Performance Analysis of Next Generation-PON (NG-PON) Architectures

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***Abstract*—Next generation passive optical networks (NG-PONs) is the natural development of PONs toward achieving higher data rates, larger counts of wavelength channels, and longer fiber ranges. NG-PON can be implemented as high speed time division multiplexing (TDM), wavelength division multiplexing (WDM), Hybrid TDM/WDM, optical code division multiplexing (OCDM) PON. Many enhancements and adaptations are occurring in order to offer higher bandwidths with higher number of subscribers. This includes coverage area that is increasing to reach of 100km and more, e.g. the LR-PON. In addition, the wireless access network is gradually going to be integrated with PON systems, e.g. FiWi network. In this paper, we examine the different promising architectures for NG-PON. A comparison between key network specifications such as data rates and power budget has been reported. Moreover, we study different state-of-the-art technologies that will potentially be used for NG-PONs. We discuss the different characteristics of NG-PON showing the important contributions and challenges of various NG-PON demonstrations.**

***Index terms*—FTTH, Next generation passive optical network (NG-PON), NG-PON architectures, LR-PON, FiWi.**

I. Introduction

Fiber-to-the-Home (FTTH) continued to make great progress in recent years. During 2011, the number of users has increased by 18 millions to reach approximately 80 millions [1]. Asia-Pacific, North America, and Europe are the leading regions in deploying FTTH. By the end of 2013, it is expected that the number of FTTH household will reach 30 millions in Japan and approximately 20 millions in US with FTTH total of 130 millions worldwide [1]. FTTH can be realized by gigabit-class passive optical networks (PONs). The two major state-of-the-art networks are the gigabit PON (GPON), widely deployed in U.S. and Europe, and the Ethernet PON (EPON), adopted in Japan and Korea. Both networks differ in the data link layer protocol used (i.e. GPON uses the GPON encapsulation method (GEM) whereas EPON uses Ethernet) [2]. ITU-T and IEEE have generated the G.984 and IEEE 802.3ah standards, respectively. In general, PON networks provide a point to multipoint transmission between the optical line terminal (OLT) and the several optical network units (ONUs). With the continuous increasing of bandwidth required by different types of users, gigabit-class PONs have been evolved into NG-PONs.

NG-PONs promise to satisfy higher performance characteristics such as higher data rates, lower maintenance cost, and larger number of users. These features can be achieved by deploying new topologies, larger counts of wavelength channels, longer fiber ranges, and higher splitting ratios. In general, NG-PON will be deployed in two stages [3]. The first stage represents the evolutionary scenario (e.g. NG-PON1) which supports the coexistence of NG-PON with legacy PON (gigabit PON) on the same optical distribution network (ODN). In this scenario, the migration is done incrementally in order to reduce the capital expenditures (CAPEX) and achieve a minimum service interruption to the subscribers that are not migrated. Second stage denotes the deploying of the new technology in a green field or the total replacement of the existing gigabit PON in order to take advantages of NG-PON features (e.g. NG-PON2).

Different architectures have been suggested in the literature so as to build the NG-PON different topologies. Firstly, TDM networks use the new standards developed by IEEE and ITU-T new to deploy a high speed TDM networks. Secondly, the high bandwidth offered by WDM network where a dedicated wavelength is assigned for every ONU attracts vendors to deploy WDM for the NG-PON. A third category integrates TDM and WDM network in one hybrid TDM/WDM system. Moreover, the maximum span of the traditional PON network (~ 20 km) has been increased to reach 100 km by deploying long reach-PON (LR-PON) architectures. Finally, FiWi networks combine the mobility of wireless networks and the high capacity of PONs.

In this paper we provide a study for the state-of-the-art architectures for NG-PONs. We compare the specifications of different next generation TDM-PON. We make a comparison of different technologies used in WDM, TDM over WDM, LR-PON, and FiWi networks and their key characteristics. Finally, the main challenges toward commercially adoption of future access networks have been discussed. The organization of the paper is as follows. In section II we review the different specifications and architectures of high speed TDM, WDM, and TDM over WDM networks. Section III and IV review the state-of-the-art technologies used in LR-PON and FiWi networks. In Section V a discussion has been reported. Section VI concludes the paper.

