Candidate Modulation Schemes for Next Generation-Passive Optical Networks (NG-PONs)

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***Abstract*— Various approaches have been developed for next generation passive optical networks (NG-PONs) in order to achieve higher data rates, larger counts of wavelength channels, and longer fiber ranges. Several modulation formats together with electronic based digital signal processing (DSP) implementations have been investigated in order to optimally design an access optical network. Besides increasing data rates, this new trend also plays a major role in reducing the cost and increasing the flexibility of NG-PON. In this paper, we survey the main promising modulations and DSP technologies for NG-PON. This includes modulation and optical OFDM schemes enumerate QPSK, MQAM, MSK, and multilevel based OFDM schemes. We discuss the different characteristics of these technologies showing most important contributions and challenges toward high performance cost-effective next generation access networks.**

***Index terms*—FTTH, Next generation passive optical network (NG-PON), Modulation schemes, and Optical orthogonal frequency division multiplexing (OOFDM).**

I. Introduction

Year 2012 has seen an aggressive growth in bandwidth demand worldwide. Wire and wireless users have increased their network usage more than 10 fold mainly in real time video entertainment. According to firm of statistics, every minute network users download 13000 hours of music, post 600 videos on YouTube, and spend more than 300,000 minutes voice chatting on Skype [1]. *Fiber-to-the-x* (FTTX) continued to make great progress in recent years. During the last three years, the number of users increased by 50% to reach approximately 90 millions. By the end of 2015, it is expected that the number of FTTH households worldwide will reach 180 millions [2]. Fig.1 shows the progress in FTTH household users all over the world. 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. In general, PON networks provide a point to multipoint transmission between the optical line terminal (OLT) and the several optical network units (ONUs). The non-stopping increase in hungry bandwidth applications, force the traditional PON to be evolved into NG-PON. .

Higher data rates, lower maintenance cost, and larger number of users are the main objectives of NG-PONs. These features can be achieved by deploying high spectrally efficient modulation formats. In general, NG-PON will be deployed in two stages, evolutionary and revolutionary scenarios. In [3], we discussed the various architectures suggested in the literature in order to build the NG-PON. This includes the high speed TDM networks which use the new standards developed by IEEE and ITU-T (i.e. IEEE 802.3av and ITU-T G.987). The high bandwidth offered by WDM network where a dedicated wavelength is assigned for each ONU. The integration between TDM and WDM networks in a hybrid TDM/WDM system. Moreover, the extension of network span (i.e. 100 km reach) by deploying long reach-PON (LR-PON) architectures. Finally, FiWi networks that combine the mobility of wireless networks and the high capacity of PONs.

Various modulation schemes have been proposed in the literature so as to achieve better performance characteristics in terms of bit rate, span distance, and cost. For the high bit rates demand of NG-PON, conventional OOK systems will require expensive electronics and optoelectronics devices. In contrast, multilevel modulation techniques such as MPSK and MQAM can overcome this problem since each transmitted symbol has M possible values which eases the speed requirements on electronic/optoelectronic components and achieves higher bit rates [4-10]. Moreover, orthogonal frequency division multiplexing (OFDM) has received a great attention in wired and wireless communication system because of its resistance to inter symbol interference (ISI). OFDM is a multicarrier modulation format where modulation and demodulation onto subcarrier is performed digitally via fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT), respectively [11]. The demand of higher data rates over the dispersive optical channel and the development of DSP technology over optical channel encourage researchers to implement NG-PON networks based on optical OFDM (OOFDM) [12-16]. Other techniques can support the existence of a novel elastic optical

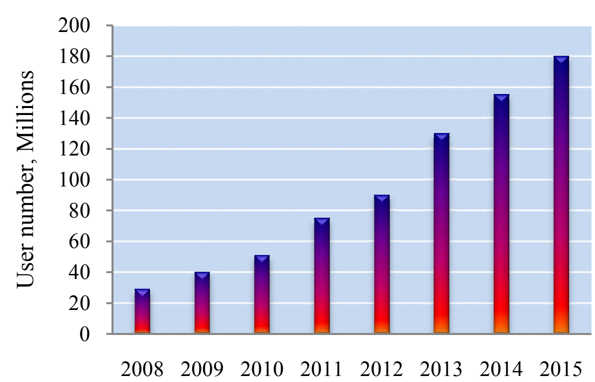


Fig. 1 FTTH household progress [2].

network with flexible data rate and spectrum allocation. As an example, the adaptively modulated optical orthogonal frequency multiplexing (AMOOFDM) changes the modulation format and data rate according to channel characteristics [17].

