

Using adaptive four-band OFDM modulation with 40 Gb/s downstream and 10 Gb/s upstream signals for next generation long-reach PON

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Abstract: In this demonstration, we propose and demonstrate an adaptive long-reach passive optical network (LR-PON) using four-band orthogonal frequency division multiplexed (OFDM) channels. The downstream traffic rates from 6.25 to 40 Gb/s (using fixed quadrature amplitude modulation (QAM) level in the four OFDM bands) and from 9.37 to 40.3 Gb/s (using variable QAM levels in the four OFDM bands) can be achieved adaptively in the optical network units (ONUs) depending on different fiber transmission lengths from 0 to 100 km. For the upstream transmission, a 10 Gb/s 16-QAM OFDM signal with pre-emphasis is experimentally performed by using a 2.5 GHz directly modulated laser (DML). Based on the simulation and experimental results, the proposed adaptive four-band OFDM system could be a promising candidate for the future LR-PON.

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1. Introduction

Due to the increase in popularity of broadband multi-services, such as the data, voice, IPTV, CATV, HD-TV, and 3D-TV etc., the passive optical network (PON) would be the promising solution for next generation broadband system [1–3]. It is believed that the data rates of 10 Gb/s or even up to 40 Gb/s are required in the future [4]. However, because of the fiber chromatic dispersion, the 40 Gb/s data signal can only be transmitted in a few km of fiber using on-off keying (OOK) or differential phase shift keying (DPSK) modulations [5]. And it cannot support the current standard-reach (SR) PON of 20 km fiber transmission. Using dispersion compensation could increase the network complexity and cost. It is also difficult to fully dispersion compensate the PON due to the different fiber lengths between the central office (CO) and optical network units (ONUs). Thus, there is a great challenge to upgrade the present 2.5 or 10 Gb/s/wavelength PON to 40 Gb/s/wavelength [6].

Furthermore, to deliver the broadband services economically, the network operators must reduce the cost to maintain the profit margins. One possible solution is to simplify the optical network architecture. Therefore the number of equipment interfaces and network components can be minimized. Hence the long-reach (LR) PONs have been proposed [7, 8]. The metro and access networks can be integrated into a single system in the LR-PON. The LR-PON also has the benefits of high capacity, high split-ratio (hence can support more users), and long transmission length (> 60 km) [9]. Multiplexing schemes, such as time division multiplexing (TDM), wavelength division multiplexing (WDM) and orthogonal frequency division multiplexing (OFDM) [10, 11], are used in the LR-PON for supporting more optical network units (ONUs). Recently, to enhance the spectral efficiency and reduce the cost of laser transmitter (Tx), optical OFDM modulation has been investigated for the PON access [12, 13]. Therefore, the current SR-PON and future LR-PON can coexist in the last mile access networks for the flexible applications.

Besides, to achieve a higher data rate in the LR-PON, using dynamically OFDM subcarrier allocation to match the effective frequency response of the optical Tx in different fiber transmission lengths has been investigated [14]. However, the fiber lengths between central office (CO) and each ONU were different in the practical LR-PON system. Hence, the ref [14], only can be used in a fixed fiber transmission, but not in point-to-multipoint LR-PON, where the distance between the CO and ONU could vary from 0 to 100 km.

In this work, we propose a 40 Gb/s OFDM LR-PON system. The downstream data rates can be changed adaptively from 6.25 to 40 Gb/s (using fixed quadrature amplitude modulation (QAM) level for the four OFDM bands) and 9.37 to 40.3 Gb/s (using variable QAM levels for the four OFDM bands) respectively, depending on the different fiber transmission lengths from 0 to 100 km between CO and each ONU. The four-band OFDM channels with fixed and various m -QAM modulation formats are applied to a Mach-Zehnder modulator (MZM) of 10 GHz bandwidth to generate the 40 Gb/s optical OFDM signal. And direct detection is used to reduce the cost of the optical receiver (Rx). In the proposed scheme, the downstream data rate can be adaptively changed in the ONU side according to the fiber transmission lengths. Besides, in the proposed network, we also experimentally demonstrate the 10 Gb/s upstream signal using 16-QAM OFDM modulation with pre-emphasis by using a 2.5 GHz direct modulated laser (DML) in the fiber transmission from 20 to 100 km.

