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A novel multi-band OFDMA-PON architecture using signal-to-signal beat interference cancellation receivers based on balanced detection

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Abstract We have proposed a novel multi-band orthogonal frequency division multiplexing and passive optical network (OFDMA-PON) architecture using signal-to-signal beat interference cancellation receivers based on balanced detection at both the optical line terminal and the optical network units (ONUs). Simulation of the full-duplex system with 20 km SSMF transmission and a 1:4 split is achieved successfully. Without a laser source and amplifier at the ONU, our proposed multi-band OFDMA-PON system reduces the signal-to-signal beat interference simply and effectively, while the space of each band can be as small as 1 GHz and optimum carrier-to-signal power ratio at about 10 dB. Simulation results show that the OSNRs of the 40 Gb/s downstream and 30 Gb/s upstream transmission are only 20 and 16 dB required at BER $= 3.8 \times 10^{-3}$, respectively.

Keywords OFDMA-PON · Multi-band OFDM · PON · Balance detection · Signal-to-signal beat interference (SSBI)

1 Introduction

Driven by the continuing increase in bandwidth demand for ever-increasing multimedia and cloud computing, the broadband optical access network will migrate to 40 Gb/s or above. Many passive optical network (PON) technologies have been proposed to provide a broadband and cost-effective access. Orthogonal frequency division multiplexing passive optical network (OFDM-PON), due to its great resistance to fiber dispersion, high spectral efficiency and the flexibility on both multiple services provisioning and dynamic bandwidth allocation, has been spotlighted as one of the strongest candidates. With the orthogonal frequency division multiple-access (OFDMA) scheme, it is possible to implement a multiple-access/multiplexing function cost-effectively. Moreover, heterogeneous services can be transparently supported with dynamic bandwidth allocation by adaptively assigning OFDM subcarriers to different services or optical network units (ONUs) [1]. However, since digital signal processing (DSP) complexity of the optical orthogonal frequency division multiplexing (OOFDM) signals scales up with the increase in data rates and effective bandwidths, it limits the data rate scalability in physical OOFDM implementation [2]. Transmission of multi-band OFDM signals becomes an effective solution to overcome the dilemma between the communication bandwidth demands and DSP complexity. The multi-band OFDM signal could transmit in each channel of the WDM network, which presents advantages of high flexibility, enabling scalability and dynamic reconfiguration [3]. However, there is a critical signal-to-signal beat interference (SSBI) issue caused by the beatings of OFDM subcarriers and different OFDM bands in the IM/DD OFDMA-PON system if the guard band is smaller than the bandwidth of the OFDM signal. To avoid the impact of SSBI, 100 Gb/s multi-band optical OFDM signal with only 40 GHz photodiode was reported in [4], while the subband gap must be wider than 100 GHz and an individual pilot carrier should be allocated in each subband, which wastes optical spectrum and transmitting power. More than 100 Gb/s DSP-based downstream (DS) polarization multiplexing OFDMA signal transmitting with an unmodulated carrier is directly detected at the ONU, while upstream (US) multi-band OFDM signal with the suppressed

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carrier is coherently detected at the optical line terminal (OLT) to remove the SSBI interference [5,6]. A multi-band OFDM signal with narrow-band gap between virtual carrier and OFDM band is detected directly, and then the DSP algorithms are required to overcome the SSBI degradation [7]. However, the above solutions, such as DSP algorithms and coherent detection [8], would increase the cost and complexity, especially for cost-sensitive PON system. Interestingly, in the direct detection optical multi-band OFDM system, an optical SSB filter is used to keep the desired signal band at the outmost position in the received spectrum and successfully makes the SSBI and desired signal nonoverlapping [9]. But a narrow-band optical filter may be a daunting task from both the technical and economic perspectives. More recently, balanced detections without the need for a careful polarization management and a large band gap are proposed to eliminate the SSBI effectively for OFDM system [10,11]. Besides, this simple balanced detection technique avoids the requirement of the narrow linewidth lasers at both transmitter and receiver, extra signal processing to solve the phase noise and frequency offset or narrow-band optical filters.

