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Editorial

Passive optical network (PON) supported networking

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ABSTRACT

In this editorial, we first set the context for the subject matter of this special issue on passive optical network (PON) supported networking. This context includes a discussion of optical networking in all segments of a global communication network and the emphasis of the importance of PONs in the access network as well as their role supporting other communication network technologies. We follow this broader context with an introduction to the articles appearing in this special issue. Lastly, we conclude this editorial with a broad outlook to the future of PONs in communication networks.

1. Introduction

Passive optical network (PON) research and technology have matured in recent years and firmly established PONs as a key component for high-speed Internet access. In many instances users' private networks do not directly connect to PONs, but rather connect to PONs through other intermediate access technologies, such as DSL or cable networks [1].

As a specific example of a PON supported network, integrated fiber-wireless (FiWi) broadband access networks are expected to become an important infrastructure and service component for telecommunications as well as other economic sectors, most notably energy and transport. Beside incumbent and alternative telecom operators, utilities along with municipalities are increasingly responsible for a significant share of households passed with fiber-to-the-home/building (FTTH/B) in Europe as well as other regions worldwide. Business models along with technological choices will play key roles in the roll-out of future smart grid communications infrastructures. Such future infrastructures call for innovative partnerships between the various involved stakeholders, such as utility companies, network operators, and network service providers, as well as integration of the involved utility and networking technologies.

With the imminent confluence of energy and data networking, PONs will interface with a widening spectrum of users and applications. These applications may have conventional human-to-human (H2H) as well as machine-to-machine (M2M) specific traffic patterns and quality of service requirements that are very different from classical data users.

This special issue of *Optical Switching and Networking* seeks to provide a snapshot of the state-of-the-art in PON Supported Networking. The editorial for this special issue is organized as follows. Section 2 gives a brief review of the progression of optical networking research that has led to the exploration of PONs and their usage in larger interconnected network structures. The section gives succinct overviews of optical networking research in core, metro, as well as access networks, and culminates in an overview of present PON supported networks, such as hybrid access networks. Section 3 introduces the papers contained in this special issue. Building on the historical development leading to PON access networks and the snapshot of present research on PON supported networking, Section 4 outlines perspectives on the future development of PON supported networking. A vision for the integration of optical access/metro networks with the smart electric grid (smart grid) and their implications for a third industrial revolution are presented.

2. Origins

Optical networking has its origins in the desire to exploit the photonic properties of optical fiber for high-speed

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communication that is imperceptible to electro-magnetic interference. Optical fiber links have found wide-spread deployment in high-speed backbone links of the growing Internet. Broadly speaking, the optical networks that evolved over the past decades in support of communication over the Internet can be classified into core networks, metro networks, and access networks. In the following subsections, we briefly review significant research advances in these different network types and outline their implications for the development of PON supported networks.

2.1. Core networks

Given the enormous traffic volumes and high number of users for core networks, many research advances have focused on increasing the capacity of core networks, as well as optimizing their resource utilization. Although the core network cost is shared by a large number of users, capacity upgrades should be performed at minimum cost possible. Signal transmission and switching in core networks tend to be performed mostly in the optical domain, with optical signals being switched using reconfigurable optical add-drop multiplexers (ROADM) in most of the nodes, and some optical-electrical-optical (OEO) nodes still employed for regeneration, traffic grooming, and wavelength conversion operations [2]. With photonic integrated circuits (PICs), it will be possible to integrate many WDM components on a chip, which can also implement new OEO switching nodes. PIC technologies furthermore minimize space and power [3].

