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Regular Articles

Real-time dual-polarization transmission based on hybrid optical wireless communications

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A B S T R A C T

We present experimental work on a gigabit-capable and long-reach hybrid coherent UWDM-PON plus FSO system for supporting different applications over the same fiber infrastructure in the mobile backhaul (MBH) networks. Also, for the first time, we demonstrate a reconfigurable real-time DSP transmission/reception of DP-QPSK signals over standard single-mode fiber (SSMF) and FSO links. The receiver presented is based on a commercial field-programmable gate array (FPGA). The considered communication links are based on 20 UDWDM channels with 625 Mbaud and 2.5 GHz channel spacing. We are able to demonstrate the lowest sampling rate required for digital coherent PON by employing four 1.25 Gsa/s ADCs using an electrical front-end receiver that offers only 1 GHz analog bandwidth. We achieved this by implementing a phase and polarization diversity coherent receiver combined with the DP-QPSK modulation formats. The system performance is estimated in terms of receiver sensitivity. The results show the viability of coherent PON and flexible dual-polarization supported by software-defined transceivers for the MBH.

1. Introduction

It has been observed that the development of Internet of Things (IoT) has enables billions of smart devices to be connected to the Internet. About 5–9 billion connected devices have been estimated in 2015 for a market size of about 700 billion. Furthermore, about 25–50 billion IoT devices are estimated to be deployed annually which correspond to about 17–32 percent annual growth [1]. The growth in the Internet traffic has call for corresponding network upgrade by the mobile network operators (MNOs). So, MNOs have been developing their systems towards 5G by exploiting inherent high capacity of optical fiber infrastructures and improving the spectral efficiency (SE) of their networks.

The current Fiber to the home (FTTH) system based on time division multiplexing passive optical network (TDM-PON) equipment employs one or two wavelengths. This might not enable it to support the envisaged bandwidth demands. Consequently, wavelength-division multiplexed passive optical networks (WDM-PONs) have been extensively considered as the future-proof architectures. WDM-PONs architectures also exhibit high scalability to dense WDM PON (DWDM-PON) and ultra-dense WDM-PON (UDWDM-PON) solutions when the channel bandwidth is reduced [2]. Moreover, optical coherent technologies can be employed to realize a flexible, robust, and spectrally efficient PONs system by using digital signal processing (DSP) supported by software-defined transceivers [3,4]. Furthermore, another way of increasing the SE and the number of users in the specified wavelength is to employ coherent PON with complex modulation and dual-polarization (DP) transceivers [5,6]. However, the potential high cost of the transceiver limits its implementation for commercial purposes by the MNOs. Hence, research into cost-effective transceiver is of high importance [7]. Also, employment of cost-effective DSP helps in relaxing the cost of hardware implementation. Moreover, DSP with polarization demultiplexing (PolDemux) scheme can help in automatic polarization control. Constant modulus algorithm (CMA) can also be employed for blind equalization and PolDemux because of its simplicity, robustness, and immunity to phase noise [8,9].

Furthermore, there are certain areas in the mobile cellular systems in which physical connections by means of optical fiber cables are impractical or in rural area that lacks fiber infrastructure, optical wireless communication (OWC), also known as free space optics (FSO) can be employed in such areas [10]. FSO has various advantages such as, ease of deployment, high bit rates, license-free operation, full duplex

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transmission, and high transmission security. Furthermore, it has been recognized as a broadband access technology that can address the bandwidth requirements of the next-generation network (NGN) [10–13]. The concept of transmitting radio signals over FSO (RoFSO) exploits high transmission capacity offers by the optical technologies and ease of deployment of wireless systems [14]. Therefore, DWDM RoFSO system have the ability to transmit multiple wireless signals simultaneously [15].

The transmission capacity and coverage of FSO can be enhanced with schemes like advanced modulation formats, coherent UDWDM, and DP. Unlike intensity-modulations (IM) schemes, DP schemes are unconstrained by the nonlinear response of the intensity modulators and insusceptible to the laser phase noise. Additionally, DP schemes are more resistant to turbulence-induced fading, since the polarization states have better conservation than the amplitude and phase of optical signal during propagation [16]. Furthermore, Coherent FSO systems offer improved receiver sensitivity and permit rejection of intentional interferences and background noise. They also allow information to be sent on the amplitude, phase, or polarization of the optical field, consequently, the system SE improves significantly. However, intensity-modulation/direct-detection (IM/DD) schemes are extensively employed because of their lower implementation complexity and cost. With current improvements in integrated coherent receivers and high-speed DSP circuits, there is high tendency to shift to coherent FSO systems [16].

In this paper, we demonstrate experimentally gigabit-capable long-reach coherent UWDM-PON and FSO systems for supporting different applications over the same fiber infrastructure in the MBH networks as depicted in Fig. 1. Also, we demonstrate for the first time, a reconfigurable real-time DSP reception of a DP-QPSK signals over the standard single-mode fiber (SSMF) and FSO. The system is supported by a commercial field-programmable gate array (FPGA). The considered MBH network is based on 20 UDWDM channels with 625 Mbaud and 2.5 GHz channel spacing. This reduced channel spacing improves network spectral efficiency and extends UDWDM applications [6]. We study signal transmission and reception over 100 km of SSMF and over a hybrid 100 km of SSMF plus 54 m outdoor FSO link. We are able to demonstrate the lowest sampling rate required for digital coherent PON by employing four 1.25 Gsa/s ADCs using an electrical front-end receiver that provides only 1 GHz analog bandwidth. We realized this by employing a phase and polarization diversity coherent receiver combined with the DP-QPSK modulation format [8]. This method is important for relaxing the required electrical digital blocks at the optical network unit (ONU) towards radio-frequency (RF) rates. It also helps in achieving the envisioned data rate for the next-generation coherent optical access networks for the 5G mobile wireless networks.

