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Standardization and Technology Trends in Optical, Wireless and Virtualized Access Systems

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SUMMARY This paper reviews access system standardization activities and related technologies from the viewpoints of optical-based PON access, mobile access systems including LPWAN, and access network virtualization. Future study issues for the next access systems are also presented.
key words: *access system, PON, standards, virtualization, wireless*

1. Introduction

Since the release of standards on the Broadband Passive Optical Network (B-PON) [1], the advances in transmission technology have been significant. After the roughly 20 years from release of B-PON, PON access under the title of Next Generation Passive Optical Network (NG-PON2) reached 40 Gbps in 2015 [2].

In many countries, the growth in the PON market has triggered the new deployment or replacement of copper access e.g., Asymmetric Digital Subscriber Line (ADSL). In 2016, the penetration rate of access at 10 Mbps or more reached 24% in developed countries, but only 6% in developing countries [3].

There are countries where broadband access has reached the mature stage. For example, in Japan, PON service is now widespread as a best-effort type service for massive numbers of users. The coverage of households in Japan reached 98% in 2017, and the number of PON access users reached 29 million in 2017 and 33 million is expected in 2020 [4], [5].

As for standardization activities, discussions for 50 Gbps or 100 Gbps level PON have started in ITU-T and IEEE. These standards are expected not only for FTTH but also for new use cases such as the mobile front-haul for 5G networks. They are also expected to be applied to IoT networks and edge computing networks.

In order to support these various networks, optical access networks must be flexible and scalable while meeting various demanding requirements. There are two key points to realize this. One is to ensure PON systems can cooperate with other network systems for network quality improvement, e.g., latency. Correlating PON standards with other network standards is the key to interoperability. The other is to make the PON easy to update or to change its functions. This is possible by introducing appropriate virtualization technologies. Open-source development of the access network has been underway in Open Networking Foundation (ONF) since 2016 as Central Office Re-architected as a Datacenter (CORD) [6], and Broadband Forum (BBF) has defined the Cloud Central Office (CloudCO) Reference Architectural Framework [7].

In this paper, we summarize access system progress from the viewpoints of optical-based PON access, mobile access systems including Low Power Wide Area Network (LPWAN), and access network virtualization. We show, as the next steps, how to utilize optical access networks for mobile access, IoT networking, and Local Area Network (LAN) solutions.

2. PON Standardization Progress

2.1 PON with Higher Bit Rates

The current generation of PON systems is based on B-PON by ITU-T and GE-PON [8] by IEEE standards: time-division multiple access (TDMA) is used as the base in both systems. After B-PON was standardized in ITU-T, G-PON [9], XG-PON [10], NG-PON2 and XGS-PON [11] were developed in 2004, 2009, 2015 and 2016, respectively. NG-PON2 is a time and wavelength division multiplexing-passive optical network (TWDM-PON) with 40 Gbps capacity, namely 4 wavelengths, each with a capacity of 10 Gbps.

Ethernet PON systems were also standardized in IEEE as GE-PON in 2005 and 10G-EPON [12] in 2010.

Most recently, IEEE has begun work on 100G-EPON from 2015 [13] and ITU-T started discussing a higher speed PON which follows IEEE 100G-EPON. Figure 1 shows the progress made in PON standards by ITU-T and IEEE.

These standards share a common wavelength plan due to the fact that the standards share the same technological and operational environment. G-PON occupies 1290–1330 nm and 1480–1500 nm. Video overlay occupies 1550–1560 nm. 10G-EPON and XG-PON occupy 1260–1280 nm and 1575-1580 nm. Recent developments assign 1524–1544 nm to NG-PON2, 1596–1603 nm to TWDM, and 1603–1625 nm to Point-to-Point (PtP) wavelength division multiplexing (WDM).

Since there literally is not much spectrum left, wavelengths for 100G-EPON and higher speed PONs at ITU-T are under discussion. Figure 2 summarizes the wavelength plan

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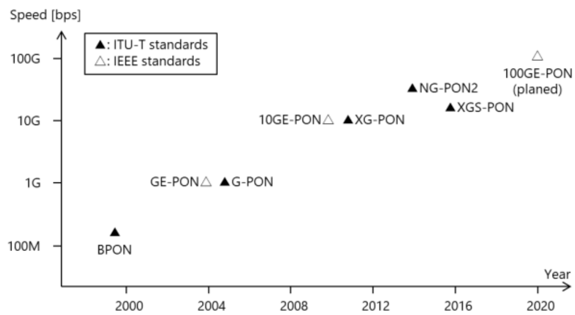


Fig. 1 Progress in PON standardization.

