Real-Time Coherent UDWDM-PON With Dual-Polarization Transceivers in a Field Trial

Ming Luo, Jie Li, Tao Zeng, Lingheng Meng, Lei Xue, Lilin Yi, and Xiang Li

***Abstract*—We propose a coherent ultra-dense wavelength-division multiplexing passive optical network (UDWDM-PON) scheme for symmetrical operations between the uplink and downlink. Then we experimentally demonstrate a field trial of coherent UDWDM-PON using real-time field programmable gate array (FPGA)-based transceivers. The optical distribution network power budget of this system is evaluated based on 40 downlink UDWDM channels with 5 GHz channel spacing in the C band. After transmission over a 40 km field-installed fiber link, the experimental demonstration can achieve power budgets of 29 dB with dual-polarization quadrature phase-shift keying formats at 10 Gb/s for each user. Twenty-four hour real-time performance testing for the field-trial transmission is also conducted to evaluate the feasibility of the real-time FPGA-based transceivers in the proposed UDWDM-PON scheme. Several parameters that may affect system performance are also investigated in the experimental demonstration.**

***Index Terms*—Blind equalizers; Optical fiber communication; Optical receivers; Wavelength division multiplexing.**

I. Introduction

Driven by the quickly increasing demand for bandwidth and download speed, technologies to realize multi-gigabit connection speeds per subscriber in residential areas have attracted much attention in the past few years to provide improved availability, data rates, and services [1]. In current passive optical networks (PONs), time-division multiplexing (TDM) technologies have been applied to provide cost-effective solutions. However, the required electrical bandwidths of the transceivers are much higher than those of each subscriber. Therefore, the TDM technologies cannot satisfy the bandwidth demand in future PONs [2,3]. In order to overcome this limitation, ITU-T has standardized the next-generation PON2 (NG-PON2), which exploits time/wavelength-division multiplexing (TWDM) techniques, providing an aggregate network data rate of 40 Gb/s [4]. However, with continuous growth in the capacity of optical access networks, wavelength-division multiplexed (WDM) technologies are more likely to be chosen due to their high level of data rate scalability and total capacity [5–7].

In current TDM-PONs, intensity modulation and direct detection (IMDD) technologies are preferred due to their characteristics of simple architecture, low digital signal processing (DSP) complexity, colorless operation, and higher laser linewidth tolerance [8–12]. Although these technologies are also suitable in WDM-PONs, the network is colored due to the arrayed waveguide grating (AWG) filter used at the remote side. Therefore, the flexibility of the network is reduced since one fixed wavelength is allocated to each subscriber [13–15].

To enable colorless operation in WDM-PONs, coherent receivers have been applied due to their inherent wavelength selectivity. The desired channel can be easily chosen by tuning the wavelength of the local oscillator (LO) laser at the optical network unit (ONU) side. The fine wavelength selectivity of coherent receivers can provide ultra-narrow channel spacing among ONUs, which are called coherent ultra-dense WDM-PONs (UDWDM-PONs). It is noted that coherent detection technologies also have the advantages of higher receiver sensitivity, higher spectral efficiency, and longer transmission distance. The higher receiver sensitivity means that a higher power budget can be achieved in the coherent UDWDM-PON, resulting in higher split ratios with more ONUs in one single feeder fiber. The higher spectral efficiency means the data rate for each subscriber can be enhanced as even more ONUs are added in the network. The longer transmission distance can increase the coverage of the optical access network, which saves on the cost of the PON systems. Therefore, although the system complexity of the coherent UDWDM-PON is increased, the system will benefit due to the reduced operational costs per subscriber with increased channel capacity and coverage area [16–18].

Several PON structures based on coherent detection technologies have been experimentally demonstrated with offline DSP for various modulation formats [19–21]. A single polarization coherent UDWDM-PON system based on Nyquist-shaped differential quadrature phase-shift keying

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M. Luo and J. Li are with the Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China.

T. Zeng, L. Meng, and X. Li (e-mail: lixiang@wri.com.cn) are with the State Key Laboratory of Optical Communication Technologies and Networks and National Information Optoelectronics Innovation Center, Wuhan Research Institute of Posts and Telecommunications, Wuhan 430074, China.