Core networks are usually based on a mesh topology and operate with wavelength division multiplexing (WDM). Other multiplexing techniques have been proposed, such as spatial division multiplexing (SDM) and optical orthogonal frequency division multiplexing (O-OFDM). SDM takes advantage of multiple mode fibers and multicore fibers to significantly multiply the capacity considering multiple wavelengths, modes, and/or fiber cores [4]. On the other hand, O-OFDM is a new elastic transmission technology that allows a highly flexible and very efficient spectrum allocation by eliminating the need for spectrum guard bands between carriers [5]. A similar concept is the flexgrid, which uses WDM techniques with a smaller spectrum slot size of about 12.5 GHz, instead of the conventional 50 GHz [6]. In this way, operators can carry more traffic. Another way to provide flexibility is through the elastic network concepts. With a flexible spectrum, a given wavelength can grow or shrink its bandwidth as required, keeping a wavelength unit as switching granularity [2]. Algorithms are required to allocate the wavelengths and the spectrum, avoiding spectral fragmentation and conflicts. Since the wavelength bandwidth is matched to the connection request, it may seem that traffic grooming is not required. However, traffic grooming is still important in elastic networks given the need to allocate the guard bands, such that the spectrum is optimally utilized [7].

With increasing bit rates, it becomes difficult to operate in the electrical domain. In order to solve this problem and add more intelligence to the optical network, optical packet switching (OPS) was proposed. However, its limitation is the technological immaturity of optical buffers. As an alternative to OPS, optical burst switching (OBS) [8,9] does not require buffering because the network switches several packets at a time, in bursts [10]. Recently, it has been shown that the core network traffic may not exhibit a pronounced bursty nature. This is a consequence of high speed multiplexing of the bursty traffic from many metropolitan and access networks, which cancels to some degree the traffic burstiness [11]. This is one reason why circuit switching still remains appropriate for the current core network traffic pattern.

Another recent advance is optical flow switching (OFS) [12], which allows scheduled end-to-end all-optical connections through the use of off-band signaling for the duration of the transfer. OFS assumes that the users (carriers/service providers and leased line users) have a long-haul laser transmitter, whose cost is expected to decrease with the future growth of the core capacity. OFS demonstrates important cost savings over other mechanisms for large transactions. The OFS-established end-to-end connections are expected to involve metro and access networks, in particular the PONs. Another recently proposed scheme is waveband switching (WBS) [13]. WBS is a technology where multiple wavelengths are grouped in a band, and each wavelength operated at 100 Gbit/s. WBS operates with multi-granular cross-connect (MG-OXC) architectures. The aim is to cope with the increasing capacity demands and to reduce the number of switching ports and the number of MG-OXCs, and thus reduce the network cost.

Software defined networking (SDN) is a concept originally developed for switching and routing in datacenter resource optimization, and now considered for application in the core network [14]. The idea of using SDN in core networks is to optimize resource utilization in core networks by centralizing the control plane, which will turn into an entity that receives and dispatches allocation requests from the network element interfaces. The baseline goal is to unify the control structures in the transport network with multiple layers and vendors. SDN may be extended to PON networking as well.

2.2. Metro networks

Metropolitan area networks (metro networks) seek to interconnect users within a metropolitan area as well as interconnect users with core networks for communication with remote metro areas. As transmission bit rates (capacities) have increased in the core network links, metro network research has strived to increase the capacities of metro networks in order to avoid a bandwidth shortage (gap) in the metro area [15]. Ring networks operating according to the synchronized optical networking (SONET) standard have became prevalent in metropolitan area networks in the 1990s. SONET is a circuit-switching technology, which is closely related to the synchronous digital hierarchy (SDH) designed for carrying voice calls. In order to efficiently carry bursty Internet packet traffic over SONET networks, traffic grooming strategies

[16,17] and packet over SONET technologies have been developed [18].

As an alternative to SONET, packet-switched optical ring networks have been investigated [19–23] for providing low-delay metro transport to bursty packet traffic [24]. The resilient packet ring (RPR) is a related standard for an optical ring network operating a single-wavelength in each of two counter-directional fiber rings [25]. RPR as well as the majority of packet ring networks allow for spatial wavelength reuse, that is, a data packet is taken (stripped) by the destination node off the ring so that the destination node or nodes downstream can use the freed wavelength for their own packet transmissions.