In this paper, we propose a novel multi-band OFDMA-PON architecture, which combines the OFDMA-PON with multi-band OFDM and achieves DS OFDMA transmission and US multi-band OFDM transmission from multiple source-free ONUs without any amplifiers over a single wavelength. The simulation of full-duplex OFDMA-PON system with 40 Gb/s DS OFDMA signal and 30 Gb/s US multi-band OFDM signal based on interference cancellation receivers based on balanced detections (ICRBDs) is achieved over 20 km SSMF plus a 1:4 power splitter with the US 3-band OFDM signal carried by the optical carrier of DS. OSNR = 20 and 16 dB for DS and US are required to achieve the BER of 10^{-3}, respectively, which demonstrates that the dominant SSBI is eliminated in our proposed system. In addition, the influence of the carrier-band gap (GB), space of each band (GB_w), and carrier-to-signal power ratio (CSPR) on the system performance is further explored.

2 Principle of multi-band OFDMA-PON

Figure 1 illustrates the proposed multi-band OFDMA-PON architecture with the ICRBD in transceivers, which consists only of an interleaver, a 2 × 2 3 dB optical coupler and balanced photodiode pair (BPD), as shown in our previous work [11,12]. Balanced detection is first applied to detect multi-band OFDM signal to overcome the SSBI in PON. For DS, the frequency and time domain partitioning of an OFDMA frame is first performed at the OLT, with the resulting time/frequency schedule broadcasted to all of ONUs over preconfigured OFDM subcarriers and time slots, as shown in Fig. 1a, b. As the traffic load, type, or user profile of the network change, the subcarrier assignment can be reconfigured accordingly, which is realized by the DSP simply. After transmission over the distribution fiber, the DS signal is split

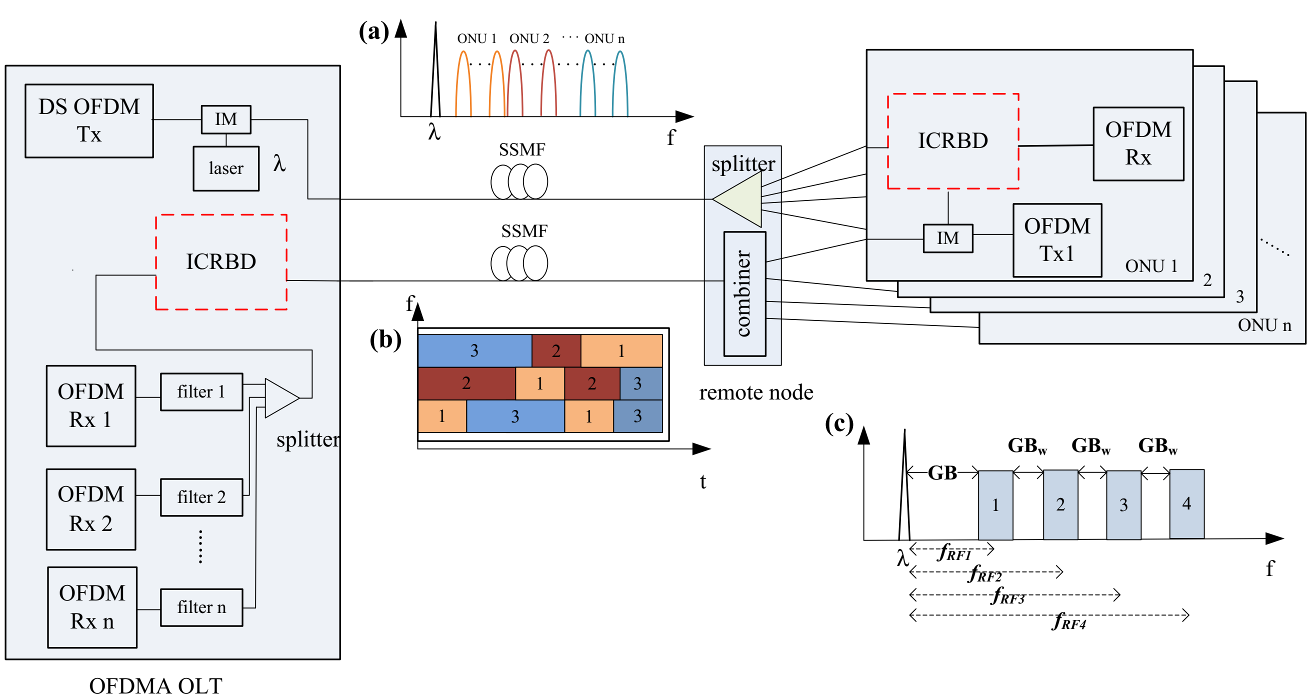

Fig. 1 Multi-band OFDMA-PON architecture. The *insets* are **a** frequency partitioning of an OFDMA signal, **b** frequency and time domain partitioning of an OFDMA frame, **c** frequency partitioning of US multi-band OFDM signal