L. Xue and L. Yi are with the State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China.

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(QPSK) and 8PSK signals over 80 km standard single-mode fiber (SSMF) is also characterized using a real-time DSP in the transmitter and a receiver supported by a commercial field-programmable gate array (FPGA) processing at 2.5 GSa/s [22]. A field trial of bidirectional coherent Nyquist UDWDM-PON based on the real-time DSP has also been reported. Coexisting with the deployed gigabit PON (GPON), RF Video Overlay, and NG-PON2 technologies, −44.5 dBm receiver sensitivity is achieved for 64-channel DQPSK at 2.5 Gb/s per channel in the downlink [23]. However, automatic polarization control is required in the optical domain for the single-polarization transmission, which is not practical in the real situation. Real-time coherent UDWDM-PON in a dual-polarization scheme over 100 km SSMF is then experimentally demonstrated with 20 WDM channels in a 2.5 GHz grid for 2.5 Gb/s DP-QPSK signal and 3.75 Gb/s DP-8PSK signal per channel, respectively [24]. Compared with other simplified coherent PON structures [16], coherent access based on a classical dual-polarization coherent optical structure can provide larger capacity with denser channel spacing. Although the cost of current coherent optical components is high, the overall cost of these components is expected to go down with the massive deployment of coherent optical modules in optical networks and development of optoelectronic integration technologies.

We have recently demonstrated the real-time field trial of 40 × 10 Gb/s coherent UDWDM-PON at 5 GHz spacing over 40 km field-installed fiber [25]. As an extension of our previous work in Ref. [25], this paper includes the following three new contributions: (i) the configuration of UDWDM-PON based on our proposed scheme is presented; (ii) we provide more details on the design and implementation of real-time DSP in the FPGA; and (iii) the experimental results are extensively extended by including the performances of 24 h real-time bit error rate (BER) measurement, nonlinear distortion effects when multi-channel optical signals are coherently detected simultaneously, and the effects of laser frequency drift in the proposed coherent UDWDM-PON scheme.

The remainder of this paper is organized as follows: Section II presents the configuration of coherent UDWDM-PON based on a multi-channel simultaneous detection scheme. Section III describes the design and architecture of the real-time DSP in a FPGA. Sections IV and V discuss the experimental setup and field-trial results of the 40 × 10 Gb/s coherent UDWDM-PON. Finally, conclusions are drawn in Section VI.

II. Configuration of Coherent UDWDM-PON

Figure 1 describes the configuration of a coherent UDWDM-PON system including both the downlink and uplink. It has a symmetrical structure with the same channel capacity between the downlink and uplink. For the sake of simplicity, we assume the configuration can support K subscribers in one fiber. In the optical line terminal (OLT) side, the K downlink optical signals are divided into M groups with N subscribers in each group. The optical signals in each group are formed by N optical signals spaced at 5 GHz. It is noted that the optical signals in each group are multiplexed by an optical coupler occupying the total bandwidth of $5N$ GHz. The optical signals among the groups are then multiplexed by AWG with the passband channel centering the middle channel in each group. It is also shown in Fig. 1 that the downlink and uplink groups are interleaved in the whole spectrum, which means that the channel spacing among downlink (or uplink) groups is larger than $5N$ GHz. It is noted that the cost of the AWG is lower with larger passband bandwidth and channel interval. Therefore, the cost of the coherent UDWDM-PON can be kept low with a large number of subscribers in each group. The structures of the OLT and ONU are the same as shown in Fig. 1, indicating symmetrical operation with the same data rate in the proposed coherent UDWDM-PON systems. Due to the opposite transmission directions of the downlink and uplink, the problem of non-flat overlap of the AWG is also avoided. The performance of each group in the downlink or uplink is not affected by the adjacent groups, and the AWG only introduces additional power loss in the system. It is also noted that simultaneous generation and detection of high-bandwidth optical signals at the OLT side can be achieved using a high-bandwidth digital-to-analog converter (DAC), analog-to-digital converter (ADC), and optical modulators and receivers [26]. Therefore, all the ONUs

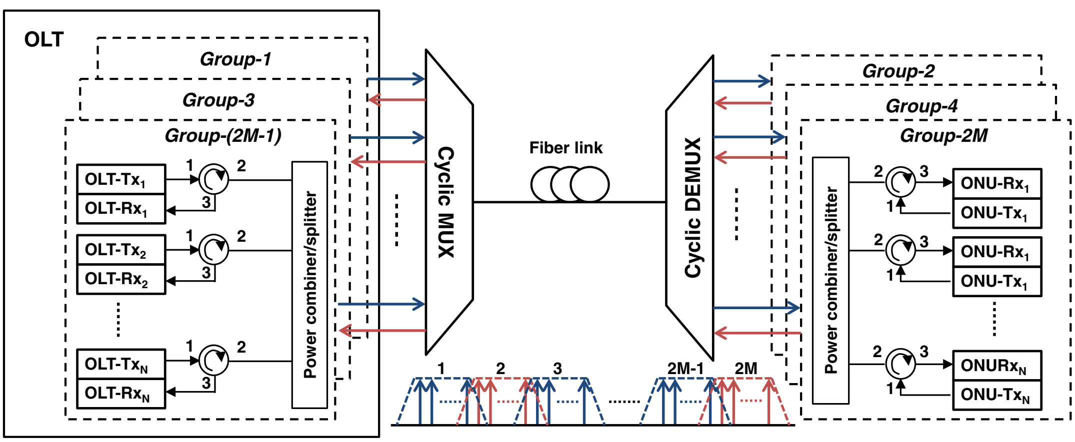


Fig. 1. Configuration of bidirectional coherent UDWDM-PON.