Ring networks pose challenging medium access and fairness control issues. For example, a particular node could send many packets, depriving downstream nodes of transmission opportunities. Networks with a star topology and coordination of transmissions through medium access control based on a knowledge base shared by all nodes avoids these fairness issues [26–29]. Initial metro star network designs were based on the passive star coupler (PSC), which broadcasts signals arriving on one port to all output ports [30]. These broadcasts are inefficient for unicast traffic whose destination is attached to a given single PSC output port, i.e., the broadcast prohibits spatial reuse of a given wavelength by nodes attached to different PSC ports. In contrast, an arrayed-waveguide grating (AWG) provides wavelength routing functionality that can be exploited in star-topology metro networks [31,32]. A number of AWG-based designs have been developed to exploit the wavelength routing functionality [33–38] for efficient optical metro networking.

Both ring and star topology metro networks have their respective strength and weaknesses [39] and can be combined in ring-star hybrid networks for improved reliability and efficiency [40,41].

In summary, the outlined core and metro optical research has paved the way for reliable high-speed data transport in metro and core networks. However, subscribers, such as private homes and businesses, can only access these high speed metro and core transport services if they are connected via high-speed access networks to the metro network.

2.3. Access networks

Access networks connect individual subscribers, such as private homes and businesses, to metro networks. Since access networks serve typically a relatively small set of subscribers in a given geographical region, relatively few traffic flows are aggregated. As a result, traffic in access networks is typically highly bursty. Packet switching with dynamic bandwidth allocation has therefore become the dominant switching paradigm in access networks. Access networks need to amortize expenditures from the relatively small set of subscribers in the geographical area served by the access network. Low-cost passive optical network technologies that rely to a large degree on passive components that do not require electrical power have therefore become the prevalent optical access network technology [42–46]. Whereas, active optical access networks [47] have generally not been considered economically viable. The International Traffic Union (ITU) as well as the IEEE have developed PON standards, namely the Gigabit PON and Ethernet PON (EPON), respectively [48]. Both standards have recently been updated to accommodate transmission bitrates up to 10 Gbps [49].

PONs have typically a tree structure with a central Optical Line Terminal (OLT) transmitting downstream traffic to distributed Optical Network Units (ONUs), whereby each ONU serves one or a few subscribers. A key challenge in operating PONs is the medium access control for the distributed upstream transmissions of the individual ONUs on the shared wavelength channels. Due to the typically high burstiness of traffic from the individual ONUs, fixed upstream bandwidth allocation akin to circuit switching results in low bandwidth utilization [50]. A wide range of dynamic bandwidth allocation (DBA) mechanisms have been proposed and evaluated to efficiently transport bursty upstream packet traffic on PONs with a single upstream channel [51–56], as well as multiple upstream wavelength channels [57–59].

Other recent research directions have focused on improving the quality of service and reliability provided by PON access networks [60–65]. Lastly, the reduction of energy consumption in access networks has received significant research interest [66–70].

As noted above the main purpose of PON access networks is to allow subscribers to effectively utilize the vast bandwidths in the metro and core networks. To facilitate inter-operation of access and metro networks, several recent research approaches have explored integrated access-metro networking [71,72].

2.4. PON supported access networks: hybrid access networks

For a variety of reasons that we discuss below, access networks have evolved into a structure that includes more than a single transmission technology. In these hybrid access networks, the popular PON access network becomes a supporting technology.

Recently, copper transmission technologies have improved to the point where a nearly 1 Gbps bitrate can be maintained using twisted pair copper over short distances (e.g., up to 250 m) [73–75]. As a result, short-term subscriber bandwidth demands can be met by keeping copper transmission distances short. An economically attractive access network solution deploys fiber transmission media to a location within 250 m of subscribers. The remaining distance to subscribers utilizes an already deployed copper transmission medium utilizing new modem technologies. Some examples of these hybrid fiber/copper access networks are PON/xDSL access networks [76] and the EPON Protocol over Coax (EPoC) access network [77].

For scenarios where an access network must be deployed rapidly or over a harsh terrain, wireless transmission must be utilized. For scenarios where device mobility is desired, wireless transmission must be utilized. These scenarios have brought about hybrid access networks that include wireless transmission. Research on the cooperation between fiber-based PON access networks and wireless local area/mesh networks has given rise to a particular type of PON supported network, the so-called fiber-wireless (FiWi) network [78,79]. FiWi networks often pose a fundamental routing problem: Should traffic be routed through wireless transmissions to the destination, or should traffic be routed to the nearest ONU, then over the PON to an ONU close to the destination, and the rest of the way with wireless transmissions? Significant research efforts have begun to develop effective structures for FiWi networks [80–83], as well as routing algorithms [84] and DBA algorithms [85–88].

