

Coherent PON for NG-PON2: 40Gbps Downstream Transmission with 40dB Power Margin using Commercial DFB Lasers and no Optical Amplification

Roberto Gaudino, Antonino Nespola, Dario Zeolla, Stefano Straullu, Vittorio Curri, Gabriella Bosco, Roberto Cigliutti, Stefano Capriata, Paolo Solina.

Abstract—We demonstrate a 40Gbps downstream PON transmission based on PM-QPSK modulation using commercial DFB lasers without optical amplifier in the ODN, obtaining 40dB power budget. We discuss this solution within NG-PON2 architectures.

Keywords—DFB lasers, Optical Coherent Receiver, Passive Optical Networks.

I. INTRODUCTION

TODAY (Spring 2011), the two most advanced physical layer (PHY) standards officially released for Passive Optical Networks (PON) are the IEEE 802.3av, usually indicated as 10G EPON, and the G.987.2, typically identified as XG-PON1. These two standards are different in their details and have different classes of power budget, but they nevertheless share some common features for the Physical Media Dependent (PMD) section, that are shortly described in the following list.

Purely passive Optical Distribution Network (ODN): no optical amplification is used between the Optical Line Terminal (OLT) and the Optical Network Unit (ONU), with power budget as high as 35dB and reach up to 40Km. The power splitting factor is at least 1x64.

Non Return to Zero (NRZ) intensity modulation with direct detection, single wavelength transmission per direction with following bit-rates: 10Gbps downstream, 2.5 or 10Gbps upstream. TDM for the downstream, TDMA for the upstream.

In Q3 2010, the FSAN group started its studies on the options for the next generation PON, in order to define a new set of specifications, that are usually indicated with the acronym NG-PON2. For the physical layer, the targeted upgrades to the aforementioned standards are along the three directions reported in the list below, that will be indicated in the rest of the paper as “NG-PON2 targets”.

Increasing of the bit rate above 10Gbps per direction, thus moving to a total throughput per direction of at least 40Gbps

and a bit rate per user moving toward 1Gbps. Upgrade to higher splitting factor, up to 1x1024: it requires an extremely high available power budget of the order of 40dB.

Extension to long reach transmission, up to several tens of kilometers to allow central office consolidation. The achievement of such targets together with low-cost constraints, in particular for the ONU side, is an extremely challenging task. On top of this, many Telecom Operators, such as the big national incumbents, would also like to avoid any modification in the ODN when they will move from XG-PON1 to NG-PON2, and thus would like to add two more constraints to the previous NG-PON2 targets. These are about keeping the optical passive splitters, thus avoiding any WDM filters in the ODN (“filter-less PON”), and maintaining the passive structure, thus avoiding any optical amplification in the ODN.

The “mainstream” direction for the R&D community, as presented at the recent ECOC and OFC conferences, seems to go in the direction of introducing the WDM technology for NG-PON2. When anyway considering the “filter-less PON” requirement, most of the proposed WDM-PON architectures are ruled out. A possible alternative option seems to be a coherent PON, that couples an extremely good receiver sensitivity with an excellent receiver tunability without the use of optical filters. An option for this class of systems was for instance proposed in [1].

In this work, we investigate on a different approach, that mostly maintains all the features of NG-PON1. In particular, it keeps the use of a single wavelength per transmission direction, and simply uses the features of coherent detection to obtain an increase in bit rate, reach and splitting factor. The rationale of the paper is to show a preliminary assessment for this solution, including power budget requirements, constraints for optical sources and a discussion on its complexity.

II. THE ANALYZED SETUP

The system we investigate in this paper emulates downstream PON transmission. It is based on a single wavelength transmission at 40Gbps using Polarization Multiplexed Quadrature Phase Shift Keying (PM-QPSK), without any optical amplification or optical filtering in the ODN and ONU, as required by a pure passive and filter-less ODN. We aimed the analysis to the attainable optical power budget and to the possibility of using commercial Distributed

R. Gaudino, V. Curri, G. Bosco, and R. Cigliutti, are with the Dipartimento di Elettronica, Politecnico di Torino, Torino, ITALY, (phone: 00390115644172; e-mail: gaudino@polito.it).

