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Simulation of FDM-Based Next Generation Passive Optical Networks

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ABSTRACT

In this paper, we study frequency-division multiplexing (FDM) as a possible solution for next generation passive optical networks (PONs) with data rates beyond 10 Gb/s as per next generation PON Stage 2 (NG-PON2) requirements. The FDM part is realized by exploiting the inexpensive intensity modulation with direct detection (IM/DD) nature of existing PONs, while adding some digital signal processing (DSP) functionalities at the transceivers to permit higher spectral efficiencies. Instead of simple on-off-keying (OOK) modulation, we consider high order M-ary quadrature amplitude modulation (M-QAM) formats. Further, root-raised cosine (RRC) pulse shaping and matched filtering are employed to improve the system spectral efficiency and control the inter-symbol-interference (ISI). The performance of the proposed FDM-based PON is assessed for uplink direction via system simulations where the uplink bit error rate (BER) performance of the proposed PON is evaluated. We focus this study on single-user simulations, but we assess the performance of the different channels by changing subcarrier frequencies. Our results reveal that a BER below the forward error correction (FEC) threshold can be achieved over a 20 km PON reach with reasonable launch power levels over a 20 km PON reach and a bit rate of 27.5 Gb/s. This proves that FDM-based PONs may be regarded as good candidates for next-generation PONs.

Keywords*: Digital signal processing (DSP), fiber-to-the-home (FTTH), frequency-division multiplexing (FDM), passive optical networks (PON).*

I. INTRODUCTION

The huge demand for high data rates and the increasing need for broadband services have made replacing copper wires with optical fibers inevitable, through fiber-to-the-home (FFTH) technology [1], [2]. Current FTTH deployments are based on either gigabit passive optical network (GPON) and Ethernet-based PON (EPON) standards for 1 Gb/s, or XG-PON and 10G-EPON standards for 10 Gb/s. However, because of the time-division multiple-access (TDMA) nature of previous standards, the user bit rates are limited to sub-gigabit per second.

Recently, the full service access network (FSAN) and the international telecommunications union (ITU- T) have determined the requirements of next generation PON Stage 2 (NG-PON2) with data rates reaching 40 Gb/s in the downlink direction and 10 Gb/s for the uplink [3], [4]. Time- and wavelength-division multiplexed (TWDM) PON has been proposed as a fast solution to meet the NG-PON2 requirements [5]. TWDM stacks four XG-PONs using wavelength-division multiplexing (WDM) to achieve an overall data rate of 40 Gb/s. Other NG-PON2 solutions such as optical code-division multiple access (OCDMA), orthogonal frequency division-multiplexing (OFDM), wavelength division multiplexing (WDM) have been proposed [6]-[8]. Frequency-division multiplexed (FDM) PONs have attracted a lot of attention in the past few years due to their ability to reach high data rates without much complexity or cost [9], [10].

In this work, we propose an inexpensive FDM solution with using intensity modulation with direct detection (IM/DD) instead of optical coherent detection already proposed in other FDM solutions. This simplifies the system architecture and moves the complexity from optics to electronics. Our scheme uses M-QAM to modulate the data of each channel instead of on-off keying (OOK) to increase the data rate and the spectral efficiency. Root raised cosine (RRC) pulse shaping and matched filtering is used to mitigate the intersymbol interference (ISI) due to chromatic dispersion and/or bandwidth limitations of optoelectronics. Further, the proposed FDM PON is compatible with current TDM architectures. It can also be associated with TDM to further increase the PON capacity. The performance of the proposed FDM PON is studied using single user simulations for the uplink direction. The rest of this paper is organized as follows: Section II shows the detailed system architecture including the details of the transceiver DSP functionalities and the physical PON architecture, Section III is devoted for discussing the system simulation which includes the simulation setup and results. Finally, the paper is concluded in Section IV.

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II. Detailed System Architecture

The proposed FDM PON architecture is fully compatible with standard 1 Gb/s and 10 Gb/s PON architectures as shown in Fig. 1. The standard 1 Gb/s PON architecture consists of a Fabry Perot (FP) laser at the optical network unit (ONU) and an avalanche photodiode (APD) at the optical line terminal (OLT) for the uplink direction. Whereas for the downlink direction; a distributed feedback (DFB) laser is used at the OLT and a *p-i-n* photodiode at the ONU. The 10 Gb/s PON uses an electro-modulated laser (EML) and a *p-i-n* photodiode in both uplink and downlink directions [3], [4]. Both 1 Gb/s and 10 Gb/s PON systems employ OOK over IM/DD yielding a spectral efficiency of 1 b/s/Hz. The proposed FDM PON simply adds a digital signal processing (DSP)-based transceiver at both OLT and ONU sides to allow for M-QAM constellations yielding higher spectral efficiencies.

