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Article

The Escape of Sisyphus or What "Post NG-PON2" Should Do Apart from Neverending Capacity Upgrades

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Abstract: The primary design goal of (r)evolutionary NG-PON1&2 was the provisioning of an ever increasing capacity to cope with video-dominated traffic and handle the explosion of mobile data traffic by means of offloading. Recently, however, questions on the future of "post NG-PON2" have surfaced whether to shift its research focus to business and operation related aspects and move access technology into a substantially different direction than continued capacity upgrades. In fact, recent studies indicate that ultimately the major factor limiting the performance of 4G mobile networks is *latency* rather than capacity of the backhaul. In this paper, we review recently proposed low-latency techniques for NG-PONs that require architectural modifications at the remote node or distribution fiber level and highlight advanced network coding and real-time polling based low-latency techniques that can be implemented in software, enable NG-PONs to carry higher traffic loads and thereby extend their lifetime, and maintain the passive nature of existent optical distribution networks. Furthermore, we elaborate on emerging trends and open challenges for future post NG-PON2 research. To better understand their true potential, we put them into a wider non-technical and historical perspective leading up to a sustainable Third Industrial Revolution (TIR) economy and its underlying Energy Internet.

Keywords: Energy Internet; golden age prosperities; low carbon society; mobile backhaul; network coding; NG-PON; offloading; real-time polling; smart grid; Third Industrial Revolution (TIR)

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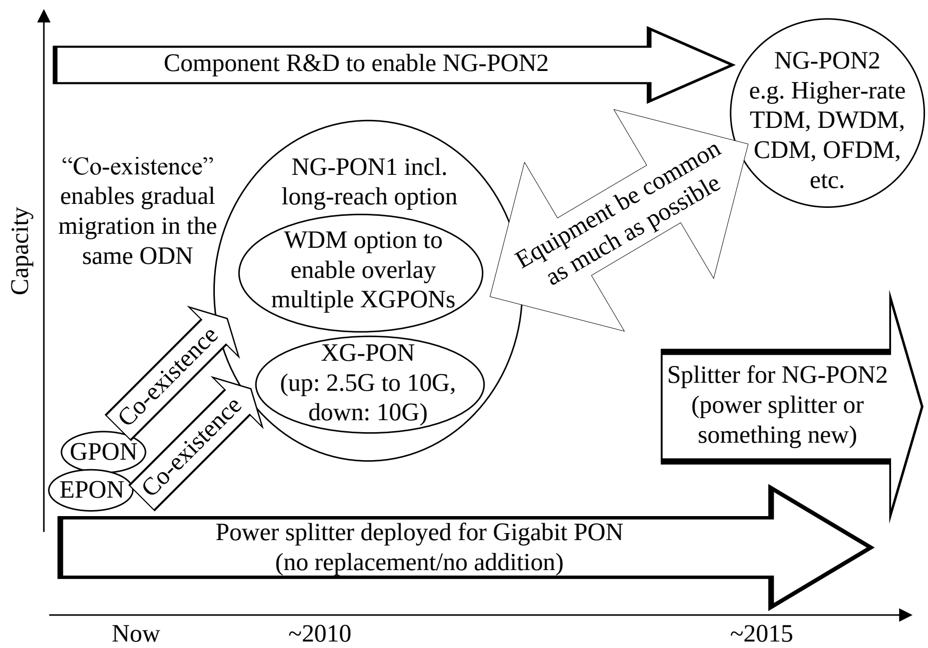
1. Introduction

Passive optical network (PON) research and technology have matured over the last three decades and have established PONs as a cornerstone of today's deep fiber access solutions [1]. Emerging next-generation PON (NG-PON) technologies come in two flavors: (i) NG-PON1 technologies for an evolutionary growth of existent Gigabit-class PONs with co-existence requirements on the same optical distribution network (ODN); and (ii) disruptive NG-PON2 technologies for a revolutionary upgrade of current PONs without any co-existence requirements with existent Gigabit-class PONs on the same ODN [2]. NG-PON solutions include a number of performance-enhancing technologies, most notably, time division multiplexing (TDM) XG-PON to support (a)symmetric 10 Gb/s or even higher-rate TDM PONs, (dense) wavelength division multiplexing ((D)WDM) PON as an option to realize an overlay of multiple XG-PONs on the ODN, reach extenders to enable long-reach PONs, as well as code division multiplexing (CDM) and orthogonal frequency division multiplexing (OFDM) PONs. Figure 1 shows the anticipated NG-PON roadmap and migration from widely deployed ITU-T G.984 GPON and IEEE 802.3 ah 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 Figure 1.

Figure 1. Next-generation passive optical network (NG-PON) roadmap as of 2009 [2].

