Power margin improvement for OFDMA-PON using hierarchical modulation

Pan Cao,[1] Xiaofeng Hu,[1] Zhiming Zhuang,[1] Liang Zhang,[1] Qingjiang Chang,[2] Qi Yang,[3] Rong Hu,[3] and Yikai Su[1,*]

[1]*State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China*
[2]*Research & Innovation Center, Alcatel-Lucent Shanghai Bell Co., Ltd, Shanghai, 201206, China*
[3]*State Key Laboratory of Optical Communication Technologies and Networks, Wuhan Research Institute of Posts & Telecommunications, Wuhan, 430074, China*
[*]*yikaisu@sjtu.edu.cn*

Abstract: We propose and experimentally demonstrate a hierarchical modulation scheme to improve power margin for orthogonal frequency division multiple access-passive optical networks (OFDMA-PONs). In a PON system, under the same launched optical power, optical network units (ONUs) have different power margins due to unequal distribution fiber lengths. The power margin of the PON system is determined by the ONU with the lowest power margin. In our proposed scheme, ONUs with long and short distribution fibers are grouped together, and downstream signals for the paired ONUs are mapped onto the same OFDM subcarriers using hierarchical modulation. In a pair of ONUs, part of the power margin of the ONU with short distribution fiber is re-allocated to the ONU with long distribution fiber. Therefore, the power margin of the ONU with the longest distribution fiber can be increased, leading to the power margin improvement of the PON system. Experimental results show that the hierarchical modulation scheme improves the power margin by 2.7 dB for an OFDMA-PON system, which can be used to support more users or extend transmission distance.

OCIS codes: (060.2330) Fiber optics communications; (060.4250) Networks.

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1. Introduction

Passive optical network (PON) is a promising solution to satisfy the exponentially growing demand of emerging high-bandwidth services [1–3]. Orthogonal frequency division multiple access-PON (OFDMA-PON) has been proposed as an attractive candidate for next-generation PON due to its high spectral efficiency, dynamic bandwidth allocation, and robust dispersion tolerance [4–6]. In the OFDMA-PON system, bandwidth allocation is controlled by optical line terminal (OLT) to meet the requirements of optical network units (ONUs). The OLT pre-assigns time/frequency slots to each ONU, and then at the ONU side, each ONU selects its own data from the pre-assigned slots.

In next-generation PON systems, distribution fiber lengths from remote node (RN) to ONUs are between 0 and 40 km [7], which lead to different transmission losses of ONUs. Thus, under the same launched optical power, ONUs have different power margins. Here, the power margin is defined as the difference between the received optical power and the required optical power to obtain the requested bit error ratio (BER) performance. The ONU with the longest distribution fiber length has the lowest power margin, which is consider as the power margin of the PON system [8].

In this paper, we propose a hierarchical modulation scheme to improve the power margin for OFDMA-PON systems. Using hierarchical modulation, signals for ONUs with long and short distribution fibers are mapped onto the first and second layers of the OFDM subcarriers, respectively. By using this method, in a pair of ONUs, the power margins of the ONUs with long and short distribution fibers are improved and degraded, respectively. As a result, the power margin of the PON system is improved since the system performance is determined by the ONU with the lowest power margin. The uplink transmission usually operates at lower bit rate that leads to better receiver sensitivity [9], and therefore a higher power margin. Thus, we mainly focus on the downlink transmission. A proof-of-concept experiment is performed to verify the feasibility of our proposal. The experimental results show that the proposed scheme improves the power margin by 2.7 dB for downlink transmission of the OFDMA-PON system, which can support more users or extend the transmission distance.

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2. Operation principle

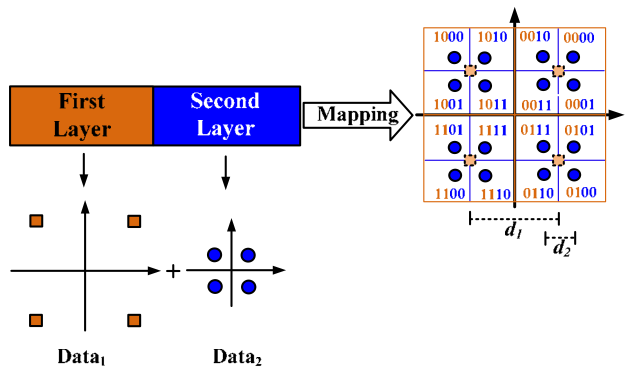

Fig. 1. Principle of hierarchical QPSK / 16-QAM mapping.