With the proliferation of multimedia communication, individual video traffic flows are expected to contribute a large portion of the traffic load on access networks. Efficient variable-bit-rate video compression produces highly variable traffic [89–93]. Building on video traffic smoothing and prefetching principles [94,95], a MAC protocol for video-dominated FiWi networks has been developed in [96] while related energy efficiency aspects are investigated in [97].

2.5. *PON supported metro networks: long-reach PONs*

To reduce network maintenance costs, the consolidation of metro and access networks has been explored. In this case, the scope of PONs is geographically extended up to 100 km. These geographic extensions of PONs are referred to as long-reach PONs. A long-reach PON places PONs in a role to support the metro area network by providing a single network technology to coalesce the metro and access networks. Long-reach PONs present a number of research challenges; see [98] for a comprehensive overview.

The first category of challenges result from large propagation delays. Large propagation delays can result in poor upstream channel utilization. Several recent DBA mechanisms have been developed and evaluated specifically for long-reach PONs to mitigate poor upstream channel utilization and other performance consequences of the large propagation delays [99–107].

The second category of challenges result from a large number of attached ONUs. As a result of the large number of ONUs, wavelength reuse and robust protection mechanisms become more significant issues. In [108], remote seed-lights for RSOA-based ONUs are studied such that the wavelengths can be reused at the ONUs for upstream transmission. Path protection of long-reach PONs has been investigated in [62,109].

3. Overview of this special issue

This special issue of Optical Switching and Networking on PON supported networking contains seven articles. There is one article on the subject of PON supported digital subscriber line (DSL) access networks, two articles on the subject of PON supported wireless networks, two articles on the subject of energy efficiency for PON supported networks, and two articles on the subject of long-reach PONs.

Hybrid fiber/copper access networks have recently begun to receive some attention from the research community spurred by the recent formation of the IEEE EPoC task force [76,77]. A challenge in these hybrid access networks is to permit "anywhere deployment" of the active device that bridges the fiber and copper segments. In the paper titled "PON/xDSL Hybrid Access Networks" by Elliott Gurrola, Michael P. McGarry, Yuanqiu Luo, and Frank Effenberger the authors consider PON supported DSL copper access networks. The authors refer to the device that interfaces the copper and fiber networks as a "drop-point" device. The drop-point device will be remotely powered from the subscriber location over the DSL to permit anywhere deployment. With remote powering, the power available to the drop-point device is limited. To address this power source limitation, the authors propose and analyze a strategy for reducing the energy consumption of the drop-point device by reducing its functional logic. Specifically, functional logic at the drop-point device is reduced by moving xDSL functional logic blocks into the OLT. The authors conduct simulation experiments to analyze the performance implications of that strategy. The authors conclude that channel utilization degradation can be kept marginal by utilizing silence suppression mechanisms.

WDM-PONs are considered a strong candidate for mobile cellular backhaul given the high volume of mobile traffic. For cost effective WDM-PON deployments it is desirable to utilize colorless transmitters [110]. Colorless transmitters simplify inventory management and subsequently lower deployment costs compared to fixed wavelength or colored transmitters. In the paper titled "Self-Tuning Transmitter for Fiber-To-The-Antenna PON Networks" by Paola Parolari, Lucia Marazzi, Marco Brunero, Alberto Gatto, Mario Martinelli, Philippe Chanclou, Qian Deniel, Fabienne Saliou, Sy Dat Le, Romain Brenot, Sophie Barbet, Francois Lelarge, Simon Gebrewold, Sean O'Duill, David Hillerkuss, Juerg Leuthold, Giancarlo Gavioli, and Paola Galli, the authors propose the implementation of self-seeded Reflective Semiconductor Optical Amplifier (RSOA) "colorless" transmitters for WDM-PON which can cover the specific requirements for backhauling cellular mobile networks. Self-seeded transmitters do not require an external light source to operate, thereby avoiding backscattering issues. The proposed colorless transmitters can achieve unprecedented data rates, as presented in the experimental results of this paper.

