View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Ghent University Academic Bibliography

# Solutions for a Single Carrier 40 Gbit/s Downstream Long-Reach Passive Optical Network

(Invited Paper)

Guy Torfs and Xin Yin
Department of Information Technology
Ghent University / IMEC
Gent, Belgium
Email: guy.torfs@intec.ugent.be

Arno Vyncke and Marijn Verbeke
Department of Information Technology
Ghent University / IMEC
Gent, Belgium

Johan Bauwelinck
Department of Information Technology
Ghent University / iMinds
Gent, Belgium

***Abstract*—This paper presents a single carrier 40 Gbit/s downstream long-reach passive optical network (LR-PON) topology as candidate for upgrading current fiber infrastructure towards higher data rates. A 100 km LR-PON network was investigated and 2 solutions to overcome chromatic dispersion were proposed. Firstly, a dispersion compensated element is added to compensate the mean length of the feeder fiber. Secondly, an advanced modulation scheme, i.e. 3-level electrical duo-binary is introduced. This scheme has the advantage of allowing lower bandwidth APDs and requires only limited additional electronics. Furthermore, to overcome the inherent discrepancy between aggregated line rate and user rate, and hence the reduced power efficiency, the BiPON protocol is added to minimize signal processing at the high line rates.**

## I. INTRODUCTION

The demand for higher bandwidth capacity in telecommunication networks is growing continuously. Among various access technologies, passive optical networks (PONs) are widely recognised as a cost-effective solution to overcome bandwidth limitations. A subset of PON networks, i.e. Long Reach PONs (LR-PONs), designed to offer an economically viable solution, were later proposed. These LR-PONs increase the PON coverage span and allow a higher split ratio by incorporating optical amplifiers in the network. This way, LR-PONs reduce the number of optical line terminals (OLTs) and allow the operators to consolidate network elements/nodes. This results in a significant decrease in energy consumption, and hence, cost. However, the higher split ratio typically employed in LR-PON scenarios reduces the sustained available bandwidth per user which requires an increased line rate to allow support for business-class applications or other bandwidth demanding services. The first demonstrated LR-PON named Super-PON [1] operated at 2.5 Gbit/s while covering a distance of 100 km and serving 2048 optical network units (ONUs). The PIEMAN [2] project has demonstrated a 10 Gbit/s LR-PON with a similar reach and a split factor of 512. One way to further increase the capacity of the LR-PON in the downstream direction is to use wavelength stacking at 10 Gbit/s, similar to the time-and-wavelength division multiplexing PON (TWDM-PON) proposal of the next generation PONs (NG-PON2) [3]. As the bandwidth continues to scale up, however, this technique is clearly a compromise solution which achieves a higher aggregate rate by duplicating the terminal optical hardware.

In this paper, as part of the evolutionary strategy for the LR-PON design, single carrier 40 Gbit/s downstream transmission with the electrical 3-level duobinary modulation is proposed as an upgrade option. A new network topology and downstream protocol is proposed and solutions to reduce the total network energy consumption are shown. This research is part of the “Discus” project funded by the EU under the 7th Framework Programme.

The remainder of the paper is organized as follows. Firstly, the new architecture will be described followed by a discussion on the duo-binary modulation scheme. Secondly, an alternative PON protocol is discussed to allow low power operation at high line rates, leading to the conclusion of this paper.

## II. LR-PON ARCHITECTURE AND SINGLE CARRIER 40 GBIT/S DOWNSTREAM UPGRADE SCHEME

The reference LR-PON design considered in DISCUS [4] is shown in Fig. 1. It shows a basic LR-PON architecture which bypasses old local exchange/central office (LE/CO) sites and terminates on the metro-core (M/C) nodes. Splitting points are located at the distribution points (DP), the primary cross connect (PCP), or the LE/CO site. The optical amplifiers are also situated in LE/CO, which has electrical power available. The optical distribution network (ODN) from the old LE/CO site is designed to support at least 10 km, while the feeder section has a distance up to 90 km with dual-homing protection as shown in the figure.

Speed upgrade from 10 Gbit/s towards 40 Gbit/s is challenging. There are several significant technical issues related to the increasing speed: Firstly, the reduction in signal quality which is induced by chromatic distortion (CD) grows with the square of the bit rate. For a given transmission distance, a 40 Gbit/s system which has 4x increase in bit rate is 16 times more susceptible to CD than a 10 Gbit/s system. To maintain the receiver SNR when increasing the bit rate by a factor of 4 requires nominally 6 dB more optical power. While APDs have been used extensively in 10 Gbit/s PON downstream to improve the receiver sensitivity, no high-speed APD devices are commercially available for 40 Gbit/s NRZ operation. Secondly, ONU electronics operating at these high line rate lead to a further increase in power consumption. Considering the vast amount of subscribers, power consumption reduction in the ONU is of major importance [5].

