Optical Fiber Technology 26 (2015) 100–107

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Invited Paper

Coherent ultra dense wavelength division multiplexing passive optical networks

Ali Shahpari [a,*], Ricardo Ferreira [a], Vitor Ribeiro [a], Artur Sousa [a], Somayeh Ziaie [a], Ana Tavares [a], Zoran Vujicic [a], Fernando P. Guiomar [a], Jacklyn D. Reis [b], Armando N. Pinto [a], António Teixeira [a]

[a] Department of Electronics, Telecommunications and Informatics, University of Aveiro and Instituto de Telecomunicações, 3810-193 Aveiro, Portugal
[b] CPqD, Division of Optical Technologies, 13086-902 Campinas, SP, Brazil

ARTICLE INFO

Article history:
Available online 15 July 2015

Keywords:
Passive optical networks
Ultra-dense wavelength division multiplexing
Coherent detection
Nyquist pulse shaping
Digital signal processing
Free space optics

ABSTRACT

In this paper, we firstly review the progress in ultra-dense wavelength division multiplexing passive optical network (UDWDM-PON), by making use of the key attributes of this technology in the context of optical access and metro networks. Besides the inherit properties of coherent technology, we explore different modulation formats and pulse shaping. The performance is experimentally demonstrated through a 12×10 Gb/s bidirectional UDWDM-PON over hybrid 80 km standard single mode fiber (SSMF) and optical wireless link. High density, 6.25 GHz grid, Nyquist shaped 16-ary quadrature amplitude modulation (16QAM) and digital frequency shifting are some of the properties exploited together in the tests. Also, bidirectional transmission in fiber, relevant in the context, is analyzed in terms of nonlinear and back-reflection effects on receiver sensitivity. In addition, as a basis for the discussion on market readiness, we experimentally demonstrate real-time detection of a Nyquist-shaped quaternary phase-shift keying (QPSK) signal using simple 8-bit digital signal processing (DSP) on a field-programmable gate array (FPGA).

1. Introduction

Coherent ultra-dense wavelength division multiplexing passive optical networks (UDWDM-PON), provide inherent high wavelength selectivity and enhanced sensitivity, allowing high number of users in extended reach optical distribution networks (ODNs) [1,2]. Coherent technology with advanced modulation formats and Nyquist pulse shaping, has demonstrated several technical highlights, such as excellent spectral efficiency with high aggregated capacity, easier network upgrade and future-proof solution for flexible bandwidth next generation optical access networks (NG-OAN) [3–6]. Therefore, it may be a natural next step towards network efficiency [7,8].

Coherent detection in optical access networks has already a long history [9–11]. The industrial version of this technology was demonstrated in [12] by proposing new architectural to support 1 Gb/s per subscriber, transmitting differential quadrature shift keying (DQPSK) modulation format at the optical line terminal (OLT) and optical network unit (ONU). However, due to constrain both on subscription rate, service requirements and availability, other simpler technologies stemmed [13–15]. Clearly, coherence requires either complex/precise analog processing or fine-tuned digital signal processing (DSP) or even excellent laser performance at the local oscillator. However, this technology has matured in order to become more costly efficient for optical access networks as well as to meet the type of services and working conditions (rate, reach, energy consumption, dedicated and shared bandwidth). Numerous efforts have been carried out by several research groups in the world in order to explore related issues to this technology [3–7,16–33].

Several research works have been reported in recent years; a 64 UDWDM channels real-time signal processing demonstration was performed in [16], while achieving 50 dB power budget for downstream transmission. The latter was extended in [4], in order to accomplish 1000 wavelengths with variable data rates from 150 Mb/s to 10 Gb/s for up to 100 km reach in metro and access networks leading finally to field trials reported in [17].

Recently, the EU-funded COCONUT project [7,18] has started tackling the cost issues related to transmitters (Tx) and receivers (Rx) of both OLT and ONU in UDWDM-PON by investigating polarization-independent coherent receivers for differential phase-shift keying (DPSK) [19] and on–off keying (OOK) [20] modulation formats using cheap distributed feedback (DFB) laser in free-running mode operation and including analog signal

* Corresponding author.
E-mail address: Ali@ua.pt (A. Shahpari).

http://dx.doi.org/10.1016/j.yofte.2015.07.001
1068-5200/

processing. Therefore, progress towards cost efficiency of coherent UDWDM-PON has been carried out opening room for further investigations although there is a path forward that must be followed in order to consider also the spectral efficiency and flexibility using advanced modulation formats in the equation.

In order to achieve the best compromise between sensitivity and dedicated data rate several polarization multiplexed schemes for coherent UDWDM-PON have been proposed [3,21,22]. The 700×2.488 Gb/s polarization division multiplexing (PDM) scheme, with DQPSK parallel upstream user channels, has also been demonstrated [23]. Using PDM transmission, the resources (balanced photodetector, modulators, drivers, digital-to-analog converters (DAC) and analog-to-digital converters (ADC)) used in the receiver and transmitter scale by about 2, resulting in increased power consumption, cost and DSP complexity in the system.