In this paper we provide a study for the state-of-the-art technologies used for NG-PONs. We compare the effect of highly spectral efficient modulation formats and DSP technologies toward increasing the network data rate and employing a cost effective access network. Finally, the main NG-PON challenges, in order to commercially adopt future access networks have been discussed. The organization of the paper is as follows. In section II we review the different modulation schemes used for NG-PONs. Section III shows the state-of-the-art technologies/modulations adopted in high speed TDM, WDM, and TDM over WDM networks, and LR-PON networks. In Section IV a discussion about the main challenges of NG-PON modulation technologies has been reported. Section V concludes the paper.

II. NG-PON Modulation Schemes

Advanced optical modulation schemes recently opened new research opportunities in optical communications. With these schemes the capacity of each single wavelength channel has increased to several 10s to 100s of Gbps. This allows the spectral efficiency of these systems to increase to M bits/s/Hz instead of 1bit/s/Hz as in intensity modulation direct detection (IM/DD) systems [18]. Furthermore, with the huge advances in digital signal processing (DSP) technology better communication performance has been achieved. In the following, we discuss the characteristic and the recent advances of different modulation techniques:

A. Non-Return to Zero Modulation (NRZ-OOK)

Non-Return to Zero OOK (NRZ-OOK) is the simplest and widest deployed optical modulation format in today fiber-optic communication systems. With this scheme, no power transition between two successive "1" bits takes place. For bit rates of 10Gbps and below, NRZ-OOK is generally generated using direct modulated lasers (DMLs) and electro-absorption modulators (EAMs) for short and intermediate reach systems and using Mach-Zehnder modulators (MZMs) for long haul applications [19]. In [5], Chow demonstrates the use of OOK in a TDM-PON for 40Gbps data transmission.

B. Binary Differential Phase Shift Keying (DPSK)

Phase modulated systems that employ delay modulation or differential detector are referred to as differential phase shift keying (DPSK). DPSK encodes information as a phase change between two adjacent bits. Where a "1" bit encoded as π phase change between adjacent bits, while "0" bit is encoded as absence of phase change. DPSK has better performance with respect to OOK modulation represented in a 3dB receiver sensitivity improvement. To perform optical phase modulation, we can use either a straight line phase modulator or a MZM [18]. For MZM case, the modulator is symmetrically driven around the zero transmission point in order to produce exactly π phase shift. In DPSK receiver, a delay interferometer (DI) is used to convert phase modulation into intensity modulation (IM) prior to photodetector (PD). In [6] DPSK signals have been used to transfer 10Gbps in the downstream direction in a hybrid TDM/WDM PON with a DI at the remote node.

C. Multilevel Modulation Schemes

Recall that conventional OOK will require expensive electronics/optoelectronics devices for high data rates systems. Multilevel modulation schemes can ease the speed requirement of these devices and achieve the desirable bit rates. Multilevel modulation techniques can be categorized into memoryless and memory mapping schemes.

In memoryless techniques, each binary sequence of length k is mapped into one of the bandpass signals $s_m(t)$ regardless of the previously transmitted signals. The waveforms $s_m(t)$ may differ in amplitude (e.g. ASK), phase (e.g. PSK), frequency (e.g. FSK), or in some combinations (e.g. QAM).

For ASK, PSK, and QAM the general representation of $s_m(t)$ is as follow [20]

$$s_m(t) = Re\left[A_m g(t) e^{j2\pi f_c t}\right] \quad ,m = 1,2,\ldots..M \qquad (1)$$

where:

$g(t)$ is the low pass pulse signal, and

$$A_m = \begin{cases} \pm1, \pm3, \ldots\ldots\ldots\ldots\ldots\ldots\ldots .real\ for\ ASK \\ e^{j\frac{\pi}{M}(m-1)} \ldots\ldots\ldots\ldots\ldots\ldots ..complex\ for\ MPSK \\ A_{mi} + jA_{mq} \ldots .general\ complex\ for\ MQAM \end{cases} \qquad (2)$$

Assuming Gray coding, the BER can be approximated for different multilevel modulation as follows:

For MASK with non-coherent detection [21]

$$P_b^{ASK}(M) \approx \frac{1}{b}\left(\frac{M-1}{M}\right) erfc\left(\sqrt{\frac{3b\gamma_b}{2(M-1)(2M-1)}}\right) \qquad (3)$$

For MPSK with coherent detection [20]