II. High speed TDM, WDM, and TDM over WDM architectures

In recent years, user bandwidth has been increased more than 10 fold; this huge increment is actually due to different user's requirements such as video on demand (VoD), high definition television (HDTV), Internet, and business

applications. In addition, the developed wireless networks such as IEEE 802.11n wireless LANs need EPON as a backhaul in order to achieve 100Mbps or higher per access point [4]. Different trends have been proposed as in follows:

A. *High speed TDM-PON*

In September 2009, IEEE 802.3av Task Force completed the development of the 10G-EPON specifications. 10G-EPON can support symmetric 10Gbps downstream and upstream, and asymmetric 10Gbps downstream and 1Gbps upstream data rates. The main differences between 10G and 1G-EPON are summarized in TABLE I [5].

TABLE I
MAIN DIFFERENCES BETWEEN 1G-EPON AND 10G-EPON

	1G-EPON	*10G-EPON*
Data rate	1G/1G symmetric	10G/10G symmetric 10G/1G asymmetric
Line coding	8B/10B overhead (20%)	64B/66B overhead (3%)
Split ratio	1:16	1:16 / 1:32
Wavelengths	1480-1500nm (DS) 1260-1360nm (US)	1575-1580 nm (DS) 1260-1280 nm (US)
FEC	RS(255,239)	RS(255,223)
Power budget classes	2 classes PR(10/20)	3 classes PR(10/20/30) PRX(10/20/30)

For the same objective, ITU-T completes its standard, ITU-T G.987, in 2010 which addressed the general requirements of 10 Gigabit-passive optical networks (XG-PON) [6]. ITU-T G.987 supports symmetric 10Gbps, and asymmetric, 10Gbps downstream and 2.5Gbps upstream, date rates. The main differences between GPON and XG-PON are summarized in TABLE II. A block diagram of high speed TDM PON is shown in Fig. 1.

TABLE II
MAIN DIFFERENCES BETWEEN GPON AND XG-PON

	GPON	*XG-PON*
Data rate	2.5G/1.2G	10G/2.5G XG-PON1 10G/10G XG-PON2
Reach distance	10km ,20km (physical distances)	20km (60 km in the logical layer)
Split ratio	1:32, 1:64	1:64, (1:256 in logical layer)
Wavelengths	1480-1500nm (DS) 1260-1360nm (US)	1575-1580nm (DS) 1260-1280nm (US)
FEC	------	RS(248,216) DS RS(248,232) US
Power budget classes	Class B+ (13-28dB optical budget)	Nominal (29-31dB) Extended (33-35 dB)

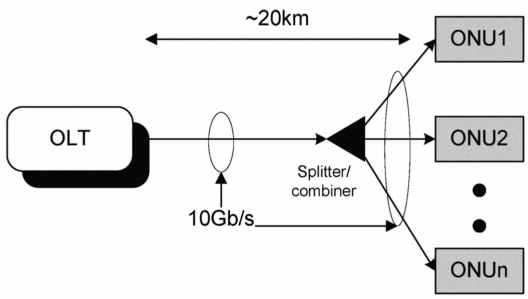

Fig. 1 Next generation TDM-PON

B. *WDM PON*

WDM-PONs have been investigated as a potential technology for NG-PON. Different architectures have been proposed to implement WDM-PONs[7], some of them are based on the legacy TDM-PON (i.e. broadcast and select) but with a band pass filter at each ONU with small insertion loss, as shown in Fig. 2 (a). A band splitter (BS) is used to differentiate between up and downstream wavelengths. This architecture is suffered from passive splitter loss, lack of security, as well as the difficulty of employing identical ONUs (colorless ONU). Another type of WDM-PONs is based on the use of an arrayed waveguide grating (AWG) instead of power splitter in order to specify a dedicated pair of wavelengths for each ONU, as shown in Fig. 2 (b). This configuration provides lower AWG's insertion loss and simpler ONU's receivers. Nonetheless, different ONU's transmitters are still needed. The mentioned configurations are based on dense WDM. The cost of WDM network can highly reduce by considering the coarse WDM (CWDM) network where the wavelength spacing is sufficiently high to relax the transmitters to be accurately controlled. TABLE III summarized the basic features of different WDM networks [7]. Note that the ONU link cost is defined with respect to GPON cost (GPON cost = 100 percent for 20 dB power budget).