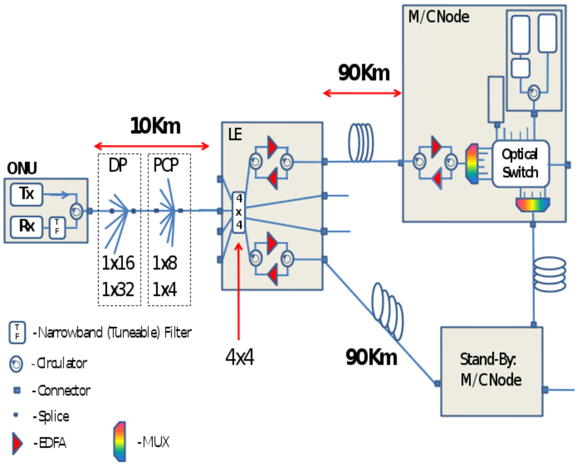

Fig. 1. Reference LR-PON architecture

## III. DUOBINARY SIGNALING

For the 40 Gbit/s downstream transmission a 3-level electrical duobinary modulation scheme is proposed to reduce the optical bandwidth of the OLT transmitter and ONU APD receivers. An electrically generated duobinary signal, in contrast with optical duobinary which modulates the phase of the optical carrier, modulates the optical amplitude with a 3-level signal. This advanced modulation format relaxes the downstream channel bandwidth requirement to $\approx$ 20 GHz thus improving the CD tolerance significantly compared to the NRZ format. This allows for 25 Gbit/s components (especially APDs) employed in ONUs, reducing the cost and power consumption. CD was generally not an issue at 10 Gbit/s rate for PONs. But it becomes a limiting factor when data rate further increases in combination with a longer reach. To extend the reach to 100 km at 40 Gbit/s the proposed scheme has to include a dispersion compensation element, such as a DCF or a fibre Bragg grating module at the OLT output. Because the DCF is shared between all users, it is not a cost-sensitive component. The extra insertion loss of DCF is of no issue as there is a downstream Erbium-doped fiber amplifier (EDFA) right before the trunk fibre (assuming insertion of DCF does not deteriorate the OSNR significantly).

Other modulation schemes such as PAM-4 are also employed to reduce the signal bandwidth, but partial response formats such as duobinary have the advantage that modulation and demodulation circuits are less complex [6]. A duobinary transmitter consists of a precoding stage followed by an encoding step. Fig. 2 shows a block diagram of a typical duobinary transmitter [7]. The precoding stage consists of a XOR gate of which one of the inputs is supplied with a 1-bit-period delayed version of the output. The encoding stage exists of a delay and add filter, having a low pass characteristic with a zero at half the bit rate as shown in Fig. 2 resulting in a bandwidth limited signal which can be modulated on an optical carrier.

A block diagram of a typical duobinary receiver structure is shown in Fig. 3. As shown, only two comparators are needed (in contrast with 3 for PAM-4). The comparators extract the two eyes from the 3-level duo-binary signal and combine them with a XOR gate to reconstruct the original NRZ signal.

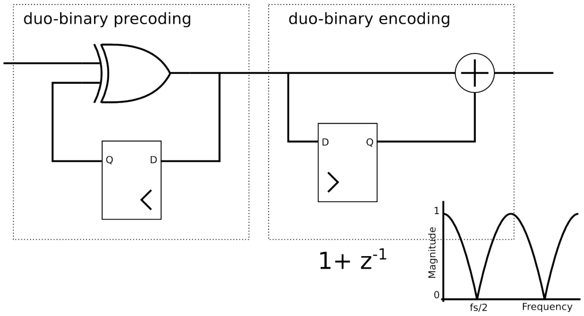

Fig. 2. Block diagram of a duobinary generator and the filter characteristic of its encoding stage