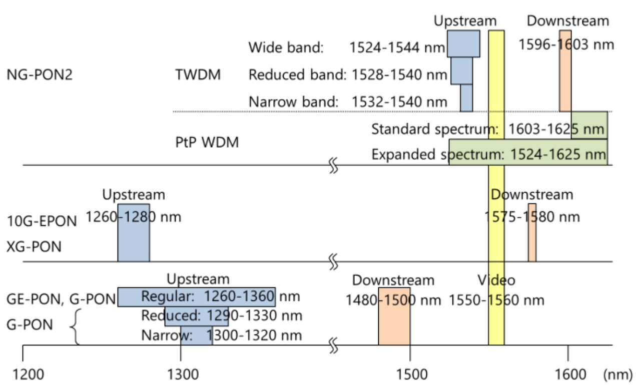


Fig. 2 Wavelength assignment plan

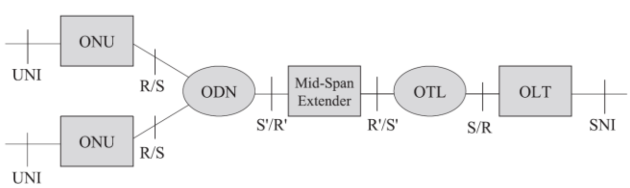


Fig. 3 Mid-span reach extended PON [14].

of G-PON, GE-PON, 10G-EPON, XG-PON, NG-PON2 and video overlay.

2.2 Challenge for Longer Reach

One key attraction of PONs is the longer reach offered by fiber. Standard systems can reach 20 km in their conventionally deployed configuration, and most systems can reach farther if the splitting ratio is reduced. Since practical and economic limits preclude reaches in excess of 40 km, a fundamentally different architecture is required.

One solution is the amplifier-based reach extension shown in Fig. 3. The reach extender connects to a typical Optical Distribution Network (ODN) via extender interface to optical distribution network (S′/R′), and to the Optical Trunk Line (OTL) via extender interface to optical trunk line (R′/S′). The OTL completes the connection to the Optical Line Terminal (OLT).

For G-PON reach extension, basic Optical amplifiers (OA) and Optical-electronic-optical (OEO) types of extenders have been defined [15]. OA operates at "layer 0", and boosts the optical power in a relatively transparent manner; OEO repeaters operate at "layer 1", and regenerate the bit stream of the PON signals. This technology has been described as a G-PON application, and similar approaches to XG-PON or other PONs are possible. In addition, to the extent possible, reach extender capabilities have been described in XG-PON Physical Media Dependent (PMD) layer specifications [16].

2.3 Recent Activities on Convergence of PON Standards

As described above, the development of PON systems has resulted in two families of standards, ITU-T PON systems and IEEE PON systems. This is not efficient, because each system requires the same development effort to create, verify, deploy, and support, while having two systems does not increase our broadband capability.

There are many technical requirements from each system and Standard Developing Organizations (SDOs) have wanted to bring these technologies into alignment for a long time. The future systems can be defined clearly and without confusion; SDOs named this alignment idea PON convergence [17].

The convergence is seen as a growing movement and an indication was provided by the recent public statement made by the leaders of all the major PON SDOs: Fiber Access Network (FAN) in BBF, Full Services Access Network (FSAN), IEEE 802.3ca, IEEE 1904, ITU-T Q2/15 [18].

3. Mobile and Wireless Access Progress

3.1 Mobile Front-Haul Based on PON

Mobile access continues to demand further capacity enhancement to meet the increasing traffic demands, and many small cells with various radio access technologies will be deployed to handle the huge traffic [19]. To realize the efficient operation of small cells, the centralized radio access network (C-RAN) architecture has been introduced. In C-RAN, a base station is divided into a central unit (CU) and several remote units (RUs) [20]. The CU and RUs are connected by optical links, called the mobile front-haul (MFH). Many optical fibers should be deployed for C-RAN and cost is a critical issue. A cost-effective MFH candidate is the time division multiplexing PON (TDM-PON) [21], [22]. This is because an optical fiber is shared by RUs in multiple small cells, which can be deployed as clusters spaced at intervals of several tens of meters. Moreover, the wireless signals for multiple RUs can be transmitted using a single wavelength.