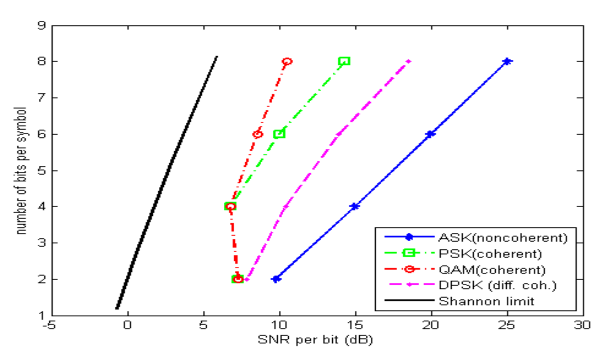


Fig. 2 Spectral efficiency vs. SNR per bit (assuming polarization multiplexing).

$$P_b^{PSK}(M) \approx \frac{1}{b} erfc\left(\sqrt{b\gamma_b} \sin\left(\frac{\pi}{M}\right)\right) \quad (4)$$

For MQAM with coherent detection [20]

$$P_b^{QAM}(M) \approx \frac{2}{b}\left(\frac{\sqrt{M}-1}{\sqrt{M}}\right) erfc\left(\sqrt{\frac{3b\gamma_b}{2(M-1)}}\right) \quad (5)$$

Using the BER equations for DPSK and different multilevel modulation formats, the SNR per bit has been computed to achieve a target BER of 10^{-3} which is a typical threshold for optical receivers employing forward error correction coding (FEC). Fig. 2 shows the spectral efficiency vs. SNR per bit for DPSK and different multilevel modulation formats (assuming transmitting data on two polarizations (polarization multiplexing)). It can be shown that, a spectral efficiency of 4 bit/sym/pol can be achieved by SNR of 25dB for ASK, 17.4dB for DPSK, 14.3dB for PSK with coherent detection, and 10.5dB for QAM with coherent detection.

D. *Orthogonal Frequency Division Multiplexing (OFDM)*

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation format where modulation and demodulation onto subcarrier is performed digitally via fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT), respectively. In OFDM, data are transmitted in parallel on a number of different frequencies. As a result, the symbol period is much larger than that of a serial system with the same total data rate. Based on the larger symbol period, inter symbol interference (ISI) affects at most one symbol and equalization is simplified. The subcarrier frequencies are chosen so that signals are mathematically orthogonal over one OFDM symbol period. Both modulation and multiplexing are achieved digitally using IFFT at the transmitter and at the receiver demodulation and de-multiplexing are performed by FFT.

The demand of higher data rates over the dispersive optical channel and the development of DSP technology over optical channel encourage researchers to implement optical networks based on optical OFDM (OOFDM) [11]. Recently OFDM has been adopted in optical transmission systems. OOFDM can be classified according to the signal synthesis method and the detection approach [22]. Based on signal synthesis, there are two categories FTT-based approach and all optical approach. In FFT approach the OFDM subcarriers are generated in electrical domain. The system's transmitter is composed of electrical OFDM transmitter and electrical to optical converter. The system's receiver is composed of optical to electrical converter and electrical OFDM receiver, as shown in Fig. 3. In the all optical approach, the generation and detection of the optical subcarriers and the optical OFDM signal are done in optical domain, as shown in Fig. 4 (a) and (b), respectively.

OOFDM detection can be achieved using direct detection (DD) or coherent detection (CO) system. In DD-OFDM, the optical carrier is send along with the OFDM signal so as to ease the detection using a single photodiode. In CO-OFDM the optical received signal is mixed with a local oscillator through a six-port 90 degree optical hybrid and a pair of balanced photo detector [18].