2. Simulation and experiment for downstream traffic

Figure 1 shows the proposed LR-PON using four-band OFDM. The downstream data rates can be changed adaptively from 6.25 to 40 Gb/s (using fixed QAM level for the four OFDM bands) and 9.37 to 40.3 Gb/s (using variable QAM levels for the four OFDM bands) respectively. Inset of Fig. 1 is the spectrum of the four-band OFDM channels for downstream transmission. The total required bandwidth is 10 GHz for all cases. First of all, the same modulation of 16-QAM OFDM is used for the four-band OFDM channels with a fast-Fourier transform (FFT) size of 512. The OFDM baseband signal is located at the channel 1 and the 40 OFDM subcarriers in channel 1 occupy 1.526 GHz bandwidth (82 MHz to 1.626 GHz) to produce a total data rate of 6.25 Gb/s. Besides, the OFDM channels 2 to 4 are up-converted to 3.164, 6.055 and 8.945 GHz by using I-Q modulation, respectively. And each up-converted channel has 72 OFDM subcarriers occupying a bandwidth of 2.813 GHz, producing the data rate of 11.25 Gb/s, as shown in inset of Fig. 1. Therefore, the proposed four-band OFDM channels have a total bandwidth of 10.35 GHz; resulting a 40 Gb/s downstream data rate if all the four-band OFDM channels are used in the proposed LR-PON. According to the proposed four-band OFDM channels, each channel only needs 5 GHz sampling rate and 5-bit effective resolution DA/AD converter on Tx/Rx respectively. This can be used to implement 40 Gb/s signal traffic in a real LR-PON. Moreover, to achieve power-saving in the proposed network, the related AD converter, which is based on 4 channel time-interleaved configuration using the adaptive digital equalization technique, has been previously proposed by ITRI research group [15]. According to the proposed topology, the energy-efficient 5 GS/s sampling rate and 5-bit AD converter can be practically implemented.

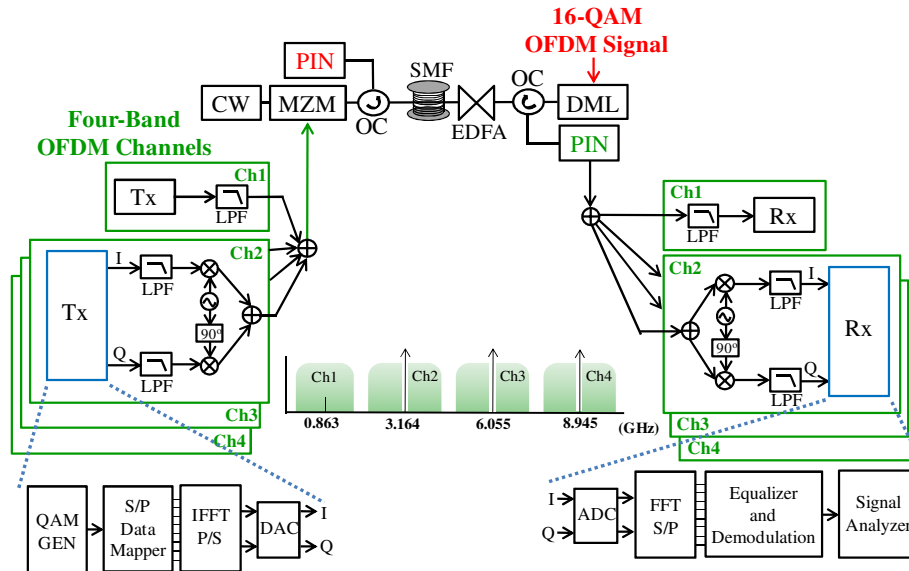


Fig. 1. Proposed LR-PON using four-band OFDM with 10 GHz bandwidth for adaptive downstream traffic rate.

Originally, each OFDM channel is designed to have 2.5 GHz bandwidth and 16-QAM OFDM modulation to achieve 40 Gb/s transmission rate. However, some higher frequency OFDM subcarriers of baseband (Ch1) would be filtered by a 2.5 GHz low-pass filter (LPF) while the 5 GS/s DAC is used. To overcome this issue, we can scale down the bandwidth of Ch1 to 1.526 GHz and increase the bandwidth of Ch2 to Ch4 to 2.813 GHz. Hence half the bandwidth for I-channel and the other half for Q-channel can fit the 5 GS/s DA/AD converter requirements for the practical 40 Gb/s LR-PON.

