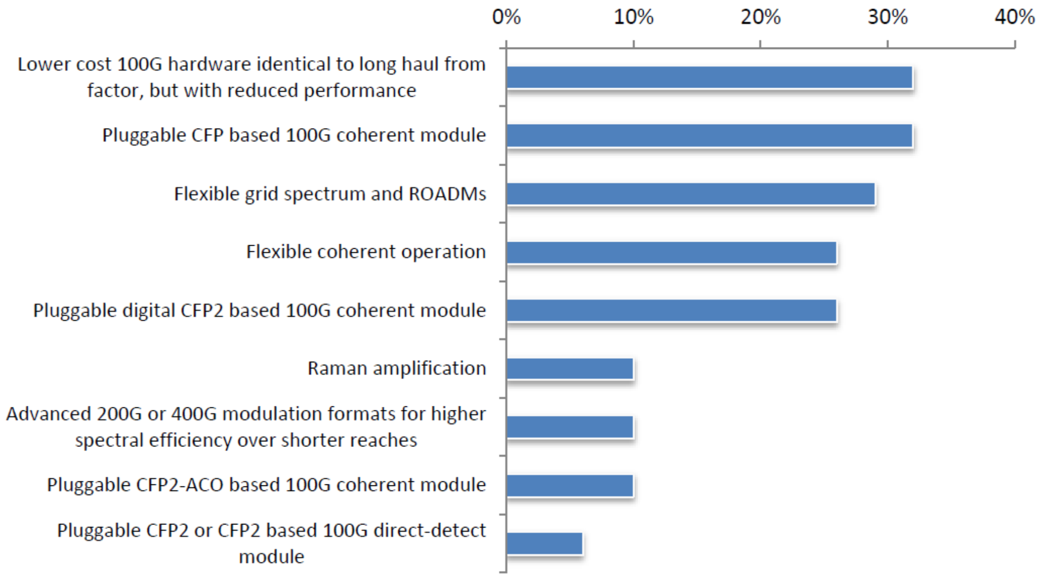

Figure 7. Results of the Infonetics survey about technologies required for metro networks [12].

In the past, the routing and wavelength assignment (RWA) problems has been widely investigated from both theoretical and practical points of view. The problem can be stated as follows: given the physical network structure and the required optical channels connections, the suitable path and wavelength have to be selected among the many possible choices for each connection, so that two paths sharing a link are not assigned the same wavelength. The RWA is an NP-complete problem that is usually divided to the more manageable routing and wavelength assignment sub-problems. For the routing sub-problem, three main approaches are known: fixed routing, adaptive routing, and semi-adaptive routing [59]. Efficient algorithms and protocols have been proposed with reference to complex mesh topologies. Since metro and access networks have simpler architectures, less complex solutions are expected to be proposed and developed to solve the RWA problem in the edge network segments.

Wavelength routing has been proposed not only for traffic routing among metro nodes, but also inside the access segment. Yin et al. [37] have proposed and demonstrated the Stanford Ultraflow access network, providing Intra-PON flow transmission with an optical software-defined reroute by using a quasi-passive reconfigurable (QPAR) node. Ultraflow architecture enables dual-mode service, conventional IP and Flow, and is based on the following devices: conventional GPON OLT and optical flow line terminal (OFLT) located at the central office (CO); conventional ONU and optical flow network units (OFNUs) located at the end-user premises; QPAR and coexistence elements (CEs) located at the remote node. Each CE is designed to combine/separate IP traffic (between OLT and ONUs) and Flow traffic (between OFLT and OFNUs). Flow routing is performed by the QPAR node and the Flow control plane, supported by the IP network, is completely decoupled from its data plane [37,38].

3.2.4. Optical Switching at the Physical Layer

Wavelength routing described in the previous paragraph is just one of the possibilities to implement optical switching at the physical layer, namely optical channel switching (OCS). OCS and other more sophisticated optical switching technologies are summarized in Figure 8, i.e., optical burst switching (OBS), optical label switching (OLS), and optical packet switching (OPS). These techniques allow the network adaptability in a most granular way to traffic variations, since they facilitate statistical multiplexing to efficiently share wavelength channels among multiple users [10].

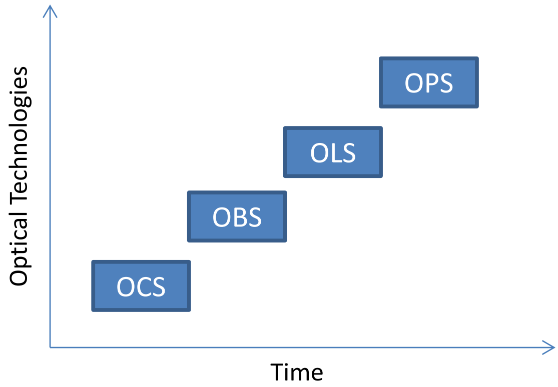

Figure 8. Optical switching technologies sorted by complexity/performance and hypothetical phases of implementation.

Optical switching techniques are receiving greater attention in recent years as a possible alternative to conventional IP-based electrical packet switching (EPS), which has been an efficient solution for relatively low-speed, bursty traffic (less than 1 Gbit/s). Emerging services, such as video streaming or large file transfer, require increased data rates, low packet latency, energy efficiency, and low switching overhead. For these applications, OCS could be the optimal solution since it enables end-to-end optical communication over dedicated lightpaths. Nevertheless, the heterogeneity and burst of the traffic, according to the scenario described in the Section 2.1, requires major flexibility [37].

The ideal approach to conjugate both needs would be to replicate the packet-switching operated by conventional EPS entirely in the optical domain, which is the aim of OPS. OPS would allow the application of the IP over WDM (IPoWDM) concept, considered the 'holy grail' of optical communications. IPoWDM would reduce OpEx by simplifying the protocol stack, since the IP packets would be switched and routed over the all-optical WDM network without excessive electronic processing in the data plane. OPS systems can be categorized in a number of ways: synchronous versus asynchronous packet switching, fixed-length versus variable-length packet switching, and store-and-forward versus cut-through packet switching [60]. The header control can be in-band, where both header and payload are carried via the same wavelength, or out-of-band, where control headers are carried via a dedicated control wavelength. There are three basic in-band header control techniques: subcarrier multiplexed, orthogonal modulation, and time-domain multiplexing [48].

Since actual technologies do not allow the complete actuation of OPS, a more practical approach is represented by OLS, where only the header (or label) is approached in the electrical domain.

An even simpler solution is OBS, where large aggregated packets with the same destination and the same QoS, i.e., bursts, are routed by processing out-of-band control signals in the electrical domain. OBS networks initially emerged as very fast reconfigurable OCS networks and are based on a complete separation of control plane and data plane. In the control plane, burst header packets (BHPs) are read using electronic processing and control the switching fabric; in the data plane, burst data packets (BDPs) are switched all-optically, as shown in Figure 9. Burst assembly and disassembly operations are performed in the edge routers, ingress, and egress respectively. OBS uses two typologies of signaling protocols for burst management by optical routers. In two-way reservation protocols, also called tell-and-wait (TAW) protocols, an acknowledgment is required from the receiving node before the burst transmission, e.g., wavelength routing (WR) protocols. In one-way protocol signaling, also called tell-and-go (TAG) protocols, no acknowledgment is required and therefore latency is reduced, e.g., just-in-time (JIT) and just-enough-time (JET) protocols. In the JET protocol, a BHP is sent on the control channel shortly before the burst transmission begins, specifying the destination of the burst and the channel on which the burst is being transmitted [60]. The offset time between BHP and BDP allows the router to be buffer-less, avoiding optical memories, such as fiber delay lines, contrarily required by OPS [52]. Moreover, while OPS requires fast switching speed (approximately in nanoseconds), OBS can be realized even with simple nodes with millisecond to microsecond switching speeds. Optical flow switching (OFS) can be considered a subcategory of OBS, where end-to-end flows are established and bursts are longer by at least hundreds of milliseconds.