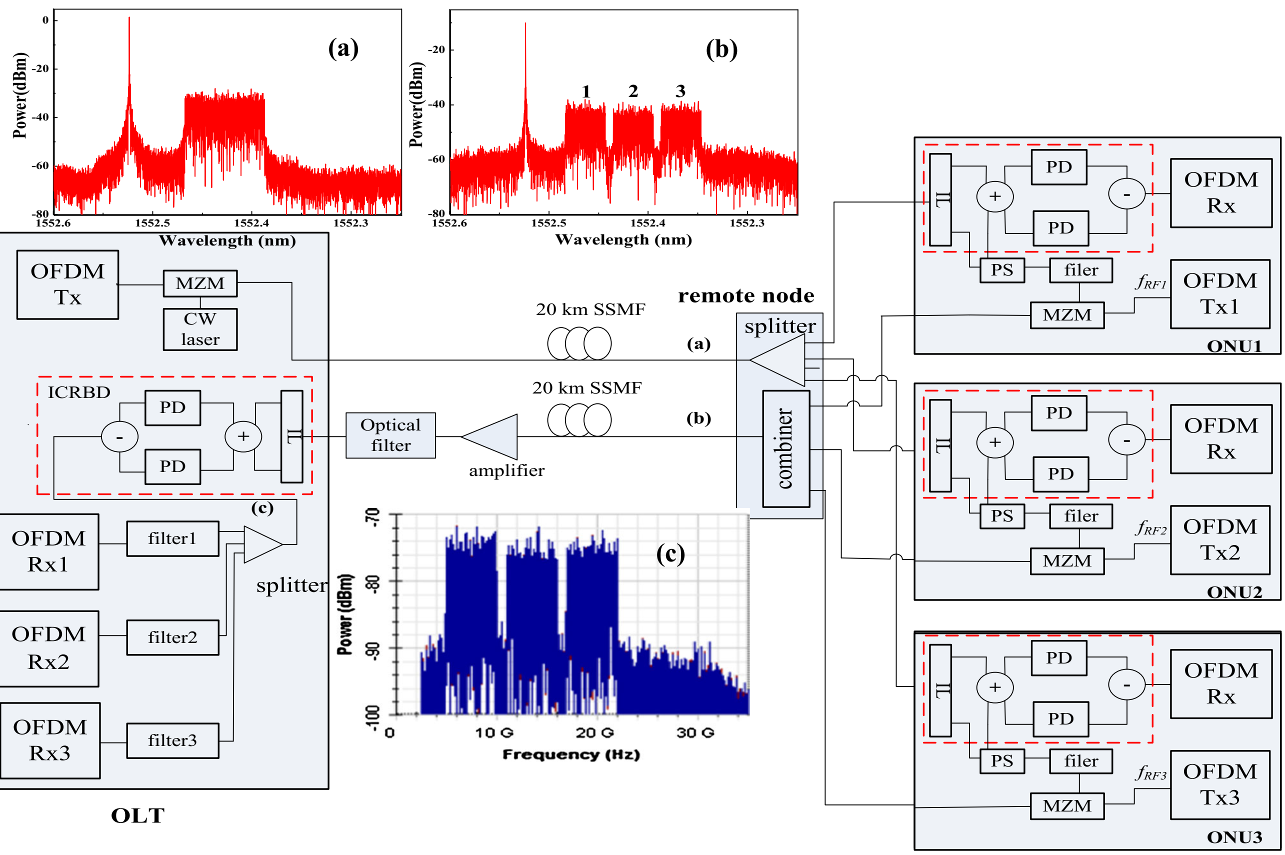

Fig. 2 Simulation link of the proposed architecture. The *insets* are the optical spectra of **a** the DS received OFDM signal, **b** the US received 3-band OFDM signal, **c** the RF spectrum of the US 3-band OFDM signal by ICRBD

by a power splitter in the remote node and fed to the ONUs over the feeder fiber. At the ONU, following ICRBD, each ONU selects its own data from its pre-assigned subcarrier(s) and/or time slots, as communicated by the OLT scheduler. To achieve source-free ONU, the optical carrier is abstracted simply by the power splitter from the ICRBD and modulated by all ONUs for US transmission.

