The Future of Passive Optical Networks

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Abstract—Future system generations of passive optical networks will be applicable to new use-cases like smart city infrastructures including mobile x-hauling and critical network segments for e.g. vehicle-to-infrastructure communications and industrial IoT. These new applications for PON systems are coming with changes on the requirements compared to traditional PON system designs. Higher throughput, lower latency, increased availability of network and reliability of applications are demanded depending on the services. In this paper, an outlook to the evolution of future PON systems will be given using the example of the smart city application. PON system generation status and developments as well as the action at the level of standardization are highlighted.

Index Terms—PON, capacity, 25GS-PON, 50G-PON, latency, slicing, convergence, reliability, availability, automation.

I. URBANIZATION: AN EXAMPLE OF FUTURE PON USE-CASES

Future passive optical networks (PON) will have an important role to play in the development of critical network infrastructures. The world continues to urbanize, which requires sustainable development depending increasingly on the successful management of urban growth, especially in low-income countries. In 1950, 30 % of the world's population was urban, and by 2050, 68 % of the world's population is projected to be urban [1]. This urbanization is associated with challenges on population growth (ageing, migration), resource scarcity (food, water, energy), climate change (disaster management and mitigation) and economic feasibility (low-carbon economy) [2]. The definition of smart cities elaborated by the ITU Focus Group on Smart Sustainable Cities (FG-SSC) reads: "A smart sustainable city is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, cultural and environmental aspects" [3].

This ICT network infrastructure needs to ensure a high quality of service / experience (QoS, QoE) for applications running in the smart city demanding to satisfy a diverse set of requirements. These demands must be considered with regard to networking properties, namely capacity, placement of network elements, fibre distances, latency, redundancy, etc. Furthermore, the network has to ensure coexistence on legacy wireless and optical systems deployed.

An example of a smart city network infrastructure [4] developed within the research project *KIGLIS* is shown in Fig. 1. This network uses PONs to provide connectivity in different network segments for mobile transport or aggregation and for various applications from broadband delivery to critical network demands for remote assistance of automated cars. All applications come with a diverse set of requirements across throughput, latency, availability, reliability, QoS, safety, etc...

II. SMART CITY NETWORK USING PONS

The backbone of the smart network infrastructure of the smart city is the optical fibre access network. PONs are used to bring fibre connectivity to households, enterprises, businesses,

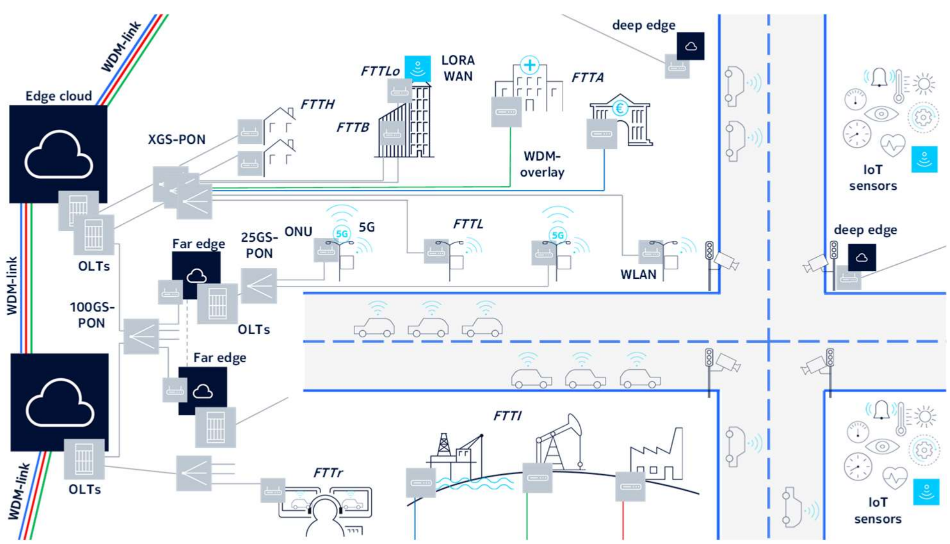

Fig. 1. Smart city infrastructure using PON as the backbone. PON provides connectivity to the households and antenna sites, and is used as a low-cost aggregation system to transport the data from far edge clouds to the main edge clouds.

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antenna sites, and towards city infrastructures. Using time-division multiplexing (TDM), optical line terminals (OLTs) located at the edge clouds will be connected with the optical network units (ONUs) located deep in the network. Such TDM-PONs combine the backhaul of the public Wi-Fi 6/7 located at, e.g., lampposts, with fiber-to-the-*x*, like *h* = home, *b* = building, *Lo* = LoRa-WAN, *r* = remote assistance of automated vehicles, *i* = industry, thus, leveraging the synergy of deployments. Today's 10-gigabit capable XGS-PON and also 25GS-PON [5] can provide the connectivity over typical fibre distances of 10 to 20 km. Moreover, PON optical distribution networks (ODN) allow for wavelength-overlays to connect local area and campus networks, e.g. of hospitals, with the data centres.