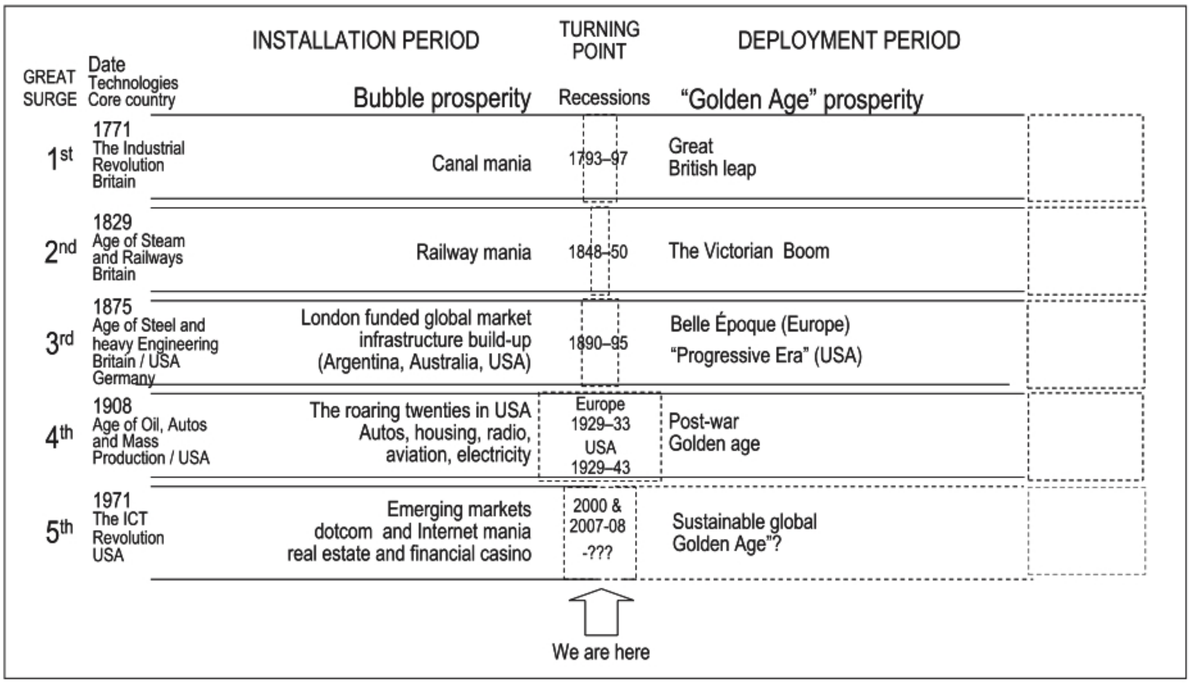


Clearly, NG-PON capacity upgrades are needed to support increasingly video-dominated traffic, handle the explosion of mobile data traffic by means of offloading, and also stimulate the creation of new services and applications. On the other hand, it is vital to the business needs of next-generation optical access (NGOA) network operators to recognize when "enough is enough." To better understand the consequences of blind capacity upgrade strategies beyond the actual need, it may be helpful to go back in history of optical networks. During the Internet bubble, the expected bandwidth requirements were hugely overestimated and way too many optical networks were built, flooding the market with unneeded capacity. As a consequence, prices for dark fiber became so low that customers, e.g., banks and corporations with large data transfer needs, started to buy up low-cost dark fibers and run their own optical links and networks. Similarly, the prices for monthly leases of optical fiber conections decreased significantly. For instance, the prices for monthly leases on 10 Gb/s links between Miami and New York City fell from around \$75,000 in 2005 to below \$30,000 at the end of 2007, and prices for 10 Gb/s connections between New York and London fell by 80% from 2002 to 2007 [3]. To make things look even dimmer for network operators (but not necessarily customers), it is worthwhile to note that about 80%–90% of the world's installed fiber is unlit, *i.e.*, is not used, and only 18% of the world submarine fiber is lit [4].

In the PON community, 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 rung than continued capacity upgrades. 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 [5] 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%. In fact, in emerging LTE-Advanced (LTE-A) heterogeneous networks (HetNets), where femtocells with small, inexpensive, low-power BSs are introduced to supplement existing macrocells for the sake of an improved (indoor) coverage, enhanced cell-edge user performance, and boosted spectral efficiency per area unit, a cellular paradigm shift is required that recognizes the importance of high-speed backhaul connections, given that most 4G research so far has been focusing on the achievable performance gains in the wireless front-end only without looking into the details of backhaul implementations and possible backhaul bottlenecks [6]. Very recently, however, 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 [7].

To help identify open key research challenges for NG-PONs and converged fiber-wireless (FiWi) broadband access networks, it is important to consider emerging trends in related areas in order to shift the post NG-PON2 research focus from mere capacity provisioning to more lucrative solution offerings by developing holistic groundbreaking solutions across multiple economic sectors other than telecommunications *per se*. Toward this end, we will first elaborate on emerging trends and open challenges for post NG-PON2 research. We will then highlight advanced techniques to reduce latency in NG-PON based backhaul infrastructures and describe them in greater detail. More interestingly, to better comprehend the true potential of the aforementioned emerging trends, it is helpful to put them into a wider non-technical context and see how they fit into the bigger picture of present (and past) economic recessions. The current global crisis is far from unexpected, but rather represents a recurrent historical event that is typical for capitalist economies. As recently explained by Carlota Perez in her excellent work on the implications of financial collapses [8], there have been four previous situations equivalent to the current crisis in the past two centuries since the first industrial revolution. Figure 2 illustrates the historical recurrence of recessions as turning points, where roughly every 50 years the installation period of new technologies, the time when financial capital shapes the economy, has led each time to a major bubble followed by a major crash. This is the time for states to come back actively to change the focus from the stock market indices to the job-creating expansion of the real economy and increase in social wellbeing and to take convergent and synergistic actions that will lead markets and society to the next golden age, or deployment period, where the benefits of new technologies are fully realized across the entire economy, thereby offering a vast innovation and growth potential across multiple economic sectors. Toward this end, according to Perez, it is vital to expand Internet access either with fiber to the home (FTTH) or with wireless broadband access and combine ICTs with massive "green" innovations in order to usher in a *sustainable global golden age*, which appears to be the only sustainable means to both stimulate the US and European economies and allow the incorporation of hundreds of millions of new consumers of a rapidly rising global middle class with more sustainable lifestyles and consumption patterns than in the past. In this paper, we argue that NG-PONs and FiWi access networks will represent a cornerstone of future broadband installations and explore ways of how they can be deployed across relevant economic sectors other than telecommunications per se. After elaborating on the rationale behind the *Third Industrial Revolution (TIR)* and its underlying Energy Internet, we will report on recent progress on low-latency techniques for NG-PON based infrastructures for mobile backhaul as well as smart power grid applications.