TABLE III
FEATURES OF BASIC WDM NETWORKS

	Splitter-based WDM PON	AWG-based WDM PON	CWDM -PON
DS/US bit rate	1,2.5,4,10 G	1,2.5,4,10 G	1,2.5,4,10 G
Wavelength grid	100, 50 GHz	100, 50 GHz	20 nm
Max. splitting ratio	1:32	1:40	1:8
Max. budget	8 dB	10 dB	13 dB
ONU link cost [relative]	242 (1G per λ)	256 (1G per λ)	122 (1G per λ)

So as to decrease the cost, simplify the maintenance, and unify the design of ONUs, different technologies have been considered to design a colorless ONU (i.e. wavelength independent ONU). Techniques for implementing a colorless ONUs include injection locking and wavelength-seeding/remote modulation, spectrum slicing, and wavelength tuning[8]. In wavelength-seeding scheme a reflective semiconductor optical amplifier (RSOA) is used in every ONU's transmitter. The received wavelength is amplified, modulated by the upstream data, and reflected back to the OLT as shown in Fig. 2(c). The up and down streams can be transmitted on different wavelengths or they can have the same wavelength with different extinction ratios (ER). In the spectrum slicing technique, each ONU's transmitter employs a broadband light source such as super luminescent diode (SLD). The lightwave is modulated by the upstream data and sent to the OLT using MUX/DeMUX device [9]. The MUX/DeMUX is used to slice the optical spectrum of each

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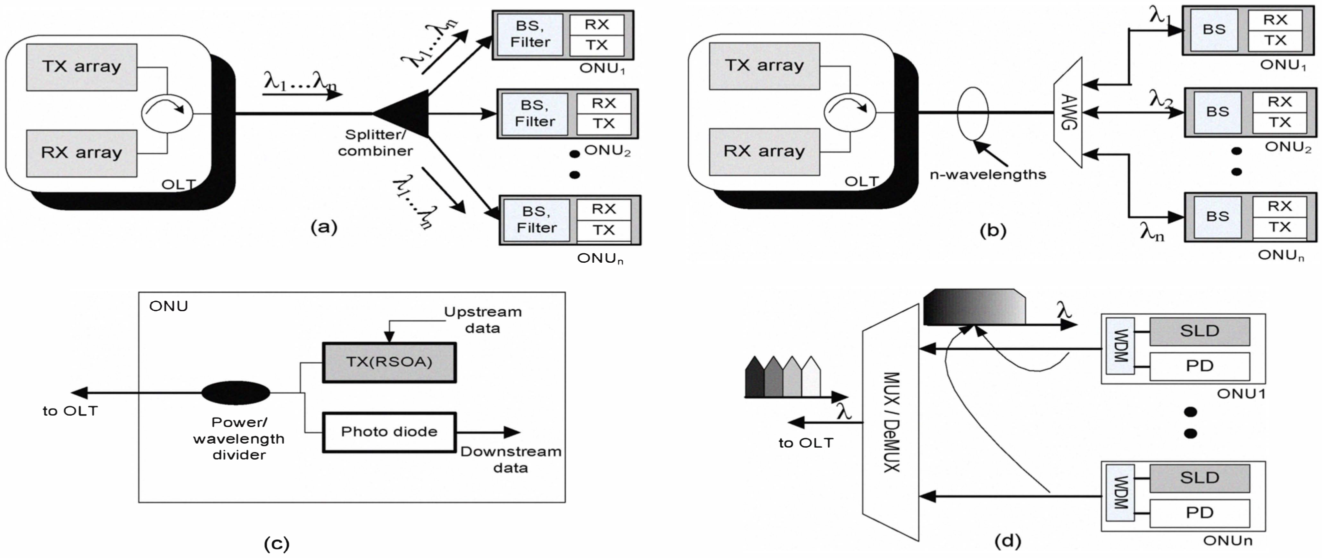

Fig. 2 Next generation WDM-PON; (a) splitter-based WDM-PON, (b) AWG-based WDM-PON, (c) RSOA-based ONU, (d)spectrum slicing- based ONU

ONU at different wavelengths, as shown in Fig. 2(d).The simplest way to incorporate a colorless-ONU is by using a tunable wavelength transmitter at each ONU. Different designs have been proposed to realize a low cost tunable laser source [10].