3.2 Cooperation of PON Dynamic Bandwidth Allocation (DBA) with CU

To meet mobile access latency requirements, latency for MFH should be minimal. Ultra-reliable low latency communications (URLLC) services for 5G mobile access set 1 ms latency for end-to-end networks, and the Third Generation

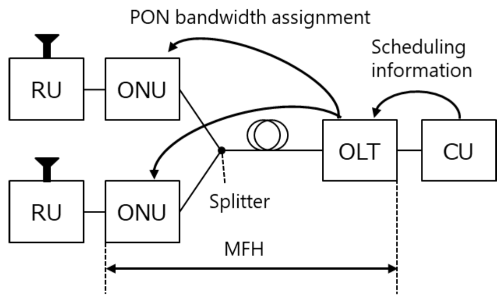


Fig. 4 DBA framework of Cooperative DBA.

Partnership Project (3GPP) sets the maximum latency limit for MFH at 250 us [23], [24]. However, PON systems incur additional latency for bandwidth allocation by DBA if the current PON system is used for MFH, and so they will not satisfy the maximum latency limit.

In order to solve the PON latency issue and thus support MFH, Cooperative DBA has proposed [25], [26]. It is a framework that utilizes the scheduling information provided by the MFH bandwidth assignment mechanism between CU and RUs to perform PON bandwidth assignment. Figure 4 shows an example of a centralized upstream bandwidth assignment mechanism that extends beyond the conventional PON DBA.

When CU controls the uplink transmission of RUs, the CU knows the arrival time and the size of the uplink transmissions. When the scheduling information is shared by CU, OLT can execute DBA without waiting for Dynamic Bandwidth Report upstream (DBRu) [9] from Optical Network Units (ONUs), which means the latency can be minimized. The difference in uplink procedure between normal DBA and cooperative DBA is illustrated in Fig. 5.

To realize Cooperative DBA, scheduling information interface with CU, named Cooperative IF is discussed in NG-PON2 TC layer [27].

3.3 LPWAN

LPWAN is a technology that allows IoT devices to be driven for several years with no battery replacement, and to communicate with a single gateway over a wireless wide area network with a radius of several kilometers or more [28]. In a high-level architecture comprising IoT devices, a gateway, storage and appreciation servers, LPWAN is applied as a communication system between the IoT device and the gateway; it utilizes the sub GHz band wireless communication method that allows the IoT device to realize low power consumption and wide area communication. Wireless communication is uniquely defined mainly in the physical and Media Access Control (MAC) layers of each alliance such as LoRa and Sigfox [29], [30].

Table 1 provides a function comparison of the technologies suggested for LPWAN implementation.

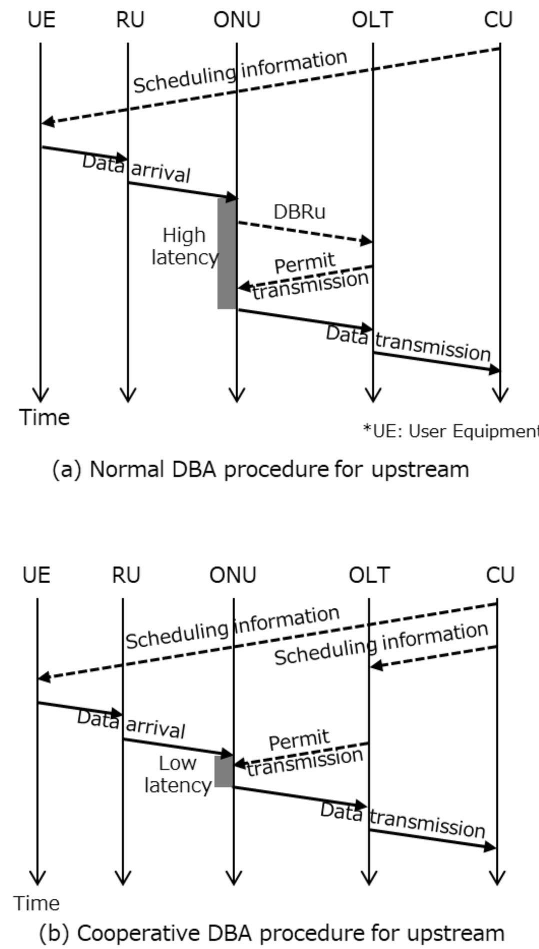


Fig. 5 Uplink procedure under normal DBA and cooperative DBA.