PONs are a natural choice to support the interconnection of large wireless sensor networks to the broader Internet. In the paper titled "Smart Grid Monitoring with Service Differentiation via EPON and Wireless Sensor Network Convergence" by Nima Zaker, Burak Kantarci, Melike Erol-Kantarci, and Hussein T. Mouftah the authors consider PON supported wireless sensor networks used for smart-grid monitoring. The authors classify the smart-grid monitoring data from the PON supported WSNs as either (i) periodic ambient data monitoring (e.g., temperature) or (ii) failure alarms. The authors propose and evaluate an upstream burst PON transmission scheme that is tuned to the unique qualities of the smart-grid monitoring data. The first quality is that the ambient data is continuously sampled and transmitted; samples that have been replaced by newer samples are useless. The second quality is that the failure alarms require prioritization for rapid delivery to the central office (CO). The authors present the results of simulation experiments that illustrate the effectiveness of their transmission scheme at delivering failure alarms within specified delay bounds.

In an era with a widespread realization that usable energy supplies are limited, energy consumption is a performance measure that deserves considerable attention. PON supported access networks are no exception to this. A significant challenge for energy efficient operation is the determination of time periods in which certain device components can be powered down without significant effect on other performance measures. In the paper titled “Energy-Efficient Next Generation Passive Optical Network Supported Access Networking” by Yuanqiu Luo, Meng Sui, and Frank Effenberger the authors design a framework that alerts customer premises equipment (CPEs), such as xDSL modems, to power off their receivers during periods in which no downstream transmissions will be destined for those devices. During time periods where all of the CPE devices attached to an ONU have their receivers powered off, then the ONU can also power off its receiver. This alerting mechanism is coupled with downstream burst transmission from the OLT. Downstream transmissions to individual CPEs are organized into bursts to minimize the cycling between the power-on and power-off states of the ONU and CPE receivers. An analysis of ONU and CPE receiver energy consumption leveraging a Markovian assumption is presented along with the results of a set of simulation experiments. The authors conclude from their presented simulation experiments that energy savings could reach 65% with the presented framework.

In the paper titled “Experimental Evaluation of a Sleep-Aware Dynamic Bandwidth Allocation in a Multi-ONU 10G-EPON Testbed” by Dung Pham Van, Luca Valcarenghi, Michele Chincoli, and Piero Castoldi the authors propose and experimentally evaluate, with a physical testbed, a dynamic bandwidth allocation (DBA) algorithm that reduces energy consumption while also adhering to QoS constraints. The DBA algorithm utilizes fixed timeslots, cycle times, and simultaneous ONU upstream/downstream transmissions to maximize the time period that ONU transceivers are in the power-off state. Using QoS parameters such as delay and bandwidth constraints, a derivation of the fixed cycle time is presented. The authors constructed a physical testbed of a PON with two ONUs. This testbed was used to conduct experiments to observe the energy consumption reduction and ability to maintain a delay constraint. The authors conclude, from the experiments conducted on their testbed, that their DBA algorithm can match the energy reduction performance of alternative mechanisms while also maintaining an upper bound on delay.

In order to support node consolidation through the integration of access and metro networks, Long-Reach PONs have been proposed as the technology of choice. However, guaranteeing a level of delay in this type of network is a challenge given the larger propagation delays, as a result of larger distances, and new high-priority and delay-sensitive traffic. In the paper titled “A PID-based algorithm to guarantee QoS delay requirements in LR-EPONs,” by Tamara Jiménez, Noemí Merayo, Ramón J. Durán, Patricia Fernández, Ignacio de Miguel, Juan C. Aguado, Rubén M. Lorenzo, and Evaristo J. Abril, the authors propose an innovative dynamic bandwidth allocation algorithm (DBA) that successfully copes with the aforementioned challenge in LR-EPONs. This DBA is based on the principle of Proportional-Integral-Derivative (PID) controllers, which allow automatic and reliable control of a parameter such as delay, and guarantee delay bounds. The authors show that this PID-based algorithm outperforms other existent DBA algorithms for LR-EPON, with the interesting note that the performance of the proposed DBA algorithm does not depend on the initial network conditions, while it is fast in fulfilling the required delay levels for high priority traffic.