All these techniques will allow to process packets, bursts, or flows on-the-fly in the framework of future photonic routers or nodes, even in the access and metro networks.

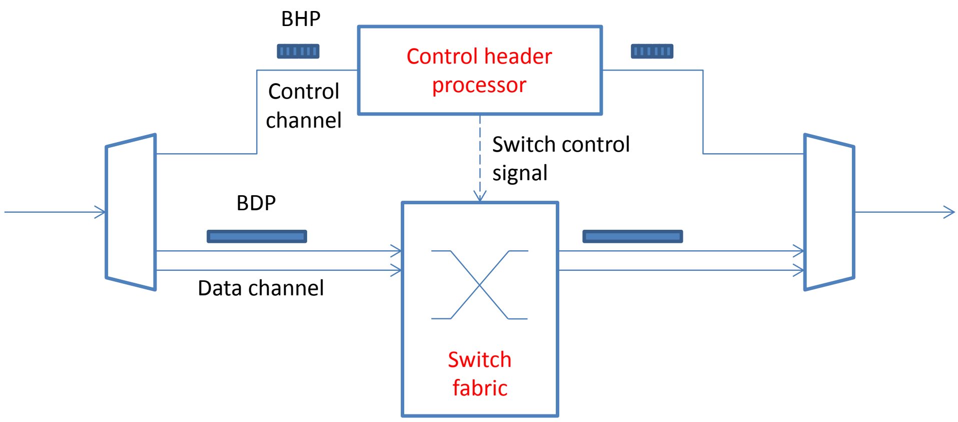

Figure 9. Schematic representation of an OBS router.

4. Photonic Devices and Components

The terms 'software defined photonics' (SDP) and 'software defined optics' (SDO) have been borrowed by the wireless field where the term 'software defined radio' (SDR) is used. In the SDR context, radio resources are programmable by software. Similarly, in the SDP and SDO context, advanced photonic subsystems are versatile enough in order to enable reconfigurations of key parameters or features by software [10]. According to the definition by Rouskas et al. [61], SDO includes not only programmable but also intelligent and self-aware optical layer devices, i.e., they can sense or measure their own characteristics and performance. In addition to software-defined devices, the next generation software-defined metro and access networks will require low-power or energetically autonomous devices. A focus on these features is provided in the next paragraphs.

4.1. Technological Platforms

Actually, the majority of the commercial telecommunication devices are hybrid integrated components based on silicon substrates and monolithically integrated devices. The choice of the technological platform for SDP will be a crucial decision, since the approaches used today for long-haul networks and data centers could not be viable or convenient in the metro and access segment. In this field, a challenging trade-off between two main requirements will be necessary: a higher density of integration, in order to reduce the size of devices, and a simpler fabrication process, since an higher production volume at a lower cost will be required. Especially at the access network level, where equipment is shared by fewer users, cost is the major issue and the evolution of photonic integrated circuits (PICs) will be essential.

Silicon photonics is universally considered a promising technology for telecommunication devices [62]. In particular, silicon-on-insulator (SOI) technology is suitable for commercial applications for two main order of reasons. SOI technology is fully compatible with conventional microelectronic fabrication processes which have been consolidated for decades to produce complementary metal-oxide semiconductor (CMOS) circuits [63]. This takes advantage in terms of cost (no complex new fabrication techniques are needed) and integration of photonic and electronic components onto the same substrate. Moreover, SOI technology is extremely versatile, since waveguides, photo-detectors, and modulators have already been demonstrated [62]. Although silicon is an indirect band gap semiconductor, even optical sources can be realized in a hybrid approach by exploiting the Raman effect to amplify the radiation generated by an external laser [64].

In order to realize SDP devices, mechanisms for tunability need to be provided. Silicon photonics can exploit several physical effects to achieve this goal, such as thermo-optical effects [65,66] and plasma-dispersion effects. Non-linear effects can be also exploited, such as stimulated Raman scattering, the Kerr effect, and two-photon absorption (TPA) inducing free-carrier absorption (FCA) [67]. Newly developed materials, such as passive polymer technology, have been also proposed in order to exploit the advantages of the simple low temperature fabrication processes, ease of integration, and low power consumption for thermally actuated optical elements [56].

4.2. Technologies for ROADMs

Remotely reconfiguring ROADMs can be considered one of the basic building blocks to support advanced functionalities in the optical channel layer.

ROADMs are already used in core networks: they can be considered key elements for the development of backbone transport networks [68]. For instance, since 2011 multi-degree ROADM are used for remote switch and rerouting in the Telecom Italia Kaλeidon network, a wholly photonic mesh network capable of transporting 80 channels at 40 Gbit/s (scalable to 100 Gbit/s) with photonic protection and restoration [69]. ROADMs are conventionally based on micro electro-mechanical systems (MEMS) and liquid crystal on silicon (LCoS) technologies. MEMS-based ROADMs use optical gratings to separate wavelengths and micro-mirrors arrays fabricated on a silicon substrate to reflect each spectral component [70].

In the last decade, a new trend has been outlined by market analysts: the so-called "new ROADM revolution from the core to the edge" [43,44]. The ROADM application in metro networks is particularly valuable because DWDM networks are increasingly deployed more extensively in this segment and ROADMs would add the flexibility in software to add/drop wavelengths for information access or to reroute carriers [40]. In other words, ROADMs can help carriers overcome the strict limitations of conventional metro DWDM networks with fixed OADMs. In addition, a migration to metro mesh architectures is a secondary driver for ROADM architectures [45]. Mesh networks make it easier to manage and direct higher volumes of traffic since they allow continuous reconfiguration around blocked paths or by allocating more bandwidth on a fiber as required [46]. Both the drives, i.e., flexibility and mesh networking, are particularly meaningful in an SDN perspective (even if they are not necessarily directly referred to the original SDN concept) since they enable re-configurability and programmability for a more efficient traffic management.

Two general types of ROADMs can be used in metro networks: two-degree ROADMs are used for add/drop functionalities related to local access traffic; multi-degree ROADMs are used for interconnecting DWDM rings or for mesh networking [41]. In recent years, ROADM vendors have made great strides and nowadays are already able to take the ROADMs closer to end users with high-bandwidth applications [42].

Although technologically mature, both MEMS and LCoS technologies are not scalable enough to be applied to metro and access networks where cost, volumes, power consumption, and reliability are extremely significant features [10]. Alternative solutions have been proposed in recent years, such as ROADM based on micro-ring resonators (MRRs) realized on SOI technological platform.

Klein et al. [71] have demonstrated thermally a tunable MRR-based ROADM for access networks. These devices have been fabricated in Si_3N_4/SiO_2 technology with a footprint of less than 2 mm^2 and they are capable of operating in the second or third telecom window.