C. *Hybrid TDM/WDM PON*

As shown in Fig. 3, hybrid TDM/WDM PON has the benefits of the high capacity offered by TDM-PON and the high number of wavelengths offered by WDM-PON. Generally, hybrid TDM/WDM PONs can be categorized into static and dynamic hybrid schemes. In static scheme, the wavelengths (US and DS) assigned for each ONU can't be changed during operation. Whereas, in the dynamic case the wavelengths are changed dynamically according to operation and communication [8]. Dynamic scheme offers some advantages to PON including load balancing, resilience, and power saving function, but in the same time the ONUs must employ burst mode receivers due to the frequent change in wavelengths. In [11], Lee et al. proposed the first commercial colorless gigabit TDM/WDM hybrid PON to be used in Korea Telecom. Hybrid WDM/TDM can operate on DWDM or CWDM grid wavelengths with the main differences listed in TABLE IV [7].

TABLE IV
HYBRID DENSE AND COARSE TDM/WDM PON

	CWDM/TDM	DWDM/TDM
DS/US bit rate	Up to 1Gbps	Up to 1Gbps
Wavelength grid	20 nm	100(50) GHz
Max. splitting ratio	1:64	1:160
Max. budget	11 dB	11 dB
ONU link cost [relative]	132 (2.5G per λ)	234 (2.5G per λ)

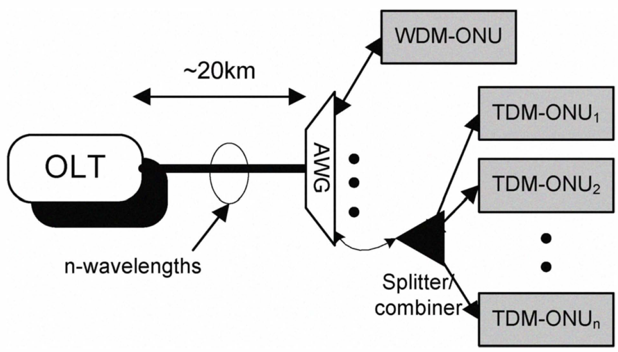

Fig. 3 Next generation WDM/TDM PON

III. LR-PON

In order to overcome the limitations of TDM and WDM passive optical networks, such as low splitting ratio and range, LR-PON has been developed as a more cost effective solution for optical access network [12]. LR-PON can simplify the network by combining the metro and access segments into one large network. This architecture can reduce the total number of optical-electrical-optical (OEO) conversions, at the expense of mid-span optical amplifiers [2].

Different LR-PON architectures have been developed, the photonics local access network (PLANET) project was initiated in mid of 1990 to develop a super passive optical network (SuperPON). SuperPON represents an upgrade version of G.983 broadband PON (BPON). It can support up to 2048 split size over a range of 100km. A long reach PON was developed for British Telecom (BT) in order to satisfy their predicted bandwidth and consolidate the number of central offices through the country. In this architecture, the split ratio was targeted to be 1024 with 100km range and 10Gbps bit rate in both down- and upstream, as shown in Fig.

4 (a). A hybrid DWDM/TDM long-reach PON was developed by Tail and Townsend [13]. This demonstration can support 17 TDM PONs each with 256 customers, total of 4352 ONUs, with total reach of 100km, shown in Fig. 4 (b). The reach of the GPON system has been increased from 20km to 135km using an OEO conversion and amplifier at the local exchange point, as shown in Fig. 4 (c). The OEO converts the burst mode GPON network to a DWDM network. Instead of OEO converter, a wavelength converter has been used in the wavelength converter PON (WC-PON) proposed by Shea and Mitchell [14]. In this demonstration, a cross-gain modulation (XGM) wavelength converter (WC) was used to convert the ONU wavelength to a standard DWDM wavelength. The reach of this network is 120 km with a total of 20 PONs each with 64 users, total of 1280 users, as shown in Fig. 4 (d). A comparison between different LR-PON architectures is summarized in TABLE V. The propagation delay time between the OLT and different ONUs is challenging for LR-PON. By increasing the distance to 100km the round trip time (RTT) will increase to from 0.2msec in traditional PON to 1msec. A multithread algorithm has been proposed to increase the number of polling threads in order to decrease the propagation delay time [15].

IV. FiWi NETWORKS

Optical access networks can provide huge bandwidth but it can't go everywhere, on the other hand wireless access networks can go everywhere but its offered bandwidth is limited [16]. By combining the capacity of optical fiber network and the mobility of wireless network fiber wireless (FiWi) network can provide customers with a quad-play services (data, video, voice and mobility) [17]. FiWi network can be developed as radio over fiver (RoF) or radio and fiber (R&F).RoF has been developed as an approach to combine optical fiber and wireless networks.