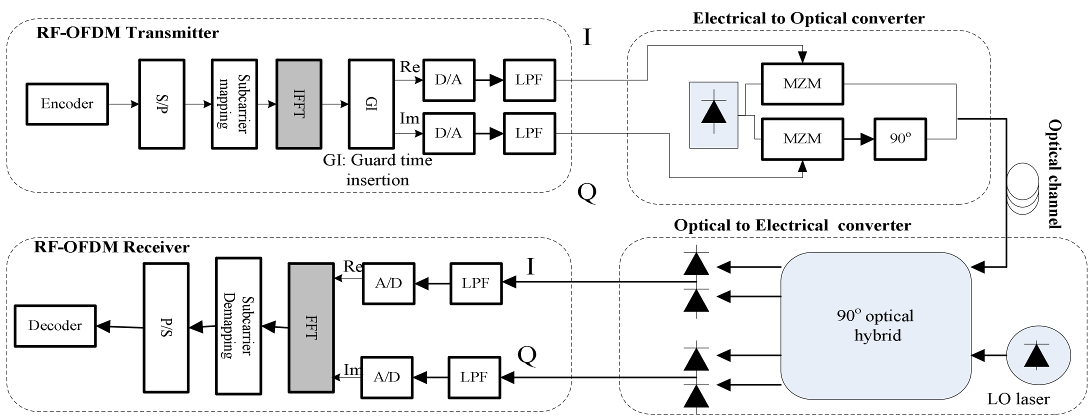
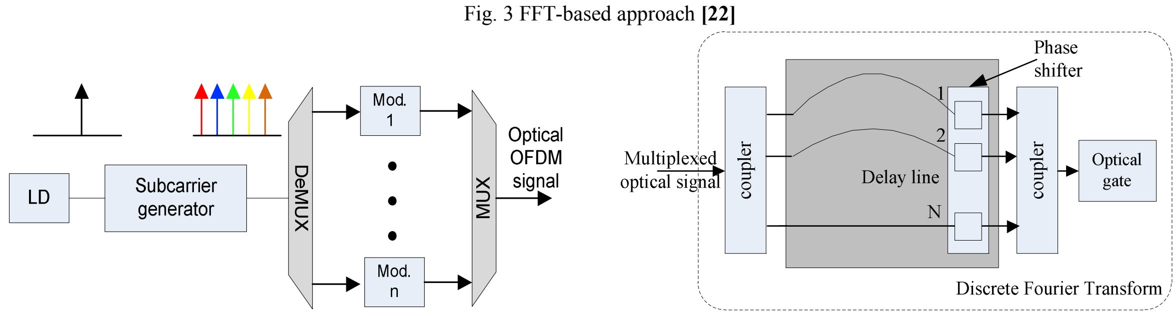


Fig. 3 FFT-based approach **[22]**



(a) (b)

Fig. 4 (a) All optical transmitter (b) All optical receiver [23]

III. NG-PON MODULATION TECHNOLOGIES

A. *Modulation Schemes for TDM NG-PON*

Recently, IEEE and ITU-T complete their standards (i.e. IEEE 802.3av and ITU-T G.987) which address the main specifications of the high speed TDM-PON [24, 25]. In[4], Kim *et al.* numerically and experimentally investigated the transmission of 10Gb/s coherent QPSK downstream signal over 20km SMF. A digital equalizer has been used to reduce the bandwidth required for the targeted data rate. This allow for a cost-effective solution. The bandwidth is approximately ¼ of the bit rate (i.e. 2.5 GHz). A 20-tap linear feed forward equalizer (LFE) has been used to compensate for the distortion caused by low bandwidth electronics. As mentioned previously, future access network demonstrations should support multi rate system. Instead of using dual rate burst mode receiver, Dayou *et al.* proposed a cost effective solution where the OLT can support multi-rate ONUs. A hybrid 2.5/10Gbps PON is successfully demonstrated based on QPSK-OFDM with a single receiver at the OLT [26]. Different DACs are used for different ONUs so as not to waste the DAC bandwidth and reduce the overall cost. Each ONU will assign different number of subcarriers. The main challenge will be in the synchronization and the orthogonality between different subcarriers at different ONUs. In [27], Dayou et al., propose another cost-effective network by replacing the coherent detection receiver by a direct detection one. The system is based on the transmission of 64/32/16 QAM- single side band (SSB)-OFDM signals that achieve 40Gbps downstream rate. The demonstration uses high speed available DAC working at sampling rate of 12Gsample/s. In the previous demonstrations, the generation and detection of the transmitted and the received signals is done based on offline processing. These systems don't consider the limitations caused by precision and speed of DSP hardware components. Real time demonstrations have the ability to generate, detect and measure the appropriated signals based on real time processing. In [28], Giddings et al., demonstrate experimentally a real time OFDM access network based on power loading technique. The optical transmission is done at a rate of 11.25Gbps. However, the data rate is further increase by 7% by considering bit and power loading algorithm for the OFDM subcarriers [29].