Figure 2. Historical recurrence of once-in-a-half-century bubble and golden age prosperities [8].



The remainder of the paper is structured as follows. Section 2 provides an overview of emerging trends and sets the stage by identifying open challenges for post NG-PON2 research. In Section 3, we describe the relationship between TIR and Energy Internet and its implications in greater detail. Section 4 briefly reviews the pros and cons of recently proposed low-latency techniques for NG-PONs and highlights advanced network coding and real-time polling based techniques to further reduce latency in NG-PONs. Finally, Section 5 concludes the paper.

2. Post NG-PON2 Research: Emerging Trends and Open Challenges

2.1. NG-PONs and Converged Fiber-Wireless (FiWi) Access Networks: State of the Art and Recent Progress

FiWi access networks, also referred to as hybrid optical-wireless access networks (HOWANs) and wireless-optical broadband access networks (WOBANs), aim at combining the reliability, robustness, and high capacity of optical fiber networks with the flexibility, ubiquity, and cost savings of wireless networks. Over the last few years, significant progress has been made on the design of hybrid optical-wireless access networks [9]. FiWi access networks include conventional radio-over-fiber (RoF) networks, which have been studied for decades as an approach to carry radio frequencies over optical fiber links between a central control station and multiple low-cost remote antenna units, e.g., distributed antenna system (DAS) connected to the BS of a fiber optic microcellular network. RoF networks are well suited to realize networks with centralized control, e.g., traditional cellular networks. The vast majority of RoF studies focused on transmission issues at the physical layer without taking higher-layer protocols into account. However, most of the recent layer-2/layer-3 networking (rather than layer-1 physical transmission) research activities have been focusing on FiWi access networks that are based on integrated low-cost and simple Ethernet passive optical network (EPON), wireless local area network (WLAN), and WiMAX technologies. A comprehensive and up-to-date overview of previously proposed cellular, EPON, WiMAX, and WLAN-mesh based FiWi access network architectures, network planning and reconfiguration, techno-economic analysis of WiMAX *vs.* EPON, wireless and integrated optical-wireless routing algorithms, powerful hierarchical frame aggregation techniques as well as quality-of-service (QoS) continuity techniques across the optical-wireless interface was provided in [10]. The challenges and opportunities of FiWi access networks were described in [11]. Although a few recent FiWi architectural studies exist on the integration of EPON with 4G LTE wireless networks, the vast majority of previous studies considered FiWi access networks consisting of a conventional IEEE 802.3 ah EPON fiber backhaul network and an IEEE 802.11 b/g/n/s WLAN-based wireless mesh front-end network [9–11].

The design of *energy-efficient "green" FiWi access networks* has been receiving considerable attention. An overview of recently proposed energy-efficient architectures as well as energy-efficient medium access control (MAC) and routing protocols for FiWi access networks was provided in [12]. The authors also proposed an optical burst switching (OBS) based dynamic bandwidth allocation (DBA) protocol for the energy-efficient integration of long-reach EPON and LTE-A technologies and investigated the tradeoffs between energy savings and QoS guarantees. The simulation and experimental work in [13] has shed some light on the tradeoff between energy saving and QoS support in FiWi access networks. A unified analytical framework for the throughput-delay performance evaluation of a wide range of FiWi network routing algorithms was developed in [14,15], taking emerging very high throughput (VHT) IEEE 802.11 ac WLAN technologies and PON fiber faults into account. Beside the energy-efficient design of FiWi access networks, their survivability has been another recent important research area. A variety of *advanced survivability techniques for NG-PONs and FiWi access networks* were investigated in [16,17]. A centralized architecture incorporating RoF and cognitive radio technologies into a unified network called cognitive WLAN over fibers by replacing WLAN access points (APs) with remote antenna units was presented in [18], including a testbed architecture built on a PON and software defined radio platform. Network coding based energy management solutions for NG-PONs were presented in [19]. The capacity and delay performance of various types of NG-PON were analyzed in [20]. A scheduling and DBA scheme that allows the co-existence of high-speed 10 Gb/s EPONs and WDM PONs on the same optical infrastructure was studied in [21]. A cost-effective and fully centralized RoF network architecture based on integrated long-reach WDM PON, with an optical fiber range of 100 km, and LTE/WiMAX networks, where the optical and wireless transmission impairment compensation is done only at the central office, was proposed and experimentally investigated for so-called quintuple-play services (high-speed data, voice, television, management, and home security) [22]. In [23], a novel MAC protocol for FiWi access networks to efficiently carry the ever increasing amount of video traffic was proposed and investigated.

Recently, the *integration of wireless and fiber optic sensors* into FiWi access networks has begun to receive increasing attention. In [24], a hybrid approach combining genetic algorithm and tabu search techniques was proposed to determine the optimal placement of optical network units (ONUs)—the CPE of a PON—in hybrid PON-wireless sensor network (WSN) based networks, whereby the ONUs' high power and processing capabilities were used to serve as cluster heads with the objective to minimize the wireless sensors' energy consumption. In [25], a DBA algorithm was developed for a hybrid PON-WSN network, where ONUs are connected to FTTH terminals or to WSN cluster heads for remote monitoring systems in a ubiquitous city, e.g., medical sensors in a hospital monitoring system. The integration of solar-powered wireless sensors and low-power fiber optic sensors into a PON was experimentally demonstrated in [26]. Finally, the research and development vision of an ideal access system architecture was outlined in [27], identifying the following three key design goals of future broadband access network architectures: (i) "adaptable;" (ii) "dependable;" and (iii) "eco-conscious". Toward this end, the authors concluded that passive (optical) network infrastructures should be used as much as possible and passive equipment may be shared in order to enable cost reduction, promote open and fair service competition, create novel value-added services, and introduce original business ideas for the realization of future-proof broadband access networks based on both wireless and fiber media.