TABLE V
DIFFERENT FEATURES OF LR-PON ARCHITECTURES

	SuperPON	Long reach PON	Hybrid DWDM/TDM PON	GPON extension	WC-PON
Reach distance	100 km	110 km	100 km	135 km	120 km
Splitting ratio	2048 (i.e. 1:16 x 1:64 x 2)	1024 (i.e. 1:4 x 1:16 x 1:16)	4352 (i.e. 17 PON x 256 user)	64	1280 (i.e. 20 PON x 64 user)
Bit rate	2.5 Gbps DS, 311 Mbps US	10 Gbps symmetric	10 Gbps symmetric	2.5 Gbps DS 1.25 Gbps US	2.5 Gbps DS 2.5 Gbps US
Bit rate/user	1.22 Mbps (DS) 0.15 Mbps(US)	9.76 Mbps(DS & US)	39 Mbps(DS & US)	39 Mbps (DS) 19.5 Mbps (US)	39 Mbps (DS&US)
BER	10^{-9}	10^{-10}	Better than 10^{-9}	Better than 10^{-10}	10^{-9}
wavelengths	1550 nm (DS) 1310 nm (US)	1550 nm for both DS, US	DWDM grid	DWDM grid	DWDM grid

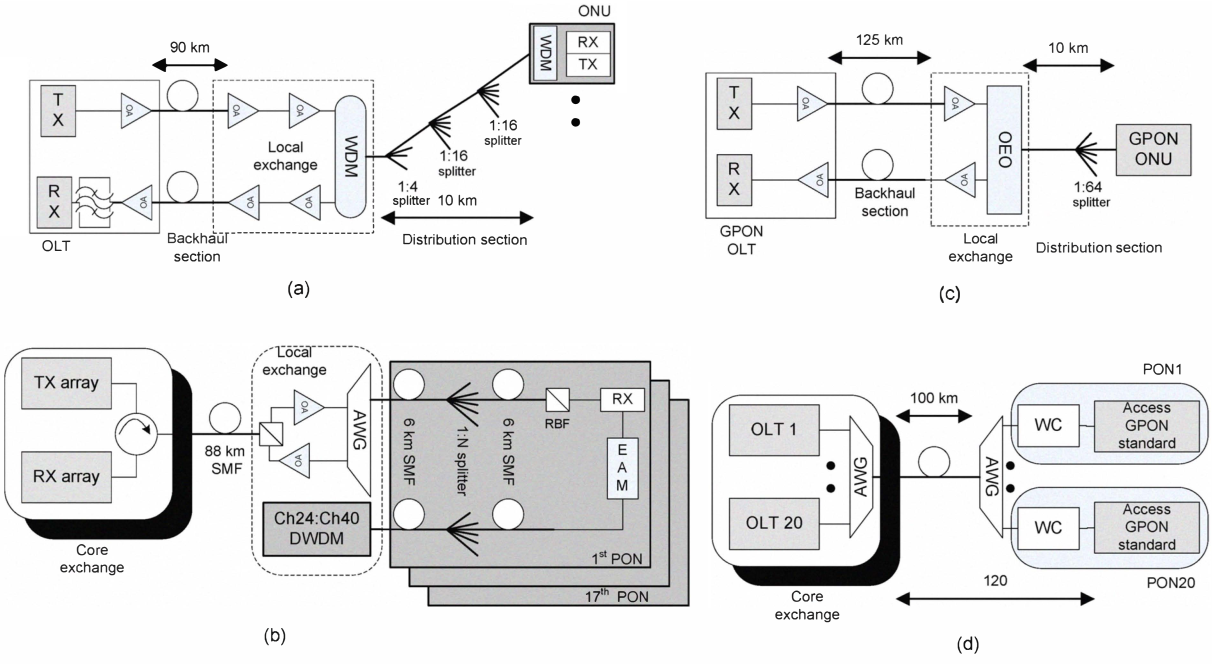

Fig. 4 Next generation LR-PON

In RoF, radio frequencies are carried over optical fiber, by means of hybrid fiber radio (HFR), between central office (CO) and multiple low cost remote antenna units (RAUs). RoF networks suffer from propagation delay which deteriorates network performance. This limitation can be avoided by employing R&F network, where the access to optical and wireless media is controlled separately from each other by using different MAC protocols in the optical and wireless media [17].