2. Experimental setup

Fig. 2(a) depicts the experimental setup employed for the validation of the performance of a UDWDM-PON system with hybrid fiber and FSO link using DP signals. In this setup, we evaluate the receiver DSP in real-time. We emulate the UDWDM grid at the OLT by injecting the light from four 100 kHz linewidth external cavity laser (ECL) to two IQ modulators (IQMs). In the setup, the wavelength λ_2 is centered at ~1549 nm. Furthermore, λ_1,λ_3 and λ_4 are shifted from λ_2 by −5, −2.5 and +2.5 GHz, respectively. The IQM_1 is feed by λ_1 and λ_2 and driven by a 65 Gsa/s arbitrary waveform generator (AWG). Similarly, λ_3,λ_4 feed IQM_2 which is driven by a 16 Gsa/s AWG. However, both AWGs produce 625 Mbaud signals from a 2^{12}–1 pseudo random bit sequence (PRBS). The resulting signal is then digitally filtered by a raised-cosine (RC) filter with 0.1 roll-off factor as well as 32-taps and 3-taps FIR filters and a simple FIR filters pre-emphasis subsystem, respectively. The modulation format employed is DP-QPSK that generates 2.5 Gb/s per end-user. The four channels are then injected into an optical comb generator after modulation so as to replicate the four channels in 20 channels with a channel spacing of 2.5 GHz. A spectral width of about 750 MHz is displayed by the UDWDM channels when this width is measured at −20 dB of the wavelength peaks. This leads to a UDWDM grid shown in Fig. 3, which was obtained through the use of a High-resolution Optical Spectrum Analyzer (APEX AP2050) with 160 fm/20 MHz resolution. The spectrum of 4-channels is shown in Fig. 3a) and and that of 20-channels is illustrated in Fig. 3(b).

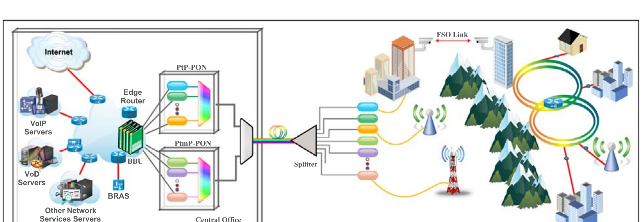

Fig. 1. Gigabit-capable long-reach coherent UWDM-PON and FSO systems for mobile backhaul (MBH) networks.

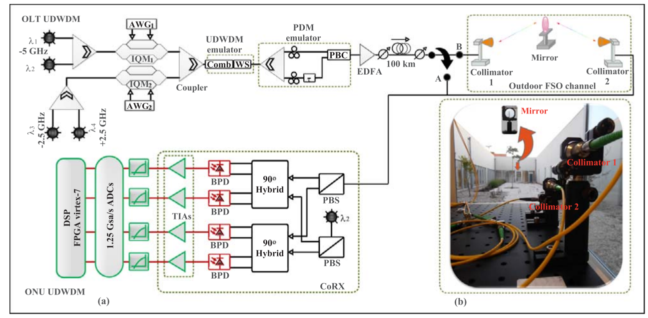

Fig. 2. (a) Experimental setup for 20 × 625 Mbaud DP-QPSK signal and (b) inset of outdoor FSO setup (WS: wavelength selective switch; EDFA: erbium doped fiber amplifier; PDM: polarization division multiplexing; PBS/C: polarization beam splitter/combiner).

In order to emulate polarization-division multiplexing (PDM) system, the signal is separated into two polarizations using an optical splitter. A delay of 12 symbols is applied to one of the signals for decorrelation purposes. The two polarized signals are then orthogonally multiplexed using a polarized beam combiner (PBC) again, resulting in a dual polarization signal. Subsequently, two transmission paths are tested (switch at A or B), as shown in Fig. 2. With the switch connected to A, the signal is transmitted by only 100 km of SSMF and at whose input the released optical power is controlled by means of an erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA). This EDFA operating in the C band had an optical gain of 20 dB and a noise figure of 4.5 dB. The input power was −10 dBm.

At the receiver side, the signal is coherently detected by means of a 4 × 90° optical hybrid using a free-running ECL with about 100 kHz linewidth that is tuned to the center channel, λ_2 as local oscillator. Moreover, the optical signal is converted into an electrical domain by four balanced detectors (BD) and then amplified via transimpedance amplifiers (TIAs). This results in the in-phase and the quadrature components of each polarization. The resulting signal is filtered by 1 GHz low-pass filter and then sampled via four 8-bit 1.25 Gsa/s ADCs. Then, the digitalized signal is forwarded to a Virtex-7 FPGA in which the entire post-detection 8-bit DSP is implemented in real-time. The employed DSP is based on [8] and performs the necessary polarization tracking through the CMA method. The bit-error rate (BER) is estimated in real-time by means of bit error counting, averaged between the two polarizations. The DSP clock is set at 156.25 MHz which results in a degree of polarization (DOP) of 8 so as to achieve a sampling rate of 1.25 Gsa/s. This is because most of our DSP operations are based on 8-bit resolution.

In addition, the possibility of an outdoor FSO communication link