Table 1 LPWAN specifications.

		LoRa	Sigfox	WAVIoT	Nwave Weightless-P
Frequency band		sub GHz	sub GHz	sub GHz	sub GHz
Modulation		CSS	BPSK	DBPSK	DBPSK
MAC layer		unique	unique	unique	unique
Encryption		AES-128	unique	XTEA-256	AES-128
Link budget		154dBm	151dBm	166dBm	147dBm
Bandwidth		300bps-50kbps	100bps	10bps-100kbps	200bps-100kbps
Distance	City	several km	5km	10km	2km
	Rural	15km	15km	50km	5km

4. Access Virtualization Progress

4.1 Open-Source Development at ONF

The ONF created the Open Network Operating System (ONOS) to ensure that communications service providers could attain the goals of scalability, high performance, and high availability. As a use case of ONOS, CORD has been defined and discussed [31]. One CORD project is the Residential CORD (R-CORD); it focuses on residential use such as PON [32]. R-CORD studies include virtualizing OLT

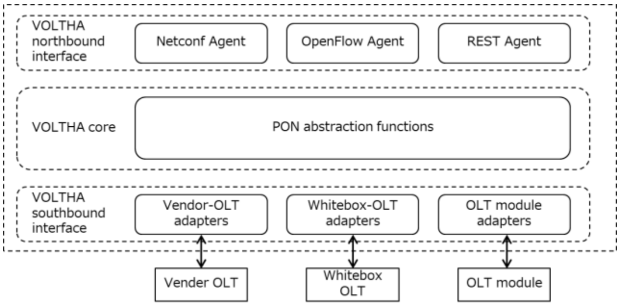


Fig. 6 VOLTHA architecture.

functions in PON and creating Virtual OLT Hardware Abstraction (VOLTHA) [33]. VOLTHA makes it easier to add and modify each function and simplifies the OLT hardware. Figure 6 shows the architecture of VOLTHA.

VOLTHA supports the CORD Project objective of multi-vendor, multi-domain "any broadband access as a service" reference implementation for the Central Office. VOLTHA provides isolation between an abstract (vendor agnostic) PON management system, and a set of vendor-specific and white-box PON hardware devices. On its northbound interface, VOLTHA provides a set of abstract APIs so that northbound systems can interact with the PON networks. On its southbound side, VOLTHA communicates with PON hardware devices using vendor-specific protocols and protocol extensions through adapters.

SDN Enabled Broadband Access (SEBA) Reference Design has recently be released as a variant of R-CORD; it supports a multitude of virtualized access technologies at the edge of the carrier network, including PON, G.Fast, and eventually Data Over Cable Service Interface Specification (DOCSIS) and more [34].

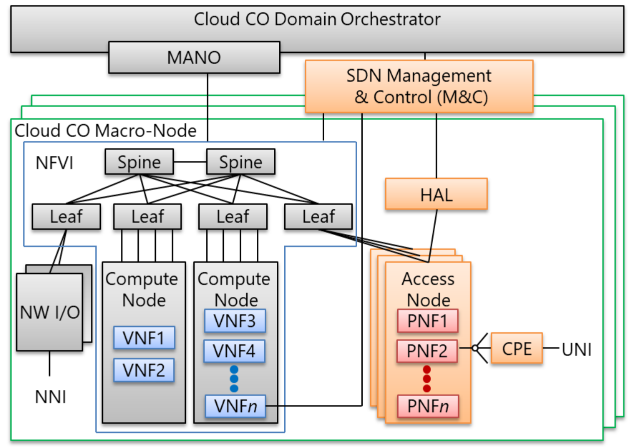
4.2 Open-Source Development at BBF

The BBF has issued the CloudCO Reference Architectural Framework [7]. The framework describes the interrelation of network functions where those network functions, or a chain of them, can all be utilized 'as-a-service', thereby allowing the rapid development of new subscriber services.