TABLE I
MODULATION SCHEMES FOR TDM NG-PON

Ref.	Modulation tech.	Data rates	Electrical Bandwidth	Detection method
[4]	QPSK	10Gbps DS*	2.5 GHz	Coherent detection
[8]	OOK DS/ 16QAM-OFDM	40Gbps** symmetric	10GHz/ 3GHz	DD
[26]	QPSK-OFDM	2.5/10Gbps hybrid US	1.25/5 GHz	DD
[27]	64/32/16QAM-OFDM	40Gbps DS	10.9/8.7/7.3GHz SSB-OFDM	DD
[29]	MQAM-OFDM	11.75Gbps	2-4 GHz	DD

* DS: downstream, US: upstream
** Multiplexing of 4 different wavelength each with rate of 10Gbps

B. *Modulation Schemes for WDM NG-PON*

WDM-PONs have been investigated as a potential technology for NG-PON. Different architectures have been proposed to implement WDM-PONs [30]. These include broadcast and select, AWG-based, and colorless ONU-based PON. WDM-PON is expected to be compatible with radio over fiber systems to serve both wire and wireless users. In [16], Liu et al., demonstrate a smooth integration between fixed and mobile users through WDM-PON in order to transfer 1Gbps wireless and 10Gbps wire signals. The wireless signal is transmitted via a mixing between 1G 32QAM-OFDM and a 20GHz RF signal. Whereas, the 10G 16QAM-OFDM wire signal is transmitted as a baseband signal.

Generally OFDM is generated using MPSK or MQAM, but due to the phase discontinuity, the DSP hardware components are more complex and unstable. Minimum shift keying (MSK), as a type of continuous phase modulation (CPM), has the property of continuous phase and fast side lobe decaying. In [14] Shao *et al.* proposed the combining of MSK coding with OFDM signaling in WDM-PON network. With MSK the effect of phase noise and carrier frequency offset diminishes which results in reducing the intercarrier interference (ICI). In[15], Zhang *et al.* proposed the multi-amplitude minimum shift keying (MAMSK) - OFDM technology for NG-PON. This scheme can achieve higher spectral efficiency (SE) than MSK-OFDM. A 5 Gb/s-2AMSK-OFDM signal successfully generated and transmitted over 20 km SMF. Although MSK-OFDM has 0.6 dB OSNR better than 2AMSK-OFDM, the SE is just half of 2AMSK.

C. *Modulation Schemes for TDM/DWDM NG-PON*

Hybrid TDM/WDM PON has the benefits of the multiuser wavelength sharing offered by TDM-PON and the high number of wavelengths offered by WDM-PON. In [6] , Cheng et al., proposed a cost effective hybrid TDM/WDM PON that uses DPSK for downlink and OOK for uplink transmission. The downlink and uplink speeds are 10 and 1.25Gbps respectively. In this demonstration a delay interferometer (DI) and NxN array waveguide grating (AWG) are shared between ONUs at remote node (RN) for cost-effective ONU purpose. The DI is used for downlink DPSK signal demodulation whereas the AWG is used to generate the seeding light. This wavelength is injected into the ONU receiver for uplink signals transmission. In [7], a hybrid network model has been proposed by Nikolaos *et al.* that

TABLE II
MODULATION SHEMES FOR WDM NG-PON

Ref.	Modulation tech.	Data rates	Electrical Bandwidth	Detection method
[16]	32QAM-OFDM ROF & 16QAM-OFDM	1Gbps ROF & 10GBps wire	40GHz for wire and wireless	DD
[14]	MSK-OFDM	2.5 Gbps	0.7GHz	DD
[15]	2AMSK-OFDM	5 Gbps	1.5GHz	DD

TABLE III
MODULATION SHEMES FOR HYBRIDE TDM/WDM NG-PON

Ref.	Modulation tech.	Data rates	Electrical Bandwidth	Detection method
[6]	DPSK DS OOK US	10Gbps/ 1.25Gbps	10 GHz/ 1.25GHz	DI DD
[7]	16QAM	10 Gbps symmetric	2.5 GHz	Incoherent detection

operates at higher speed, 10Gbps symmetric transmission. The modulation is done using 16QAM for both directions. For the same purpose of low cost design, the signal demodulation is done incoherently.

D. Modulation Schemes for 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 . 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.