2.2. Emerging Trends and Open Challenges

The explosion of mobile data traffic has mandated the need for a new cellular architecture. *Femtocells*, which need to be more autonomous and self-adaptive than traditional *small cells*, are now widely deployed as small, inexpensive, low-power BSs. Beside economic and regulatory issues, the new key challenges arising in femtocell deployments are (i) interference coordination; (ii) cell association and biasing; (iii) mobility and soft handover; and (iv) self-organizing networks (SONs) [28]. Key to the cost-effective deployment and operation of small-cell networks will be the sharing of already existing high-capacity *FTTx backhaul infrastructures* [29]. The importance of high-capacity and low-latency fiber backhaul infrastructures in HetNets is also emphasized by the introduction of CoMP, one of the important performance-enhancing features of 3GPP LTE-A Release-11, which will have a major impact on the backhaul and will demand a careful design of backhaul links between BSs in order to provide high data rates and very low latency in the range of 1 ms or lower for the efficient coordination of transmission and reception among multiple BSs [30]. When migrating from macro-only to HetNet environments, mobility management becomes more challenging due to increased interference and decreased (femto)cell radius. According to [31], there is a clear trend toward including additional mobility enhancements in future LTE releases to ensure a smooth migration from traditional network controlled to *user equipment (UE) assisted mobility* as a remedy for reducing signaling overhead via fiber interconnections between macrocells and small cells. Among other mobility-based UE distribution techniques, *traffic steering* represents a promising approach for both load balancing and minimization of unnecessary handovers in HetNets [32]. Moreover, the introduction of SON technologies holds great promise to not only optimize network capacity, coverage, and service quality, but also to substantially reduce (i) the complexity of interference coordination and, arguably more importantly; (ii) both operational and capital expenditures (OPEX/CAPEX) of LTE-A HetNets by minimizing human intervention [33]. Among the various SON functionalities, *self-healing* has so far received the least attention as opposed to widely studied self-configuration and self-optimization, making the development of real-time fault-compensation algorithms a key research topic in LTE-A HetNets [34].

Recall from above that the vast majority of previous FiWi network studies considered architectures based on low-cost simple EPON fiber backhaul and capacity-centric WLAN solutions. With the advent of high-speed IEEE 802.3 av 10G-EPON and commercially available multichannel WDM PONs in conjunction with the emergence of Gigabit-class IEEE 802.11 ac VHT WLAN technologies providing raw data rates of up to 6,900 Mb/s, future FiWi access networks will give rise to fiber backhaul and wireless front-end infrastructures of unprecedented capacity. In the past, WiFi and cellular radio access networks (RANs) have been in constant competition, until recently when tighter integration of both capacity-centric WLAN and coverage-centric mobile networks has emerged as a necessary paradigm [35]. The WLAN mesh front-end of FiWi access networks may be used to provide *WiFi offloading* of rapidly increasing mobile data traffic from cellular networks, thereby avoiding the need for capacity upgrades while at the same time helping reduce the complexity of future mobile networks. An interesting precursor of this trend is Deutsche Telekom's recently announced deal with crowdsourced WiFi hotspot provider FON, whose subscribers have signed up to mutually share their home broadband services in order to provide free "WiFi To Go" service on millions of hotspots worldwide. Complementing fast evolving HetNets with already widely deployed WiFi access points in addition to femtocells, which together are projected to carry over 60% of the global data traffic by 2015, represents a key aspect of the strategy of today's operators to offload mobile data traffic from their cellular networks [36]. It was recently shown by means of real-world iPhone measurements that significant offloading as well as battery power saving gains can be obtained if data transfers are delayed with some deadline until users enter a WiFi zone, though the achievable performance gains highly depend on given user mobility and spatial/temporal WiFi coverage patterns [37]. Beside traffic-aware scheduling, *backhaul sharing* is gaining significant importance to enhance the performance of cellular networks overlaid with WiFi offloading hotspots [35].

Another important trend is the convergence of mobile cellular networks and WSNs in order to support *machine-to-machine (M2M) communications*. It was shown by means of simulation that the throughput-delay performance and lifetime of WSNs can be remarkably increased in such a converged network, but a number of essential issues still need to be resolved, most notably jointly optimized channel access techniques, two-level resource allocation schemes, and robust re-selection algorithms [38]. Especially for event-driven M2M communications, where a large number of devices become activated within a short period of time, traffic-aware random MAC protocols were shown to provide superior delay performance and robustness [39]. According to a recent OECD report on the future digital economy, one of the most promising applications of M2M communications is smart metering, which represents one of the first steps toward realizing the vision of the *smart power grid* [40]. The European Union (EU) has mandated the use of smart meters by 2020 in Directive 2006/32/EC, creating a market for around 180 million meters at a rate of one per household. Beside 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 [41]. Smart grids will be the backbone of the future electricity network of the EU integrating the high penetration of renewable energy sources and enabling the flexible participation of customers, as witnessed by the EcoGrid EU project, which establishes the first prototype to provide a market-based platform and information and communication technology infrastructure of the future European intelligent power grid [42]. Today, Internet technology and renewable energies are beginning to merge in Europe, North America, and other regions worldwide in order to create an interactive, integrated, and seamless *Energy Internet* infrastructure for the so-called *Third Industrial Revolution (TIR)* 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 [43], as discussed in more detail next.

3. The Third Industrial Revolution (TIR) and Energy Internet

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, DC 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.

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 TIR economy, which 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 [43]. 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 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) [44]. 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 *reliable* and *fast* 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.

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. "Deutsche Telekom delivers virtual power plants". Importantly, note that business models, arguably more than technological choices, play a key role in the roll-out of smart grid communications infrastructures. According to [45], 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 [46] 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 [45]. One of the most 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. "China's smart grid drive creates $1.5 billion opportunity for PON vendors, says Ovum".