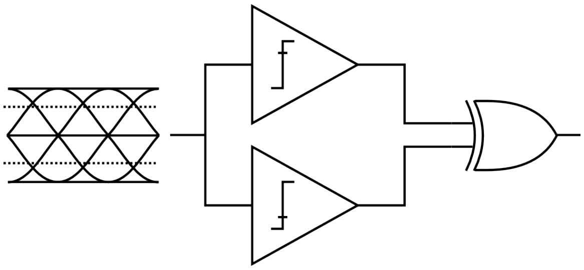

Fig. 3. Block diagram of a duobinary receiver

TABLE I. SIMULATED DISPERSION POWER PENALTY IN DB

| Distance (km) | 40G NRZ APD-Rx | 40G 3-level duobinary APD-Rx |
|---|---|---|
| 2 | 0.1 | 0.1 |
| 4 | 0.5 | 0.6 |
| 6 | 3.1 | 1.3 |
| 8 | / | 2.6 |
| 10 | / | 5.8 |

## IV. 40 GBIT/S DOWNSTREAM SIMULATION RESULTS

The big advantage of the 3-level duobinary modulation over NRZ modulation is its better chromatic dispersion tolerance. An experiment of a 26 Gbit/s transmission over 40 km has been demonstrated using duobinary detection at $\lambda$=1314nm [8]. To emulate this technology for DISCUS LR-PON, the proposed 40 Gbit/s downstream architecture has been simulated using a system simulator built with RSoft Optsim and Matlab. Because a dispersion compensation module will be included at the output of the OLT to compensate the common optical path, i.e. backhaul, the maximum differential reach is 10 km in the access section. The simulated eye-diagrams of 40 Gbit/s NRZ for reaches of 0, 2km, 4km, 6km, 8km, and 10km are shown in Fig. 4. Looking at the figures, it is clear that the NRZ eyes are almost closed after 6 km. As a comparison, the eye-diagrams of 40 Gbit/s 3-level duobinary signal after 0, 2km, 4km, 6km, 8km, and 10 km are shown in Fig. 5. Even after 10 km, a 3-level signal is still able to be recognised from the eye-diagram.

In order to illustrate the benefit of choosing 3-level duobinary modulation, we have simulated the impact of chromatic dispersion using Monte-Carlo techniques. Specifically, we have run simulations of both 40 Gbit/s NRZ and 3-level duobinary system for different fibre lengths and observed the power penalties with respect to their back-to-back cases. We assumed APD receivers used and a pre-FEC BER threshold of 1E-3 for

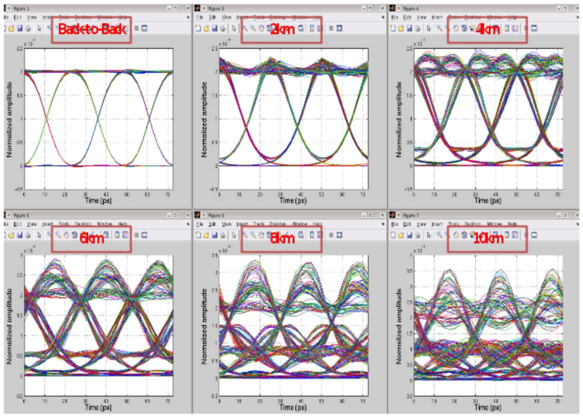

Fig. 4. Eye-diagram of 40 Gbit/s NRZ for various reaches

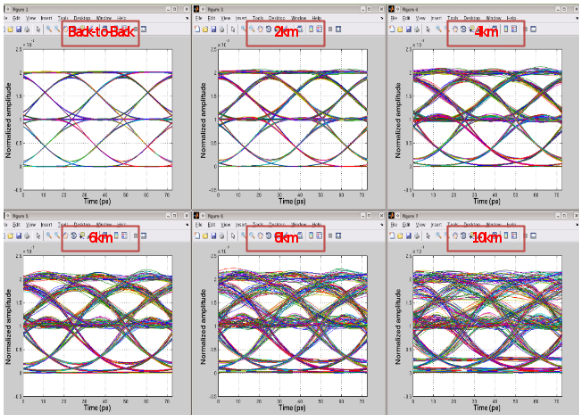

Fig. 5. Eye-diagram of 40 Gbit/s 3-level duoninary signals for various reaches

sensitivity penalty calculations. The resulting power penalties for these two modulation formats are listed in Table I. For the 40 Gbit/s NRZ signal, it cannot meet pre-FEC of 1E-3 when the transmission length is higher than 6 km. Furthermore, at transmission length of 6 km, the power penalty of 40 Gbit/s 3-level duobinary transmission is much smaller than that of 40 Gbit/s NRZ signal (1.3 dB versus 3.1 dB). Given a differential reach of 10 km, the nominal dispersion length should be chosen as the mean of the distance of the shortest and the longest reach. For the 40 Gbit/s architecture discussed so far, the shortest reach is 90 km and the longest is 100 km. Thus the dispersion compensation element should compensate about 95 km of fibre, which leaves uncompensated length of ± 5 km. In the following analysis, we will assume that the system margin should be larger than the dispersion power penalty for 6 km reach (i.e., 5 km plus 1 km extra margin assumed).

