Optical Fiber Technology 36 (2017) 255–264

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Power budget of direct-detection ultra-dense WDM-Nyquist-SCM PON with low-complexity SSBI mitigation

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ARTICLE INFO

Article history:
Received 26 September 2016
Revised 6 April 2017
Accepted 24 April 2017

Keywords:
Nyquist pulse-shaping
Passive optical network
Power budget
Signal-to-signal beat interference
Subcarrier multiplexing
Ultra-dense wavelength division multiplexing

ABSTRACT

The power budget (PB) of a direct-detection ultra-dense wavelength division/subcarrier multiplexing (SCM) passive optical network (PON) is assessed numerically for downstream, when a low-complexity iterative signal-to-signal beat interference (SSBI) mitigation technique is employed. Each SCM signal, inserted in a 12.5 GHz width optical channel, is comprised of two or three electrically generated and multiplexed 16-quadrature-amplitude-modulation (QAM) or 32-QAM Nyquist pulse-shaped subcarriers, each with a 7% forward error correction bit rate of 10.7 Gbit/s. The PB and maximum number of optical network units (ONUs) served by each optical line terminal (OLT) are compared with and without SSBI mitigation. When SSBI mitigation is realized, PB gains up to 4.5 dB are attained relative to the PB in the absence of SSBI mitigation. The PB gain enabled by the SSBI mitigation technique proposed in this work increases the number of ONUs served per OLT at least by a factor of 2, for the cases of higher spectral efficiency. In particular, for a SCM signal comprised of three subcarriers, the maximum number of ONUs served per OLT is between 2 and 32, and between 8 and 64, in the absence of SSBI mitigation, and when SSBI mitigation is employed, respectively, depending on the fiber length (up to 50 km) and order of QAM.

1. Introduction

The exponential growth of global traffic provisioning demands establishes high capacity granularity, spectral efficiency, upgradability, transparency, low power consumption, and cost-efficiency needs for metropolitan and access networks [1–6].

Wavelength division multiplexing (WDM) passive optical networks (PONs) and direct-detection (DD) have been appointed as promising candidates to address the needs aforementioned [5–7]. In addition, subcarrier multiplexing (SCM) is seen as an excellent complement to WDM [3]. SCM consists on generating and multiplexing several subcarriers on the electrical domain [8], where each subcarrier can be assigned to a subscriber. High orders of quadrature amplitude modulation (QAM) and Nyquist pulse-shaping of each subcarrier result in high spectral efficiency, contributing to a higher number of subcarriers per optical channel and thus to the relaxation of the number of optical modulators required at each optical line terminal (OLT).

Multi-band (MB) orthogonal frequency division multiplexing (OFDM) is seen as another suitable candidate for spectrally efficient and low-cost transmission in optical networks [9–11]. Compared to the Nyquist-SCM format, MB-OFDM employs a cyclic prefix to mitigate linear optical transmission impairments resulting in lower spectral efficiency [12]. In addition, MB-OFDM requires a more complex electrical system architecture and suffers from high peak-to-average power ratio [7]. On the other hand, MB-OFDM allows for higher flexibility in performance optimization through adaptive modulation techniques [13].

The performance of DD systems can be highly impaired by signal-to-signal beat interference (SSBI) [14,15], for both MB-OFDM and Nyquist-SCM modulation formats. While the SSBI impairment can be avoided by adopting a frequency guard band between the signal to detect and the optical carrier (OC) higher than the bandwidth of the signal, this approach leads to remarkable loss of spectral efficiency. In order to achieve high spectral efficiency without compromising system performance, SSBI mitigation techniques have been proposed and widely adopted in DD systems [15]–[18]. In [15], a SSBI mitigation technique consisting of a dual photo-detector was proposed. While this technique allows for quick and very accurate SSBI estimation, it doubles the amount of photo-detectors at each optical network unit (ONU), resulting in higher costs and extra power loss. The extra power loss is a consequence of optical power splitting at the ONU and insertion loss of the optical filter (OF) used to suppress the OC. In [16], an iterative digital signal processing post-compensation tech-

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http://dx.doi.org/10.1016/j.yofte.2017.04.007
1068-5200/

nique is used for SSBI mitigation, and combined with a SSBI pre-distortion technique in [17] in order to relax the number of iterations needed for SSBI mitigation. Recently, a novel low-complexity SSBI post-compensation technique was proposed, allowing for SSBI estimation without hard-decision [18]. This technique is of special relevance for Nyquist-SCM (and MB-OFDM) systems, since it eliminates the necessity to demodulate all the subcarriers comprising the Nyquist-SCM signal in order to perform SSBI mitigation. This advantage leads to remarkable relaxation of system complexity compared to the technique proposed in [16].

An iterative version of the technique reported in [18] is proposed and analyzed through numerical simulation in this work. Iterative SSBI post-compensation is performed without significantly increasing the complexity of the system. In fact, since no demodulation of all the subcarriers comprising the SCM signal is needed for SSBI estimation in each iteration, the system complexity increase with the number of iterations is very reduced, and independent of the number of subcarriers comprising the SCM signal. In this paper, the iterative SSBI mitigation technique is used to improve the power budget (PB) of a DD ultra-dense (UD) WDM Nyquist-SCM PON.