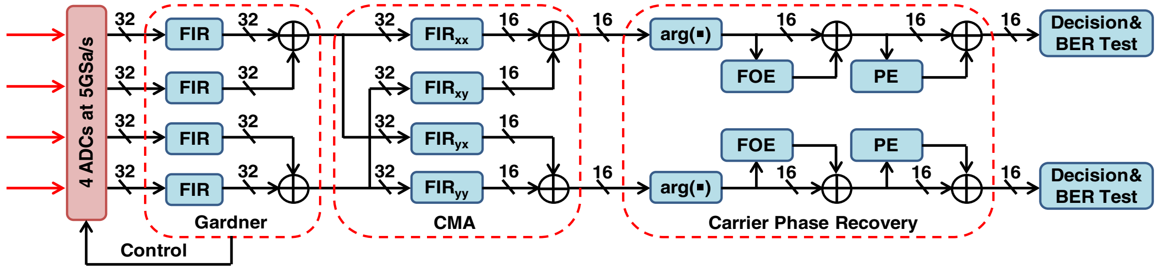


Fig. 2. Proposed DSP for the OLT/ONU transmitters and receivers for dual-polarization QPSK modulation formats with coherent detection.

in one group can share one high-bandwidth coherent optical transceiver at the OLT side, which further reduces the cost of the coherent UDWDM-PON.

In order to achieve symmetrical operation, the AWGs used in the optical distribution network (ODN) are cyclic AWGs [27], which can separate optical signals in the downlink and uplink to avoid backscattering. It is also noted that the optical power is divided by N for all ONUs in each group. The subscriber in each ONU can collect all the high-bandwidth optical signals in the corresponding group. The multi-channel nonlinear distortions in the coherent optical receivers may affect the receiver sensitivity. Therefore, the optical power and the number of subscribers in each group have to be seriously investigated to balance the system performance and cost.

III. DSP Architecture

At the OLT or ONU transmitter, the digital QPSK signal is generated by four streams of the electrical 2.5 Gb/s $2^{23}-1$ PRBS in the transceiver of an Altera Stratix V FPGA, which is working at 156.25 MHz with a parallelization level of 16. The generated electrical signals at the output of the FPGA transceivers are then passed through four low-pass filters with bandwidth of 1.8 GHz to mitigate the interferences from adjacent channels.

Figure 2 shows the proposed DSP architecture for dual-polarization quadrature phase-shift keying (DP-QPSK) signals at the receiver side. The real-time DSP is also implemented in the Altera Stratix V FPGA with 8-bit resolution and 156.25-MHz operating frequency. The four streams of digital signals are obtained after sampling by four ADCs at 5 GSa/s to achieve two samples per symbol (SPS). The parallelization level is 32 to ensure the 5-GSa/s real-time processing. For clock recovery, the timing errors are calculated by using the Gardner algorithm [28]. A voltage controlled oscillator (VCO) is then used to adjust the sampling frequency by minimizing the timing errors. The timing errors are estimated from all four streams to improve the accuracy, as shown in Fig. 2. For channel equalization, four FIR filters based on a constant modulus algorithm (CMA) are applied in a multiple-input and multiple-output (MIMO) scheme. The number of filter taps is 7, which is sufficient to compensate for the linear channel distortions due to chromatic dispersion and limited bandwidth of optoelectronic devices. It is noted that the digitized signals in all 32 parallel channels are equalized. However, only the output of one channel among the 32 outputs of 32 parallel channels is selected to update the channel coefficients in CMA to ensure the real-time processing for the 10-Gb/s DP-QPSK signal. After channel equalization, the signal becomes one SPS with the parallelization level of 16. Then, the fourth-power algorithm is applied to achieve the carrier phase recovery (CPR). The frequency offset is tracked by differentiating the adjacent symbols with a feedback control. A Viterbi & Viterbi algorithm with feedforward control is used to recover the phase in blind mode with a filter tap number of 32. A coordinate rotation digital computer (CORDIC) algorithm is used to convert the complex signal into angle signal, which further reduces the computational complexity in the carrier phase recovery process by using only the add operation [29].