The DSP transmitter starts with the M-QAM modulator/mapper where each group of $k = \log_2 M$ bits are mapped into a QAM symbol. The generated M-QAM symbols are pulse shaped by an RRC filter with a certain roll off factor γ and filter order denoted by RRC(γ,n). After RRC pulse shaping, the filtered signal is electrically upconverted to an RF subcarrier and then passed to a digital-to-analog converter (DAC) with a reasonable resolution to minimize the quantization error before directly modulating the LD.

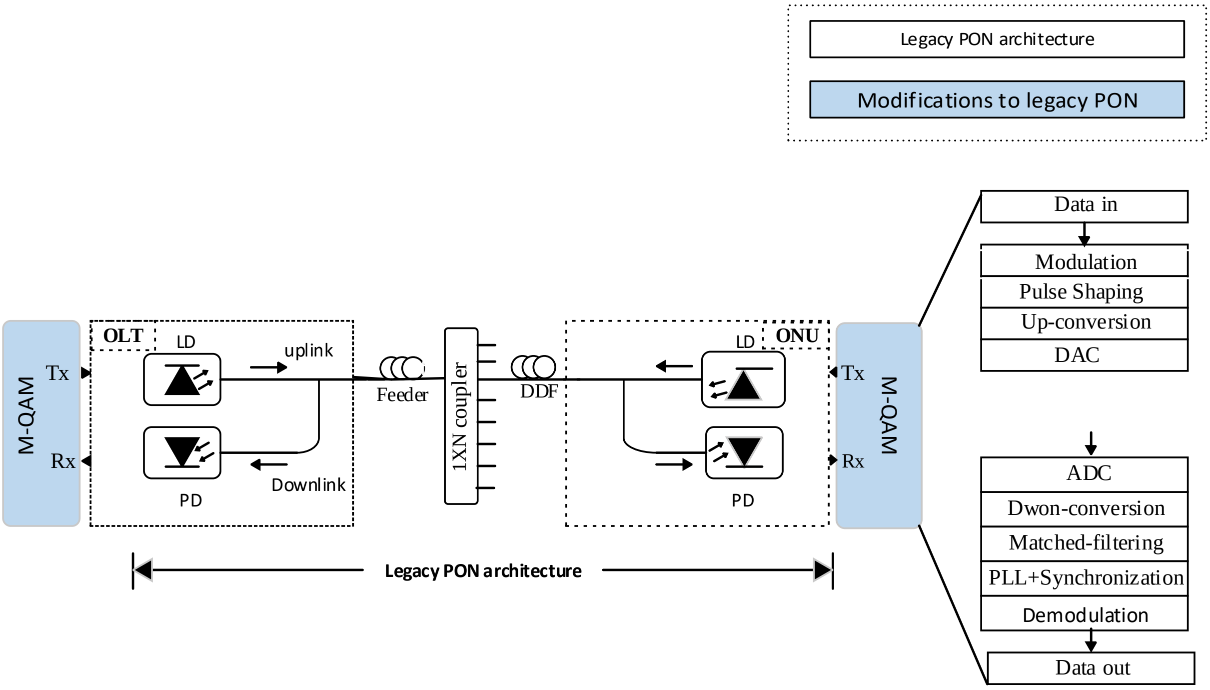

Fig. 1: Proposed scheme architecture over the existing legacy PON architecture (DDF: distribution drop fiber, LD: laser diode, PD: photodiode, Rx: receiver, Tx: transmitter).