CloudCO is a recasting of the Central Office (CO) hosting infrastructure wherein SDN, NFV and cloud technologies are used to support network functions. In doing so, it defines the architectures of the access and aggregation networks, and defines a new, cloud-based architecture; it sets the stage for further development.

Reference architecture of CloudCO is shown in Fig. 7.

This architecture was created based on the authors' understanding of some figures and corresponding content of BBF TR384 [7]. In Fig. 7, the CO and the network between the CO and the customer's premises are called the CloudCO Macro-Node. They are composed of network input/output (NW I/O), network functions virtualization infrastructure (NFVI), access nodes, customer premises equipment (CPE), and a hardware abstraction layer (HAL). The NW I/O is an



CO: Central Office
CPE: Customer Premises Equipment
HAL: Hardware Abstraction Layer
I/O: Input/Output
MANO: Management and Orchestration
NFVI: Network Function Virtualization Infrastructure
NNI: Network to Network Interface
NW: Network
PNF: Physical Network Function
SDN: Software Defined Network
SW: Switch
UNI: User to Network Interface
VNF: Virtual Network Function

Note: This figure was depicted according to the authors' comprehension from Figs. 10, 13, and 15 in BBF TR-384

Fig. 7 CloudCO reference architecture.

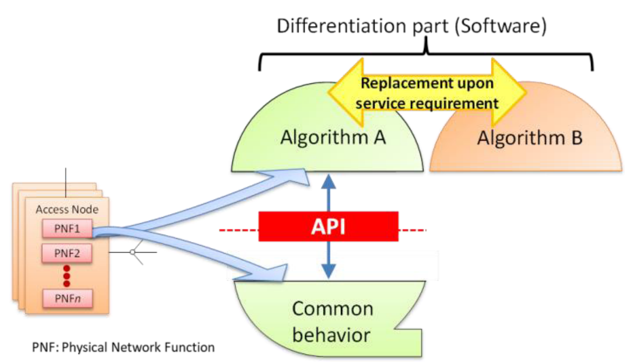


Fig. 8 Schematic image of algorithm disaggregation.

interface between CloudCO Macro-Node and a metro network. Similar to CORD, the NFVI consists of SW fabric (leaf/spine SWs) and compute nodes based on commodity servers that implement virtual network functions (VNFs).

The PON Abstraction Interface for Time Critical Applications (TCAs) such as DBA has been discussed [35]. This offers flexible time-critical functions, Application Programming Interface (API) to modify or to extend the functions, and defines a disaggregating algorithm from common behavior in time-critical functions. Figure 8 shows an image of the interface between the algorithm part and common engine. As shown in the figure, common behaviors such as engine and message exchanges should be defined under the API while algorithms that depend on use cases must be able to be implemented above the API.

4.3 Activities Led by Operators

AT&T and other operators have started the Open Source

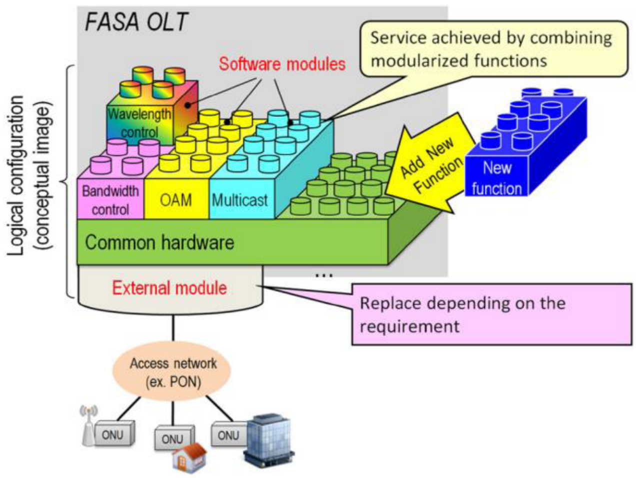


Fig. 9 FASA concept.

Fig. 10 SFP-type OLT.

Access Manager project (OSAM) [36]. OSAM is a vendor agnostic operation suite for managing consumer broadband network elements and capabilities that are disaggregated from proprietary monolithic Access Network hardware and Environmental Management Systems (EMS). A key to simplifying multi-vendor support is connection with VOLTHA via API and making use of the CloudCO architecture.