Hierarchical modulation, also termed as layered modulation, was proposed to provide unequal error protections for different signals in broadcast systems [10,11]. In the hierarchical modulation, several data sources are multiplexed into a symbol stream. Figure 1 shows the principle of a 16 quadrature amplitude modulation (16-QAM) hierarchical modulation with two layers. The hierarchical 16-QAM signal can be viewed as a combination of two quadrature phase shift keying (QPSK) signals. $Data_1$ and $Data_2$ denoted by solid squares and solid circles are defined as the first and second layers, respectively. d_1 and d_2 are the distances between adjacent points in the constellations of $Data_1$ and $Data_2$, respectively. Since the minimum distance between adjacent points in the constellation of $Data_1$ is larger than that of $Data_2$, $Data_1$ can achieve better BER performance than that of $Data_2$ in the same system [12,13]. Here, we define a hierarchical parameter α ($\alpha = d_1 / d_2$), which can be used to adjust the performance difference between the two layers. With the increase of α, the performance difference between the two layers becomes large.

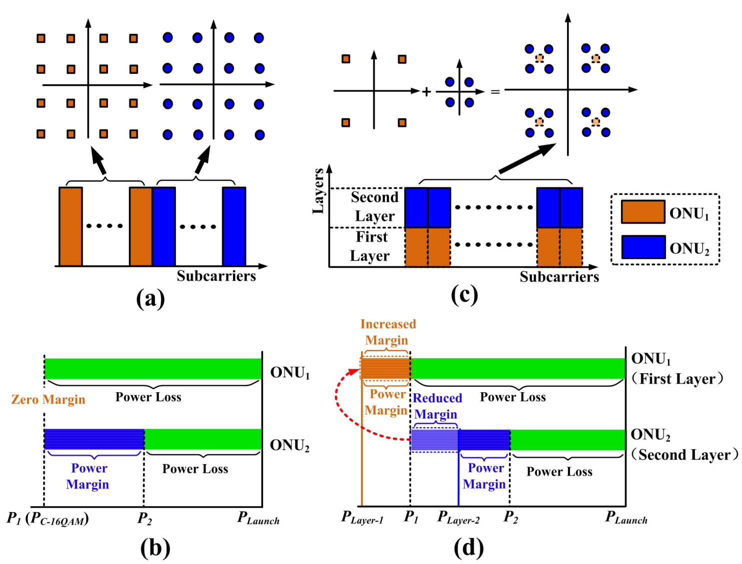

Fig. 2. Schematic diagrams of resource allocations and power margins of the OFDMA-PON system using conventional 16-QAM mapping (a, b) and proposed hierarchical 16-QAM mapping (c, d).

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Figure 2 illustrates the principle of the power margin improvement based on the hierarchical modulation, where ONU_1 and ONU_2 have long and short distribution fibers, respectively. To simplify the analysis, we assume that the two ONUs require the same number of subcarriers and all the subcarriers use 16-QAM format. In Fig. 2(a), signals for the two ONUs are mapped onto OFDM subcarriers with conventional 16-QAM mapping. If the received optical power of ONU_1 (P_1) is the same as the receiver sensitivity of the conventional 16-QAM mapping ($P_{C\text{-}16QAM}$), ONU_1 has zero power margin. Due to different link losses, the received optical power of ONU_2 is P_2, and ONU_2 has a power margin of $P_2 - P_{C\text{-}16QAM}$, as illustrated in Fig. 2(b).