Different demonstrations based on multilevel modulation and OOFDM schemes have been developed. Yeh et al. [5], propose a simple LR-TDM-PON demonstration in order to achieve 40Gbps symmetric transmission. This design is based on the multiplexing of 4 different wavelengths each working at 10Gbps with OOK modulation. The system penalty achieved is in the range of 3.5 dBs. However, the cost of ONU is relatively high since 4 laser sources are needed for each ONU. In [9], Lavery et al., propose a LR-WDM-PON that can be implemented without a midspan repeater or amplifier by employing a digital coherent receiver that can increase the loss budget of the PON. The transmission is done at speeds of 10Gbps in both directions by modulating a 3.125Gbaud PDM-QPSK onto CW light source. In [10], Jung et al., generate a non-ideal QPSK signal by directly modulating a RSOA with the proper 4-level electrical signal. The transmission is achieved with speed of 5Gbps without using any optical amplifier or electronic equalizers. The output constellation is asymmetric due to RSOA's chirp which causes different amplitude for the constellation points. In spite of 1 dB system penalty, this demonstration has 5.6dB better sensitivity than the traditional 4-level PAM. In [13], Hsu et al., take the benefit of OFDM to increase the spectral efficiency of the PON network by using higher order QAM modulation format. For the purpose of simplicity and cost, the optical transmitter is designed using electro absorption modulator (EAM). The trade of between the chirp-related power fading and the transfer function linearity of the EAM is overcome by the proper selection of the EAM's bias voltage. The transmission is done based on 128QAM through a bandwidth of 3GHz to achieve 21Gbps. In [17] , Neto et al., compared the performance of amplified and unamplified LR-TDM-PON for a specific splitting ratio. The system is based on AMOOFDM and IMDD for cost purpose. By AMOOFDM, the modulation level and power per subcarrier are adaptively changed according to channel frequency response. The amplification scenario is done either by using an EDFA at the transmitter (booster mode) or at the receiver (pre-amplification mode). Results show that the pre-amplified system achieves better performance in terms of bit rate-distance product than the booster mode. For 1:32 splitting ratio, a 1400Km.Gb/s at 70km is realized for pre-amplification while 1150km.Gb/s is achieved at 50Km for booster mode.

IV. DISCUSSION

The demonstrations discussed above show that OOK techniques offer the simplest hardware design in low data rete (~10Gbps). However, for higher data rates (~40^{+}Gbps) the hardware implementation is challenging. Multilevel modulation and OFDM systems provide cost effective and high spectral efficiency access networks. Multilevel modulations allow the designers to reduce the bandwidth required for data transmission. Furthermore, continuous phase modulation schemes has the property of mitigating the effect of phase noise, carrier frequency offset, and as a result reduces the inter-carrier interference (ICI). Besides increasing the spectral efficiency, OFDM also provides a robust resistance to fiber impairments such as CD and PMD. Moreover, by the proper signal processing techniques, OFDM allows the integration of NG-PON with legacy PON on the same infrastructure as the first challenging step to deploy NG-PON.

Flexibility and scalability are major challenges for future optical access networks. Recently, significant research has been developed to provide an elastic optical network in terms of network architecture and enabling technologies. Compared with conventional OOFDM, adaptive systems based on AMOOFDM have the capability to adapt the modulation format and data rates, in a cost effective manner, based on the channel quality, in order to maximize achievable signal transmission capacity. The real time demonstration of highly spectral efficient networks, shows that the limitation caused by available hardware speed and precision, affects the data rate.

TABLE IV
MODULATION SHEMES FOR LR-PON

Ref.	Modulation tech.	Architecture	Data rates	Electrical Bandwidth	Detection method
[5]	OOK	TDM-PON	40Gbps symmetric	10 GHz	DD
[9]	PDM-QPSK	WDM-PON	10Gbps symmetric	3.125 GHz	Coherent detection
[10]	QPSK	WDM-PON	5Gbps upstream	2.5 GHz	Coherent detection
[13]	OFDM-128QAM	TDM-PON	21Gbps downstream	3 GHz	DD
[17]	AMOOFDM(BPSK-128QAM)	TDM-PON	Up to 40Gbps	---	DD

The deployment of these technologies in the market will depend on the availability and cost of some key components and devices. This includes the cost of high speed DAC and MZM modulator. Also, a technology such as optical OFDM is considered in its early stage of implementation and it is expected to be commercially available on the long term.

V. Conclusion

NG-PONs should be able to handle the ever-increasing number of internet users and bandwidth hungry applications. Numerous modulation schemes are extremely needed to increase the performance of NG-PON in order to increase the bit rate within the minimum bandwidth. This survey gives an up-to-date picture about the different candidate modulation technologies explored for NG-PON. Multilevel modulation techniques suffer from complex hardware implementation especially for higher rate transmission systems (40^+ Gbps). With digital signal processing (DSP), OFDM and its derivatives such as AMOOFDM provide high performance candidate for future elastic NG-PON architecture.

VI. Acknowledgment

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