Similar challenges are also present in LR-GPON. They are solved in the paper titled “An Efficient Dynamic Bandwidth Allocation for GPON Long-Reach Extension Systems” by Vicent Sales, Josep Segarra, and Josep Prat. The authors propose a novel bandwidth allocation scheme that, contrary to other previously proposed schemes, uses a short polling cycle in order to minimize the waiting time before data is being reported. This is possible by implementing forced reports, and by keeping track of the already reported data that is waiting in the ONUs' queues. The ONUs have the task to subtract the already reported traffic still waiting in its queue before submitting the report information. In this way, it was possible to achieve lower delays and lower buffers sizes compared to other relevant bandwidth allocation schemes for LR-GPON.

4. Outlook

Fig. 1 shows the anticipated next-generation PON (NG-PON) roadmap and migration from widely deployed ITU-T G.984 GPON and IEEE 802.3ah EPON to near-term NG-PON1 and mid- to long-term NG-PON2 broadband access solutions, as envisioned and widely agreed upon back in 2009. Beside resolving the notorious cost and complexity issues of cost-sensitive access networks, the primary design goal for future NG-PON1&2 broadband access networks was the provisioning of an ever increasing capacity over time, as illustrated in Fig. 1. Clearly, NG-PON capacity upgrades are needed to support increasingly

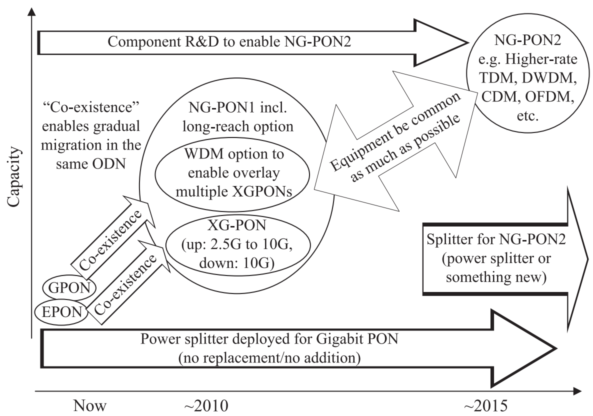

Fig. 1. The old next-generation passive optical network (NG-PON) roadmap as of 2009 [111].

video-dominated traffic and also stimulate the creation of new services and applications.

In the PON community, however, researchers from both industry and academia have begun to contemplate on what the future may hold for NG-PON1&2 and beyond. Recently, at the 2013 OFC/NFOEC conference, a workshop on "Post NG-PON2: Is it More About Capacity or Something Else?" was held to find out whether it is reasonable to ever increase the system bandwidth or rather explore service and application as well as business and operation related aspects, which motivate access technology to move into a substantially different direction in the long run than continued capacity upgrades.

4.1. Wireless backhaul awareness

Clearly, NG-PONs are expected to play an important role in the support of coordinated multipoint (CoMP) coordination schemes among base stations (BSs) in 4G LTE/WiMAX networks. For instance, it was shown in [112] that by using XG-PONs instead of point-to-point fibers, fiber backhaul deployment costs in 4G CoMP architectures can be reduced by up to 80%. Similarly, emerging LTE-Advanced (LTE-A) heterogeneous networks (HetNets) may require a paradigm shift that emphasizes the importance of addressing bottlenecks in the backhaul [113]. LTE-A HetNets introduce femtocells with small, inexpensive, low-power BSs to supplement existing macrocells for the sake of an improved (indoor) coverage, enhanced cell-edge user performance, and boosted spectral efficiency per area unit. Most 4G research so far has been focusing on the achievable performance gains in the wireless front-end only. However, there is a growing consensus that a paradigm shift in wireless cellular research is required that recognizes the importance of high-speed backhaul connections. Without incorporating the details of backhaul implementations into wireless cellular research, possible backhaul bottlenecks can severely limit wireless cellular services [113].