In the proposed scheme, by using hierarchical modulation, data for ONU_1 and ONU_2 are mapped onto the first and second layers, respectively, as shown in Fig. 2(c). The two ONUs have the same bit rate as ONUs with the conventional 16-QAM mapping in Fig. 2(a), since the numbers of subcarriers and spectral efficiencies of the two ONUs are doubled and halved, respectively. The signal on the first layer has better transmission performance than that of the signal on the second layer [12,13]. As illustrated in Fig. 2(d), the receiver sensitivities of signals on the first layer ($P_{Layer\text{-}1}$) and the second layer ($P_{Layer\text{-}2}$) are improved and degraded, respectively. Thus, an inequality $P_{Layer\text{-}1} < P_1$ ($P_{C\text{-}16QAM}$) $< P_{Layer\text{-}2}$ can be obtained. If the received optical powers of the ONUs satisfy the inequalities $P_{Layer\text{-}1} \le P_1$ and $P_{Layer\text{-}2} \le P_2$, the hierarchical modulation can be utilized to balance the transmission performances between the two ONUs, which means that part of the power margin of ONU_2 can be re-allocated to ONU_1. Then the power margins of ONU_1 and ONU_2 become $P_1 - P_{Layer\text{-}1}$ and $P_2 - P_{Layer\text{-}2}$, respectively. Therefore, the power margin of the PON system is improved by $P_M = min\ (P_1 - P_{Layer\text{-}1},\ P_2 - P_{Layer\text{-}2})$. In order to achieve high power margin for the PON system, the two ONUs should have nearly the same power margin ($P_1 - P_{Layer\text{-}1} \approx P_2 - P_{Layer\text{-}2}$), which can be obtained by choosing a proper hierarchical parameter α.

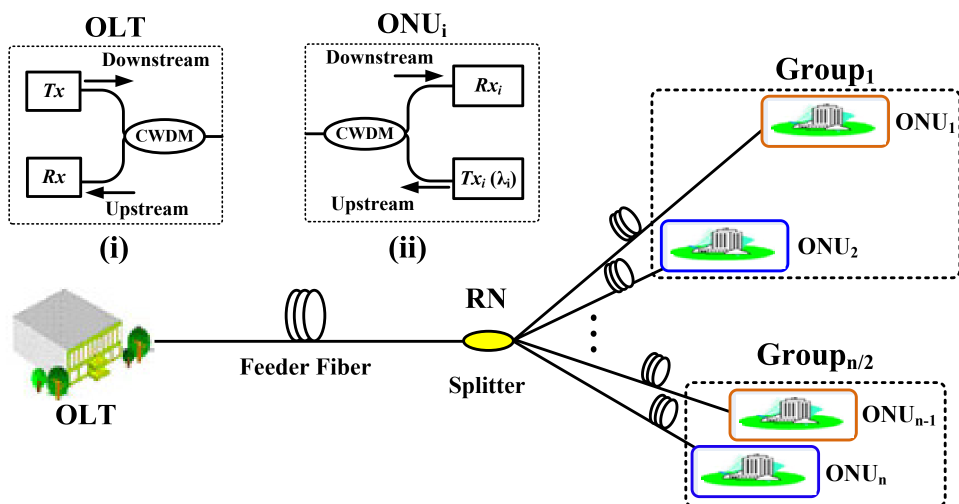

Fig. 3. Schematic diagram of the proposed OFDMA-PON using hierarchical modulation.

Figure 3 shows the schematic diagram of the proposed OFDMA-PON architecture using hierarchical modulation, where the distribution fibers have different transmission lengths. The ONUs are divided into several groups according to their distribution fiber lengths: two ONUs with the longest and the shortest distribution fiber lengths are paired together as $Group_1$, two ONUs with the second longest and the second shortest distribution fiber lengths are grouped as $Group_2$, and the rest ONUs are paired by the same method. At the ONU sides, the uplink signals are carried by different wavelengths from the downlink transmission [14], where the Rayleigh noise is effectively mitigated [15], as shown in the insets of Fig. 3.

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3. Experimental setup and results

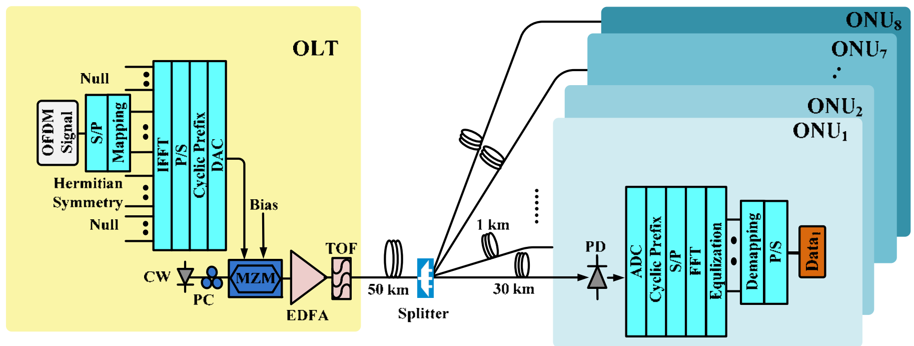

Fig. 4. Experimental setup of the proposed OFDMA-PON system based on hierarchical modulation.