For US transmission, ONUs can be categorized into four groups based on their different geographical areas. Each ONU in one group shares one OFDM band and maps its data to its assigned OFDM subcarrier(s) or time slots, nulls all remaining subcarriers or time slots, and then performs SSB-OOFDM modulation to generate a complete frame. After upconverted by RF, the OFDM signal is carried by the optical carrier abstracted from the DS and then fed to the uplink fiber. In the remote node, the multi-band OFDM signals from the different ONUs are combined together without conflict. At the OLT, the whole OFDM signals are detected by ICRBD and separated by a splitter and band-pass filters. The GB_w between OFDM bands can be reduced small to improve the spectral efficiency, as shown in Fig. 1c. The proposed multi-band OFDMA-PON with the flexible transmission, the relatively small bandwidth space, and TDM mechanism can achieve coexistence with the previous generations of PONs in the legacy optical distribution network and is extensible to the emerging applications [13].

3 Simulation setup

To verify our proposed architecture, 40 Gb/s DS 16-QAM and 30 Gb/s US 4-QAM SSB-OOFDM transmission system is built based on the software platform of OptiSystem, as depicted in Fig. 2. At the OLT, a 40 Gb/s pseudorandom bit sequence (PRBS) is mapped into 16-QAM signal and then put into OFDM module for serial–parallel conversion and an inverse fast Fourier transform (IFFT) of size 256 and parallel–serial conversion. Here 128 subcarriers are allocated for bearing the signals, whereas the others are zero-padded for oversampling. A cyclic prefix (CP) of 32 samples is added preceding each OFDM symbol. In addition, two training symbols are used preceding the whole OFDM symbols, which is optimized for channel estimation after numbers of simulations. After digital-to-analog converter (DAC), the 10 GHz baseband OFDM signal is upconverted by the IQ modulator with the radio frequency (RF) at $f_{RF} = 12$ GHz.

Thus, GB is equal to 7 GHz and less than 10 GHz, as shown in Fig. 2c, which has been discussed in [11]. The EVM still remains below the FEC limit even after the GB reduces to 2 GHz. The electrical in-phase (I) and quadrature (Q) component of the RF-OFDM signal drive the two arms of Mach–Zehnder modulator (MZM) to modulate the lightwave from a CW laser diode with the central wavelength of 1552.52 nm and the linewidth of 8×10^{-6} nm. The CSPR can be adjusted flexibly via the DC bias voltage of MZM. Finally, the resulting output SSB-OOFDM signal obtained by SSB filtering is sent to the 20 km SSMF with the launch power of 5.5 dBm and split by a 1:4 splitter in the remote node. The power loss of SSMF is 0.2 dB/km, and the dispersion is 16 ps/nm km. At the ONUs, the received SSB-OOFDM signal is fed into the ICRBD where the signal is separated into the optical carrier and the OOFDM signal by an interleaver. The optical carrier in the lower branch is divided into two parts by a power splitter such that each ONU reuses the optical carrier as US optical carrier. Then the other part of the carrier and the OOFDM signal in the upper branch are input into a 2×2 OC. The two outputs of the OC are detected by the BPD, respectively. Note that both PDs in BPD have the same responsivity of 1 A/W and thermal noise of 10^{-22} W/Hz. Additionally, the shot noise and enough white noise have been added before BPD in the simulation. After optoelectrical conversion and subtraction, the photocurrent with only the RF-OFDM signal is obtained. Following the reverse operations as in the OFDM signal transmitter, including IQ demodulator, analog-to-digital converter (ADC), serial–parallel conversion, CP removal, FFT, channel estimation, and parallel–serial conversion, the transmitted 16-QAM data are obtained. Here, for the sake of analysis simplicity, the BERs of all the DS subcarriers are calculated.