A. Nespola, D. Zeolla, and S. Straullu are with PhotonLAB ISMB, Torino, ITALY, (phone: 00390112276308; email: nespola@ismb.it).

S. Capriata and P. Solina are with Telecom Italia, Torino, ITALY, (email: paolo.solina@telecomitalia.it).

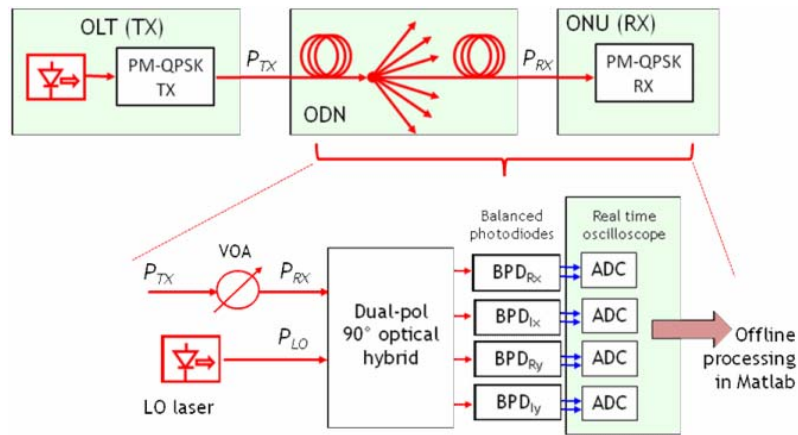


Fig. 1 Mapping nonlinear data to a higher dimensional feature space

Feed Back (DFB) lasers rather than more expensive External Cavity Lasers (ECL). The experimental system setup is shown in Fig. 1. We use a PM-QPSK transmitter at 40Gbps, connected to a variable optical attenuator that emulates the optical loss of the ODN. The received signal is sent to a coherent homodyne PM-QPSK receiver followed by a real time oscilloscope and an off-line digital signal processing (DSP) [2] based on the CMA algorithm implemented as MatlabTM code. The transmitted wavelength is 1551.59nm, the local oscillator (LO) power is set to $P_{LO}=11\text{dBm}$ and we collected 1MSymbol for the off-line DSP.

We wanted to investigate the system performance using different types of lasers for the Tx and local oscillator. In a first experiment, we used two laboratory tunable ECL lasers, having a very high stability and narrow linewidth (few tens of KHz). For the second experiment, we employed two commercial DFB lasers (Mitsubishi FU-68PDF-V510MxxB), whose datasheet specifies a 3dB spectral linewidth up to 20MHz.

III. THE EXPERIMENTAL AND SIMULATIVE RESULTS

The experimental and simulative results are given in Fig. 2 as measurement of BER vs. the received power. The sensitivity at a Bit Error Rate (BER) equal to 10^{-4} is -28.2dBm, while at $\text{BER}=10^{-3}$ it is around -30dBm. The difference in performance between the ECL and DFB cases is marginal, of the order of 0.2dB at most. From these experimental results, we can draw the important remarks listed below.

1. If we assume to maintain the same FEC standard of the current XG-PON1, corresponding to a BER threshold equal to 10^{-3} and to operate with $P_{TX}=10\text{dBm}$ at the output of the PM-QPSK transmitter (a level that is easily in the range of a SOA used as a booster at the OLT side), the proposed system shows a 40dB optical power budget, reaching one of the main targets set for NG-PON2.
2. The performance of the combination of the two DFBs is surprisingly good, considering that the nominal 3dB bandwidth specified in the datasheet is 20MHz for each of the two lasers used in Tx and as LO. The
3. Overall 3dB sum linewidth equal to 40MHz should have given an unacceptably high penalty at 40Gbps

PM-QPSK due to the impact of phase noise, even for the best-in-class carrier phase estimation (CPE) algorithms. Using results of [3], the product of the (sum) linewidth Δf_{tot} multiplied by the symbol duration T_s is in our case $\Delta f_{tot} \cdot T_s = 4 \cdot 10^{-3}$, corresponding to a theoretical penalty of more than 2dB (see [3], Fig. 7).