Table I summarizes the resource usages of DSP modules for real-time processing at the receiver side. The evaluated resource usages include adaptive look-up tables (ALUTs), adaptive logic modules (ALMs), dedicated logic registers, block memory bits, and DSP blocks. It is noted that the ALUTs and dedicated logic registers are basic cells in the FPGA. The ALUTs and dedicated logic registers are included in the ALM to realize combinatorial logic and sequential logic operations. Block memory bits present the ability to store the data. DSP blocks can implement a multiple-bit multiplier. It can be seen that the channel equalization module based on CMA consumes most DSP blocks where a certain number of multipliers is required to update the channel coefficients and output symbols. Fewer DSP blocks are required in the carrier phase recovery process due to CORDIC operation at the expense of most ALUTs, ALMs, and logic registers.

TABLE I
Consumed DSP Resource Comparison for Different Modules

	CDR	CMA	CPR
ALMs	4280	7972	40,545
ALUT	5051	6672	43,985
Logic registers	7633	15,461	78,250
Block memory bits	0	8800	1588
DSP blocks	12	509	9

IV. Experimental Setup

Since the proposed coherent UDWDM-PON scheme is symmetrical, we only demonstrate the downlink in one AWG channel for simplicity, as shown in Fig. 3. In the OLT side, 40 external cavity lasers (ECL) with linewidth less than 100 kHz are divided into odd and even groups at a channel spacing of 10 GHz. The frequencies of the corresponding odd and even channels are shifted by 5 GHz. The optical spectrum of 40 laser sources is shown in Fig. 4(a). In the OLT side, the laser sources in two groups are launched into two DP IQ modulators (DP-IQMs), respectively. Each DP-IQM is driven by four independent electrical 2.5-Gb/s $2^{23} - 1$ PRBSs from the output of the transceivers. Therefore, the optical signals among adjacent channels are uncorrelated. The bias of the DP-IQM is adjusted by a specifically designed automatic controller to track the drift of the bias [30]. After electrical to optical conversion, the optical signals in odd and even groups are combined by one optical coupler, which results in a UDWDM grid of 5 GHz occupying the total bandwidth of 200 GHz. In our designed symmetrical coherent UDWDM-PON scheme, optical amplifiers are not required as indicated in Fig. 1. All the power losses are assumed to be compensated by the LO at the receiver side. However, due to the unequal power distribution of the output 40 ECLs, two erbium doped fiber amplifiers (EDFA) are used for the respective odd and even groups to control the total transmitted optical power of 5 dBm for the 40 channels, corresponding to the optical signal power of 5 dBm for each transmitter before the optical coupler. It is noted that the typical maximal output power of an ECL is 16 dBm and the loss of a DP-IQM can be lower than 10 dB [31]. This means that the optical power of the modulated optical signal can achieve 5 dBm without the requirement of an optical amplifier at the OLT side. Therefore, the cost of the coherent UDWDM-PON can be reduced by using only the LO for channel selection and power amplification.

The total optical signal is transmitted over a round trip field-installed fiber link with total transmission distance of 40 km. The round trip link is chosen between Minhang campus and Qibao campus of Shanghai Jiaotong University (SJTU), as shown in the inset of Fig. 3. Both the OLT and ONU transceivers are located at Minhang campus. It is noted that the total loss of the fiber link in the field demonstration is 18 dB due to the aging of the fiber underground and non-professional fiber arrangement in the campus. The optical spectrum at the transmitter side is shown in Fig. 4(b). In the field demonstration, a variable optical attenuator (VOA) is used to emulate the 1:40 passive optical splitter for the 40 subscribers at the ONU side. At the receiver side, the DP-QPSK channels are selected by tuning another ECL as the LO and coherently detected in an integrated coherent receiver (ICR). As described in Fig. 1, all the 40-channel DP-QPSK signals are launched into the ICR and no passive narrow band optical filter is used at the ONU side to simplify the structure of the PON system and enable symmetrical operation between the downlink and uplink.