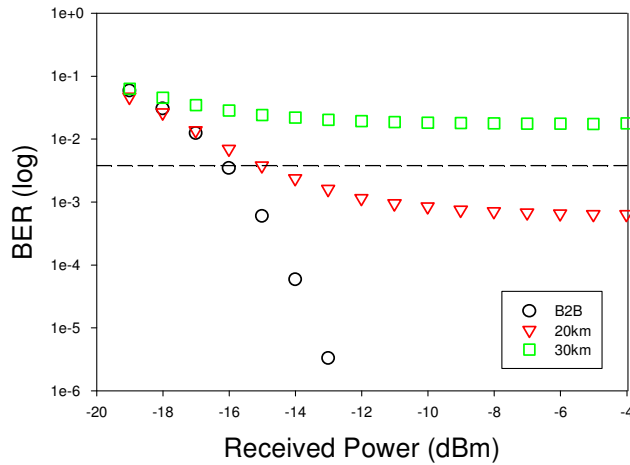


Fig. 2. Simulated BER performances of 40 Gb/s OFDM downstream using proposed 16-QAM OFDM four-band channels at the B2B, 20 and 30 km SMF transmissions, respectively.

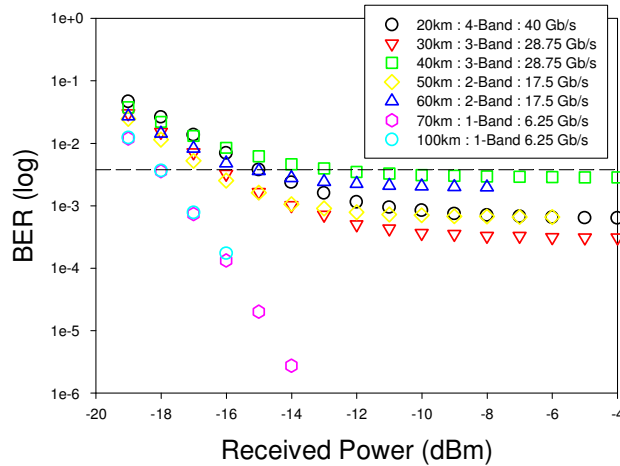


Fig. 3. Simulated BER measurements of adaptive downstream rate of 6.25 to 40 Gb/s by dynamically receiving different multi-band OFDM channels under the different SMF lengths of 20 to 100 km.

For the downstream transmission, we analyze the transmission performance using the commercial software (VPI Transmission Maker V7.5). Here, the baseband electrical OFDM signal is generated by using Matlab[®] programs. And the signal processing of the OFDM Tx is constructed by serial-to-parallel conversion, QAM symbol encoding, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). The proposed modulation of four-band 16-QAM OFDM channels is applied to a MZM with a chirp parameter of 0.2. A continuous-wave (CW) optical signal at wavelength of 1540.0 nm is launched into the MZM to produce the optical OFDM signal, as illustrated in Fig. 1. The OFDM downstream signal passes through 20 to 100 km single-mode fiber (SMF) without dispersion compensation. They are directly detected by a 10 GHz PIN Rx at the ONU side. The received downstream OFDM signal is captured by using Matlab[®] programs for signal demodulation. To demodulate the vector signal, the off-line DSP program is employed. And the demodulation process includes the synchronization, FFT, one-tap equalization, and QAM

symbol decoding. The erbium-doped fiber amplifier (EDFA) with 27 dB gain and 5 dB noise figure is used to compensate the losses of passive components. The bit error rate (BER) would be calculated according to the observed signal-to-noise ratio (SNR) of each OFDM subcarrier.

Figure 2 presents the simulated BER performances of 40 Gb/s OFDM downstream using the proposed four-band 16-QAM OFDM channels at the back-to-back (B2B), 20 and 30 km SMF transmissions, respectively. The Rx sensitivity is -16.0 dBm at the forward error correction (FEC) threshold (BER of 3.8×10^{-3}) at back-to-back (B2B). After 20 km SMF transmission, the power penalty of 1.0 dB is measured at the BER of 3.8×10^{-3} . This shows a better BER performance than that of 40 Gb/s/wavelength OOK or DPSK modulations in our previous studies [1, 2] after 20 km fiber link. When the SMF length is increased to 30 km, the measured BER cannot achieve the FEC threshold (3.8×10^{-3}) due to the power fading and fiber chromatic dispersion. It is worth to mention that the issue of chromatic dispersion is severe for the higher frequency OFDM bands.