4. We further investigated the phase noise issue. We found out that the actual short-term (nanosecond acquisition time frame) DFB laser linewidth is much smaller. We used the method presented in [4], finding that the short term linewidth for two DFB lasers used in the experiments was 2.7MHz and 1.9MHz (thus much less than what it is declared in the datasheet), for an actual value $\Delta f_{tot} \cdot T_s = 4.6 \cdot 10^{-4}$. Using again [3], Fig. 7, the resulting phase noise penalty is expected to be negligible, confirming our experimental results. This is due to the actual implementation of the CPE within the Rx DSP, which is based on the Viterbi&Viterbi (or "Power-law average" [3]) algorithm: it averages the phase over few symbols and consequently its performance is determined by the short-term laser linewidth.

We further studied the actual cause of the obtained sensitivity (about -30dBm at $\text{BER}=10^{-3}$) running a set of detailed simulations using the commercial simulator OptSimTM, matching all the experimental system parameters in order to identify the most relevant contributions to the power budget. The BER was evaluated through direct error counting over 106 bits. Since our system is not optically pre-amplified and the impact of phase noise is negligible, the most relevant noise sources leading to the actual sensitivity, besides other second order effects, should be shot-noise in the photo-detection process and thermal noise in the receiver transimpedance amplifiers (integrated in the balanced photodiodes in our setup). We thus introduced these two noise sources in our simulations: the results are shown as solid curves in Fig. 2. Considering a target BER of 10^{-3} , the experimental results have a 2.9dB penalty with respect to the shot-noise only curve, while there is nearly a perfect matching when also including the thermal noise of the balanced photodiodes. Note that, due to the small received signal level,

the Rx ADC dynamic was not entirely used. Analyzing the experimental results, we estimated that only 4 resolution bits out of the nominal 7 were used. Therefore, in the simulations with thermal noise we used that value, obtaining the displayed excellent agreement. Moreover, we were able to estimate by simulation the quantization penalty to be about 0.3dB, predicting that a further reduction to 3 resolution bits would give a larger extra penalty of about 1dB.

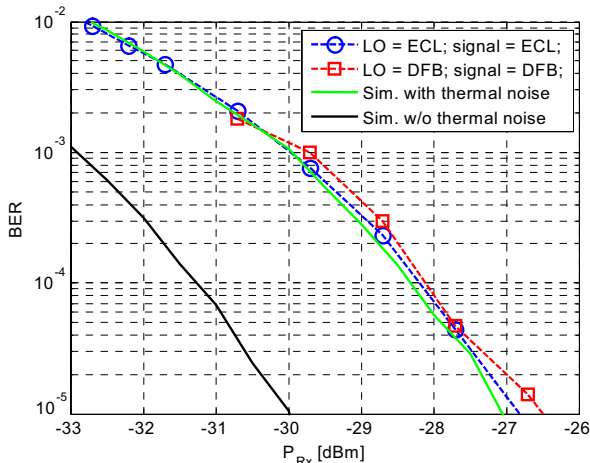


Fig. 2 BER vs. received power: experimental and simulative results

IV. CONCLUSION

We can conclude that our system is about 3.2dB apart from the quantum limit. Note that the sensitivity refers to P_{RX} in Fig. 1, i.e., to the output of the ODN and before the Rx optical hybrid (that in our case has approximately 8dB attenuation on both the signal and LO paths). Thus, for a sensitivity $P_{RX} = -30$ dBm, the signal power reaching each photodiode is lower than -38dBm. The system sensitivity can thus be potentially improved by decreasing the optical hybrid insertion loss and/or by a reduction of the effect of the thermal noise, which in turn can be obtained by either using lower noise balanced photodiode, or by increasing the LO power (P_{LO} in Fig. 1). We also demonstrated that commercial DFB lasers can be used as Tx and LO optical sources and that the ADC introduces a limited penalty down to 4 bit quantization.

Even though PM-QPSK has received so much research attention for the optically amplified long-haul case, the results presented in this paper show the potential interest of coherently received PM-QPSK also in the non amplified scenario, for next generation NG-PON2. The key point would be in the integration of the required optical and electronic components, that today have exceedingly high costs for PON applications. Still, the roadmap for NG-PON2 is years ahead, so there is space for cost reduction through optoelectronic integration and mass-volumes.