Four main features are considered necessary for new generation ROADMs in order to rapidly respond to new service innovations made possible by SDN. In legacy architectures, each add/drop port is restricted to be used to transmit/receive only a specific wavelength channel to/from a given output/input fiber, i.e., a specific direction. Recent ROADM architectures should relax this restriction by allowing a single add/drop port to accept any wavelength channel, i.e., the colorless feature, and/or to bridge the signal to/from any direction, i.e., the directionless feature. The usefulness of a third feature, called contention-less, is still the subject of discussion. Contention occurs in case the same wavelength channel is to be used in two or more add/drop ports of the same add/drop structure. Contention-less means that wavelengths can be more easily reused multiple times without any manual configuration. The capability of routing wavelengths belonging to a flexible grid wavelength is called the grid-less feature [10]. Colorless, directionless, contention-less, and grid-less (CDC/G) ROADMs offer significant reductions in the network TCO. Since CDC/G nodes route wavelength in the photonic domain, rather than electrically, OpEx can be 35% lower than with conventional alternatives. Thanks to photonic operations, CDC/G ROADMs are more power efficient (about 30%–40% less power needed) and introduce less wavelength service latency. Moreover, CDC/G ROADMs offer major scalability, since they are capacity independent, and have major agility to adjust wavelengths to recover capacity. It has been estimated that this technique can allow the recovery of 30% of network capacity, and thus a 30% CapEx savings, through deferring expensive network upgrades [11].

Nowadays, CDC/G ROADMs are a solution designed exclusively for core networks but, in the opinion of the authors, some of their features could be implemented also in the next generation of metro networks. Sub-optimal solutions are already ordinarily used in metro networks, such as tunable optical add drop multiplexers (TOADMs) which employ tunable filters to select and add/drop a channel or band without the need for demultiplexing and multiplexing [47]. Metro ROADMs (especially CDC/G) are not a cheap solution, but over the long-term, they could represent the most reliable, robust, and cost effective option to reduce OpEx, increase network reliability, and manage more traffic [46].

4.3. Technologies for Optical Processing

In the Section 3.2.4, optical switching was presented with efficient techniques to switch optical signals in a re-configurable network. Optical switches can thus be ascribed to the category of SDP devices, since their switching table (implemented in the switch fabric) can be considered a key feature re-configurable by software, i.e., through the header information. Several solutions have been proposed in order to implement header (or label) processing wholly in the optical domain.

In particular, nonlinear optical (NLO) transfer functions of optical components can be exploited for signal processing. Optical logic gates have been proposed: ultrafast nonlinear interferometers (UNIs) can be used to realize a high-speed logic processor, as well as cascaded semiconductor optical amplifier-Mach-Zehnder interferometers (SOA-MZIs) can be used to construct an optical XOR logic gate useful for header detection and processing [72]. Moreover, SOA-MZI can be used as a building block to implement other subsystems, such as wavelength converters, label/payload separation, clock-recovery circuits, or optical flip–flops [73]. All-optical subsystems based on SOA-MZIs capable of performing on-the-fly packet clock recovery, 3R regeneration, label/payload separation, and packet routing have been reported by Kehayas et al. [74].

A different approach for label pattern recognition is using optical code-division-multiple-access (O-CDMA) techniques to code the header. If such a coding is used, correlation techniques based on fiber Bragg gratings (FBGs) can be used to perform label detection [72].

Hu et al. [75] have proposed an innovative packet switching mechanism for OPS and OBS, based on cross-phase modulation (XPM) in a silicon nanowire fabricated in SOI technological platform. When the OOK control signal at the wavelength λ_C is 'on', the packet at the wavelength λ_D is switched out at the wavelength $\lambda_C + \Delta\lambda$, as sketched in Figure 10a. If different wavelengths $(\lambda_{C1}, \lambda_{C2}, \ldots \lambda_{CN})$ are used as control signals, the incoming packet can be switched out at different wavelengths $(\lambda_{C1} + \Delta\lambda, \lambda_{C2} + \Delta\lambda, \ldots \lambda_{CN} + \Delta\lambda)$ to different outputs, as sketched in Figure 10b.

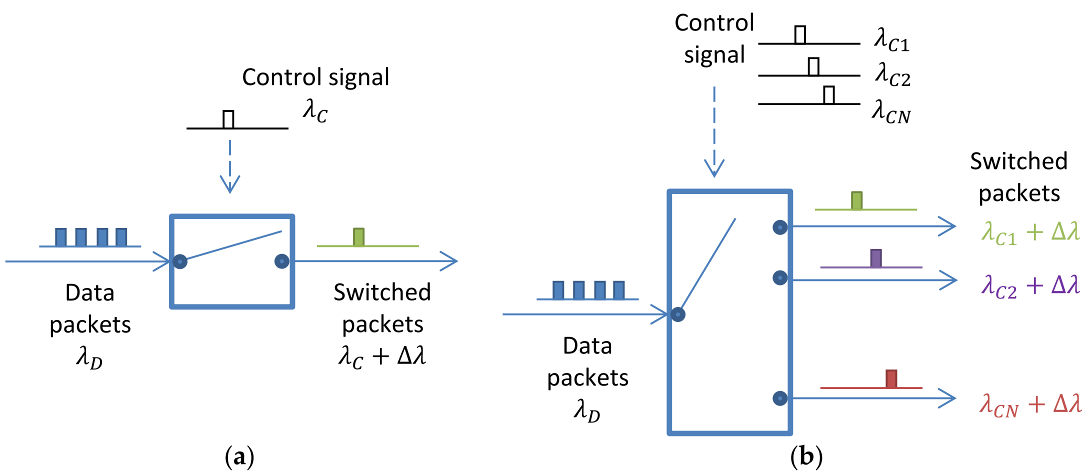

Figure 10. Schematic representation of the packet switching technique proposed by Hu et al. [75]: (**a**) one control wavelength; (**b**) different control wavelengths.

4.4. Technologies for Energy Harvesting

In the metro and access segments, the software-defined nodes providing physical-layer re-configurability to the network are expected to be placed also in street environments and not only in COs, since most of the operators have plans to consolidate the number of COs in order to reduce real estate costs [76]. This means that the provisioning of power supply will become an increasingly critical issue, given the major complexity of a field-installed supply. This reason, added to the obvious necessity to reduce the power consumption to achieve OpEx saving, underpins the research for energy harvesting/scavenging mechanisms. In fact, one of the main roadblocks that could prevent the introduction of flexible optical networking technology in the access segments is to retain a fully passive outside fiber plant [39].

In some of the metro-access topologies which will be introduced in the Section 5.2, erbium doped fiber amplifiers (EDFAs), remotely pumped from the CO, are used in the remote nodes (RNs) to compensate both fiber attenuation and insertion losses. On one hand, this configuration avoids local power supply provisioning but, on the other hand, the total amount of pump power demanded for the CO is an important limitation of the network.

Baptista et al. [77] have proposed an improved energetically-efficient RN able to select a different EDFA optimized to the necessary gain, thus reducing the total amount of pump power. Moreover, in particular conditions, the pump extra-power is used to convert to electrical power by a special harvesting device and stored electrically in order to be used to control the switches, thus keeping the network fully passive.

Shrenk et al. [39] have demonstrated a fully-passive yet reconfigurable optical cross-connect (FOX), i.e., a special ROADM for metro-access networks, based on micro-opto-electro-mechanical system (MOEMS) technology, which is fed through energy scavenging at the optical network layer through a photovoltaic PIN diode.