In the electrical domain at the ONU side, the signal is sampled by four 8-bit 5 GSa/s ADCs with an analog bandwidth of ~2 GHz. The amplitude of the electrical signal is adjusted by appropriately setting the LO power and transimpedance amplifiers (TIA) in the ICR. After analog-to-digital conversion, the digitalized signal is sent to the FPGA where all DSP is implemented in real time. The applied DSP has been discussed in the previous section. The BER is calculated in real-time on a personal computer with respect to the transmitted PRBS. The optical transceivers, including both the transmitter and receiver modules, are integrated in one electrical board (see inset II of Fig. 3), where both uplink and downlink operations can be achieved according to the scheme in Fig. 1. It is noted that the experimental setup is a special case of the proposed scheme in Fig. 1, which contains 40 channels

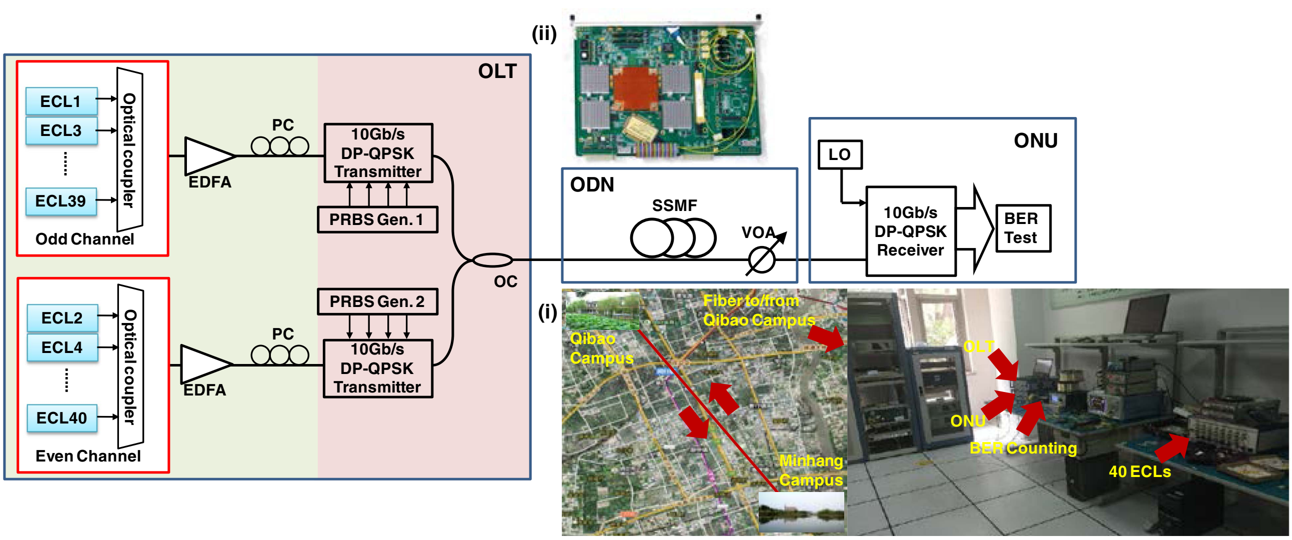


Fig. 3. Field-trial setup for coherent UDWDM-PON. Inset: (i) map view of the field-trial connection with laboratory infrastructure; (ii) electrical board including the coherent optical transmitters and receivers.

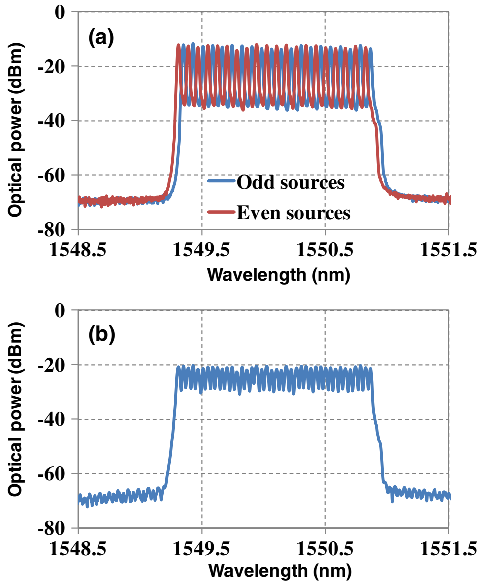


Fig. 4. (a) Optical spectrum of 40 optical sources at the OLT side; (b) optical spectrum of transmitted optical signals at the OLT side.