Taking the power margins shown in Table II in to account, the dispersion penalties at 6 km for the APD receiver should be subtracted to evaluate the final system margin. Therefore a 40 Gbit/s APD receiver using 3-level duobinary almost cannot support 100 km reach and 128-split all together (only 0.1 dB margin). If we use a strong FEC, assuming 2dB sensitivity improvement, the power margin would be 2.1dB.

TABLE II. OPTICAL POWER MARGIN FOR 40 GBIT/S DOWNSTREAM WITH APD RECEIVER

| | Standard FEC (pre-FEC BER = 1e-3) | Strong FEC (2dB improvement) |
|---|---|---|
| 128 split | 1.4 | 3.4 |
| 256 split | negative margin | 0.0 |

## V. BIT-INTERLEAVING CLOCK AND DATA RECOVERY

To further decrease the ONU power consumption, we propose a 40 Gbit/s bit-interleaving multiplexing PON (BiPON) scheme [9], [10]. Theoretically, the lower limit for the power-consumption in ONUs is dictated by the actual user-rate, which typically is a fraction of the aggregated PON line-rate. While conventional TDM-PON protocols are inherently operating at line-rate. Fig. 6 shows a simplified block diagram of a XG-PON ONT. As illustrated in red, the XG-PON protocol is defined such that a series of complex receiver functions must be performed at the receiving line rate, i.e. 10 Gbit/s in the case of XG-PON. At the end of this chain, the XG-PON encapsulation method (XGEM) receiver selects the useful information targeted to the particular ONT. Assuming an average user rate of 100-Mbit/s on a PON with 40 Gbit/s line rate, more than 99% of the data processed along this chain is therefore discarded at the XGEM receiver. While operating at a full line rate, the circuits implementing these functions clearly dominate the total power consumption of an ONT. To address this inefficiency, the ITU-T has introduced a cyclic sleep mode mechanism in its recent specification [11]. This sleep mode allows some part of the ONT functions to be turned off (or “sleep”) periodically. However, in order to support this mode, the transmitter will have to accumulate data and deliver it in a batch. The side effects of this mode are that the transmitter will incur an additional buffering and the quality of service (QoS), specifically, the packet delay and jitter will be greatly affected [12]. Other sleep mode schemes, adaptive link rate (ALR) techniques and combinations of both have been proposed, though all share the mentioned disadvantages[12]. To lower energy consumption, the sleep period will have to be sufficiently long. A long sleep state translates to larger buffering, longer delay and larger delay variation.