5. Architectures

Network re-configurability at the physical layer is treated in this paragraph from an architectural point of view. Firstly, the necessity for all-optical operations is described. Then, several proposals for metro-access and fixed-mobile network convergence are briefly reviewed.

5.1. All-Optical Operations

In a whole optical network, the greatest part of operative costs is related to optical transponders, i.e., tunable lasers and photo-receivers. For example, in the Italian network, their cost is about 60%–70% of the whole network cost [70]. In order to reduce costs, the number of transponders (so, the number of optical-electro-optical (O-E-O) conversions) has to be reduced. Reducing the power consumption is a critical issue not only for cost reduction but also for a greener environment. It has been estimated that, in 2007, 37% of the total carbon emissions of the whole ICT industry was due to the network infrastructure and devices. By 2020, ICT is expected to account for around 2% of the global carbon emissions [78]. In 2007, metro and access networks consumed the 60% of the total power amount used in the entire telecommunication network [79]. In 2013, the total contribution to energy consumption due to legacy fixed access, fiber-to-the-X (FTTx) new generation access, aggregation, and transmission networks, is about 40% of the total energy consumption in the telecommunication system [78], as shown in Figure 11.

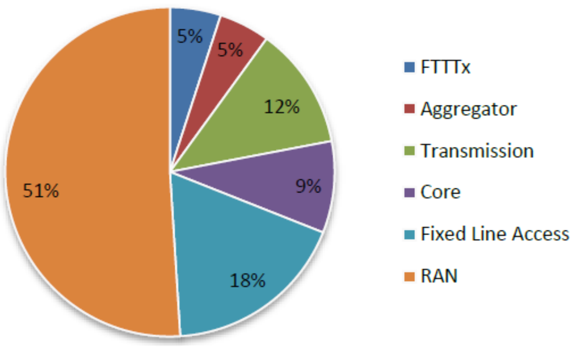

Figure 11. Distribution of power consumption across different network segments [78].

In order to reduce the power consumption also in the metro and access segment, a different approach is needed. All-optical networks (AONs), where O-E-O transponders are used only at the network edge, have been proposed a quarter of a century ago and, despite the progress made in the last decades, their acceptance has encountered skepticism regarding optical impairments [80]. It can be envisioned that AONs could get new emphasis from the possible application in re-configurable metro and access networks, where launch power is lower and distances are shorter, so optical impairments are less impactful. While O-E-O regenerations in opaque networks do not allow 'analog transparency' since they reshape optical waveforms, AONs allow transparency for both digital content of signals ('digital transparency') and their analog waveform. AONs also allow 'spectral transparency', i.e., flexibility in the placement of wavelengths within the optical spectrum [80]. Analog, digital, and spectral transparency allowed by AONs appears particularly attractive for the deployment of flexible transceivers, flexible grids, and optical switches for future software-defined metro and networks.

5.2. Unified Metro-Access Networks

Unified all-optical metro-access networks represent one of the best possible solutions to realize re-configurability at the physical layer in these network segments [10]. Several converged metro-access architectures have been proposed in recent years, where a certain number of PON access stress is merged with a metro ring through ROADMs. Today, the large-scale deployment of optical fiber in the access segment provides a common transmission medium to both access and metro networks [81]. Moreover, the WDM-PON architectures can even extend the application range of PONs when compared to conventional GPONs. Higher per-ONU bandwidth and splitting ratios in conjunction with extended power budgets enable the use of PON technologies for a unified metro-access network [10]. Nevertheless, in a short-term perspective, a cost-effective and scalable solution could be to increase the transmission capacity deploying WDM in the former metro part, while TDM could be kept in the former access part [81].

These TDM/WDM metro-access networks will face some technical challenges: the backward compatibility with existing PON systems have to be preserved; a higher network reach must be accomplished, thus amplification in the RNs will be needed; burst-mode upstream transmission has to be managed, due to the TDM operation in this network segment.

One of the first proposals to merge the metro and access segments has been the metro and access ring integrated network (MARIN) in 2007 [82]. MARIN is based on several interconnected DWDM rings, each one with its own CO to manage the traffic related to the WDM-PONs linked to the ring. Two kinds of nodes are considered: (i) the MARIN gateways, which manage add/drop functionalities towards PON trees, as shown in Figure 12; (ii) the MARIN switches, which manage metro traffic routing. The nodes are equipped with tunable transmitters and use OBS.

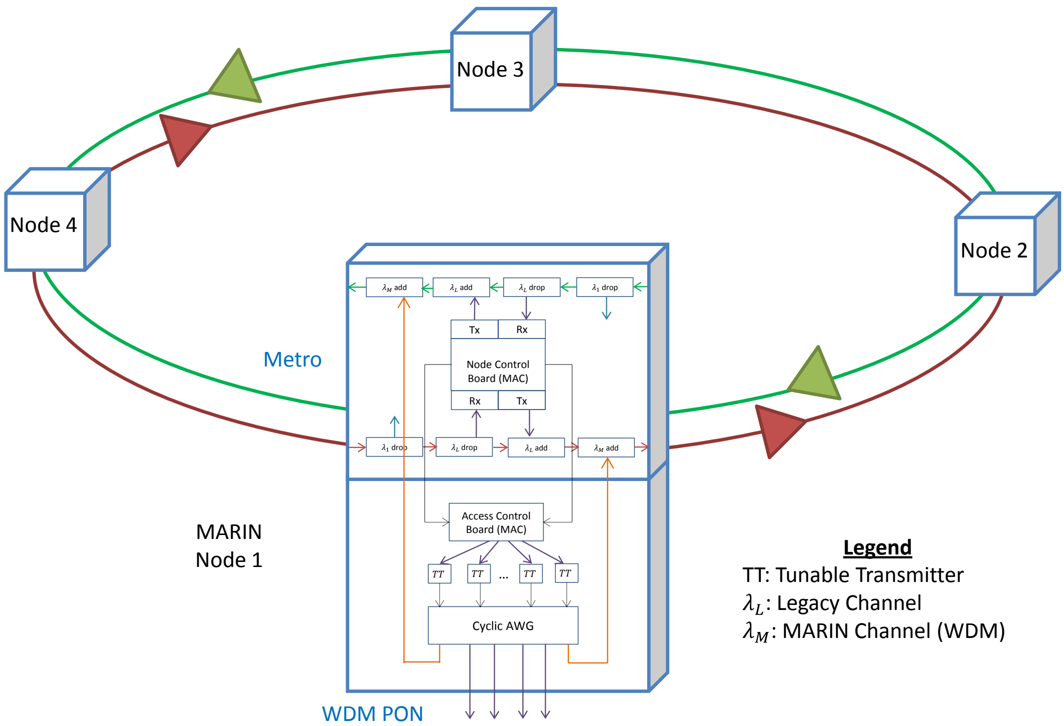

Figure 12. The MARIN architecture [82].

The scaled advanced ring-based passive dense access network architecture (SARDANA) architecture has been proposed in 2011 [83]. This metro-access architecture is based on a bidirectional WDM ring with 32 wavelength channels; the ring is merged with 10 Gbit/s TDM PON trees through RNs capable of channel add/drop functionalities, as shown in Figure 13. All the network nodes are passive except to the OLT placed in the CO of the WDM ring. The RNs are equipped with splitters and remotely pumped EDFAs. The ONTs are equipped with colorless transceivers based on reflective semiconductor optical amplifiers (RSOAs), which reflect and modulate the downstream traffic signal to generate the upstream signal. The ring topology enhances network resiliency and ensures double links between OLT and ONTs, with a recovery time of less than 50 ms in case of failure.