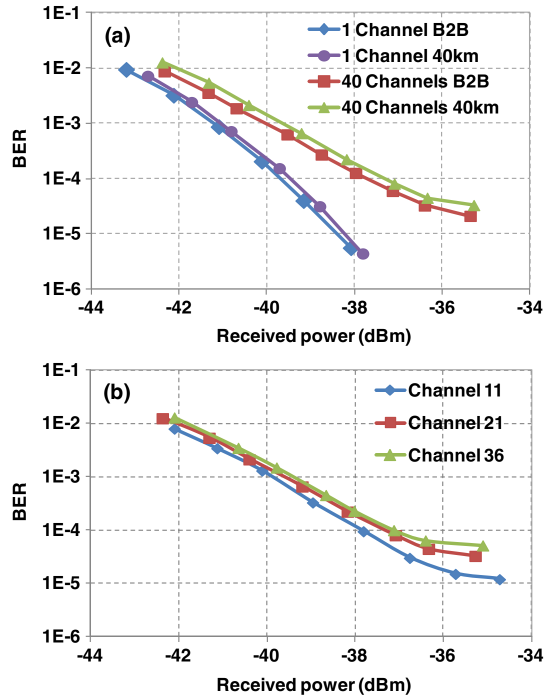


Fig. 5. (a) BER performances of the middle channel with 1 and 40 optical channels in the cases of B2B and 40 km fiber transmission; (b) BER performances of selected channels with 40 optical channels after 40 km fiber transmission.

as one group in the downlink. In this case, the cyclic AWG is not required in the downlink demonstration. When more groups are included in the bidirectional transmission link, the cyclic AWG can be used to achieve larger channel capacity, as described in Fig. 1. Considering the fact that there is no interaction effect between adjacent groups, the experimental results in this paper can basically reflect the performance of the proposed coherent UDWDM-PON structure.

V. Results and Discussion

We first evaluate the BER performances of the middle channel (21st), as shown in Fig. 5(a). For the single channel case, the receiver sensitivity can achieve −41 dBm at the BER threshold of 3.8×10^{-3}. For 40 DP-QPSK channels, the receiver sensitivity is degraded to −40 dBm, which is mainly due to the nonlinear effects as four-wave mixing (FWM) in the fiber link and power saturation when all the 40-channel optical signals are converted into the electrical signals in one ICR. The transmission penalty is negligible when compared with the back-to-back (B2B) case. The BER versus receiver power for the 11th, 21st, and 36th channels are shown in Fig. 5(b), which correspond to the best-, middle-, and worst-performance channels. It is noted that the total optical power is 5 dBm after the optical coupler, corresponding to the optical power of −11 dBm for each channel. Therefore, the power budget can reach 29 dB based on the proposed coherent UDWDM-PON scheme. Considering the 16 dB power loss of the 1:40 power splitter at the receiver side and less than 5 dB insertion loss in the AWGs [32,33], the ODN can support 40 km SSMF with a loss of 0.2 dB/km.

Then, we measure the BER performances for all 40 optical channels at a receiver power of −40 dBm for each channel. As shown in Fig. 6, the performances of all the 40-channel optical signals can achieve a BER threshold of 3.8×10^{-3}. The optical spectrum of the received signals is also shown in Fig. 6. Next, the BER performance of the middle channel after ~24 h real-time measurements is shown in Fig. 7. The variation of the BER throughout 24 h is small, and the average value of the BER is 1.2×10^{-3}, well below the BER threshold of 3.8×10^{-3}.

We compare the performances of the proposed coherent UDWDM-PON with NG-PON2, which are summarized in Table II. The main benefits over NG-PON2 are (i) more channel wavelengths are transmitted at 10 Gb/s; (ii) narrower channel spacing of 5 GHz, indicating larger spectral efficiency; (iii) no requirement of optical filters for channel

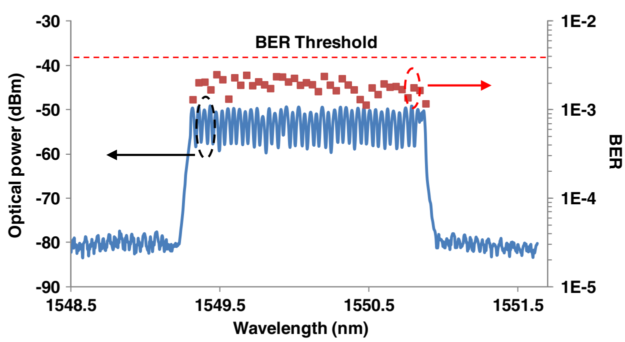
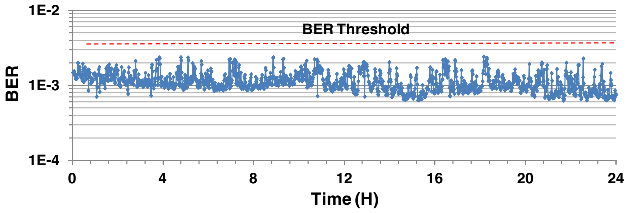


Fig. 6. BER performances of all the channels at a received power of −40 dBm for each channel with the corresponding optical spectrum at the ONU side.