A plethora of wired and wireless networking technologies exists to realize smart grid communications infrastructures [47]. 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 [48].

In [49,50], we recently described a variety of advanced techniques to render NG-PONs and converged bimodal FiWi broadband access networks *dependable*, including optical coding based fiber fault monitoring techniques, localized optical redundancy strategies, wireless extensions, and availability-aware routing algorithms, in order to improve their reliability, availability, survivability as well security and safety. Recall from above that beside reliability, *latency* is a key requirement of not only smart grid communications but also LTE-A fiber backhaul infrastructures. Toward this end, we elaborate on various techniques to lower the latency of NG-PON based smart grid communications and mobile backhaul infrastructures in the following.

4. Low-Latency Techniques for NG-PON Based Smart Grid Communications and Mobile Backhaul Infrastructures

The integration of LTE and IEEE 802.3 av 10G-EPON networks was studied in [51], where 10G-EPONs are used as the backhaul to LTE with the objective to enable intercommunication between neighboring BSs, which are attached to collocated ONUs, via LTE's X2 interface. The authors proposed the following three integration architectures: (i) native 10G-EPON/LTE integration architecture (NGLIA); (ii) loopback integration architecture (LIA); and (iii) remote node integration architecture (RNIA). NGLIA is a simple integration architecture that cascades 10G-EPON and LTE networks without requiring any ODN modifications. At the downside, all upstream traffic coming from collocated ONU/BSs and destined to neighboring ONU/BSs or stemming from handovers between a given pair of ONU/BSs has to traverse the OLT, resulting in an increased latency and non-negligible packet delays. Both LIA and RNIA are able to avoid this shortcoming, at the expense of architectural modifications of the ODN. In LIA, the splitter/combiner at the remote node is replaced with an $(N + 1) \times (N + 1)$ passive star coupler (PSC), to which each of the N ONU/BSs is connected via an additional fiber to provide a loopback path and enable direct optical communication among all ONU/BSs through the PSC without having to traverse the OLT. It is worthwhile to mention that LIA uses the same (single) upstream wavelength channel of 10G-EPON, *i.e.*, does not require any additional transmitter at the ONUs. However, LIA does require that each ONU is equipped with an additional receiver to receive the loop-backed packets. Also note that LIA allows the bandwidth allocation to be handled in a distributed manner by the ONU/BSs (instead of the central OLT) due to the fact that each upstream packet is looped back to all ONU/BSs, thereby giving rise to the implementation of distributed MAC protocols. Clearly, the modified loopback architecture of LIA helps reduce latency (and free up downstream bandwidth between OLT and ONUs) by throwing hardware at the problem, which might violate given budget constraints of cost-sensitive access networks. Similarly, RNIA relies on inserting *active* remote nodes in the distribution fibers of the ODN. These active remote nodes have the intelligence to perform MAC layer functionalities, e.g., packet filtering, storing, and forwarding. The basic idea behind RNIA is to replicate the MAC layer functionalities of the central OLT in distributed proxies and place them closer to ONU/BSs in order to decrease latency. In doing so, this results not only in additional costs but also, and arguably more importantly, in losing the trademark of PONs, their completely unpowered nature.

In the following, we highlight advanced techniques that are able to significantly lower the latency in NG-PONs, while aiming at minimizing the amount of required ODN modifications and hardware upgrades as well as maintaining the passive fiber infrastructure.

4.1. Network Coding

The rationale behind network coding is to extend the functionality of nodes in communications networks from traditional routing, switching, and forwarding individual packets on a per-packet basis to performing bit- or packet-level operations on multiple packets by generally using linear algebraic approaches, leading to an improved network performance in terms of throughput, delay, reliability, and other metrics. For illustration, Figure 3 shows the potential of network coding to increase the bandwidth efficiency and thus throughput of a conventional power-splitting PON. In the considered scenario, two packets are exchanged between two ONUs. Owing to the PON's directional splitter/combiner, ONUs may communicate only through the intermediary of the OLT. In conventional PONs, such an exchange is usually performed in four separate packet transmissions, with the OLT receiving and then broadcasting each packet individually (see Figure 3a). With NC, the OLT may code the received packets into a single packet using a simple bitwise exclusive-OR (XOR) operation, denoted by $\oplus$ (see Figure 3b). Upon receiving the coded packet, the ONUs decode the packets destined to them using a copy of their previously transmitted packets. NC hence achieves the packet exchange in only three packet transmissions, using 50% less downstream bandwidth than conventional PONs. Importantly, note that the above network coding operations could be implemented in software without requiring any hardware modifications of EPON and thus making the upgrade easy and less costly.

To showcase the beneficial impact of network coding on not only the throughput but also delay performance, Figure 4 depicts simulation results on the performance gains of a network coding enhanced EPON with 16 ONUs equidistantly located at 20 km from the OLT.

Figure 3. Network coding in a power-splitting PON.