The feasibility of DD, WDM and SCM techniques in PONs has been studied in the past [2,19,20]. In [19], <1 Gbit/s/user transmission was experimentally demonstrated for a WDM-SCM-PON. In [2], a 10 Gbit/s/λ bidirectional PON, using optical SCM and a reflective scheme to realize the upstream was demonstrated experimentally and, in [20], a 1 Gbit/s/user WDM-Nyquist-SCM PON with a hybrid coherent-direct detection scheme was proposed. Compared to [19,20], the low-cost DD UDWDM-Nyquist-SCM PON analyzed in this work provides higher capacity granularity (10 Gbit/s/user, up to 30 Gbit/s/λ), while relaxing the number of optical modulators needed at the OLT relative to the architecture proposed in [2].

A complete list of all the acronyms used in this paper can be found in Appendix A.

2. UDWDM-Nyquist-SCM PON

2.1. UDWDM-Nyquist-SCM PON architecture

The downstream PON architecture and UDWDM-Nyquist-SCM signal generation, transmission and detection are described in this subsection. Each ONU is served by a subcarrier, electrically generated at the OLT. Fig. 1 illustrates the PON architecture, using signal generation and detection detailed in Fig. 2: 1) at the electrical transmitter, the binary data stream is mapped into QAM symbols; 2) a root raised cosine (RRC) filter is used for Nyquist pulse-shaping [21]. Nyquist pulse-shaping is used in order to mitigate intersymbol interference and to increase spectral efficiency [21]; 3) the in-phase (I) and quadrature (Q) components of the baseband signal are separated and an IQ modulator is used for up-conversion, which results in the generation of an electrical

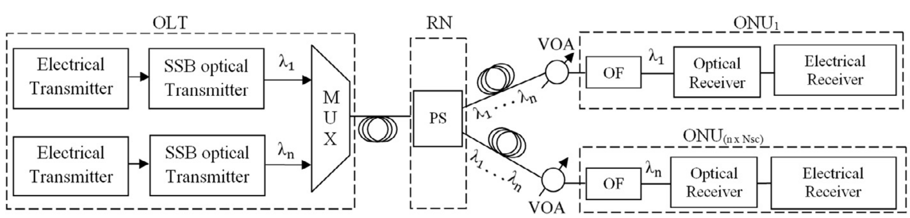

Fig. 1. Downstream UDWDM SCM PON architecture. OLT – optical line terminal, CDPC – chromatic dispersion pre-compensation, SSB – single sideband, MUX - optical multiplexer, RN – remote node, PS - power splitter, ONU – optical network unit, OF – optical filter, VOA – variable optical attenuator.

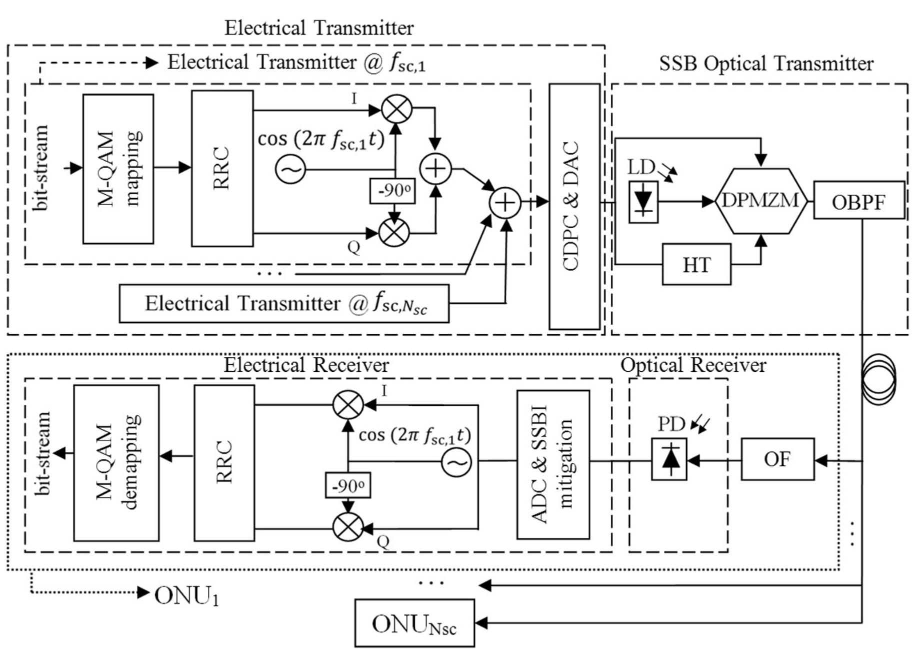

Fig. 2. SCM signal generation, transmission and detection. M-QAM – *M*-th order quadrature amplitude modulation, DAC – digital to analogue converter, RRC – root raised cosine, CDPC – chromatic dispersion pre-compensation, SSB – single sideband, LD – laser diode, HT – Hilbert transform, DPMZM – dual parallel Mach–Zehnder modulator, OBPF – optical band pass filter, OF – optical filter, PD – photodiode, SSBI – signal to signal beat interference, ADC – analogue to digital converter. Variables used in the figure: $f_{sc,1}$ – central frequency of the first subcarrier, $f_{sc,N_{sc}}$ – central frequency of the N_{sc}-th subcarrier, where N_{sc} is the total number of subcarriers comprising the SCM signal.