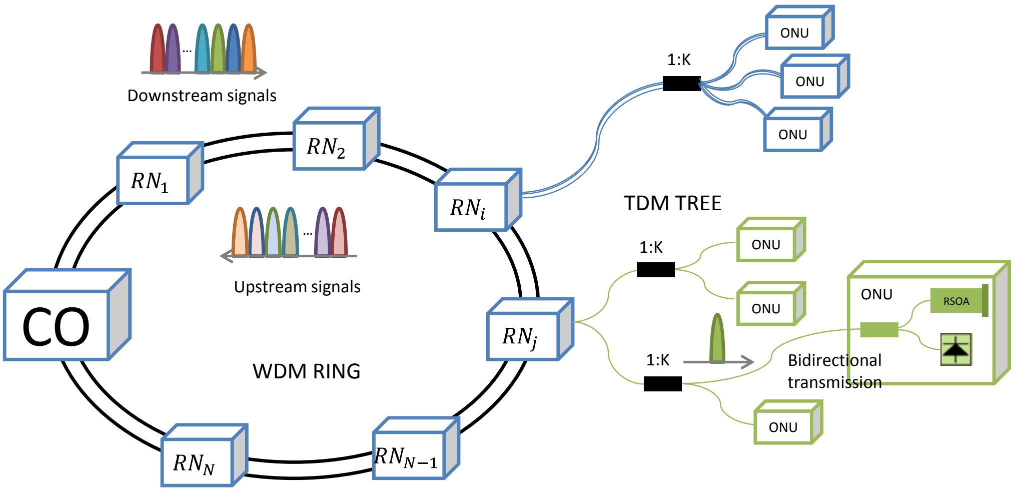

Figure 13. The SARDANA architecture [83].

A proposal for the application of the OBS technique in a metro-access network has recently been advanced in order to ensure all-optical operations in a SDN-like optical architecture which offers the possibility to manage traffic data thanks to re-configurability in the physical layer and a centralized controller [49].

A SDN-based metro-access architecture has also been proposed by Sarmiento et al. [84]. The network is based on cost-effective, energy-efficient, and flexible nodes and transceivers, remotely managed by a SDN controller, able to support 5G services.

The following proposals for converged metro-access networks have been reviewed by Guo and Tay [85]. Super passive optical networks (SuperPON) have been developed based on the old G.983 broadband PON (B-PON) architecture, upgradable through a larger splitting factor and longer reach. Townsend and Talli [86] have proposed a hybrid DWDM-TDM long-reach PON. The architecture proposed by Segarra et al. [50] leverages the concept of an OBS multiplexer to transparently interface to distant metro routers in an all-optical manner. Stanford University ACCESS (SUCCESS) network is a hybrid WDM/TDM architecture based on a single-fiber collector ring and stars attached to it, designed for practical migration steps from current TDM-PONs to WDM optical access networks.

Finally, a reconfigurable metro-access network which can be used for dynamic inter-PON bandwidth allocation for optimal bandwidth availability to the end-user has been discussed by Roy and van Etten [87].

5.3. Converged Fixed-Mobile Networks

In Section 2.2, the reasons to adopt the SDN model in the metro and access networks was described with reference to the requirement of future 5G cellular networks. The re-configurability required by mobile RAN systems will be reflected in the fixed line access networks. Therefore, similarly to the convergence of metro and access segments, a convergence between the fixed and mobile service environments and networks, sometimes referred as fixed mobile convergence (FMC), can be envisioned.

The schematic representation of a generic fixed-mobile metro-access network architecture is shown in Figure 14. The figure shows metro switches and both MBH and MFH links. A centralized

SDN controller can drive all the switches involved to provide connections at the different required granularities and ensure the cooperation among BBUs, as will be required by 5G.

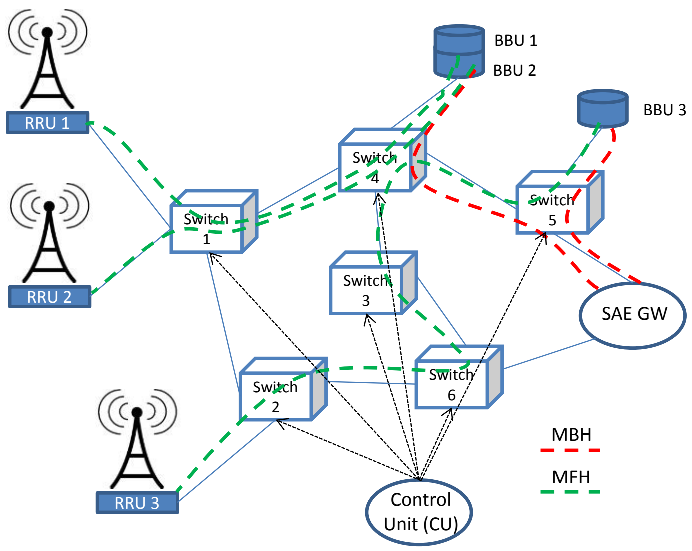

Figure 14. Possible architecture for converged metro-access MBH/MFH network.

SDN concepts applied to efficient 5G MBH and MFH networks have been proposed by Jungnickel et al. [88], in order to enable multiple operators to share the same physical infrastructure. In particular, for the use of SDN in the MFH network, CPRI over Ethernet (CoE) is proposed as a new transport protocol.

Several concrete proposals have been brought forward in recent years to merge fixed and mobile access networks.

Roger and Niger [51] have proposed a metro-access network architecture which makes use of PON-based access, optical cross-connect metro, and WR-OBS transport. Flexible resource allocation mechanisms and mobility management procedures allow the native support of mobile services in a fully integrated mode.

Schmuck et al. [89] have presented a trial demonstration based on flexible operating access nodes within a shared metro-access reconfigurable infrastructure. Virtual paths are proposed to transport mixed data format/rates carrying different services. One of the services provided by the network is an OFDM transmission system operating at 2 Gbit/s per channel for interconnecting neighboring 4G mobile nodes using coordinated multi-point processing [89].

6. Conclusions

The application of the SDN paradigm to reconfigurable and programmable optical metro and access networks has been described. This concept has been widely contextualized in the general scenario of SDN technology, with reference also to the related market place evolution.

Firstly, the reasons for SDN extension to the edge network segments have been presented, considering the metro and access traffic evolution, the future 5G RAN requirements, the trends of data centers interconnect and edge cloud, the benefit in terms of end-user quality of experience, and the TCO savings.

Then, the practical solutions for SDN metro and access networks have been outlined with reference to both higher-layer and physical-layer re-configurability. Physical-layer solutions have been focused on in more detail and its major trends have been overviewed: flexible transceivers, super-channels and flexible grids, optical routing and switching.

After that, several SDP devices and components have been reviewed, especially ROADMs and optical switches, also taking into account the technological aspects and mechanisms for energy harvesting.

Finally, possible future architectures for SDN metro and access networks have been envisioned. Given that all-operations will represent one of the major requirements, several proposals for converging metro-access and fixed-mobile networks have been presented.