For US, 10 Gb/s 4-QAM OFDM signal with 5 GHz bandwidth is upconverted by IQ modulator with the RF frequency varying from f_{RF1} to f_{RF2} and to f_{RF3}, respectively. Note that f_{RF1}, f_{RF2}, and f_{RF3} make the joint influence on GB and GB_w (the band gap of OFDM bands). The abstracted optical carrier passes through a narrow bandwidth filter to suppress interference from the DS signal and then is modulated by the RF-OFDM signals. In the remote node, these different signals are combined to form 30 Gb/s US signal without conflict. The ONU1, ONU2, and ONU3 occupy the band 1, band 2, and band 3, respectively, as shown in Fig. 2b. Then the whole multi-band OFDM upstream signal is transmitted over 20 km SSMF. At the OLT, the multi-band OFDMA-PON signal is detected by ICRBD, then separated by the electrical band-pass filters at different central frequency (according to the RF), and sent to demodulators in the electrical domain. The RF spectrum of the received multi-band OFDM signal is shown in Fig. 2c.

4 Results

To further study the performance of our proposed multi-band OFDMA-PON architecture, in this section we firstly demonstrate the robustness of the proposed system against interferences and noises and then explore the impact of DS CSPR, US GB, and GB_w on the system performance.

Figure 3 shows BERs versus the OSNR for DS OFDMA signal and 1-band, 2-band, and 3-band US OFDM-PON signal transmission, respectively. And the responding US RF spectra after ICRBD detection are shown in Fig. 3a–c. If the 3-band signal is directly detected in traditional way, there exists a triangle outline of the noises, as shown in Fig. 3d. The noises, concluding the SSBI interference, the shot noise, and thermal noise, would greatly degrade the desired signal. However, Fig. 3c reveals that the dominant SSBI has been removed in our proposed system and so the desired signal is almost 20 dB better than the remaining SSBI and noise from RF spectrum of the received multi-band OFDM signal. The elimination of SSBI is independent of how many bands are transmitted, but more noises and the interference of band-beating affect the signal because of increased bands, as shown in Fig. 3a, b. The transmission performance with BER $= 10^{-3}$ achieves at OSNR about 20 dB/0.1 nm and 16 dB/0.1 nm for DS and 3-band US transmission, respectively. For the 1-band and 2-band US OFDM signals, the required OSNR is 4 and 2 dB better. Because 1-band and 2-band have less band-beating interference than the 3-band, a smaller OSNR is needed to obtain the same BER. Here the measurements of OSNR are done using an optical spectrum analyzer before PD. Besides, because ONU2 has two neighbors while the ONU1 and ONU3 only interfere with one neighbor, ONU2 has the poorest performance than the other two ONUs, which shows that the GB_w between the bands has influence on the system performance and the detailed analysis will be given as shown in Fig. 3.

Table 1 gives two cases of GB and GB_w for US transmission. Here B is the bandwidth of each US OFDM signal. In the first case, GB increases from 3 to 9 GHz, while GB_w is fixed at 1 GHz. The BER versus the GB for the 3-band OFDM signals is shown in Fig. 4a. The BER curve of ONU1 falls sharply as the GB increases from 3 to 5 GHz since there some SSBI interference remains below 5 GHz. As the GB increases further, the BERs of all ONUs reach a floor. In the second case, GB_w increases from 1 to 5 GHz, while GB is fixed at 5 GHz. Figure 4b shows that GB_w larger than 1 GHz does not significantly affect the signal. But a narrow-band and expensive filter must be required at receivers if the GB_w is smaller than 1 GHz. Both cases indicate that GB $=$ 5 GHz and GB_w $=$ 1 GHz are trade-offs between the performance and spectral efficiency, and further increasing GB from 5 GHz and GB_w from 1 GHz cannot improve the performance significantly due to more interferences in high frequency.