Crosstalk and nonlinear impairments such as cross-phase modulation (XPM) and four-wave mixing (FWM) in fiber may cause non-negligible penalties impairing UDWDM networks if power and frequency channels are not properly optimized [24]. Additionally, back reflection in bidirectional systems can be a major limiting factor [25]. Nyquist pulse shaped 16-ary quadrature amplitude modulation (16QAM) has been proposed in UDWDM-PON to deliver 10 Gb/s bidirectional data rate achieving very high spectral occupation and reduced Rayleigh backscattering (RBS) [5]. Later, this work was extended to further investigate the resilience to linear and nonlinear crosstalk by numerical simulations [26] and the technical issues regarding digital implementation of Nyquist spectral shaping for low-symbol-rate systems [27]. An ultra-high capacity unidirectional PON (1200×10 Gb/s) was demonstrated by using zero roll-off Nyquist pulse shaping and independent sideband (ISB) modulation across positive and negative frequencies [28]. A proof of concept fully loaded bidirectional ultra-high capacity PON ($2 \times 1008 \times 8.3$ Gb/s) was also presented in [29]. This was achieved using partial spectral overlap, Nyquist shaping, digital frequency shifting, self-homodyne detection, and pilot tone re-modulation, which simplifies the DSP in the ONU by mitigating the impact of the frequency shifting in the received signal [30]. In this system, the ONU requires clock recovery and a simplified version of the phase recovery subsystem [31]. Nyquist pulse shaping filter and DSP pre-distortive subsystem can also be incorporated in the OLT to mitigate nonlinearities or pre-equalize bandwidth limitations. For the upstream signal, only Nyquist filtering is necessary at the ONU transmitter and at the OLT (receiver), whereas advanced DSP algorithms for carrier frequency and phase recovery can be used, since cost at the OLT (receiver) is not the main cause of concern.

Coexistence of coherent UDWDM-PON (either based on QPSK or Nyquist pulse shaped 16QAM) with legacy systems and video overlay has also been studied in [4,30,33] to optimize both launch power per UDWDM channel and the required guard band. The benefit of using DSP in the coherent receiver is the improvement on the nonlinear crosstalk tolerance (XPM and FWM) from other coexisting technologies in UDWDM channels. In addition, narrower guard bands between UDWDM and coexisted technologies may be achieved [4,17]. In the case of video overlay scenario, Raman crosstalk introduced by other baseband modulated signals disturbs the lower frequencies of the RF-video signal due to stimulated Raman scattering (SRS) [33]. Due to the constant optical intensity of the signals in QPSK, Raman crosstalk reduction is achieved. This may result in a higher number of UDWDM channel coexisting with analog or digital videos [4,33]. However, for Nyquist pulse shaped UDWDM systems, SRS reduction can be obtained by digital frequency shifting the signal from the DC component such that the power spectral density of modulated signal in lower frequency [30] is decreased.

Mobility and ubiquitous coverage are two crucial pillars for future access networks. Being generally reliable and well understood, radio frequency (RF) has been the technology of choice to support these complementary features. However, RF-based communications are physically limited in terms of capacity and reach, requiring very high power consumption devices for moderate to high data-rate links [34]. In contrast, free-space optical communications can be an option offering the highest capacity with license-free wireless spectrum domain and fast installation of the equipment for the minimization of service outages caused by disasters and civil conflicts [35]. PONs with free-space optics (FSO) should connect very efficiently, since they work in the same wavelengths with a transparent link and can support both the flexibility from wireless systems and the high-capacity from optical fiber. Recently, a great attention has been given to merge WDM with FSO. Although turbulence and variable attenuation in FSO links are still the main impairment, these hybrid solutions have been intensively studied in the last years [36], paving the way to future commercial deployments. In [37], a simultaneous wired and wireless 1.25 Gb/s bidirectional WDM-radio over fiber transmission scheme has been reported and the authors in [38] experimentally demonstrated a $2 \times 8 \times 10$ Gb/s DWDM with 10 m FSO link. The 32×40 Gb/s WDM FSO over 200 m [39] and 16×100 Gb/s PDM-QPSK in 80 m building to building FSO have been demonstrated in [40]. Coherent UDWDM can fully utilize the bandwidth and increase the transmission capacity of an FSO link [41–43].

A future PON requires high flexibility besides capacity and reach, with a feasible and low cost solution, and at same time with efficient power consumption [43–46]. DSP enhances the flexibility of coherent transceivers systems in terms of the modulation formats, symbol rate and enables a network with high performance and low power consumption [47]. Simple DSP-based ONU for digital coherent PON systems using single polarization requires at least clock and carrier recovery subsystems to recover a transmitted signal modulated in phase [6,48]. However, the challenge for a real-time coherent PON system is the low operating symbol rate, which brings issues in the digital control of the frequency shift and phase noise of the signal [6,49]. Nyquist shaping brings also some challenges for real-time implementations, such as the number of taps required for the generation of the pulse, as well as the reconstruction of the ideal sampling instant in the receiver side (clock recovery), if the shaping roll-off factor tends to zero the clock information of the signal tends to be lost [50]. With Nyquist, the peak-to-average power ratio (PAPR) of the signal also increases, requiring higher effective number of bits (ENOB) in the DACs and ADCs devices, as well as higher bit DSP resolution to achieve the same performance as achieved with a non-return-to-zero (NRZ) pulse.

In this paper, we present recent activities of our group regarding Nyquist pulse shaped UDWDM-PON systems [6,42]. Firstly, we propose and experimentally demonstrate a coherent bidirectional PON system to increase the capacity of optical access networks in offline DSP operation. Reduced impact of RBS is achieved due to Nyquist pulse shaping and digital frequency-shifting. A successful transmission of bidirectional 12×10 Gb/s UDWDM over 80 km fiber followed by 56 m point-to-multipoint (PTMP) FSO is experimentally demonstrated. We extend the network reach to 80 km with 30.5 dB ODN power budget. Secondly, we experimentally demonstrate an 8-bit real-time operation of DSP-based ONU architecture for coherent Nyquist UDWDM-PON using field-programmable gate array (FPGA) with 8×2.5 Gb/s QPSK channels.

The remaining of this paper is organized as follows: Bidirectional demonstration over a fiber link with FSO setup is reported in Section II. Section II also presents the performance analysis and the characterization of the UDWDM system in a