Figure 4 shows the experimental setup of the proposed scheme, where intensity modulation/direct detection (IM/DD) is employed to realize a simple and low-cost configuration [16–18]. In the experiment, the OFDM signal is generated offline by MATLAB. A frequency guard band equal to the data bandwidth is employed to separate the OFDM signal from the optical carries [19]. In order to obtain IM/DD OFDM signal, Hermitian symmetry is applied before the IFFT. Then the OFDM signal is output by an arbitrary waveform generator (Tektronix 7122C) with 5-GSample/s sampling rate and 10-bit resolution of digital-to-analog conversion (DAC). Therefore, the raw bit rate of the OFDM signal is 5 Gb/s.

We experimentally demonstrate two ONUs: ONU_1 with 30-km distribution fiber and ONU_2 with 1-km distribution fiber. Using hierarchical modulation, the signals for ONU_1 and ONU_2 are paired together and mapped onto the first and second layers of the OFDM subcarriers, respectively. Based on the analysis in section 2, the power margin of the system can be improved with a proper choice of α, since part of the power margin of ONU_2 is re-allocated to ONU_1.

A continuous-wave light from a tunable distributed feedback (DFB) laser at 1550 nm is fed into a single-drive Mach-Zehnder modulator (MZM), which is biased at the quadrature point and modulated by the OFDM signal. The output signal of the MZM is amplified by an erbium doped fiber amplifier (EDFA). A following tunable optical filter (TOF) is used to suppress the amplified spontaneous emission (ASE) noise. The launched optical power of the downstream signal is set to 8 dBm to meet the sensitivity requirements of the used photo-detectors (PDs).

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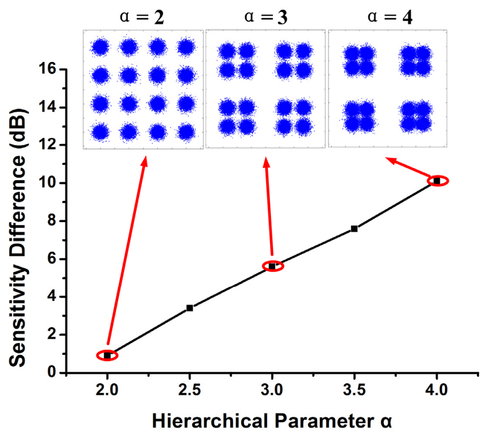

Fig. 5. Recovered constellations and sensitivity differences between the two layers with different hierarchical parameter α.

After transmission over 50-km standard single mode fiber (SSMF) [20], at the RN, a 9-dB attenuator is used to emulate a 1:8 optical splitter. It is noted that higher splitting ratio can be obtained if high-sensitivity receivers are employed at the ONU sides [21]. The downstream data is then routed to each ONU, where the OFDM signal is directly detected by a PD. The output signal of the PD is sampled by a real-time oscilloscope (Tektronix DSA70804) with 25-GS/s sampling rate. The sampled data are processed offline using MATLAB, and the recovered constellations are shown in the insets of Fig. 5. The information bits on the first and second layers are determined by the quadrants and the sub-quadrants where the symbol vectors are located, as depicted in Fig. 1. By using hierarchical modulation, the two layers require different received optical powers to achieve a BER of 10^{-3} [22]. As shown in Fig. 5, the sensitivity differences between the two layers are 0.9 dB, 5.6 dB, and 10.1 dB when α is 2, 3, and 4, respectively. In the experiment, the distribution fiber lengths are 1 km and 30 km, resulting in 5.8-dB received optical power difference between the two ONUs. In order to effectively balance the power margins for the paired ONUs, we chose the hierarchical parameter α = 3 to improve and degrade the signal performances on the first and second layers, respectively. It should be noted that the hierarchical parameter α can maintain the same if the power difference keeps the same in different scenarios.