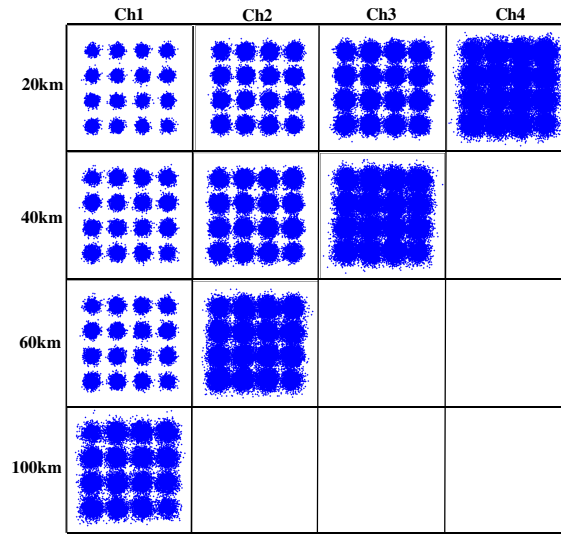


Fig. 4. Corresponding constellation diagrams of four-, three-, two- and one-band OFDM channels used, respectively, under the SMF length of 20, 40, 60 and 100 km long.

Therefore in this work, we propose the multi-band OFDM channels for the adaptive downstream data rate adjustment from 6.25 to 40 Gb/s according to the different fiber lengths. Figure 3 shows the simulated BER measurements of the adaptive downstream rate from 6.25 to 40 Gb/s by dynamically receiving different multi-band OFDM channels under different SMF lengths of 20 to 100 km. As seen in Fig. 3, the Rx sensitivities are -15.0 , -13.1 , -15.2 and -18.0 dBm with the total downstream bit rates of 40 (four bands), 28.75 (three bands), 17.5 (two bands) and 6.25 Gb/s (one band), respectively, at the 20, 40, 60 and 100 km SMF transmissions. In practical implementation, during the initial process, each ONU will receive and demodulate all the four-band OFDM channels. By analyzing the performance of different bands, the number of required OFDM band can be determined. Once the number of required OFDM band is fixed, this ONU only need to demodulate the required OFDM band. This can be done via the optimal protocol adjustment in medium access control (MAC) layer [16].

Figure 4 shows the corresponding constellation diagrams of four-, three-, two- and one-band OFDM channels used, respectively, under the SMF lengths of 20, 40, 60 and 100 km. When the fiber length is increased, the OFDM band at higher frequency will be severely affected due to the power fading and fiber chromatic dispersion. As a result, 6.25 to 40 Gb/s downstream traffic can be adaptively and effectively allocated for each ONU depending on the fiber transmission lengths in our proposed multi-band OFDM PON.

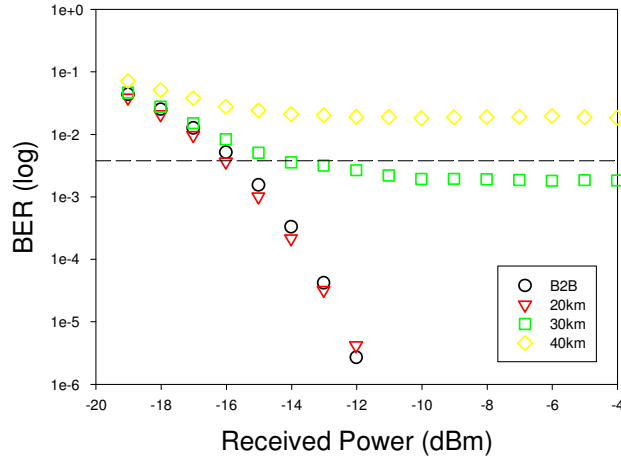


Fig. 5. Simulated BER performances of 40.3 Gb/s OFDM downstream using proposed 64-QAM, 32-QAM, 16-QAM and 4-QAM OFDM four-band channels at the B2B, 20, 30 and 40 km SMF transmissions, respectively.