Very recently, in their seminal work on quantifying the impact of different backhaul topologies (mesh vs. tree) and backhaul technologies (e.g., WDM PON) on the performance of cellular networks, Biermann et al. have shown that ultimately the major factor limiting CoMP performance in 4G mobile networks is *latency* rather than capacity of the backhaul [114]. Thus, there is a need for the development of low-latency techniques for NG-PONs and integrated FiWi access networks. We refer the interested reader to [115] for further information about post NG-PON2 research, reviewing recently proposed low-latency techniques for NG-PONs that require architectural modifications at the remote node or distribution fiber level. The review in [115] also highlights advanced network coding and real-time polling based low-latency techniques that can be implemented in software. The reviewed low-latency techniques enable NG-PONs to carry higher traffic loads and thereby extend their lifetime, and maintain the passive nature of existent optical distribution networks.

There is a tacit consensus among researchers and practitioners in the PON community that the fault-tolerant design and key dependability properties, such as availability and survivability, will become increasingly important in emerging NG-PONs. More specifically, service and business continuity guarantees are expected to play a more prominent role in future optical access networks given that NG-PONs carry significantly increased traffic loads on multiple WDM channels, each operating at 10 Gb/s or higher. Also, long-reach NG-PONs hold great promise to achieve major cost savings by consolidating access and metropolitan area networks and thereby serving much larger areas covering hundreds or even thousands of ONUs. A number of promising survivability techniques for NG-PONs and FiWi access networks exist, including ONU dual homing, hitless protection switching by means of equalization delays, interconnection fibers, protection rings, meshed PON topologies, wireless protection, and advanced in-service monitoring techniques for fault detection and localization in PON distribution fibers [116].

4.2. Smart grid communications infrastructures

Highly reliable NG-PONs and FiWi access networks can be used to enable or enhance the dependability of one or more other critical infrastructures. In fact, NSERC, Canada's federal research agency, postulates that broadband access networks become "*less an end in itself than a means to an end*" by exploiting them not only for telecommunications per se but also other relevant economic sectors, such as energy and transportation, for the sake of synergies and increased overall impact [117].

Recently a number of major telecommunication service providers, such as KT and Telecom Italia, have started to move into the energy market. An interesting example is Deutsche Telekom's new offering of virtual power plants, where homes deploy combined heat and power plants (CHPPs) on site to locally supply both hot water and power, thereby reducing the load on the power grid and avoiding transmission line losses.[4] Importantly, note that business models, arguably more than technological choices, play a key role in the roll-out of future *smart grid communications infrastructures*. According to [118], utilities along with municipalities are responsible for 22% of households passed with fiber-to-the-building/home (FTTB/H) in Europe. These investments enable utilities and/or municipalities to (i) leverage their existing duct, sewer, and other infrastructure, (ii) create a new source of revenue in the face of ongoing liberalization of the energy sector, particularly in smart grid solutions, and (iii) provide services completely independent from incumbents' infrastructures.

Furthermore, it was recently shown in [119] that cooperation among different utilities in the roll-out phase may drive down the CAPEX of FTTB/H deployments by 17%. Innovative partnerships enable utilities and other players to share smart grid communications infrastructures investments by transitioning from the traditional vertical network integration model towards splitting the value chain into a three-tier business model that consists of network infrastructure roll-out, network operation/maintenance, and service provisioning [118]. One of the most

[4] "Deutsche Telekom delivers virtual power plants," April 2012, Online available at: http://www.telekom.com/media/enterprise-solutions/121194.