To offer cost-efficient 5G radio access network (RAN) solutions for large scale deployment, virtualized RAN with cloudification of radio processing functions offers significant benefits by pooling of computing resources and simplifying antenna sites. The *KIGLIS* smart city envisions the use of 5G small cell fronthaul transport links with capacity requirements dependent on the user data traffic and radio channel conditions. This enables the use of multiplexing technologies such as TDM-PON for fronthauling [6], e.g. by employing 25GS-PON. Fronthaul links, however, come with stringent latency requirements in the range of hundreds of µsec, which calls for locating the OLTs and most RAN entities into far edge clouds with less than 10 km fibre distance to small cell antenna sites. Far edge clouds, in turn, need to be optically connected with the centralized edge clouds. This can be done via high-capacity TDM-PONs, e.g. 100 Gbit/s PONs for aggregation.

In the *KIGLIS* smart city, we envision the optical connectivity between edge clouds to be realized by point-to-point fibres using wavelength-division multiplexing (WDM) and systems with 100 Gbit/s and beyond per wavelength.

Radio core functionalities of latency critical wireless solutions are centralized within the edge clouds. In our proposal, these functions are moved much deeper into the network compared to today's network infrastructures. This way the overall service latency is targeted to reduce down to approximately 1 msec which will increase the QoS.

Services with high latency (100 msec - few sec) and low bandwidth demands are well suited to be transported by the long range (LoRa) - wide area network (WAN). Sensor data are aggregated in centralized LoRa-WAN receiving units that are optically connected to the edge cloud data centres.

Public Wi-Fi 6/7 offloads data from 5G RAN, e.g., for applications requiring large bandwidth and moderate latency (10-50 msec), while 5G RAN is used in particular for enhanced mobile broadband and ultra-reliable low latency communications with down to 1 msec latency targets.

The content, processing and storage functionality as part of the data centre cloud is distributed according to the bandwidth and latency needs of the services. Few large centralized edge clouds for moderate and low demanding services, a larger number of in-field far edge clouds for stringent services requirements, and a few service-dedicated deep edge cloud solutions, allowing for local processing and data offloading, are part of the smart city infrastructure.

III. Requirements, Options and ongoing PON system improvements

In this chapter, the requirements that PON systems need to fulfil for the realization of such smart city infrastructures are outlined in general. Subsequently the corresponding activities at the level of standardization and research are highlighted.

A. Directions for future PON

The realization of the smart city infrastructure demands from PON systems the combination of the advantages of increased throughput with lower latency designs, and increased availability and reliability and network automation. This in fact calls for convergence in the access space in multiple directions:

Broadband system convergence: The existence of multiple wireless system solutions demands for an optical transport solution, i.e. a PON for transport of e.g. 5G RAN or Wi-Fi data. Various RAN configurations and radio split implementations need to be supported from PON systems.

Network edge convergence: Smart city infrastructures will use multiple fixed access technologies, i.e. copper, cable and fibre depending on existing deployment. Further, a larger degree of networking elements deep inside the city network need to be connected. These trends call for a low-cost but performant aggregation network between access and cloud data centre located at the metro edge. Higher capacity PON solutions can be envisioned for aggregation.

Service convergence: A larger amount of services with a diverse set of requirements need to be supported. PON system designs have been optimized for best effort data in the past, while existing knobs or necessary design trade-offs to deliver services with low latency and bounded jitter have been applied to limited extend only so far. Thus, beyond increasing PON capacity, the PON systems have to ensure to deliver high-quality of experience to the end-users requiring for increased QoS control, smart scheduling, resilience and protection as well as network slicing with automated instantiation.

B. PON System Capacity: present and future

<u>10-gigabit capable PONs</u> are available commercially in different variants, 10GEPON, XG-PON, XGS-PON. The XGS-PON is the symmetric solution (same downstream (DS) and upstream (US) line rate) that has received more traction in the industry compared to the asymmetric XG-PON version. The XGS-PON deployments have started in 2018 and are ramping up these days accelerated by the increase in access capacity due to Covid-19 pandemic situation.