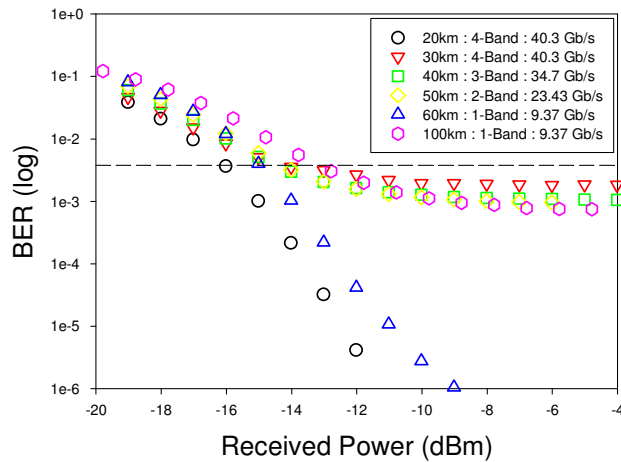


Fig. 6. Simulated BER measurements of adaptive downstream rate of 6.25 to 40 Gb/s by dynamically receiving different multi-band OFDM channels under the different SMF lengths of 20 to 100 km.

As we know, the SNR of the OFDM subcarrier at higher frequency would be dropped gradually due to the power fading and fiber dispersion when the fiber transmission length increases. Thus, different level of OFDM-QAM modulations can be used in the multi-band OFDM channels. Here, we also demonstrate using 64-QAM, 32-QAM, 16-QAM and 4-QAM OFDM modulations in Ch1 to Ch4, respectively, for the adaptive four-band OFDM channels. Hence, the Ch1 to Ch4 can achieve the data rates of 9.37, 14.07, 11.25 and 5.62 Gb/s, respectively. A total downstream data rate of 40.3 Gb/s can be achieved if all the four-band OFDM channels are used. To achieve 64-QAM OFDM modulation, we need the 5 GS/s sampling rate and 7 bits resolution DAC to implement the 40.3 Gb/s OFDM traffic in a practical LR-PON.

Figure 5 shows the simulated BER performances of 40.3 Gb/s OFDM downstream signal at B2B, 20, 30 and 40 km SMF transmissions. Here, the Rx sensitivities are -16.0 , -16.1 and -14.1 dBm at the BER of 3.8×10^{-3} at B2B, 20 and 30 km fiber transmissions, respectively.

After 20 and 30 km SMF transmissions, the power penalties of 0.1 and 1.9 dB are measured at the BER of 3.8×10^{-3} . When the SMF length increases to 40 km, the measured BER cannot achieve the FEC threshold. Compared with the four-band channels having same 16-QAM OFDM modulations, the adaptive four-band OFDM channels can extend the SMF length to 30 km.

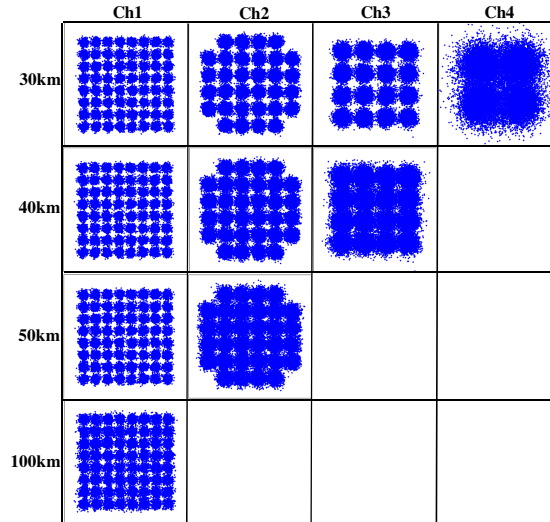


Fig. 7. Corresponding constellation diagrams of four-, three-, two- and one-band OFDM channels used, respectively, under the SMF length of 30, 40, 50 and 100 km long.

Figure 6 shows the simulated BER measurements of the adaptive downstream data rate from 9.37 to 40.3 Gb/s by receiving different four-band OFDM channels, under different fiber lengths of 20 to 100 km. As illustrated in Fig. 6, the Rx sensitivities are -14.1 , -14.4 , -14.5 and -13.2 dBm with the total downstream bit rates of 40.3, 34.7 and 23.43 and 9.37 Gb/s, respectively, at the 30, 40, 50 and 100 km fiber transmissions.