promising examples of such a multi-tier business model is the Swiss Fibre Net of OPENAXS, an association of currently 22 regional electricity utilities throughout Switzerland (see also `www.openaxs.ch`). The goal of Swiss Fibre Net is to create added value for consumers by having 30% of FTTB/H connected households by 2013 and 80% by 2020. The power utilities are responsible for the installation of the network infrastructure as well as its operation and maintenance, but leave its access open to all (e.g., triple-play voice, video, and data) service providers on a nondiscriminatory basis. Another interesting example is the recent interest of Chinese utility companies, e.g., State Grid Corporation of China (SGCC), in PON equipment to not only backhaul electric data on usage and outages of their power networks but also, and arguably more interestingly, to offer FTTH services to consumers and businesses.[5]

A plethora of wired and wireless networking technologies exists to realize smart grid communications infrastructures [120]. It is important to note, however, that in general the goal of utilities is to use only a small number of low-cost, simple, reliable, and future-proof smart grid communications technologies that remain in place for decades after installation. It is also worthwhile to mention that IEEE P2030, one of the first smart grid standards, does not specify any communications technology of choice for the future smart grid gradually evolving between now and 2030, though it is favorable to rely on the exceptionally low latency characteristics of fiber optic facilities, either owned or leased by the smart grid operator, and wireless technologies, where fiber is available to some but not all points in the system [121]. More precisely, besides wireless technologies the superior security and immunity features of PON based communications infrastructures, which are already installed in many countries, will be leveraged for the realization of large-scale sensor-actuator networks in support of future smart grid applications [122].

Many vital building blocks, organizations, and activities of today's society depend on the continued operation of various large and widespread critical infrastructures, including telecommunications networks and transportation systems. In particular, energy generation and distribution systems play a crucial role. Electrical power grids represent one of the most important critical infrastructures of our society. Current power grids with their aging infrastructure become increasingly unreliable and are poorly suited to face increasingly frequent outages, e.g., the three-day blackout due to trees falling on power lines in the Washington D.C. area early July 2012, the lengthy power blackout in the states of New York and New Jersey due to hurricane "Sandy" in October 2012, or more recently in February 2013, the power outage during Super Bowl 2013, which lasted for 34 min.

4.3. A sustainable third industrial revolution economy

In coming years, power grids in the United States, Europe, and other regions worldwide are expected to undergo major paradigm shifts. Today, Internet technology and renewable energies are beginning to merge in order to create the infrastructure for the so-called *Third Industrial Revolution* economy, which goes well beyond current austerity measures and has been officially endorsed by the European Commission as economic growth roadmap toward a competitive low carbon society by 2050 and has been implemented by several early adopting countries such as Germany, England, and Italy, as well as cities such as San Antonio, TX, USA, among others [123]. It has been receiving an increasing amount of attention by other key players, e.g., the Government of China most recently. In the coming era, millions of consumers will produce their own renewable energy and share it with each other via an integrated and seamless *Energy Internet*, similar to the way we use to create and share information online nowadays.

The future Energy Internet aims at not only addressing the aforementioned reliability issues of current power grids but also offering several additional major benefits. The Energy Internet will be instrumental in realizing the vision of the smart grid by incorporating sophisticated sensing, monitoring, information, and communications technologies to provide better power grid performance, engage customers to play an interactive role, and support a wide range of additional services to both utilities and consumers. Potential smart grid applications include substation and distribution automation, advanced metering infrastructure (AMI), wide-area situational awareness (WASA), home energy and demand response management, outage management, distributed generation and renewables, and grid-to-vehicle/vehicle-to-grid (G2V/V2G) electricity storage and charging applications for plug-in electric vehicles (PEVs) [124]. The authors also quantified the communications requirements of the aforementioned smart grid applications in terms of latency, bandwidth, reliability, and security, and concluded that a *fast* and *reliable* smart grid communications infrastructure is necessary to enable real-time exchange of data among distributed power grid elements, e.g., power generators, energy storage systems, and users.

Hence, in addition to the aforementioned low-latency NG-PON technologies, there is a need for the design of dependability enhancing techniques to improve the reliability, availability, survivability as well as (cyber) security and (physical) safety of both converged bimodal FiWi smart grid communications infrastructures and underlying power distribution networks. Indeed, the majority of power outages occur in the power distribution networks, and these networks offer the most opportunities for energy efficiency and integration of renewable distributed energy resources (DERs), e.g., solar panels and wind turbines [125].

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