The transmission bandwidth of a specific RF channel at f_{sc} taking into account the effect of the RRC filter roll off factor can be expressed as follows

$$\mathrm{BW_{Ch}} = (1+\gamma)\times \mathrm{R_{baud}}$$

where $\mathrm{R_{baud}}$ is the baud rate. Assuming a total available bandwidth BW_{total}, the number of the RF channels N_{RF} is simply

$$N_{RF} = \left\lfloor \frac{BW_{total}}{BW_{ch}} \right\rfloor$$

Here $y = \lfloor x \rfloor$ denotes the largest integer not larger than x. Note that reducing the filter roll off factor reduces the channel bandwidth which increases the number of channels, but at the expense of being more vulnerable to timing jitter and ISI. Therefore, selecting the proper RRC filter roll off factor that improves the system capacity (i.e., spectral efficiency) while maintaining an acceptable bit error rate (BER) is not straightforward.

The DSP receiver simply reverses the functionalities of the transmitter DSP stack. After photodection and analog-to-digital conversion (ADC), the signal is electrically downconverted to baseband. An RRC matched filter is then used to reconstruct the signal and eliminate the ISI. Carrier recovery is performed using a simple phase locked loop (PLL) and synchronization algorithm before the *M*-QAM symbols demodulation.

III. BER Performance Of The Proposed FDM PON

As a proof of concept, we focus our simulation only on the uplink direction for single-user transmission. The simulation setup of the proposed PON architecture based on a XG-PON infrastructure is illustrated in Fig. 2. The transmitted signal was generated using MATLAB and then passed to OPTISYSTEM to an electro-absorption modulated laser (EML) modeled by a laser diode (LD) followed by an electro-absorption modulator (EAM). An erbium-doped fiber amplifier (EDFA) followed by a variable optical attenuator (VOA) are used to control the launch power. After passing through the optical distribution network (ODN) where the remote node losses are emulated using another VOA, the signal is photodetected, RF amplified, and then sent back to MATLAB for processing.

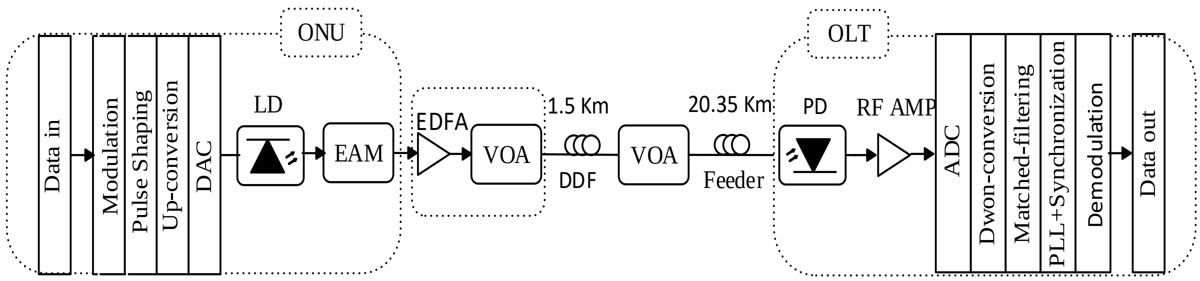

Fig. 2: Uplink Simulation setup (DAC: digital-to-analog converter, EAM: electroabsorption modulator, EDFA: Erbium doped fiber amplifer, VOA: variable optical attenuator, AMP: amplifier, ADC: analog-to-digital converter).

The baud rate of the system is chosen to be 1.25 Gbaud resulting in a 2.5 GHz channel bandwidth for unity RRC roll off factor. Thus the 10 GHz available BW of X-GPON would allow up to four RF channels assuming an RRC roll off factor $\gamma = 1$. Reducing the baud rate to 625 Mbaud would simply double the number of RF channels. Lowering the roll off factor introduces guard band between channels, or would allow to increase the number of RF channels (i.e. the system capacity). To meet the low power requirements of NG-PON2 the launch power of the ONU was set to 2.6 dBm [11]. We assume the use of forward error correction codes (FEC) as recommended by 10G-PON standards.

The remote node (RN) losses are varied from 0 dB to 18 dB to evaluate the maximum losses that the system can tolerate while maintaining a BER ~10^{-3} below the FEC threshold. Multiple *M*-QAM orders (4-QAM, 16-QAM, 64-QAM and 256-QAM) and different subcarrier frequencies were examined. Fig. 3 shows the BER versus the RN losses for the different system parameters.