Figure 7 shows the corresponding constellation diagrams of four-, three-, two- and one-band OFDM channels used, respectively, under the fiber length of 30, 40, 50 and 100 km. When the fiber length is increased, the OFDM band at higher frequency will be severely affected due to the power fading and fiber chromatic dispersion. Therefore, 9.37 to 40.3 Gb/s downstream traffic can be adaptively and effectively allocated for each ONU depending on the fiber transmission lengths in our proposed multi-band OFDM PON with the QAM level adjustment.

To evaluate the proposed four-band OFDM network, an experiment is performed. Due to unavailable of three different electrical clock sources in our lab for the OFDM up-conversion and down-conversion, each OFDM band can only be measured individually in the proposed architecture. Here, we use a 10 GHz bandwidth MZM. The operation conditions are the same as mentioned above. And each OFDM band is modulated at 16-QAM OFDM format. Figure 8 shows the BER measurements of the four-band OFDM channels at B2B and 20 km SMF transmission. The Rx sensitivities are -21.78 , -19.25 , -16.65 and -16.48 dBm at B2B at the BER of 3.8×10^{-3} . And the measured power penalties are 0, 0.47, 1.44 and 6.28 dB after 20 km fiber transmission. We can also observe the higher frequency OFDM band has higher measured power penalty. This agrees with the simulation results. In the experiment, a single band OFDM (Ch1) can successfully transmit 100 km SMF, as also shown in Fig. 8. As a result, according to the simulation and experimental results, the proposed adaptive four-band OFDM system can be a promising candidate for the future LR-PON.

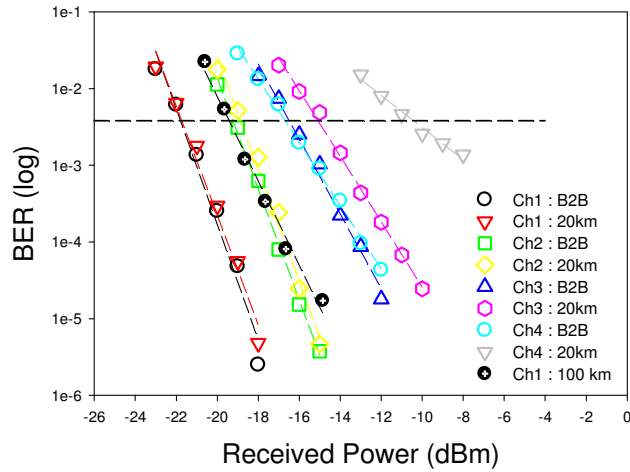


Fig. 8. BER measurements of each OFDM channel at the B2B and 20 km fiber transmission, when each channel is modulated at 16-QAM format.

3. Experiment for upstream traffic

For the upstream transmission, we employ a 1550 nm DML with 2.5 GHz bandwidth. The baseband electrical 16-QAM OFDM signal is produced by an arbitrary waveform generator (AWG) using Matlab® program. The sampling rate and DAC resolution are 5 Gb/s and 5-bit respectively, and the CP of 1/64 is used in the measurement. Here, 128 subcarriers of 16-QAM OFDM formats occupy near 2.5 GHz bandwidth from 1.95 MHz to 2.50 GHz, with a FFT size of 512. Hence, this produces an upstream data rate of 10 Gb/s. The upstream signal is directly detected by 2.5 GHz PIN Rx at the CO. The received upstream OFDM signal is captured by a real-time sampling oscilloscope for signal demodulation.

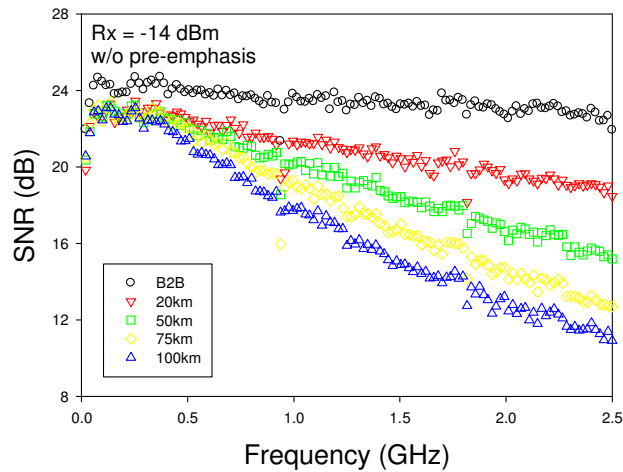


Fig. 9. The upstream SNR of each OFDM subcarrier within 2.5 GHz bandwidth at the B2B, 20, 50, 75 and 100 km fiber transmissions, respectively, at optical received power of -14 dBm without pre-emphasis.