<u>MSA-based 25GS-PON</u>: In October 2020 ten major communication industry operators and vendors have announced a multi-source agreement (MSA) for a symmetric-rate 25 Gbit/s TDM-PON. The MSA group has defined the 25GS-PON specification needed to address the gap between today’s mature 10 Gbit/s XGS-PON and a future 50G-PON [7]. 25GS-PON provides a cost-effective and timely network upgrade path that can meet the needs of the mobile 5G era and large-scale enterprises, where symmetrical connections become increasingly important. 25GS-PON leverages optical specifications of the IEEE 802.3ca 25GEPON standard and an

extension of the XGS-PON transmission conversion (TC) layer. 25GS-PON is commercially available from 2021 onwards.

50-gigabit capable PON: ITU-T G.9804.3 (50G PMD physical media dependent) addresses amongst others the physical layer architecture and the optical layer interface parameters. The recommendation has been consented in April 2021. The DS line rate is 50 Gbit/s, while there are two US line rates: 25 and 12.5 Gbit/s, all using NRZ OOK line code. A 50 Gbit/s US line rate is for future study. The DS and US wavelengths are chosen in O-band, respectively. The considered loss budget classes for multi-PON modules are: N1 (29 dB) and C+ (32 dB). G.9804.3 is the first PON recommendation build around a bandwidth-limited receiver using digital signal processing (DSP)-based equalization. Such 50G-PON systems are expected to be available commercially from 2025 onwards. The companying ITU-T G.9804.2 (comTC) recommendation addresses the framing architectures, FEC definition, etc. The LDPC(17280, 14592) FEC-code is slightly modified from the IEEE 802.3ca mother code resulting in a code-rate efficiency of 84.4% and a primary pre-FEC BER target of 1E-2.

100-gigabit capable PON: The introduction of DSP comprising of the toolbox of equalization, FEC and shaping capabilities is also enabling fundamentally new opportunities to bring flexibility into the optical access networks. In [8], we have demonstrated that the throughput can be flexibly adjusted on the physical layer to available signal-to-noise ratio of individual ONUs in the network. This way up to 100 Gbit/s line rate is shown with 25 G-class optics and adjustable DSP. Such high-speed PONs are not yet under standardization.

C. *Latency improvements in PON*

Low-latency MAC: The latency in the DS direction is given by equipment-internal serialization/deserialization stages, but not particularly affected by PON protocol features. However, the US latency is impacted by inherent TDM medium access control (MAC) and burst-mode (BM) US transmission. This results in a trade-off between the frequency of burst allocation per node and the overall bandwidth efficiency as the BM transmission includes certain physical layer overhead. Thus, the higher the burst allocation frequency, the lower is the bandwidth efficiency. When using TDM-PON for low-latency services, a trade-off between latency and bandwidth efficiency should be considered for an optimal configuration. The allocation of up to four burst/ONU/frame is considered a good choice [9].

Cooperative transport interface (CTI): ITU-T G.Sup.coDBA describes cooperative (co)-dynamic bandwidth assignment (DBA) to reduce the US latency in a PON when applying variable bandwidth allocations to follow a variable bitrate traffic pattern. It is based on the notification of information about this traffic from a different entity (e.g. a distributed unit in case of mobile fronthaul) to the OLT. The PON OLT needs to support a signalling interface, the interpretation and processing of the exchanged notifications into co-DBA, the availability of a common time reference, and possibly other features [10].

D. *Network availability, reliability and automation*

End-to-end slicing is one of the fundamental building blocks of future networks. It enables service providers to rapidly create custom services by segregating traffic and delivering specific sets of key performance indicators for each of them. Service providers use network slicing to create and run separate logical networks on underlying cloud infrastructure. These independent network instances enable service-specific service level agreements for connectivity, mobility, capacity, security, redundancy and QoS/QoE. The slicing needs to be ensured from core to access, thus, over the PON transport segment requiring multi-slice and multi-tenant DBA schemes. ITU-T SG15/Q2 is about to continue work on slicing in G.sup.PONslicing.

Resilience and protection: The availability of the network has to be ensured and maintained for critical service types also on the hardware level. The physical elements of OLT, ONUs and ODN need to be protected even in the face of faults and challenges to normal operation [11]. OLT and ONU hardware could be replicated and monitoring and supervision of network elements can be applied to increase the resilience and increase the level of network robustness.

Automation: The application space of future PON systems can reach from transport for RAN, industrial applications to FTTH applications to name a few. PON systems need to quickly and flexibility adapt to the application mix and the service requirements. Further, network slicing needs to be dynamically instantiated and released across the network segments in real-time and across multiple tenants. Automating the network configuration and leveraging artificial intelligence to further optimize the network management is a key success factor for operators as the number of services and slices continue to surge.

IV. SUMMARY

Applications of present and future PONs as part of critical smart city networks were outlined, requirements summarized and directions in standardization and research presented.

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