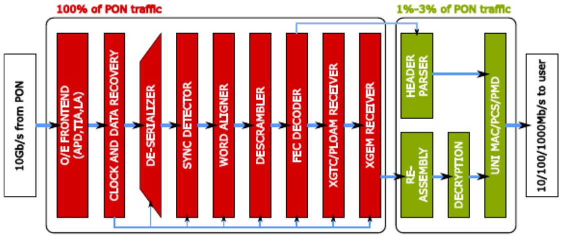

Fig. 6. Downstream architecture of XG-PON ONT

To overcome the issue in the XG-PON protocol and allow a reduction of energy consumption in next-generation access networks, this paper proposes a Bi-PON protocol which modifies the framing structure of the transmission. Figure 7 explains how the protocol works, different colors are used to denote bits intended for different ONTs. The Bi-PON frame has a fixed length of 125 us corresponding to the XG-PON frame length. It consists of a header section and a payload section. The header section is further divided into a synchronization field, a bandwidth map field and an operation, administration and maintenance (OAM) field. The main distinguishing feature of the Bi-PON frame is that all information bits residing in all sections are organized in a bit-interleaved fashion according to the targeted ONTs. This scheme contrasts the XG-PON framing where groups of information bits targeted to a particular ONT are placed in various, irregularly spread locations in a frame. Because of this regular structure in a Bi-PON frame, each ONT only needs to extract its own information in a simple periodic fashion. clear when comparing Fig. 6 and Fig. 8, the number of functional blocks required to operate at full line rate has been reduced significantly. Immediately after the conversion of the incoming optical signal into the electrical domain by the O/E front-end receiver, the clock and data recovery (CDR) circuit extracts the clocking/timing information and recovers the raw information bits. The Bi-PON protocol supports a fixed number of ONTs, e.g. 256. By matching a synchronization pattern and its own ONT identifier, an ONT only need to “listen” to one of the 256 ONT-channels. While the bit allocation scheme in the header section is fixed, the Bi-PON protocol adopts a flexible dynamic bandwidth allocation (DBA) mechanism in the payload section. Within the BW map field, it carries bandwidth allocation information specified as a tuple (Si, Ki) where Ki is the sampling rate and Si is the starting offset of an ONT i. Based on this information, the decimator can extract the payload bits that belong to the designated ONT in the payload section. As the OLT composes (Si , Ki ) for all ONTs, it may update this allocation in a frame by frame basis according to the instantaneous traffic profile of the ONTs. As illustrated in Fig. 7, the protocol also includes an OAM field in the header. The OAM field carries commands such as ranging, encryption keys, etc. A useful OAM command is the “SLEEP CMD” in which the target ONT is instructed to enter a sleep state for the duration of time specified in command argument (in terms of number of frames). During the sleep duration, an ONT shuts off most of the downstream operation except the CDR, decimator and bit-counter to save energy. The bit-interleaving structure together with the fixed number of ONTs reduces the decimation operation into a simple down-sampler. This contrasts to a more complex deserialization and word alignment operation found in the XG-PON protocol. And, more importantly, the information rate after the decimator is significantly reduced, from the line rate (i.e., 40 Gbit/s) to the user rate, typically below 1 Gbit/s as bits intended for other users are immediately discarded. This allows all subsequent operations to be run at a much lower clock rate than the ones in XG-PON. Hence, dynamic power consumption of a Bi-PON ONT is significantly lower. This paper only focuses on the downstream protocol because it largely dominates the total power consumption of an ONT. The upstream data path is considered energy efficient given that there is no unrelated traffic being processed. The burst-mode behavior at the upstream transmission is also inherently energy efficient.

An ASIC design incorporating a 40 Gbit/s CDR and the BiPON digital processing has been implemented and is currently being fabricated. The simulated power consumption is 200 mW, running at a user rate of 10 Gbit/s, significantly lower than typical XG-PON FPGA implementations consuming 3W and more.

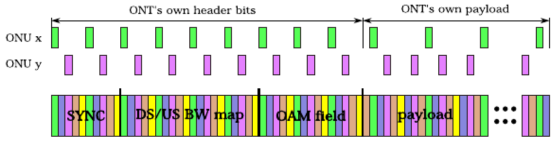

Fig. 7. BiPON transmission frame structure

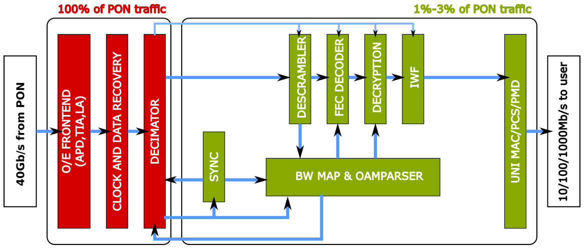

Fig. 8. Downstream architecture of BiPON ONT

## VI. Conclusions

As part of the evolutionary strategy, 40 Gbit/s transmission in the downstream direction is investigated as an upgrade option. To upgrade to a single-carrier 40 Gbit/s downstream in LR-PONs, a 3-level duobinary modulation scheme with downstream BiPON protocol is proposed. The 3-level duobinary relaxes the component bandwidth requirement at ONU and shows better tolerance for chromatic dispersion. The BiPON protocol would further reduce the power consumption and enable cost-effective implementation of advanced FEC codes because the FEC decoder only needs to operate at the user rate. The 40 Gbit/s downstream topologie with an APD receivers has been analysed in terms of power and OSNR budget. Assuming a strong FEC with 2 dB power budget improvement, an APD receiver would support a 90 km backhaul, a 10km ODN and a 128-way split at 40 Gbit/s.

## Acknowledgment

The research leading to this article has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 318137 (Collaborative project “DISCUS”).

## References

[1] I. Van de Voorde, C. Martin, J. Vandewege, X.Z. Qui, *The SuperPON Demonstrator: an exploration of possible evolution paths for optical access networks*, IEEE Communications Magazine, vol. 38, no. 2, pp. 74-82, Feb. 2000.