First, we investigate experimentally the SNR performance under different fiber transmissions. Figure 9 shows the measured upstream SNR of each OFDM subcarrier in the frequency bandwidth from 0.0195 to 2.5 GHz at the B2B, 20, 50, 75 and 100 km fiber

transmissions, respectively, without pre-emphasis at the received power of -14 dBm. When the fiber transmission length increases, the subcarriers at high frequency will also experience SNR penalty and cannot achieve FEC threshold due to the fiber chromatic dispersion. In this measurement, the measured SNR of all the OFDM subcarriers are > 16.5 dB (BER = 3.8×10^{-3}) within 2.5 GHz bandwidth at B2B and 20 km fiber transmission, as also seen in Fig. 9. This means that the 10 Gb/s OFDM upstream signal can be successfully transmitted over 20 km SMF using a DML.

Figure 10 shows the experimental BER measurements of 10 Gb/s upstream traffic using 16-QAM OFDM modulation without pre-emphasis at the B2B, 20, 50, 75, and 100 km SMF transmissions, respectively. The received sensitivities are -19.1 , -18.1 , -16.8 , -12.8 and -8.2 dBm at B2B, 20, 50, 75 and 100 km fiber transmissions, respectively, at the FEC threshold. As shown in Fig. 10, the power penalties of 1.0, 2.3, 6.3 and 10.9 dB are measured after 20, 50, 75 and 100 km SMF transmissions, respectively, at the BER of 3.8×10^{-3} . As shown in Fig. 10, the upstream signal can achieve the BER of 3.8×10^{-3} reluctantly after 100 km fiber transmission.

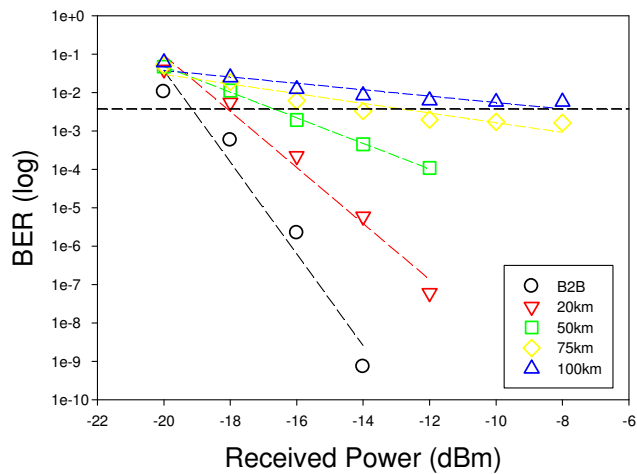


Fig. 10. Experimental BER measurements of 10 Gb/s upstream traffic using 16-QAM OFDM modulation without pre-emphasis at the B2B, 20, 50, 75, and 100 km SMF transmissions, respectively.

To obtain the better SNR of each OFDM subcarrier after different SMF transmission lengths, we can use pre-emphasis design for each OFDM subcarrier before transmitting. Thus, Fig. 11 shows the measured upstream SNR of each OFDM subcarrier in the frequency bandwidth from 0.0195 to 2.5 GHz at the B2B, 20, 50, 75 and 100 km fiber transmissions respectively, with pre-emphasis at the received power of -14 dBm. The pre-emphasis can properly arrange the electrical power of each subcarrier to obtain the better SNR. Figure 11 presents that the SNRs are larger than 16.5 dB (BER = 3.8×10^{-3}) within the bandwidth of 2.5 GHz at the B2B, 20, 50, 75 and 100 km fiber transmissions respectively.

Figure 12 shows the experimental BER measurements of 10 Gb/s upstream traffic using 16-QAM OFDM modulation with pre-emphasis at the B2B, 20, 50, 75, and 100 km SMF transmissions, respectively. In Fig. 12, we observe the received sensitivities are -19.1 , -18.3 , -17.7 , -17.2 and -16.1 dBm at B2B, 20, 50, 75 and 100 km fiber transmissions, respectively, at the FEC threshold level. And the measured power penalties are 0.8, 1.4, 1.9 and 3.0 dB after 20, 50, 75 and 100 km SMF transmissions, respectively, at the BER of 3.8×10^{-3} . The inserts are the corresponding constellation diagrams measuring at the FEC threshold. As a result, the power penalty can be reduced by about 3 dB after 100 km fiber transmission using

the pre-emphasis. And the 10 Gb/s upstream traffic for 100 km fiber link can be accomplished by using 16-QAM OFDM modulation generated by a DML.