Different FiWi architectures have been proposed in the literature. Muralidharan *et al*. [17] proposed a hybrid integrated fiber wireless networking (HiFi-WiN), where the connection between the central office (CO) and the wirless access points (WAPs) is done via a unidirectional fiber ring, as shown in Fig. 5 (a). Each WAP unit provides a wireless access to the mobile users in the service area. In this architecture the CO is responsible for assigning channels to accommodate different services. A self–healing architecture has been proposed by Lin *et al*. in [18]. As shown in Fig. 5 (b), the configuration is based on a two level bidirectional path protected ring (BPR). The CO is connected to the remote nodes via dual fiber ring. Each RN connects many WAP by means of concentration nodes (CN). Finally, each WAP wirelessly served different users. In this architecture, the WAP assigns at least 5 MHz channel bandwidth and covers up to 16 users. The distributed controllers placed at CO and each RN provides a self-healing property for this architecture. Bhandari and Park proposed a hybrid star/ring wireless access network that has the property of providing bandwidth on demand [19]. As shown in Fig. 5 (c), the central office connects many ring networks via optical switches, which has full wavelength capability. In addition, the optical switch connects each ring network to two neighbor rings in order to provide network protection. The network is periodically monitored in order to balance the load or add new lightpath according the load and bandwidth offered, respectively. In [20], Shaw *et al.* proposed a hybrid optical wireless access network that consists of optical WDM ring and wireless mesh networks (WMNs) connected together via a different PONs, as shown in Fig. 5 (d). Wireless gateways are used to bridge the PONs and the WMNs. The system provides configurability according the load traffic. The features of the different state-of-the-art architectures are summarized in TABLE VI.

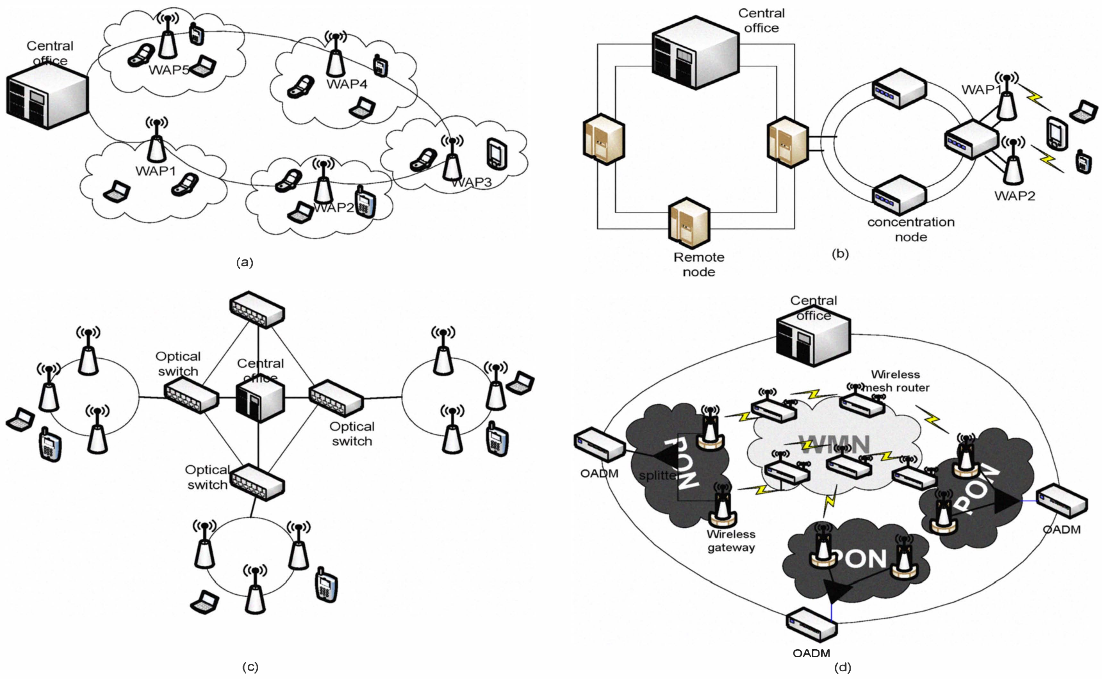

Fig. 5 Next generation FiWi network

TABLE VI
DIFFERENT FEATURES OF FIWI ARCHITECTURES [17]