REFERENCES

- [1] H. Rohde *et al.*, "Next generation optical access: 1 Gbit/s for everyone," ECOC 2009, paper 10.5.5.
- [2] E. Torrenco *et al.*, "Transoceanic PM-QPSK Terabit superchannel transmission experiments at Baud-rate subcarrier spacing," ECOC 2010, paper We.7.C.2.
- [3] M. Taylor, "Phase Estimation Methods for Optical Coherent Detection Using Digital Signal Processing," *J. Light. Technol.*, vol. 27, n. 7, pp. 901-914, April 2009.
- [4] K. Kikuchi *et al.*, "Characterization of Semiconductor-Laser Phase Noise with Digital Coherent Receivers," OFC 2011, paper OML3.

Roberto Gaudino Ph.D., is currently assistant Professor at Politecnico di Torino, Italy. Dr. Gaudino's main research interest is in the long haul DWDM systems, fiber non-linearity, modelling of optical communication systems and on the experimental implementation of optical networks. Starting from his previous researches on fiber modelling, on new optical modulation formats, such as duo-binary, polarization or phase modulation, and on coherent optical detection, he is currently investigating on packet switched optical networks, and on short-reach optical links using plastic optical fibers. Dr. Gaudino spent one year in 1997 at the Georgia Institute of Technology, Atlanta, as a visiting researcher, where he worked in the realization of the MOSAIC optical network test-bed. He also co-operates with several Italian Universities and research centers on joint research programs. From 1998, he is with the team that coordinates the development of the commercial optical system simulation software OptSim (Artis Software Corp., now acquired by RSoft Design). He has consulted for several companies and he is author or co-author of more than 80 papers in the field of Optical Fiber Transmission and Optical Networks. He has been the coordinator of the EU FP6-IST STREP project "POF-ALL" and currently is the scientific coordinator of the EU FP7-ICT STREP project "POF-PLUS".

Antonino Nespola received his M.S. and Ph.D. degrees in Electrical Engineering from the Politecnico di Torino, in 1995 and 2000, respectively. From 1997 to 1998, he was a Visiting Researcher in the Photonics Laboratory of the University of California Los Angeles. From 1999 to 2003 he was Member of Technical Staff and R&D Lab Director in Corning, Milan, where he conducted research in high-speed opto-electronics. In 2003, he joined Pirelli Labs, Milan, as senior researcher. He is currently senior researcher at ISMB. Antonino Nespola has published over 60 journal and conference papers, and holds 4 U.S./European patents.

Dario Zeolla received the Master of Science in telecommunications engineering from the Politecnico di Torino, Torino, Italy, in 2009, with a thesis about the bidirectional transmission over a single step-index plastic optical fiber. He is currently with the Istituto Superiore Mario Boella, Torino, Italy, where he is a researcher in the field of communication systems based on plastic optical fibers.

Stefano Straullu graduated in telecommunications engineering in 2005 from the Politecnico di Turin, Turin, Italy, with a thesis about the project, the realization and the testing of opto-electronic subsystems for packet-switched optical networks, realized in the PhotonLab of Istituto Superiore Mario Boella of Turin. In 2006, he joined the Integration Testing team of Motorola Electronics S.p.A. of Turin, working on the mobile devices and live network testing. Since May 2009, he has been a researcher at the Istituto Superiore Mario Boella, Turin, Italy, with responsibilities of project, realization and testing measurements of opto-electronic systems and he has published more than 20 journal and conference papers.

Vittorio Curri was born in Ivrea (Italy) in 1970. He received the Laurea degree cum laude in electrical engineer in 1995, and the Scientific Doctoral degree in optical communications in 1999, both at Politecnico di Torino, Torino, Italy. He is currently Assistant Professor at Dipartimento di Elettronica, Politecnico di Torino, Torino, Italy. He has been visiting researcher at Stanford University and UC at Santa Barbara in 1997-98. He has been a member of R&D department of Artis Software Inc. in 1998-2002. His major research interests are modeling of fiber nonlinearities, system performance estimation, advanced modulation formats, Raman amplification, Tx/Rx design for optical coherent modulation and simulation and modeling of optical communication systems. Dr. Curri is an IEEE member since 1999 and has co-authored more than 90 technical publications.