[2] P. Ossieur, C. Antony, A.Naughton, A.M. Clarke, H.G. Krimmel, X. Yin, X.Z. Qiu, C. Ford, A. Borghesani, D. Moodie, A. Poustie, R. Wyatt, B. Harmon, I. Lealman, G. Maxwell, D. Rogers, D.W. Smith, S. Smolorz S., H. Rohde, D. Nesset, R.P. Davey and P.D. Townsend, *Demonstration of a 32 x 512 Split, 100 km reach, 2 x 32 x 10 Gb/s hybrid DWDM-TDMA PON using tunable external cavity lasers in the ONUs*, Journal of Lightwave Technology, vol. 29, no. 24, pp. 3705-3718, December 15, 2011.

[3] Yuanqiu Luo, Xiaoping Zhou, F. Effenberger, Xuejin Yan, Guikai Peng, Yinbo Qian, Yiran Ma, *Time- and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation PON Stage 2 (NG-PON2)*, Journal of Lightwave Technology, vol. 31, no. 4, pp. 587-593, Feb. 15, 2013.

[4] M. Ruffini, L. Wosinska, M. Achouche, J. Chen, N. J. Doran, F. Farjady, J. Montalvo, P. Ossieur, B. O'Sullivan, N. Parsons, T. Pfeiffer, X. Z. Qiu, C. Raack, H. Rohde, M. Schiano, P. D. Townsend, R. Wessly, X. Yin, and D.B. Payne, *DISCUS: An end-to-end solution for ubiquitous broadband optical access*, IEEE Communications Magazine, vol. 52, no. 2, pp. S24-S32, February 1, 2014.

[5] X. Yin, X.Z. Qui, G. Torfs, C. Van Praet, R. Vaernewyck, A. Vyncke, J. Verbrugghe, B. Moeneclaey, M. Ruffini, D.B. Payne and J. Bauwelinck, *Performance Evaluation of Single Carrier 40-Gbit/s Downstream for Long-Reach Passive Optical Networks*, ONDM 2014, Stockholm, Sweden, 19-22 May, 2014.

[6] J. Sinsky, A. Adamiecki, M. Duelk, H. Walter, H. J. Goetz, and M. Mandich. *10 Gb/s Duobinary Signaling over Electrical Backplanes*, Lucent Technologies, Sept. 2004

[7] J. Verbrugghe, R. Vaernewyck, B. Moeneclaey, X. Yin, G. Maxwell, R. Cronin, G. Torfs, X.Z. Qiu, C.P. Lai, P.D. Townsend and J. Bauwelinck, *Multi-Channel 25 Gb/s Low-Power Driver and Transimpedance Amplifier Integrated Circuits for 100 Gb/s Optical Links*, Journal of Lightwave Technology, accepted for publication

[8] D. van Veen, V. Houtsma, P. Winzer, and P. Vetter, *26-Gbps PON Transmission over 40-km using Duobinary Detection with a Low Cost 7-GHz APD-Based Receiver*, ECOC 2012, paper Tu.3.B.1.

[9] H. Chow, D. Suvakovic, D. Van Veen, A. Dupas, R. Boislaigue, R. Farah, M. F. Lau, J. Galaro, G. Qua, N. P. Anthapadmanabhan, G. Torfs, C. Van Praet, X. Yin and P. Vetter, *Demonstration of Low-Power Bit-Interleaving TDM PON*, 38th European Conference and Exhibition on Optical Communication (ECOC), Mo.2.B.1, 2012.

[10] C. Van Praet, H. Chow, D. Suvakovic, D. Van Veen, A. Dupas, R. Boislaigue, R. Farah, M. F. Lau, J. Galaro, G. Qua, N. P. Anthapadmanabhan, G. Torfs, X. Yin and P. Vetter, *Demonstration of low-power bit-interleaving TDM PON*, Optics Express, vol. 20, no. 26, December 10, 2012, pp. B7-B14

[11] Telecommunication standardization sector of International telecommunication union (ITU-T), *10-Gigabit- capable passive optical network (XG-PON) systems: Definitions, abbreviations, and acronyms G.987*

[12] R. Kubo, J. Kani, H. Ujikawa, T. Sakamoto, Y. Fujimoto, N. Yoshimoto, and H. Hadama, *Study and demonstra- tion of sleep and adaptive link rate control mechanisms for energy efficient 10G-EPON*, IEEE Journal of Optical Communications and Networking, vol. 2, no. 9, pp. 716729, Sept. 2010.