	HiFi-WiN	Bidirectional ring	Hybrid star/ring	Hybrid ring/WMN
Reconfiguration	yes	No	yes	yes
Protection	No	yes	yes	yes
Channel assignment	CO	WAP	WAP	ONU-wireless gateway
PON used	No	No	No	yes
WMN	No	No	No	yes

V. Discussion

According to the different implementations discussed in the literature, a comparison between different NG-PON architecture's features is summarized in TABLE VII. The new TDM standards, IEEE 802.3av and ITU-T G.987, enforce technical challenges in terms of power budget and design of dual rate burst mode OLT's receivers. ONU's cost is another challenging aspect for high speed TDM networks. 10GE-PON and XG-PON provide smooth migration from gigabit class access networks to higher data rates PON. The migration will maintain the main infrastructure components that are already deployed. WDM network provide the main user requirements in terms of higher bandwidth and security. The high cost of WDM networks can be reduced by deploying CWDM networks in combination with DWDM networks. The design of low cost and high efficiency colorless ONU are the main challenges in order to have a cost-effective user's ONU. Recently, CIP company introduced a TO-CAN packaged reflective SOA at about 200 $ price. In addition, the deployment of hybrid TDM over WDM networks will provide users with higher bandwidth and lower cost access network. The main challenges in this demonstration will be in the design of efficient dynamic bandwidth allocation (DBA) schemes as well as dynamic wavelength allocation (DWA) algorithms for the dynamic hybrid system. Also, tunable transmitters are still required for the dynamic hybrid scheme.

LR-PON has the capability to reduce the maintenance of the network and increase its distance. The deployed architecture should be accurately selected so as to reduce the propagation time which is a main challenging point in LR-PON. A tradeoff between the splitting ratio and the power budget for different LR-PON layouts has to be considered. FiWi networks should consider new approaches to take benefits of the huge bandwidth offered by optical access network. Moreover, new reconfigurability algorithms and routing protocols are still needed so as to optimally balance the unexpected traffic conditions. Self-healing FiWi network is another challenging point to increase the network survivability. The cost of FiWi network is a major challenge toward widely deploying FiWi networks commercially.

Mid-term and long-term PONs can support higher bit rates, 40, 100, and even Tera bit/s, by considering bandwidth-effective modulation techniques. Various modulation schemes can achieve better performance characteristics in terms of bit rate, span distance, and cost. Multilevel modulation techniques such as MPSK and MQAM in addition to polarization diversity ease the speed requirements on electronic/optoelectronic components and achieve higher bit rates. Additionally, OCDMA has unique features such as asynchronous transmission, low latency access, soft capacity on demand, and optical layer security. These features make OCDMA a good candidate for NG-PON networks. The demand of higher data rates over the dispersive optical channel and the development of DSP technology over optical channel will encourage researchers to implement NG-PON networks based on optical OFDM (OOFDM). OOFDM not only increases the spectral efficiency and provides good resistance to fiber impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD), but also it provide a natural compatibility with DSP-based systems.

VI. Conclusion

NG-PON is the best solution for the ever-increasing number of internet users and hungry bandwidth applications. Different architectures have been considered to fulfill the NG-PON requirements including high speed TDM, WDM, Hybrid TDM/WDM, LR-PON, and FiWi PON networks. High speed TDM-PON provides the easiest migration scenario to short term incrementally upgrades for exiting PONs. Colorless-ONU WDM network is a promising candidate for NG-PON and already found a rich market in Korea. In addition, TDM over WDM provides a cost effective solution for NG-PON. The reach distance of LR-PON topologies can simplify the network by combining the metro and access segments. The combination of wire and wireless networks can support future broadband services and wideband mobiles on the same infrastructure. Different modulation schemes are extremely needed to increase the performance of NG-PON in order to increase the bit rate within the minimum bandwidth.

VII. Acknowledgment

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TABLE VII
A COMPARISON BETWEEN NG-PON ARCHITECTURES

	TDM	WDM	Hybrid WDM/TDM	LR-PON	FiWi
Cost	Low	High	Medium	High (need amplifiers)	High
Bit rate	Low	High	Medium	Low	Low
Reach distance	Low	Low	Low	High	Low
Splitting ratio	High	Low	High	High	Low
Subscribers / backhaul fiber	64 or higher	Less than 64	More than 128	~Thousand	Less than 32

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