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References

1. Calvi, A.; Ferraris, G. Integrazione fra la rete IP e la rete di trasporto ottica. *Not. Tec. Telecom Ital.* **2016**, *1*, 34–45.
2. Goransson, P.; Black, C. *Software Defined Networks: A Comprehensive Approach*; Morgan Kaufmann Publishers Inc.: Waltham, MA, USA, 2014.
3. Astuto, B.N.; Mendonca, M.; Nguyen, X.N.; Obraczka, K.; Turletti, T. A Survey of Software-Defined Networking: Past, Present, and Future of Programmable Networks. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1617–1634.
4. Guardini, I. Network Automation. *Not. Tec. Telecom Ital.* **2016**, *1*, 60–68.
5. Buyukkoc, C.; Manzalini, A.; Peterson, L. From CORD to the 5G era. *Not. Tec. Telecom Ital.* **2016**, *1*, 20–33.
6. Weldon, M.K. *The Future X Network: A Bell Labs Perspective*; CRC Press: Boca Raton, FL, USA, 2016.
7. Clauberg, A. The software defined operator. *Not. Tec. Telecom Ital.* **2016**, *1*, 98–105.
8. Ruffini, M.; Slyne, F.; Bluemm, C.; Kitsuwan, N.; McGettrick, S. Software Defined Networking for next generation converged metro-access networks. *Opt. Fiber Technol.* **2015**, *26*, 31–41. [CrossRef]
9. Auster, M.; Balakrishnan, S.; McBride, M.; Nehib, G.; Ong, L.; Shirazipour, M.; Shukla, V.; Tong, A.; Vissers, M. OpenFlow-Enabled Transport SDN. ONF Solution Brief 2014. Available online: https://www.opennetworking.org/images/stories/downloads/sdn-resources/solution-briefs/sb-of-enabled-transport-sdn.pdf (accessed on 29 December 2016).
10. Muciaccia, T.; Pileri, S. Riconfigurabilità nelle reti di accesso e metro-access. *Not. Tec. Telecom Ital.* **2016**, *1*, 108–121.
11. Alcatel-Lucent Application Note, Bringing Wavelength Agility and Efficiency to Software-Defined Networks. Available online: https://resources.alcatel-lucent.com/theStore/files/Nokia_Bringing_Wavelength_Agility_Efficiency_Application_Note_EN.pdf (accessed on 29 December 2016).
12. Schmitt, A. 100G+ and ROADM Strategies: Global Service Provider Survey. Available online: https://www.infinera.com/wp-content/uploads/2015/07/Infonetics-100G_and_ROADM_Strategies_Global_Service_Provider_Survey.pdf (accessed on 29 December 2016).
13. Next Generation Mobile Networks. 5G White Paper. 2015. Available online: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf (accessed on 29 December 2016).
14. Castoldi, P.; Valcarenghi, L.; Cugini, F.; Cavaliere, F.; Iovanna, P. What Role for Photonics in Xhaul Networks of 5G Systems? In Proceedings of the Asia Communications and Photonics Conference, Hong Kong, China, 19–23 November 2015.
15. Öhlén, P.; Skubic, B.; Rostami, A.; Laraqui, K.; Cavaliere, F.; Varga, B.; Fonseca Lindqvist, N. Flexibility in 5G Transport Networks: The Key To Meeting The Demand For Connectivity. *Ericsson Technol. Rev.* **2015**, *92*, 1–15.
16. Bercovich, D.; Contreras, L.M.; Haddad, Y.; Adam, A.; Bernardos, C.J. Software-Defined Wireless Transport Networks for Flexible Mobile Backhaul in 5G Systems. *Mob. Netw. Appl.* **2015**, *20*, 793–801. [CrossRef]
17. Bell Labs. Metro Network Traffic Growth: An Architecture Impact Study. Alcatel-Lucent Strategic White Paper 2013. Available online: http://www.tmcnet.com/tmc/whitepapers/documents/whitepapers/2013/9378-bell-labs-metro-network-traffic-growth-an-architecture.pdf (accessed on 29 December 2016).
18. Cisco Visual Networking Index: Forecast and Methodology, 2014–2019. Available online: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.pdf (accessed on 20 April 2016).
19. Kerpez, K.J.; Cioffi, J.M.; Ginis, G.; Goldburg, M.; Galli, S.; Silverman, P. Software-defined access networks. *IEEE Commun. Mag.* **2014**, *52*, 152–159. [CrossRef]

20. Public Consultation on the Needs for Internet Speed and Quality Beyond 2020. Available online: https://ec.europa.eu/digital-single-market/en/news/public-consultation-needs-internet-speed-and-quality-beyond-2020 (accessed on 29 December 2016).
21. Public BEREC Expert Workshop on "Regulatory implications of SDN and NFV". Available online: http://berec.europa.eu/eng/events/berec_events_2016/104-public-berec-expert-workshop-on-regulatory-implications-of-sdn-and-nfv (accessed on 29 December 2016).
22. European Commission. Regulatory, in Particular Access, Regimes for Network Investment Models in Europe. Available online: http://bookshop.europa.eu/en/regulatory-in-particular-access-regimes-for-network-investment-models-in-europe-pbKK0216979/ (accessed on 29 December 2016).
23. Amokrane, A.; Hwang, J.; Xiao, J.; Anerousis, N. Software defined enterprise passive optical network. In Proceedings of the International Conference on Network and Service Management, Rio de Janeiro, Brazil, 17–21 November 2014.
24. Yang, H.; Zhang, J.; Zhao, Y.; Wu, J.; Ji, Y.; Lin, Y.; Han, J.; Lee, Y. Experimental demonstration of remote unified control for OpenFlow-based software-defined optical access networks. *Photonic Netw. Commun.* **2015**, *31*, 568–577. [CrossRef]
25. Ruckert, J.; Bifulcoy, R.; Rizwan-Ul-Haq, M.; Kolbey, H.; Hausheer, D. Flexible Traffic Management in Broadband Access Networks using Software Defined Networking. In Proceedings of the IEEE Network Operations and Management Symposium, Krakow, Poland, 5–9 May 2014.
26. Dai, E.; Dai, W. Towards SDN for Optical Access Networks. In Proceedings of the Spring Technical Forum, Boston, MA, USA, 16–18 May 2016.
27. Woesner, H.; Fritzsche, D. SDN and OpenFlow for Converged Access/Aggregation Networks. In Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, Los Angeles, CA, USA, 17–23 March 2013.
28. Li, C.; Guo, W.; Wang, W.; Hu, W.; Xia, M. Programmable bandwidth management in software-defined EPON architecture. *Opt. Commun.* **2016**, *370*, 43–48. [CrossRef]
29. Cornaglia, B.; Young, G.; Marchetta, A. Fixed Access Network Sharing. *Opt. Fiber Technol.* **2016**, *26*, 2–11. [CrossRef]
30. Rottondi, C.; Tornatore, M.; Gavioli, G. Optical ring metro networks with flexible Grid and distance-adaptive optical coherent transceivers. *Bell Labs Tech. J.* **2013**, *18*, 401–412. [CrossRef]
31. Vacondio, F.; Bertran-Pardo, O.; Pointurier, Y.; Fickers, J.; Ghazisaeidi, A.; de Valicourt, G.; Antona, J.; Chanclou, P.; Bigo, S. Flexible TDMA access optical networks enabled by burst-mode software defined coherent transponders. In Proceedings of the European Conference and Exhibition on Optical Communication, London, UK, 22–26 September 2013.
32. Zhou, L.; Peng, G.; Chand, N. Demonstration of a novel software-defined Flex PON. *Photonic Netw. Commun.* **2015**, *29*, 282–290. [CrossRef]
33. Rottondi, R.; Tornatore, M.; Pattavina, A.; Gavioli, G. Routing, Modulation Level, and Spectrum Assignment in Optical Metro Ring Networks Using Elastic Transceivers. *J. Opt. Commun. Netw.* **2013**, *5*, 305–315. [CrossRef]
34. Forzati, M.; Gavler, A. Flexible next-generation optical access. In Proceedings of the 15th International Conference on Transparent Optical Networks (ICTON), Barcelona, Spain, 23–27 June 2013.
35. Cvijetic, N.; Tanaka, A.; Ji, P.; Sethuraman, K.; Murakami, S.; Wang, T. SDN and OpenFlow for dynamic flex-grid optical access and aggregation networks. *J. Lightw. Technol.* **2014**, *32*, 864–870. [CrossRef]
36. Li, B.; Gan, L.; Feng, Z.; Fu, S.; Shum, P.P.; Tong, W.; Tang, M. Experimental Demonstration of Symmetric WDM-SDM Optical Access Network over Multicore Fiber. In Proceedings of the Conference on Lasers and Electro-Optics, San Francisco, CA, USA, 13–18 February 2016.
37. Yin, S.; Shen, T.S.; Kazovsky, L.G. UltraFlow: Elastic, Flexible and Dual-Mode Long-Reach Optical Access Network. In Proceedings of the International Conference on Computing, Networking and Communications, Anaheim, CA, USA, 16–19 February 2015.
38. Yin, S.; Shen, T.S.; Bi, Y.; Jin, J.; Oyama, T.; Kazovsky, L.G. A Novel Quasi-Passive, Software-Defined, and Energy Efficient Optical Access Network for Adaptive Intra-PON Flow Transmission. *J. Lightw. Technol.* **2015**, *33*, 4536–4546. [CrossRef]
39. Schrenk, B.; Poppe, A.; Stierle, M.; Leopold, H. Fully-Passive Optical Switch Introducing Dynamicity and Flexibility to Metro-Access. *IEEE Photonics Technol. Lett.* **2015**, *27*, 486–489. [CrossRef]