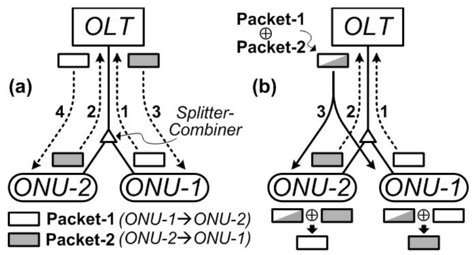
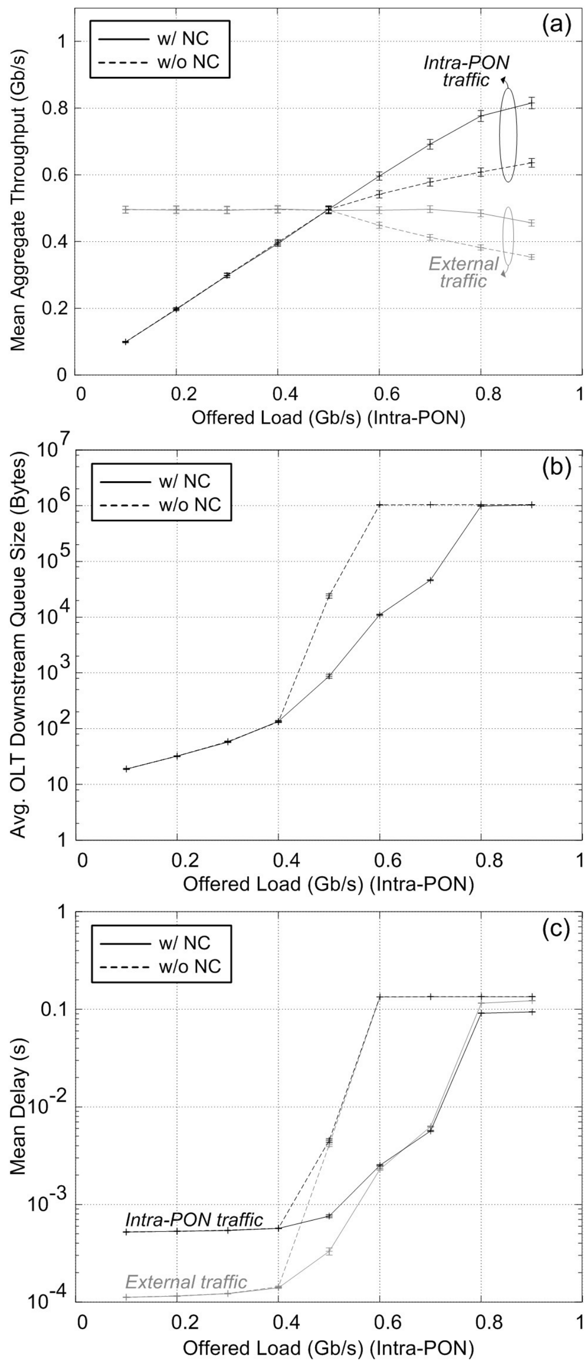


Figure 4. Performance enhancements of an EPON through network coding.



For arbitration of upstream transmissions, the well-known interleaved polling with adaptive cycle time (IPACT) algorithm, a benchmark DBA algorithm for EPON, with limited service of 15 kbytes per ONU in each polling cycle is deployed. Under the assumption of uniform Poisson traffic with a packet size uniformly distributed over the interval [64, 1,518] bytes, intra-PON traffic is generated by any given ONU and is destined to any of the remaining ONUs. Whereas external traffic represents downstream traffic originating from the OLT and destined to ONUs. In the following, the external traffic rate is fixed to 0.5 Gb/s and the intra-PON traffic rate is varied from 0.1 Gb/s to 0.9 Gb/s.

The aggregate throughput plots of Figure 4a show that coding gains appear at the point of congestion, when the intra-PON traffic load is 0.5 Gb/s. This point corresponds to the input aggregate traffic level (of both intra-PON and external packet streams) reaching the downstream data rate. As the OLT downstream queues backlog grows, more coding opportunities arise, and the coding gain increases almost to 30% (0.2 Gb/s) for intra-PON traffic. Note that throughput gains are also achieved by the uncoded external traffic stream, reaching 27% (0.1 Gb/s) at the highest intra-PON traffic load. Importantly, Figure 4a clearly demonstrates that with network coding a mean aggregate throughput well above the nominal EPON data rate of 1 Gb/s can achieved. In other words, a network coding enhanced EPON is able to carry higher offered traffic loads beyond the point of congestion by reducing the volume of carried traffic via network coding. In doing so, network coding is a powerful technique to avoid or at least postpone costly capacity upgrades of current EPONs and thereby extend their lifetime significantly. Figure 4b depicts the average steady-state size (*i.e.*, occupancy) of the corresponding OLT downstream queues. We observe that the downstream queues at the OLT for the network coding enhanced EPON saturates at significantly higher traffic loads compared with a conventional EPON. Note that the capability of network coding to drain the downstream queues at higher rates hence provides a window of operation (0.5–0.8 Gb/s), where the information rate exceeds the data rate (*i.e.*, 1 Gb/s in EPON), translating into a higher throughput, as mentioned above. Figure 4c shows the mean packet delay for intra-PON and external traffic, defined as the average value of the delay experienced by packets from the moment they are queued at their source ONU (intra-PON traffic) or OLT (external traffic) to the moment they arrive at their destination ONU. As the load increases, packets are coded more often, thus spending less time in the queue. Remarkably, this translates into a delay reduction of more than one order of magnitude as the aggregate traffic rate rises above the downstream data rate (intra-PON traffic loads of 0.6 Gb/s and 0.7 Gb/s) for both intra-PON and external traffic. As queues approach saturation in the network coding enhanced EPON, packet delays remain below conventional EPON levels.