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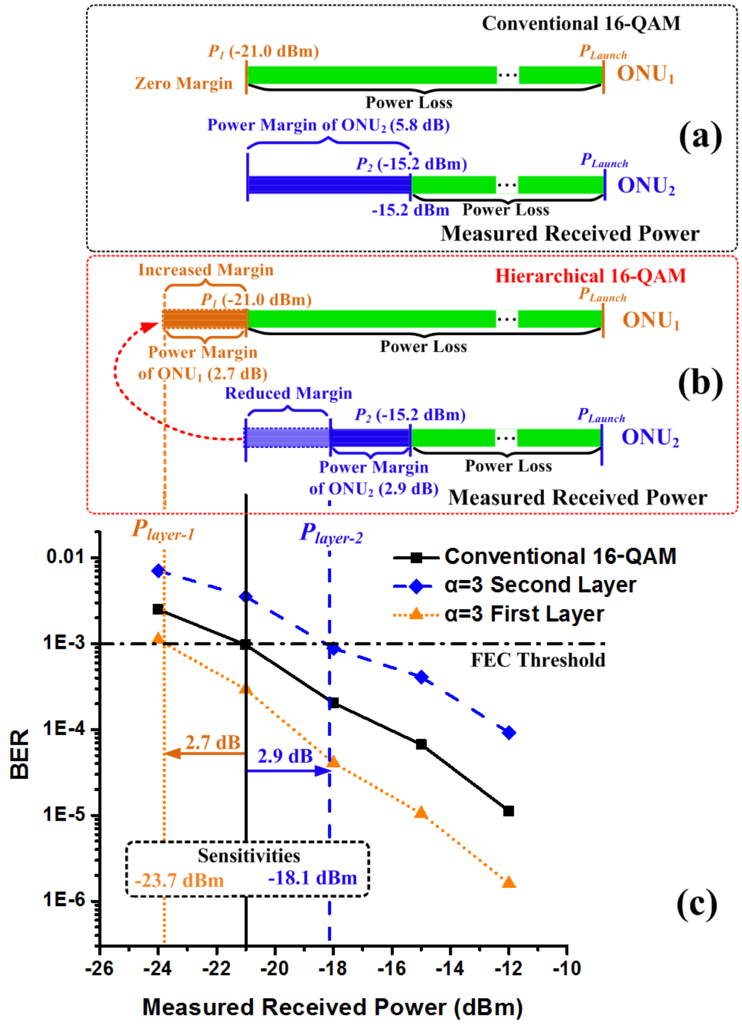

Fig. 6. Power margins and BER performances of conventional 16-QAM mapping and hierarchical 16-QAM mapping with α = 3.

After fiber transmission, the requested optical power to obtain a BER of 10^{-3} is −21.0 dBm using conventional 16-QAM mapping, as shown in Fig. 6(a). The received optical powers of ONU_1 and ONU_2 are −21.0 dBm and −15.2 dBm, respectively, leading to 0-dB and 5.8-dB power margins for the two ONUs. Thus the PON system has zero power margin determined by ONU_1. As illustrated in Figs. 6(b) and 6(c), when the hierarchical parameter α is 3, the receiver sensitivity of ONU_1 is improved to −23.7 dBm ($P_{Layer-1}$), while that of ONU_2 is degraded to −18.1 dBm ($P_{Layer-2}$). Since the received optical powers are −21.0 dBm for ONU_1 and −15.2 dBm for ONU_2, the power margins of ONU_1 and ONU_2 are 2.7 dB and 2.9 dB, respectively. Therefore, the power margin for the PON system is improved by 2.7 dB. Figure 6(c) shows the BER performances of the signals with the conventional 16-QAM mapping and the two layers of the hierarchical 16-QAM mapping in the case of α = 3. In addition, if the difference of the distribution fiber lengths increases, a larger hierarchical parameter α should be chosen to balance the power margins between the paired ONUs and further improve the power margin for the OFDMA-PON system.

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4. Conclusion

We have proposed and experimentally demonstrated a new method to improve power margin for OFDMA-PON system using hierarchical modulation. In the experiment, signals for ONUs with 1-km and 30-km distribution fiber lengths are paired together and mapped onto the two layers of the OFDM subcarriers. Part of the power margin of the ONU with 1-km distribution fiber length is transferred to the ONU with 30-km distribution fiber length. Thus the power margin of the ONU with 30-km distribution fiber is improved, leading to the power margin improvement for the OFDMA-PON system. Compared with the conventional 16-QAM modulation, the proposed hierarchical modulation improves the power margin of the system by 2.7 dB, which can be used to support more subscribers or extend transmission distance.

Acknowledgments

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