40. Strasser, T.A.; Wagener, J.L. Wavelength-Selective Switches for ROADM Applications. *IEEE J. Sel. Top. Quantum Electron.* **2010**, *16*, 1150–1157. [CrossRef]
41. Homa, J.; Bala, K. ROADMs for reconfigurable metro networks. *Proc. SPIE* **2009**, *7235*, 723508.
42. Strasser, T.A.; Taylor, J. ROADMS Unlock the Edge of the Network. *IEEE Commun. Mag.* **2008**, *46*. [CrossRef]
43. Information Gatekeepers Inc. *The Edge ROADM Revolution*; B & C Consulting: Brighton, MA, USA, 2010.
44. Information Gatekeepers Inc. *ROADMs from the Core to the Edge*; B & C Consulting: Brighton, MA, USA, 2008.
45. Clavenna, S. ROADMS and the future of metro optical networks. *Heavy Read.* **2005**, *3*, 1–5.
46. Enablence Technologies Inc. No Limits: The Next-Generation ROADM Network. White Paper 2010. Available online: http://www.enablence.com/media/mediamanager/pdf/770-enablence-article-thenextgenerationroadmnetwork.pdf (accessed on29 December 2016).
47. Eldada, L. Optical add/drop multiplexing architecture for metro area networks. *SPIE Newsroom* **2008**. [CrossRef]
48. Yuang, M.C.; Lin, Y.; Wang, Y. A Novel Optical-Header Processing and Access Control System for a Packet-Switched WDM Metro Ring Network. *J. Lightw. Technol.* **2009**, *27*, 4907–4915. [CrossRef]
49. Muciaccia, T.; Passaro, V.M.N. Performance characterization of a novel DWDM all-optical SDN-like metro-access network. In Proceedings of the 24th International Conference on Software, Telecommunications and Computer Networks, Split, Croatia, 22–24 September 2016.
50. Segarra, J.; Sales, V.; Prat, J. An all-optical access-metro interface for hybrid WDM/TDM PON based on OBS. *J. Lightw. Technol.* **2007**, *25*, 1002–1016. [CrossRef]
51. Roger, C.; Niger, P. Fixed mobile convergence in an all-optical metro network. In Proceedings of the International Conference on Transparent Optical Networks, Munich, Germany, 27 June–1 July 2010.
52. Casoni, M.; Raffaelli, C. TCP Performance over Optical Burst-Switched Networks with Different Access Technologies. *J. Opt. Commun. Netw.* **2009**, *1*, 103–112. [CrossRef]
53. Hillerkuss, D.; Leuthold, J. Software-Defined Transceivers in Dynamic Access Networks. In Proceedings of the Optical Fiber Communication Conference, Los Angeles, CA, USA, 22–26 March 2015.
54. Choi, H.Y.; Liu, L.; Tsuritani, T.; Morita, I. Demonstration of BER-Adaptive WSON Employing Flexible Transmitter/Receiver with an Extended OpenFlow-Based Control Plane. *IEEE Photonic Technol. Lett.* **2013**, *25*, 119–121. [CrossRef]
55. Iiyama, N.; Kim, S.-Y.; Shimada, T.; Kimura, S.; Yoshimoto, N. Co-existent downstream scheme between OOK and QAM signals in an optical access network using software-defined technology. In Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, Los Angeles, CA, USA, 4–8 March 2012.
56. Katopodis, V.; Spyropoulou, M.; Tsokos, C.; Groumas, P.; Felipe, D.; Keil, N.; Beretta, A.; Vannucci, A.; Johansen, T.K.; Quagliotti, M.; et al. Polarization-, Carrier-, and Format-Selectable Optical Flow Generation Based on a Multi-Flow Transmitter Using Passive Polymers. In Proceedings of the International Conference on Transparent Optical Networks, Trento, Italy, 10–14 July 2016.
57. Rafique, D.; Rahman, T.; Napoli, A.; Kuschnerov, M.; Lehmann, G.; Spinnler, B. Flex-grid optical networks: Spectrum allocation and nonlinear dynamics of super-channels. *Opt. Express* **2013**, *21*, 32184–32191. [CrossRef] [PubMed]
58. Oliveira, J.; Siqueira, M.; Curiel, G.; Hirata, A.; van't Hooft, F.; Macedo, D.; Colazza, M.; Rothenberg, C. Experimental testbed of reconfigurable flexgrid optical network with virtualized GMPLS control plane and autonomic controls towards SDN. In Proceedings of the International Microwave and Optoelectronics Conference, Rio de Janeiro, Brazil, 4–7 August 2013.
59. Zang, H.; Juez, J.P.; Mukherjeey, B. A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks. *Opt. Netw. Mag.* **2001**, *1*, 47–60.
60. Yoo, S.J.B. Optical Packet and Burst Switching Technologies for the Future Photonic Internet. *J. Lightw. Technol.* **2006**, *24*, 4468–4492. [CrossRef]
61. Rouskas, G.N.; Dutta, R.; Baldine, I. A new internet architecture to enable software defined optics and evolving optical switching models. In Proceedings of the International Conference on Broadband Communications, Networks and Systems, London, UK, 8–11 September 2008.
62. Reed, G.T. *Silicon Photonics. The State of the Art*; John Wiley & Sons, Ltd.: Chichester, UK, 2008.