As expected, the BER degrades with increasing the RN losses which maps the number of ONUs in the network i.e. splitting losses at the RN due to the reduction of the received power level at the PD and in turn causes deterioration of the BER. In addition, the system performance degrades at higher *M*-QAM orders as expected. For all channels, the BER of 4-QAM is below the FEC threshold for RN losses up to 18 dB (i.e. 64 ONUs) achieving a bit rate of 2.5 Gb/s. While 16-QAM can be used for channels one and two with RN losses up to 18 dB (64 ONUs) and for channels three and four it can tolerate up to 15 dB RN losses (32 ONUs) with bit rate of 5 Gb/s. As for 64-QAM it can be used for all channels up to 12 dB RN losses (16 ONUs) except for channel four it can tolerate up to 9 dB RN losses (8 ONUs) with bit rate of 7.5 Gb/s. 256-QAM can only be used for channels one and two up to

9 dB RN losses (8 ONUs) with bate rate of 10 Gb/s. Therefore, over the available 10 GHz bandwidth with 16 ONUs in the network 64-QAM can be used for channels one, two and three while 16-QAM can be used for channel four achieving an aggregate bit rate of 27.5 Gb/s i.e. a spectral efficiency of 2.75 b/s/Hz. If the number of ONUs is is increased to 32 ONUs, then 16-QAM is used for all channels achieving an aggregate of 20 Gb/s and spectral efficiency of 2 b/s/Hz. Finally increasing the number of ONUs to 64 would result in an aggregate bit rate of 15 Gb/s and spectral efficiency of 1.5 b/s/Hz.

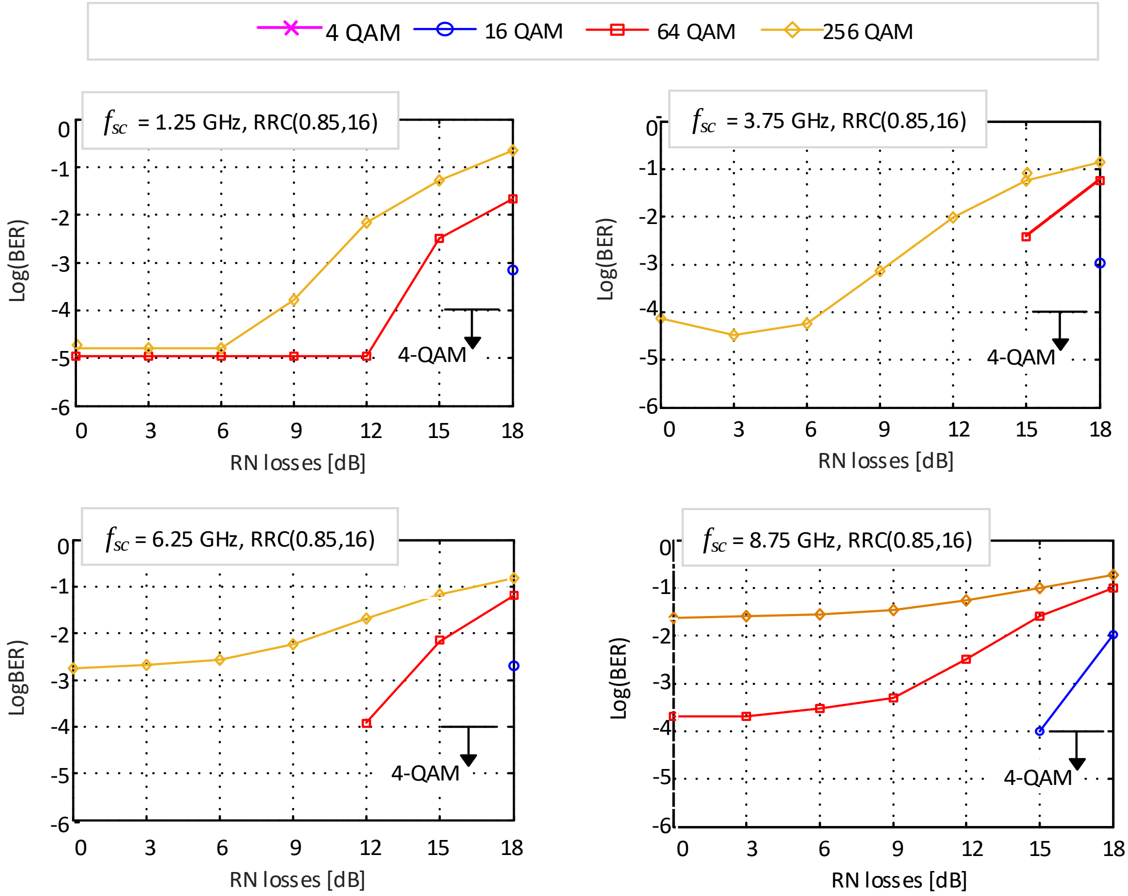

Fig. 3: BER versus RN losses for different QAM orders and subcarrier frequencies at 1.25 Gbaud.