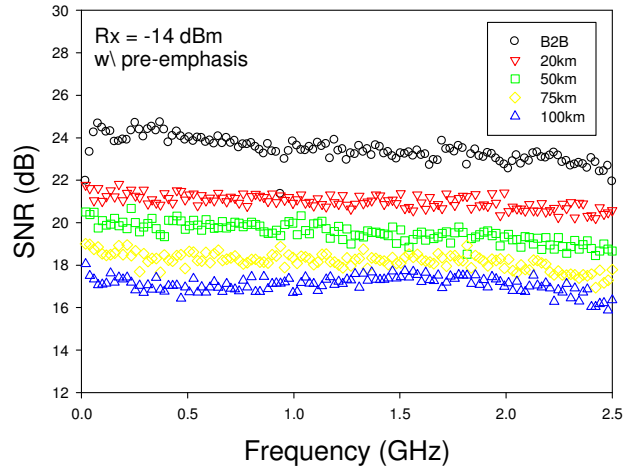


Fig. 11. The upstream SNR of each OFDM subcarrier within 2.5 GHz bandwidth at the B2B, 20, 50, 75 and 100 km fiber transmissions, respectively, at optical received power of -14 dBm with pre-emphasis.

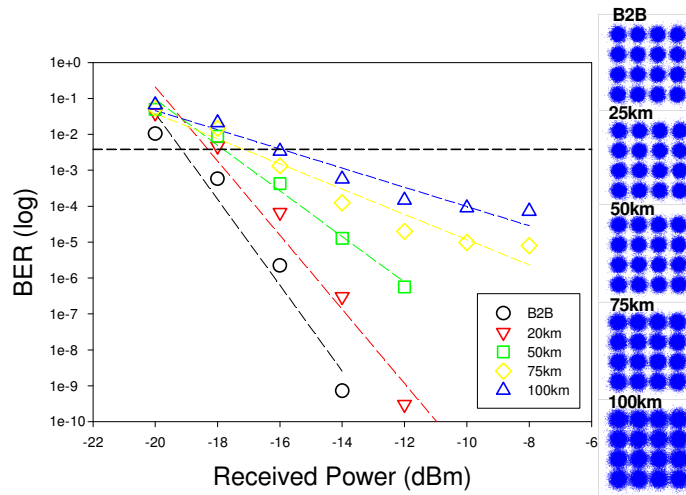


Fig. 12. Experimental BER measurements of 10 Gb/s upstream traffic using 16-QAM OFDM modulation with pre-emphasis at the B2B, 20, 50, 75, and 100 km SMF transmissions, respectively. Inserts are the corresponding constellation diagrams.

5. Conclusion

We proposed and demonstrated an adaptive LR-PON using four-band OFDM channels. The downstream traffic rates from 6.25 to 40 Gb/s (using fixed QAM level in the four OFDM bands) and from 9.37 to 40.3 Gb/s (using variable QAM levels in the four OFDM bands) can be achieved adaptively in the ONUs depending on different fiber transmission lengths from 0 to 100 km. between the CO and the ONUs. Only 10 GHz Tx bandwidth is required in all cases. In the fixed QAM-level case, when the fiber length is between 0 and 20 km, 20 and 40 km, 40 and 60 km, and 60 and 100 km, respectively, the corresponding ONUs among these fiber length ranges only require to demodulate the four-, three-, two- and one-band fixed

OFDM signals for the adaptive downstream traffic of 40, 27.85 and 17.5 and 6.25 Gb/s. In the variable QAM-level case, when the fiber length is between 0 and 30 km, 30 and 40 km, 40 and 50 km, and 50 and 100 km, respectively, the corresponding ONUs among these fiber length ranges only require to demodulate the four-, three-, two- and one-band adaptively OFDM signals for the adaptive downstream traffic of 40.3, 34.7 and 23.43 and 9.37 Gb/s. For the upstream transmission, a 10 Gb/s 16-QAM OFDM signal with pre-emphasis is experimentally performed by using a 2.5 GHz directly modulated laser (DML). And, after 100 km transmission, about 3.0 dB power penalty is observed at the BER of 3.8×10^{-3} .