63. Bogaerts, W.; Baets, R.; Dumon, P.; Wiaux, V.; Beckx, S.; Taillaert, D.; Luyssaert, B.; van Campenhout, J.; Bienstman, P.; van Thourhout, D. Nanophotonic waveguides in silicon-on-insulator fabricated CMOS technology. *J. Lightw. Technol.* **2005**, *23*, 401–412. [CrossRef]
64. Rong, H.; Jones, R.; Liu, A.; Cohen, O.; Hak, D.; Fang, A.; Paniccia, M. A continuous-wave Raman silicon laser. *Nature* **2005**, *433*, 725–728. [CrossRef] [PubMed]
65. Passaro, V.M.N.; Magno, F.; Tsarev, A.V. Investigation of thermo-optic effect and multireflector tunable filter/multiplexer in SOI waveguides. *Opt. Express* **2005**, *13*, 3429–3437. [CrossRef] [PubMed]
66. Tsarev, A.V.; de Leonardis, F.; Passaro, V.M.N. Thin heterogeneous SOI waveguides for thermooptical tuning and filtering. *Opt. Express* **2008**, *16*, 3101–3113. [CrossRef] [PubMed]
67. Xu, Q.; Almeida, V.R.; Lipson, M. Micrometer-scale all-optical wavelength converter on silicon. *Opt. Lett.* **2005**, *30*, 2733–2735. [CrossRef] [PubMed]
68. Notarnicola, G.; Rizzelli, G.; Maier, G.; Pattavina, A. Scalability Analysis of WSS-based ROADMs. In Proceedings of the European Conference on Networks and Optical Communications (NOC), Vilanova i la Geltru, Spain, 20–22 June 2012.
69. Ferraris, G.; Mariani, S.; Mercadante, P. Tutti i bit passano per il trasporto. *Not. Tec. Telecom Ital.* **2011**, *2*, 28–36.
70. Augusto, S.; Brizi, V.; Tavilla, R. L'evoluzione della trasmissione ottica. *Not. Tec. Telecom Ital.* **2009**, *1*, 60–89.
71. Klein, E.J.; Urban, P.; Sengo, G.; Hilderink, L.T.H.; Hoekman, M.; Pellens, R.; van Dijk, P.; Driessen, A. Densely integrated microring resonator based photonic devices for use in access networks. *Opt. Express* **2007**, *15*, 10346–10355. [CrossRef] [PubMed]
72. Kurumida, J.; Yoo, S.J.B. Nonlinear Optical Signal Processing in Optical Packet Switching Systems. *IEEE J. Sel. Top. Quantum Electron.* **2012**, *18*, 978–987. [CrossRef]
73. Martinez, J.M.; Herrera, J.; Ramos, F.; Marti, J. All-Optical Address Recognition Scheme for Label-Swapping Networks. *IEEE Photonics Technol. Lett.* **2006**, *18*, 151–153. [CrossRef]
74. Kehayas, E.; Tsiokos, D.; Bakopoulos, P.; Apostolopoulos, D.; Petrantonakis, D.; Stampoulidis, L.; Poustie, A.; McDougall, R.; Maxwell, G.; Liu, Y.; et al. 40-Gb/s All-Optical Processing Systems Using Hybrid Photonic Integration Technology. *J. Lightw. Technol.* **2006**, *24*, 4903–4911. [CrossRef]
75. Hu, H.; Ji, H.; Pu, M.; Galili, M.; Yvind, K.; Oxenløwe, L.K. 160-Gb/s Silicon All-Optical Packet Switch for Buffer-less Optical Burst Switching. *J. Lightw. Technol.* **2015**, *33*, 843–848. [CrossRef]
76. Kavak, N.; Wilkinson, A.; Larkins, J.; Patil, S.; Frazier, B. The central office of the ICT era: Agile, smart, and autonomous. *Ericsson Technol. Rev.* **2015**, *93*, 1–13.
77. Baptista, A.; Ferreira, M.; Quinta, A.; Lima, M.; Teixeira, A. Remotely reconfigurable remote node for hybrid ring-tree passive optical networks. In Proceedings of the Conference on Telecommunications, Porto, Portugal, 20–25 September 2009.
78. Makkar, H. Green telecom layered framework for calculating carbon footprint of telecom network. *Int. J. Res. Eng. Technol.* **2013**, *2*, 425–431.
79. Castoldi, P.; Valcarenghi, L.; Cerutti, I. Efficienza energetica nelle reti a larga banda. *La Comun.* **2011**, *57*, 37–42.
80. Saleh, A.A.M.; Simmons, J.M. All-Optical Networking—Evolution, Benefits, Challenges, and Future Vision. *Proc. IEEE* **2012**, *100*, 1105–1117. [CrossRef]
81. Pato, S.; Pedro, J.; Santos, J.; Silva, H.; Pires, J.; Monteiro, P. All-Optical Remote Node for Cost-Effective Metro-Access Convergence. In Proceedings of the Conference on Telecommunications, Porto, Portugal, 20–25 September 2009.
82. Wong, S.; Shaw, W.; Balasubramanian, K.; Cheng, N.; Kazovsky, L. MARIN: Demonstration of a Flexible and Dynamic Metro-Access Integrated Architecture. In Proceedings of the IEEE Global Telecommunications Conference, Washington, DC, USA, 26–30 November 2007.
83. Hoover, J.; van Horne, J. SARDANA Tackles the Bandwidth Challenge. Broadband Communities, 2011. Available online: http://www.bbpmag.com/2011mags/october11/BBC_Oct11_Sardana.pdf (accessed on 29 December 2016).
84. Sarmiento, S.; Montero, R.; Altabas, J.A.; Izquierdo, D.; Agraz, F.; Pagès, A.; Perello, J.; Gene, J.; Alonso, M.; Pascual, A.; et al. SDN-Enabled Flexible Optical Node Designs and Transceivers for Sustainable Metro-Access Networks Convergence. In Proceedings of the 18th International Conference on Transparent Optical Networks (ICTON), Trento, Italy, 10–14 July 2016.

85. Guo, C.; Tay, T.T. On Scalability, Migratability and Costeffectiveness of Next-Generation WDM Passive Optical Network Architectures. In Proceedings of the International Conference on Signal Processing and Communication Systems, Gold Coast, Australia, 12–14 December 2012.
86. Talli, G. Hybrid DWDM-TDM long-reach PON for next generation optical access. *J. Lightw. Technol.* **2006**, *24*, 2827–2834. [CrossRef]
87. Roy, R.; van Etten, W. Case for dynamic reconfigurability in access networks. In Proceedings of the European Conference on Networks & Optical Communications & Optical Cabling and Infrastructure, Krems, Austria, 1–3 July 2008.
88. Jungnickel, V.; Habel, K.; Parker, M.; Walker, S.; Bock, C.; Ferrer Riera, J.; Marques, V.; Levi, D. Software-defined open architecture for front- and backhaul in 5G mobile networks. In Proceedings of the 18th International Conference on Transparent Optical Networks (ICTON), Trento, Italy, 12 July 2016.
89. Schmuck, H.; Bonk, R.; Poehlmann, W.; Pfeiffer, T. Field trial demonstration of open shared metro-access infrastructure. In Proceedings of the ITG Symposium Photonic Networks, Ilmenau, Germany, 3–7 March 2013.