In Fig. 4, the BER is plotted versus the filter roll off factor for both 64- and 256-QAM, at a subcarrier frequency 1.25 GHz and RN losses of 9, 12, and 15 dB. It can be noticed that reducing the filter roll off factor requires increasing the filter order to obtain a sharper filter in the frequency domain. The simulation was repeated at subcarrier frequency (f_{sc}) 6.25 GHz. The BER deteriorates as the roll off factor decreases and/or as the subcarrier frequency increases. Although reducing the RRC roll off factor improves the spectral efficiency, the BER performance degrades because of the associated ripples and timing jitter sensitivity as per the eye diagrams in Fig. 5 where the inphase components of a 64-QAM signal is plotted at roll off factors 0 and 0.85. The eye diagram of the signal at roll off factor 0 shows how the signal is more subjected to ISI as the eye is nearly closed and thus degrading the BER.

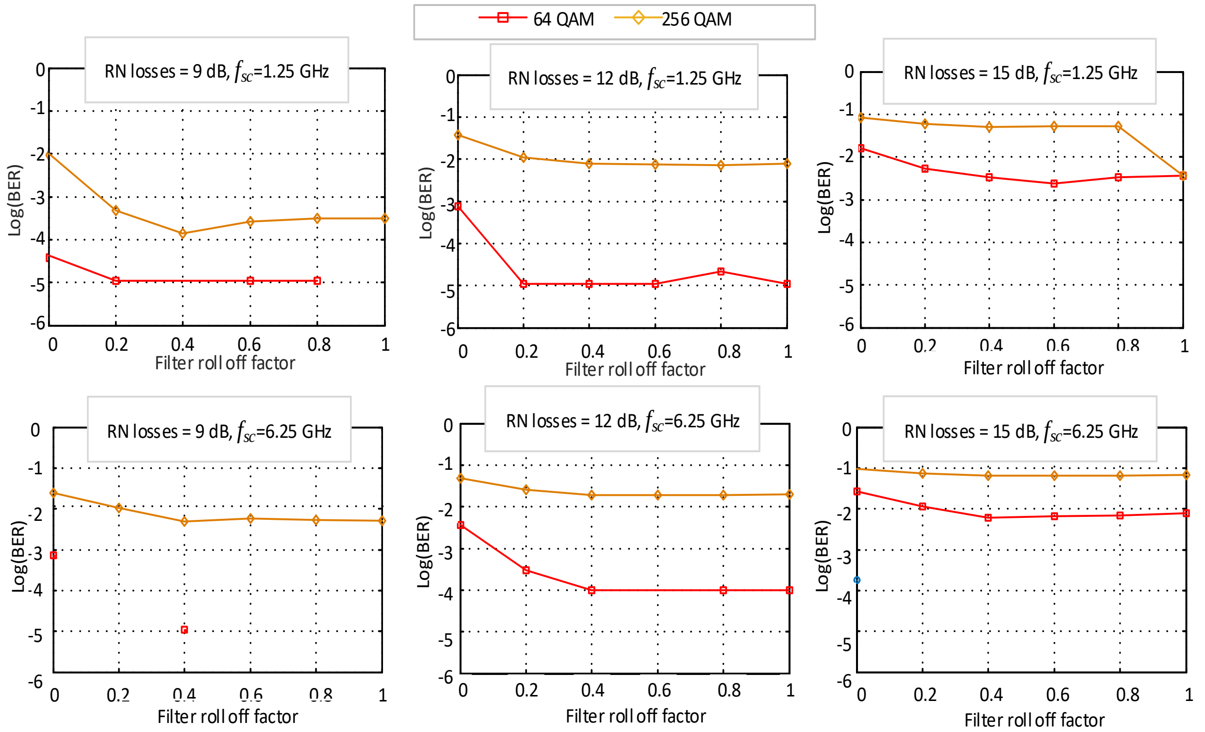

Fig. 4: BER versus filter roll off factor at 1.25 Gbaud, 2.6 dBm launch power and different QAM orders.