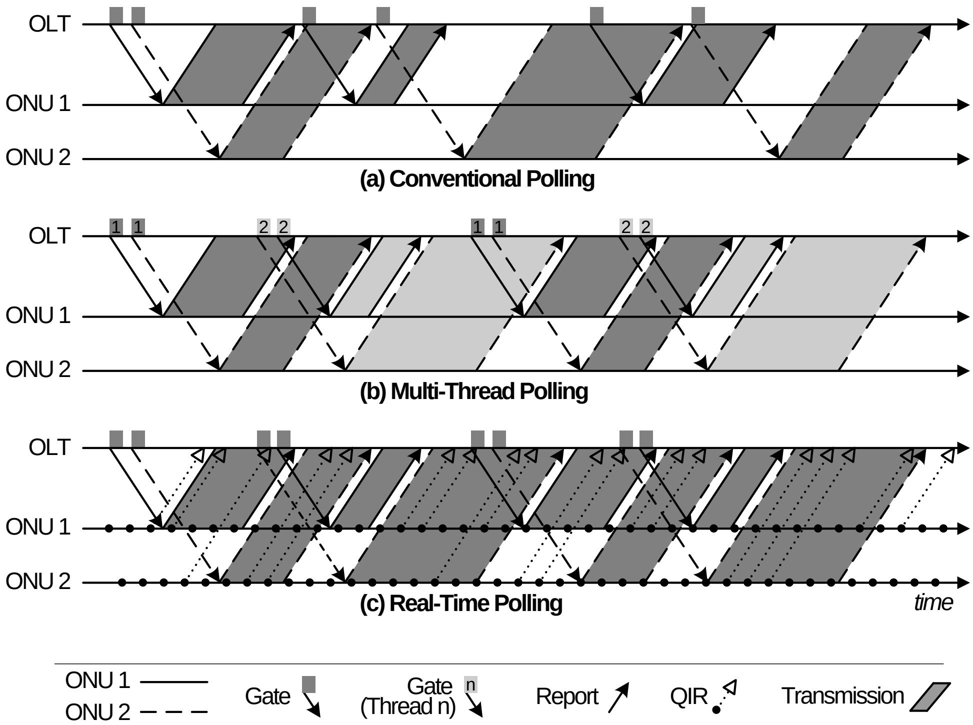
In summary, we have seen that network coding is a simple yet powerful technique that can be cost-efficiently implemented in software, enables existent EPONs to carry higher traffic loads and thereby extend their lifetime, while at the same time decreases their mean delay dramatically. For further information on network coding in NG-PONs we refer the interested reader to [52].

4.2. Real-Time Polling

Next-generation long-reach PONs are expected to span optical ranges of up to 100 km. Moreover, long-reach PONs are expected to operate at a line rate of 10 Gb/s and accommodate 2,000 to 4,000 ONUs. The increased propagation delay of long-reach PONs may lead to a significantly increased idle time and delay if ONUs use conventional report-grant mechanisms, as specified in the multipoint control protocol (MPCP) of IEEE 802.3 ah EPON via the so-called REPORT and GATE messages.

Figure 5a shows an example of conventional polling in an EPON with two ONUs. Conventional polling imposes a critical constraint on the downstream transmission of GATE messages: they may not be transmitted before the arrival of the REPORT message to the OLT. Since the OLT cannot generate a GATE before receiving a REPORT, the cycle duration in conventional polling cannot fall below the maximum round-trip time $\mathrm{RTT}_{\mathrm{max}}$ between the OLT and the most distant ONU. This feature is the crucial limitation of conventional polling: it places an upper-bound on the frequency of REPORTs and data transmissions emanating from any ONU. As a result, the average frame delay grows with increasing round-trip propagation delay. To illustrate this, consider the worst-case scenario where a frame is generated an infinitesimal time after the transmission of a REPORT message. In that case the frame experiences a delay equal to the cycle duration before its bandwidth requirement is reported to the OLT. The fact that the cycle duration is lower-bound by $\mathrm{RTT}_{\mathrm{max}}$ hence compounds the delay and capacity problem in next-generation long-reach PONs.

Figure 5. Conventional and low-latency polling schemes.



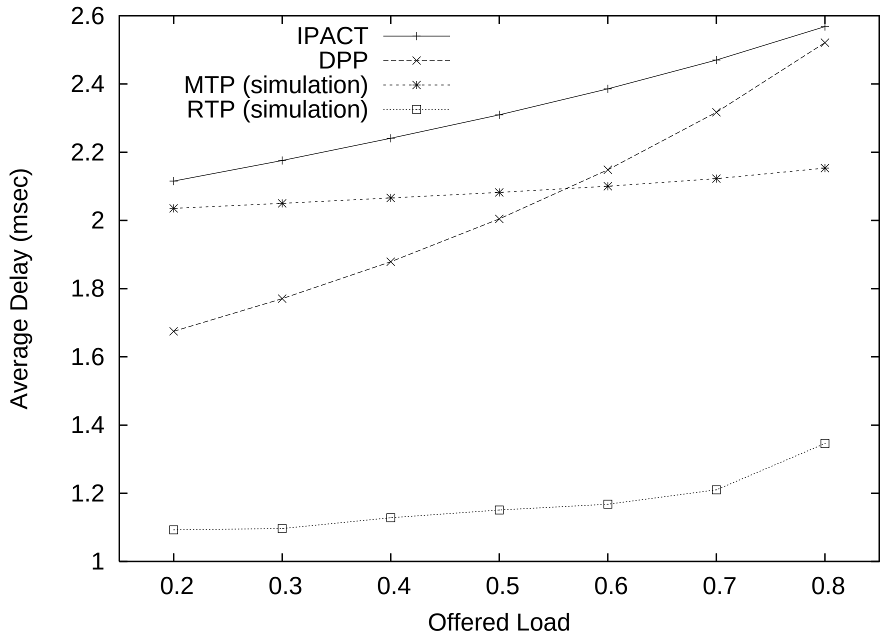
The first candidate to alleviate the delay problem of conventional polling in next-generation long-reach PONs is the well-known multi-thread polling (MTP). MTP creates multiple interleaved polling cycle instances, *i.e.*, "threads". This is illustrated in Figure 5b, where the REPORTs, GATEs, and data transmissions are identified by a thread number. Each thread is a complete polling cycle process, where all ONUs are polled once. MTP succeeds in reducing frame delays by giving ONUs multiple opportunities to report their queue size and to transmit data within the RTT time-period.