NTT proposed the Flexible Access System Architecture (FASA) concept in 2016 as a solution to the problems posed by future access [37]. Figure 9 illustrates its general concept. To make it possible to add and change functions in access systems, the functions necessary for access are modularized into small components and combined on a general platform. The distinctive feature of FASA is that it selectively uses appropriate functions realized by software and appropriate module based on required situation [38], [39].

5. Next Steps in Access Systems

5.1 Mobile Access with Flexibility and High Quality

Mobile technologies and standards have been updated frequently, and their development has been rapid. Mobile standards will continue to evolve rapidly even after 5G. Therefore, when a PON is used for MFH, it must be able to not only transfer data with low latency but also follow the wireless evolution. From the upgradability point of view, adopting the virtualized PON is good approach for MFH, and to implement an architecture that permits the functions e.g., bandwidth or latency to be updated, added and removed one by one.

Besides PON virtualization, mobile standards specifications need to be compatible with those of PON standards. A latency requirement of Sect. 3.2 is a typical example. As a means to shorten the latency, the transfer of scheduling information from CU to OLT is being discussed for both PON standards and mobile standards. From the perspective of other functions, it is expected that PON standards and mobile standards will collaborate closely with each other.

5.2 New Architecture for IoT Networking

It is forecasted that IoT devices will explode in number and developments will be dynamic. The commonly assumed architecture of IoT systems is that a wireless network such as LPWAN is used for the last one mile while the fixed network is used as the backbone hosting computing resources. One of the requirements for the backbone will be low latency to the computing resources, which means that a low latency network, computing resources and high processing speeds are needed. In particular, very low latency is seen as essential for autonomous driving car systems to avoid traffic accidents. In this case, computing resources have the role of controlling a number of cars by providing image processing capabilities to each car.

To realize quick response from computing resources, it seems that computing resource servers must be placed in every central unit or central office, which significantly increases investment costs. Since virtualized access systems also have the same architecture, which means there are servers at central offices, it has high affinity with the IoT networking.

Along with the development of IoT technologies, computing resources must support high speed processing and high flexibility for various uses. It is also expected that the virtualized PON will be a critical solution as an important part of IoT systems.

5.3 LAN Solutions Based on Virtualized PON

Other use cases for the virtualized PON exist in factories and rural areas. Each of these use cases may set different requirements such as bandwidth allocation and monitoring functions, so extensive customization is required. If the PON is based on SEBA or CloudCO, customer demands can be met more easily and flexibly and disaggregation makes it possible to improve any function smoothly.

As for factory applications, the virtualized PON has an affinity for edge computing. This is because both the virtualized PON and edge computing require computing nodes, and servers for computing can be shared by both uses, which yields cost reductions.

As for rural area cases, smaller OLTs are needed in order to set OLTs at small central offices.

By OLT virtualization, only the minimum OLT functions related to traffic transport need be installed in the OLT main body; other functions can be placed on the remote server. With this architecture, in addition to shrinking the OLT, outage of the OLT main body will be reduced due to fewer component chips. Figure 10 shows a prototype of the Small Form-factor Pluggable (SFP) type OLT.

6. Conclusion

This paper discussed progress in PON standardization, mobile access, and access virtualization. After reviewing overall access system activities, we proposed the next steps in access system development, chiefly mobile access with flexibility and high quality, new architecture for IoT networking, and LAN solutions based on the virtualized PON.