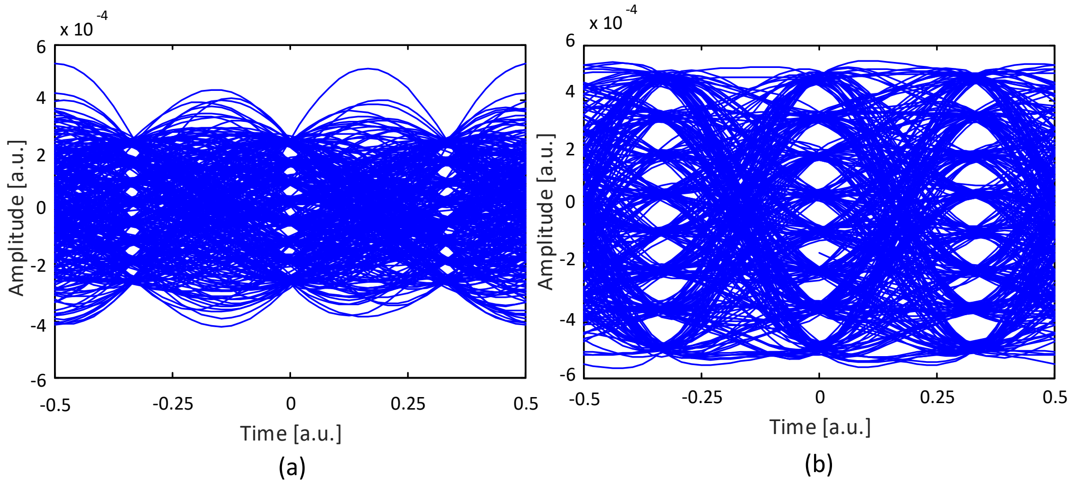

Fig. 5: Eye diagrams of the in-phase component of a 64 QAM signal at subcarrier frequency 1.25 GHz a) roll off factor = 0 (b) roll off factor = 0.85.

Finally, the launch power versus the maximum reach for each modulation order is plotted in Fig. 6. This determines the maximum distance that could be reached by each *M*-QAM order while maintaining a BER below the FEC threshold. In this study, the RN losses was set to 9 dB and the subcarrier frequency to 3.75 GHz. As shown in Fig. 7, the higher the *M*-QAM order the more launch power it needs to increase the PON reach. For 5 dBm launch power all *M*-QAM orders can easily achieve 20 km PON reach, a 40 km PON reach can be achieved up to 64-QAM, (4-QAM, 16-QAM) can reach 60 km PON reach, and 4-QAM can achieve a PON reach of 80 km.

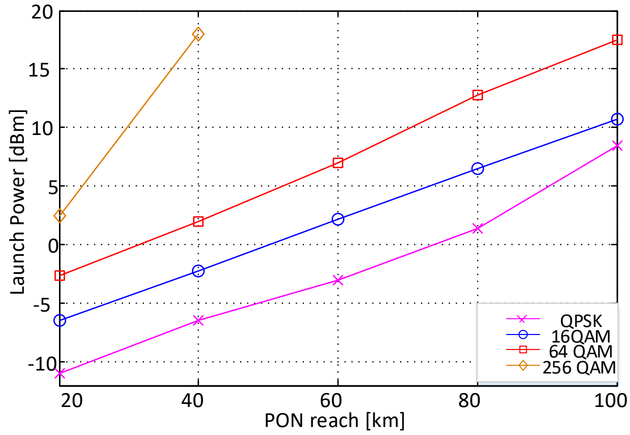

Fig. 6: Launch power versus PON reach for different QAM orders at subcarrier frequency 3.75 GHz.

IV. CONCLUSION

We proposed an FDM solution for NG-PON2 based on simple architecture and low cost IM/DD transceivers, while being compatible with current TDM-based PONs. The proposed solution uses *M*-QAM instead of OOK to achieve data rates beyond 10 Gb/s reaching an aggregate bit rate of 27.5 Gb/s over the available 10 GHz bandwidth with 16 ONUs in the network or equivalently an aggregate bit rate of 20 Gb/s with 32 ONUs in the network. RRC pulse shaping and matched filtering are also used to mitigate the ISI and further improve the spectral efficiency. The solution was evaluated via system simulations.

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