The second polling candidate for next-generation long-reach PONs is our proposed *real-time polling (RTP)*, illustrated in Figure 5c. RTP uses an additional separate reporting channel that allows ONUs to report increases in their queue size in real time. By using a separate control channel, reporting can be done independently of the upstream data traffic transmission on the legacy upstream data wavelength channel, *i.e.*, upstream data and control transmissions are decoupled. Each ONU has the opportunity to report a queue increment of Δ_Q bytes every reporting period T_s by transmitting a Queue Increment Report (QIR) to the OLT. In addition, REPORTs continue to be issued at the end of each granted data transmission window on the conventional upstream wavelength channel. RTP can be realized by using optical coding (OC). OC-enabled ONUs apply remote encoding, reflection, and ON-OFF modulation of a pulse stream generated at the OLT. The applied codes may be orthogonal and the operation is performed in an interference-free environment. The minimum queue increment size is equivalent to the minimum frame size, leading to $T_s = 5$ µs in 1G-EPON. This means that the pulse train is generated at a frequency of 200 KHz, which is practical using off-the-shelf switches. Smaller increment sizes do not yield higher performance as the Ethernet frames are not fragmented to lower granularity. These OC enhancements allow the OLT to receive out-of-band queue status updates, *i.e.*, QIRs, every $T_s \geq 5$ µs, which is much faster than in conventional PONs, thus enabling more accurate grant sizing. Note that there are two crucial differences between QIRs and REPORT messages. First, QIRs are pulses that can be transmitted instantaneously and at significantly higher frequencies. Second, QIRs carry incremental information about the queue, whereas REPORTs carry its entire size. Therefore, the OLT needs to keep track of the queue size by adding up QIRs until the arrival of the next REPORT. QIRs enable ONUs to reduce the waiting time of frames prior to their reporting. In addition, they enable the OLT to increase the granted transmission windows on a shorter notice, hence significantly reducing the total frame delay. Unlike thread-specific REPORTs in MTP, the generation of QIRs in RTP does not trigger GATE messages.

Figure 6 shows simulation results for comparing the average delay performance of MTP and RTP with that of the aforementioned benchmark IPACT as well as the so-called double phase polling (DPP), which has recently been found to give the best delay-throughput performance among single-thread polling mechanisms in next-generation long-reach PONs [53]. Note that in Figure 6 the offered load is normalized to the capacity of a 100 km range 1G-EPON, *i.e.*, 1 Gb/s. We observe that MTP achieves only a somewhat lower delay than IPACT as the multiple threads tend to degenerate to a single thread. That is, one thread carries the bulk of the requested grants and the other threads send only small grants or empty REPORTs. DPP provides some delay reduction compared to IPACT and MTP, if the offered traffic load is low to moderate; for high loads the DPP delay approaches the IPACT delay. Note that RTP achieves the smallest delays across all loads compared to the other polling frameworks.

Note that RTP leaves the passive ODN untouched, but requires an additional wavelength channel for out-of-band signalling. Ideally, this out-of-band signalling wavelength may reuse the U-band (1,625–1,675 nm), which was approved in ITU-T recommendation L.66 for in-service maintenance of PONs. In-service monitoring of NG-PON's fiber infrastructure without disturbing ongoing services is expected to become increasingly important in order to avoid the OPEX and large service restoration times of offline troubleshooting. Furthermore, note that the aforementioned OC-enabled ONUs can be realized by using low-cost fiber Bragg gratings (FBGs) for remote encoding, reflection, and modulation, which are completely unpowered components and thus help maintain the passive nature of NG-PONs [54]. For further information on RTP and OC-enhanced NG-PONs we refer the interested reader to [55].

Figure 6. Delay performance comparison.



5. Conclusions

Drawing lessons from the history of optical networks, it is vital to the business of NGOA network operators not to overestimate the expected bandwidth requirements and flood the market with unneeded capacity. Optical (and wireless) access technologies may move into a substantially different direction in the long run than continued capacity upgrades. In fact, in emerging 4G LTE-A HetNets a cellular paradigm shift is required that recognizes the importance of high-speed (fiber) backhaul connections and look into possible backhaul bottlenecks that might deteriorate the achievable performance gains in the wireless front-end. Beside explaining the role of NG-PON1&2 and beyond in realizing high-capacity and low-latency mobile backhaul infrastructures, we elaborated on the implications of the current global crisis and historical recurrence of once-in-a-half-century recessions as turning points, where the benefits of bimodal FiWi networking technologies may be fully realized across the entire economy, thereby offering a vast innovation and growth potential across multiple economic sectors and ushering in a sustainable global golden age. In coming years, power grids in the United States, Europe, and other regions worldwide are expected to undergo major paradigm shifts, calling for reliable and fast smart grid communications infrastructures that rely on wireless technologies and leverage the superior security and immunity features of widely installed PONs in order to create an interactive, integrated, and seamless Energy Internet infrastructure for the TIR economy and a competitive low carbon society. Recently, several major telecommunication service providers started to move into the energy market. On the other hand, utilities and municipalities are increasingly involved in offering FTTH/B coverage to households and businesses. An interesting example for this ongoing convergence is the recent interest of Chinese utility companies, e.g., SGCC, in leveraging PON equipment for both smart grid and FTTH/B applications, which creates new business opportunities for PON manufacturers and vendors after major FTTX buildouts in China will be completed soon. In this paper, we have touched on network coding and real-time polling techniques to lower the latency in NG-PON based smart grid communications and mobile backhaul infrastructures. We have discussed their respective pros and cons, paying particular attention to their cost-efficient implementation and achievable performance gains. Possible future post NG-PON2 research activities include the integration of wireless and fiber optic sensors, M2M communications for smart grid applications as well as emerging device-to-device (D2D) communications for efficient mobile data offloading, and fiber backhaul sharing among converged cellular, broadband, and sensor networks.

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Conflicts of Interest

The author declares no conflict of interest.

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