Rate	Timer	TX/RX Pattern	BER Count	Error Count	BER
10 Gb/s	87126s	PN23	8.7×10^{14}	1.04×10^{12}	1.2×10^{-3}

Fig. 7. BER performances of the middle channel after 24 h real-time measurement.

TABLE II
Key Characteristics of NG-PON2 and Proposed Scheme

	NG-PON2	This Paper
Wavelength channels	4–8	40
Channel spacing	50–100 GHz	5 GHz
Channel bit rate	2.5 Gb/s, 10 Gb/s	10 Gb/s
Capacity	40 Gb/s, 80 Gb/s	400 Gb/s
Receiver sensitivity (dBm)	−30(2.5 Gb/s, 10^{-4}) −28(10 Gb/s, 10^{-3})	−39.5(10 Gb/s, 10^{-3})

selection; and (iv) higher receiver sensitivity and power budget.

We then investigate the nonlinear effects on the performance of the proposed coherent UDWDM-PON. Figure 8 shows the BER versus received power with different numbers of optical channels in the B2B case. It is shown that when multi-channel optical signals are injected into the ICR directly, the BER performance degrades when the received optical power is higher than −35 dBm. The performance degradation at higher received power is mainly due to the nonlinear distortions when multi-channel optical signals are simultaneously collected by one ICR. The nonlinear distortions are more severe at higher received power in the ICR. The result is different from a conventional PON scheme, where better performances can be obtained with larger received power. It indicates that there is an optimal value of optical received power in the proposed coherent UDWDM-PON scheme.

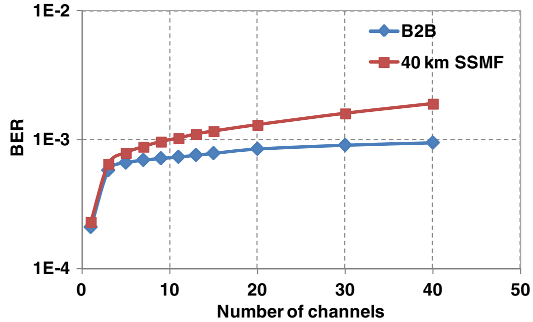


Fig. 9. BER versus the number of optical channels under the received power of −40 dBm per channel.

The BER versus the number of optical channels is shown in Fig. 9 under the received power of −40 dBm per channel. Additional performance degradation is observed after 40 km SSMF transmission when compared with the B2B case. The larger penalty occurs with the increasing number of channels, which means more FWM noise is generated in the fiber link. It is also noted that performance degradation is most significant when the number of optical channels is increased from 1 to 3, even in the B2B case. This means that the channel crosstalk and nonlinear distortions in ICR are the main factors that affect the system performance. Therefore, although the cost can be reduced if more subscribers can share one AWG channel, the overall performance will be degraded with an increasing number of subscribers. The choice of the number of optical channels (subscribers) may be dependent on the system bandwidth, fiber link, and receiver sensitivity requirements in the coherent UDWDM-PON.

Finally, we investigate the tolerance of the frequency drift of the ECLs located at both the transmitter and receiver sides for the 21st channel. The transmitter and received powers are fixed at −11 dBm and −40 dBm for each channel, respectively. We first fix the frequency of the ECL at the receiver side and change the frequency of the ECL at the 21st transmitter. The result is shown in Fig. 10, where the frequency tolerance is ±800 MHz at the BER threshold of 3.8×10^{-3}. Then we fix the frequency of the ECL at the transmitter side and change the frequency of the ECL at the receiver side. The performance of the 21st channel is

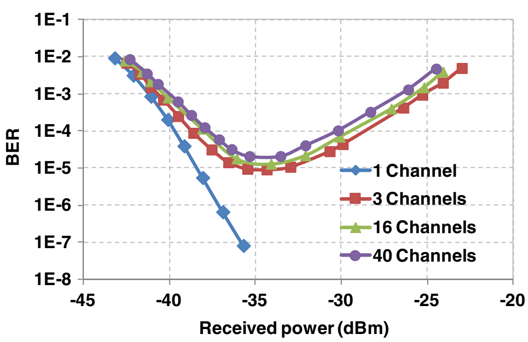


Fig. 8. BER versus received power with different number of optical channels in the B2B case.