Gabriella Bosco was born in Ivrea, Italy, in 1973. She received the Degree in Telecommunication Engineering in 1998 (thesis on the non-linear effect of the propagation in WDM optical systems) and the PhD in Electronic

and Communication Engineering in 2002 (thesis on the performance analysis of optical communication systems), both from Politecnico di Torino, Italy. In 2000 she was a visiting researcher at OCPN (Optical Communication and Photonic Network) group at University of California at Santa Barbara (CA), directed by Prof. Blumenthal, working on polarization-mode dispersion monitoring techniques. She currently holds a post-doctoral position in the Optical Communication Group at the Department of Electronics of Politecnico di Torino. Her main research interests are focused on the performance analysis of optical transmission systems and the application of DSP techniques in optical links. She co-authored more than 90 papers in leading journals and conferences.

Roberto Cigliutti (M'00) was born in Savona (Italy) in 1965. He received the M.S. degree (cum laude) in Electronic Engineering from the University of Genova (Italy) in 1991 with a thesis on coherent optical systems carried out at GEC-Marconi Hirst Research Centre, Wembley (London-UK). From 1991 to 1995, he was with Marconi S.p.A., in Genova, where he was involved in the design of opto-electronic units for SDH and ATM-PON applications. In 1995, he joined Pirelli Cables and Systems in Milano (Italy), working on the design of CATV units and systems, and from 1997 being the responsible for the design of the Pirelli submarine optical repeater deployed in international submarine contracts.

From 1999 to 2004, he has been the responsible of the System Transmission Laboratory within the R&D Group of Pirelli Submarine Telecom Systems where he occupied about the study and the design of repeatered submarine optical transmission systems. During 2004 - 2010, he was with Pirelli Broadband, Pirelli Labs and PGT Photonics working on modeling of optical components. In 2010 he joined Optical Communication Group at Politecnico di Torino. His current scientific interests are in mathematical modeling of optical propagation. He was co-author of 13 papers on optical communication topics, and he held an international patent on erbium doped fiber amplifier for submarine application.

Stefano Capriata graduated in telecommunications engineering in 1982 from the Politecnico di Turin, Turin, Italy, with a thesis about the project, the realization and the testing of a digital PLL for dejittering digital signals. From July 1984 until November 1988 he was with TELETRA, R&D lab for digital signal processing as HW designer of systems and equipments for coding and transmission of video signals; covering this role he patented two "variable length coding" systems. In November 1988 he joined AET telecomunicazioni where held the job of project leader for data/voice equipments and 2 Mbit/s multiplex until January 1993. From January 1993 until July 2001 he was with Italtel holding the job of functional specification, feasibility analysis, cost evaluation and product management for access equipments, network equipments and transmission systems over cable or over optical fiber, "turn-key" data/voice access networks, digital switch matrix in the Socrate project for Telecom Italia, XDSL products analysis and evaluation, SDH STM1 Multiplex. From August 2001 he joined Telecom Italia with responsibilities of testing XDSL products first, and then of opto-electronic equipments in the access network focusing on GPON systems and of evaluation of new optical products (components, subsystems), modulation techniques and architectures to be used in the New Generation Access Network.

Paolo Solina started his activity in Telecom Italia Lab (formerly CSELT, Centro Studi E Laboratori Telecomunicazioni) as Hardware Designer, in 1974. He contributed to the design and development of high bit rate optical communication systems within several European Projects, like the RACE Project BAF (first APON 622 Mbit/s symmetric), the ACTS Project PLANET (first SuperPON prototype) and the IST Project GIANT (Gigabit Access Network), which provided a fundamental contribution to the GPON standardization process. He is member of the FSAN (Full Service Access Network) Group since 1996. He has been the Editor of the ITU-T Recommendation G.984.2, which specifies the Physical Layer of the GPON systems. In Telecom Italia Lab he is responsible, as Project Manager, for activities related to emerging optical technologies for the Access Network. Since October 2006 he represents Telecom Italia at the FSAN Management Committee. He has been the Co-Chair of the FSAN Interoperability Task Group from May 2007 to June 2009. Since June 2009 he is the Chair of the FSAN Group.