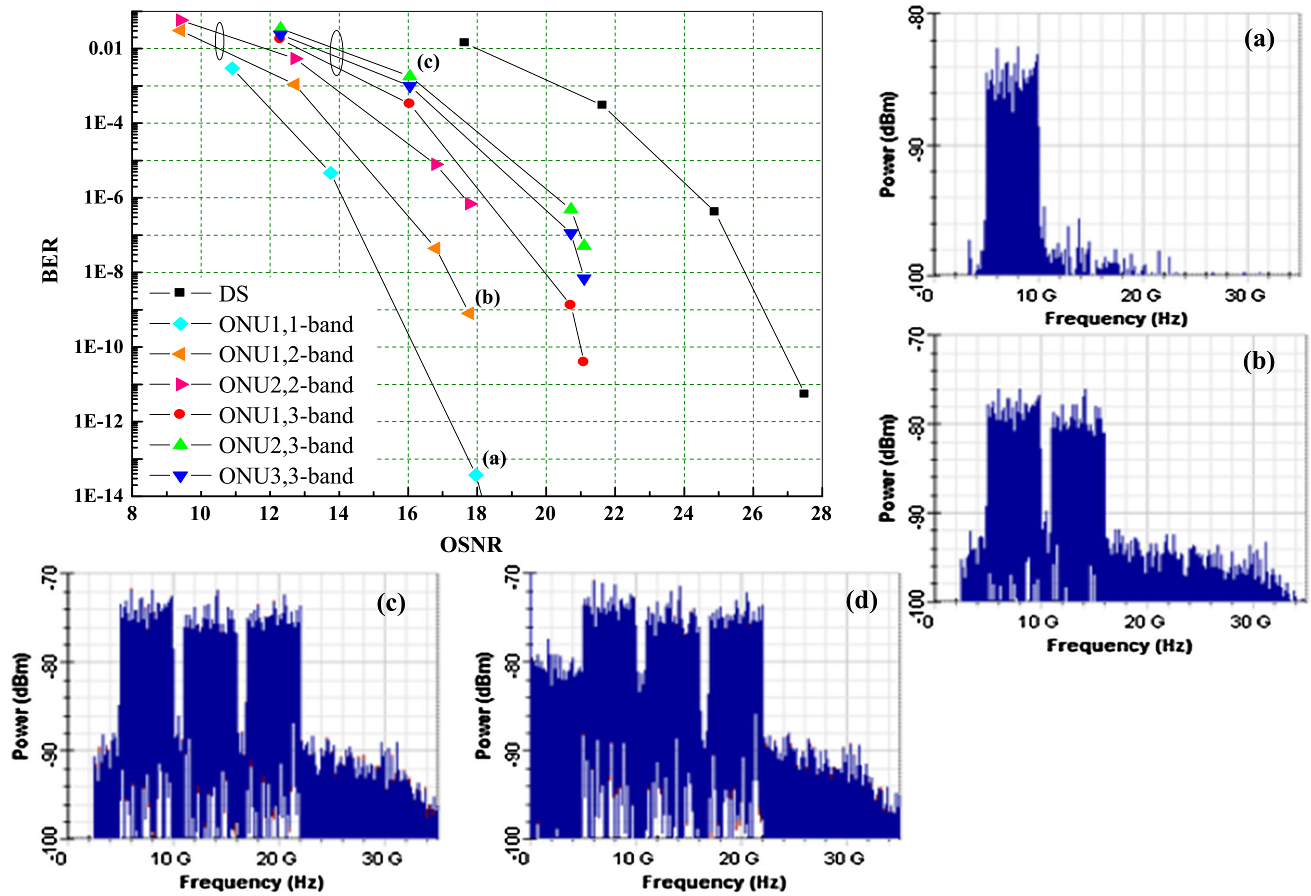

Fig. 3 BER performance results for the multi-band OFDMA-PON with DS CSPR = 8 dB, GB = 5 GHz and GB_w = 1 GHz. The *insets* are the RF spectra of **a** the 1-band OFDM signal, **b** 2-band OFDM signal, **c** 3-band OFDM signal by ICRBD; and **d** the RF spectrum of 3-band OFDM signal by direct detection

Table 1 Bandwidth setting

GB (GHz)	GB_w (GHz)	Bandwidth (GHz)
Case 1		
3	1	20
5	1	22
7	1	24
9	1	26
Case 2		
5	1	22
5	2	24
5	3	26
5	5	30

Since the US OFDM signals would strongly depend on the DS optical carrier, the DS CSPR could be critical to the performance of the proposed multi-band OFDMA-PON system. Therefore, to investigate the influence of the DS CSPR, it is varied by tuning the DC bias voltage of MZM. Here US CSPR = 1 dB, OSNR = 27 dB/0.1 nm, GB = 5 GHz, and GB_w = 1 GHz are set firstly. Figure 5 shows the BERs versus DS CSPR for 40 Gb/s DS OFDM signal and 30 Gb/s 3-band US OFDM signals. For DS, the best performance for all subcarriers is achieved at CSPR = 0 dB, because the best receiver sensitivity is obtained [14]. As the CSPR increases, the performance deteriorates. However, for US, the BER performance of three ONUs improves about 30 dB as the DS CSPR increases and reaches a floor at CSPR = 12 dB. This is attributed to the fact that the high DS CSPR will supply a high US launch power, which resists the optical noise in some degree. Therefore, since the US optical carrier reuses the DS optical carrier and no amplifiers are used at the ONU side in our proposed scheme, the DS CSPR has influence on both the DS and US transmission. At the same time, considering the BER of each curve almost reaches a floor after CSPR > 10 dB, a trade-off between the DS and US performances for the CSPR is chosen at about 10 dB from the three crossovers of the curves according to Fig. 5.