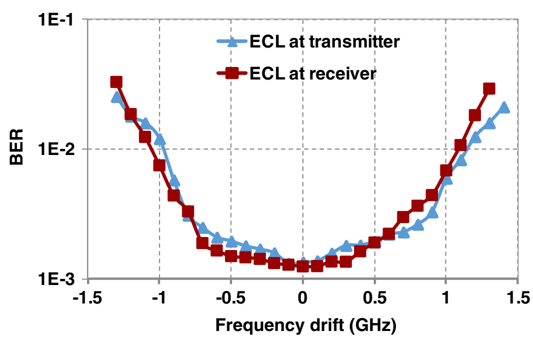


Fig. 10. BER versus frequency drift of ECLs at both transmitter and receiver sides.

also selected for measurement. It is also shown that the frequency tolerance is ±800 MHz at the BER threshold of 3.8×10^{-3}. However, considering the frequency drift among the adjacent channels, the frequency tolerance is reduced to be ±400 MHz in the proposed scheme.

VI. Conclusion

We experimentally demonstrate a real-time coherent UDWDM-PON system after a 40 km field-installed fiber link with channel capacity of 40×10 Gb/s DP-QPSK at 5 GHz spacing. The real-time digital signal processing for the generation and detection of 10 Gb/s DP-QPSK are realized in a FPGA. The system performances are evaluated in 24 h mode for all the ONUs, which can achieve a power budget of 29 dB based on the proposed coherent UDWDM-PON scheme. Nonlinear-tolerance experimental investigations indicate that the number of subscribers in one AWG channel requires further optimizations to balance the system cost and performance. Finally, we show that the system performances can be maintained at the tolerance of a laser frequency drift of ±400 MHz.

Acknowledgment

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M. Luo received his B.S. and M.S. degrees in electronic science and technology in 2005 and 2007, respectively, from Huazhong University of Science and Technology, China. Since May 2011, he has worked in the State Key Laboratory of Optical Communication Technologies and Networks, Wuhan Research Institute of Posts and Telecommunications, as an optical communication engineer. His work fields include fiber optical communication and information optical engineering. He is currently pursuing a Ph.D. in optical engineering at Huazhong University of Science and Technology, China.

J. Li received her M.Sc. degree in electric and information technology from Huazhong University of Science and Technology in July 2005. She has worked in the State Key Laboratory of Optical Communication Technologies and Networks, Wuhan Research Institute of Posts and Telecommunications, since 2010. She is currently pursuing a Ph.D. at Huazhong University of Science and Technology, with thesis work on digital signal processing (DSP) for flexible optical access networks.

T. Zeng received a B.S. degree in optoelectronics from the Huazhong University of Science and Technology in 1994, an M.Sc. degree in radio engineering from the Beijing University of Posts and Telecommunications in 1997, and a Ph.D. from Huazhong University of Science and Technology in 2015. His current research interest focuses on the development and implementation of real-time FPGA-based DSP for coherent optical communications.

L. Meng received his M.Sc. degree in communication and information systems from Wuhan Research Institute of Posts and Telecommunications, China, in April 2013. Since May 2013, he has worked in the State Key Laboratory of Optical Communication Technologies and Networks, Wuhan Research Institute of Posts and Telecommunications as an optical communication engineer. His current research interest focuses on the development and implementation of real-time FPGA-based DSP for coherent optical communications.

L. Xue received a B.S. degree in communication engineering from the School of Information Science and Engineering, Hunan University, Hunan, China, in 2015. He is currently working toward a Ph.D. in the Future Ready Optical Network Technology Research Group, State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai, China. His research interests include optical access networks and short-reach optical interconnection.

L. Yi received B.S. and M.S. degrees from Shanghai Jiao Tong University (SJTU), Shanghai, China, in 2002 and 2005, respectively. He received a Ph.D. from Ecole Nationale Supérieure des Télécommunications (currently named Telecom ParisTech), Paris, France, and from SJTU, in March and June 2008, respectively, as a joint-educated Ph.D. student. After graduation, he worked with Avanex R&D center as a Product Development Manager. Since 2010, he has been with the State Key Laboratory of Advanced Optical Communication Systems and Networks, SJTU, and now he is a full professor. He has authored or coauthored more than 120 papers in peer-reviewed journals and conferences, which have been cited more than 1200 times (Google Scholar). His research interests include optical access networks, optical signal processing, and secure optical communications. He was the recipient of the "National Excellent Ph.D. Thesis in China" award and the "National Science Fund for Excellent Young Scholars of China" award. He is the track/symposium co-chair of IEEE.

X. Li received an M.Sc. degree in optical and electronic information from Huazhong University of Science and Technology in July 2011 and a Ph.D. in electrical and electronic engineering from Nanyang Technology University in May 2016. Currently, he is a research engineer in the Wuhan Research Institute of Posts and Telecommunications. His research interest focuses on the development and implementation of high-speed coherent optical communications. He has more than 80 scientific papers published in top conferences and journals in the optical communications community.