References

[1] ITU-T Recommendation G.983, "Broadband optical access systems based on Passive Optical Networks (PON)," 2005.
[2] ITU-T Recommendation G.989, "40-Gigabit-capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms," 2015.
[3] ICT facts and figures 2017, https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2017.pdf, 2017.
[4] http://www.soumu.go.jp/main_content/000371278.pdf
[5] http://ictr.co.jp/report/20170724.html
[6] https://opencord.org/
[7] Broadband Forum Technical Report TR-384, "Cloud Central Office Reference Architectural Framework," 2018.
[8] IEEE Standard 802.3ah, "CSMA/CD access method and physical layer specifications Amendment: Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks," 2004.
[9] ITU-T Recommendation G.984 series, "Gigabit-capable Passive Optical Networks (G-PON)," 2008.
[10] ITU-T Recommendation G.987, "10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms," 2012.
[11] ITU-T Recommendation G.9807, "10-Gigabit-capable symmetric passive optical network (XGS-PON)," 2016.
[12] IEEE Standard 802.3av, "CSMA/CD Access Method and Physical Layer Specifications Amendment 1: Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks," 2009.
[13] http://www.ieee802.org/3/ca/
[14] ITU-T Recommendation G.9807.2, "10 Gigabit-capable passive optical networks (XG(S)-PON): Reach extension," 2017.
[15] ITU-T Recommendation G.984.6, "Gigabit-capable passive optical networks (GPON): Reach extension," 2008.
[16] ITU-T Recommendation G.987.2, "10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification," 2016.
[17] F. Effenberger, "PON convergence," IEICE Trans. Commun., vol.E101-B, no.4, pp.947–951, April 2018.
[18] http://www.lightreading.com/gigabit/fttx/sdos-team-up-on-pon-convergence/d/d-id/731234
[19] T. Nakamura, S. Nagata, A. Benjebbour, Y. Kishiyama, T. Hai, S. Xiaodong, Y. Ning, and L. Nan, "Trends in small cell enhancements in LTE advanced," IEEE Commun. Mag., vol.51, no.2, pp.98–105, 2013.
[20] China Mobile Research Institute, "C-RAN the road towards green RAN," White Paper, v.3.0, 2013.
[21] T. Tashiro, S. Kuwano, J. Terada, T. Kawamura, N. Tanaka, S. Shigematsu, and N. Yoshimoto, "A novel DBA scheme for TDM-PON based mobile fronthaul," OFC2014, Tu3F.3, 2014.
[22] N. Shibata, S. Kuwano, J. Terada, and N. Yoshimoto, "Dynamic compression method using wireless resource allocation for digitized radio over TDM-PON system," OFC2014, Tu3F.4, 2014.
[23] 3GPP TR 38.913, "Study on scenarios and requirements for next generation access technologies," 2017.
[24] 3GPP TR 38.801, "Study on new radio access technology: Radio access architecture and interfaces," 2016.
[25] H. Uzawa, H. Nomura, T. Shimada, D. Hisano, K. Miyamoto, Y. Nakayama, K. Takahashi, J. Terada, and A. Otaka, "Practical mobile-DBA scheme considering data arrival period for 5G mobile fronthaul with TDM-PON," ECOC2017 M.1.B, 2017.
[26] K. Takahashi, H. Nakamura, H. Uzawa, K. Miyamoto, Y. Nakayama, T. Shimada, J. Terada, and A. Otaka, "NG-PON2 demonstration with small delay variation and low latency for 5G mobile fronthaul," ECOC2017 SC.8, 2017.
[27] ITU-T Recommendation G.989.3, "40-Gigabit-capable passive optical networks (NG-PON2): Transmission convergence layer specification," 2015.
[28] TTC Technical Report, "Overview of Signal Transmission Technologies for IoT Area Network," 2017.
[29] https://www.lora-alliance.org/
[30] https://www.sigfox.com/
[31] https://www.opennetworking.org/cord/
[32] https://wiki.opencord.org/display/CORD/Residential+CORD
[33] https://wiki.opencord.org/display/CORD/VOLTHA
[34] https://www.opennetworking.org/news-and-events/press-releases/onf-hits-the-ground-running-with-execution-of-new-strategic-plan/
[35] Broadband Forum Technical Report WT-402, "Functional model for PON abstraction interface," 2018.
[36] https://wiki.onap.org/display/DW/OpenSource+Access+Manager
[37] FASA white papers Ver. 1.0 and 2.0, http://www.ansl.ntt.co.jp/e/global/FASA/index.html, 2016 and 2017.
[38] J. Kani, M. Yoshino, K. Asaka, H. Ujikawa, T. Yamada, K. Nishimoto, K. Suzuki, and A. Otaka, "Flexible access system architecture (FASA) to support diverse requirements and agile service creation," J. Lightwave Technol., vol.36, no.8, pp.1510–1515, April 2018.
[39] A. Otaka, "Access system virtualization for sustainable and agile development," IEICE Trans. Commun., vol.E101-B, no.4, pp.961–965, April 2018.

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