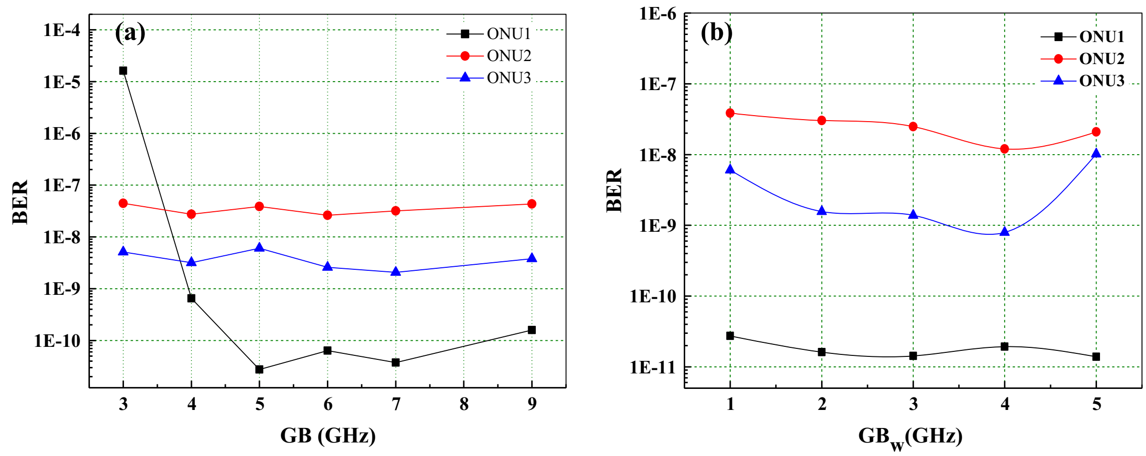

Fig. 4 **a** BERs versus GB; **b** BERs versus GB_w for the US 3-band OFDM with OSNR = 27 dB/0.1 nm

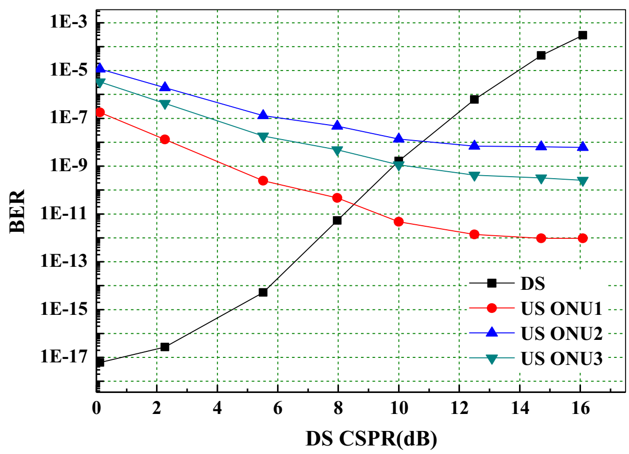

Fig. 5 BERs versus DS CSPR for the 3-band OFDM system with the OSNR = 27 dB/0.1 nm

5 Conclusion

A novel multi-band OFDMA-PON system based on ICRBD with high spectrum effective has been proposed and demonstrated by simulation. The GB and GB_w for US transmission can be reduced to 5 and 1 GHz, respectively, while the CSPR is achieved at the optimal value of about 10 dB in this proposed architecture, in which the dominant SSBI interference can be reduced effectively. A required OSNR for BER = 3.8×10^{-3} of 20, 16 dB has been obtained for both DS and US in the 20 km 3-band OFDM system, respectively. Besides, the ONU is free from the lightwave source since the US optical carrier reuses the DS optical carrier and no amplifiers are used at the ONU side in our proposed scheme. So in our proposed system, the US launch power is relatively low, at about −12 dBm, and the splitter is small. By increasing the launch power of the optical OFDM signal and improving the receiver sensitivity, the system scalability can be enhanced. This needs to be further studied in our future work.

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