Increasing Transmission Capacity of Long-reach OFDM-PON by Using Hierarchical Modulation

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Paper Summary
We introduce a novel modulation scheme termed hierarchical modulation to increase the transmission capacity of OFDM transmitter with limited bandwidth in a long-reach OFDM-PON. A proof-of-concept experiment is performed to verify the feasibility of our proposal.

Introduction

By integrating metro and access networks, long-reach passive optical network (PON) is considered as one of the future PON architectures to reduce the capital and operational expenditures for network operators. Diverse multiplexing schemes, such as the time division multiplexing (TDM), wavelength division multiplexing (WDM), and orthogonal frequency division multiplexing (OFDM), are used in long-reach PONs to support optical network units (ONUs) within a broad coverage. Due to high spectral efficiency and robust dispersion tolerance, long-reach OFDM-PON has attracted much attention in the past few years [1-2].

In order to provide bandwidth-intensive application services such as Internet protocol television and ultra-high definition television for customers, the transmission capacity of OFDM transmitter (Tx) in the optical line terminal (OLT) of long-reach OFDM-PON shall be increased to 10 Gb/s or even 40 Gb/s in the near future. Using high-bandwidth electrical and optical components to generate such high-data-rate OFDM signals could be cost-prohibitive for a PON system. Therefore, it is desired to increase the transmission capacity of OFDM Tx with a limited bandwidth. A technique, often referred to bit loading [3-4], was proposed to maximize the throughput of OFDM Tx by performing adaptive bit allocation in the subcarriers with different signal-to-noise ratios (SNRs). Nonetheless, this approach does not fully utilize the limited bandwidth offered by OFDM Tx when some subcarriers still have SNR margins which are however not enough to upgrade the modulation formats to higher order constellations, e.g. from quadrature phase shift keying (QPSK) to 16 quadrature amplitude modulation (16QAM). In this paper, we introduce a novel modulation scheme from wireless communications, termed hierarchical modulation [5-7], to further increase the capacity of OFDM Tx in the OLT of long-reach OFDM-PON by multiplexing data of multiple subcarriers with SNR margins onto one subcarrier.

Operation Principle

Hierarchical modulation is a technology for multiplexing and modulating multiple data streams into one single symbol stream, which can be implemented in many high order modulation formats, such as 16QAM and 64QAM. For simplicity, we limit our discussions to hierarchical 16QAM format in this paper. Fig. 1(a) describes the principle of 16QAM hierarchical modulation. Two independent and separate data streams, $data_1$ and $data_2$, are mapped onto $layer_1$ and $layer_2$ with QPSK format,

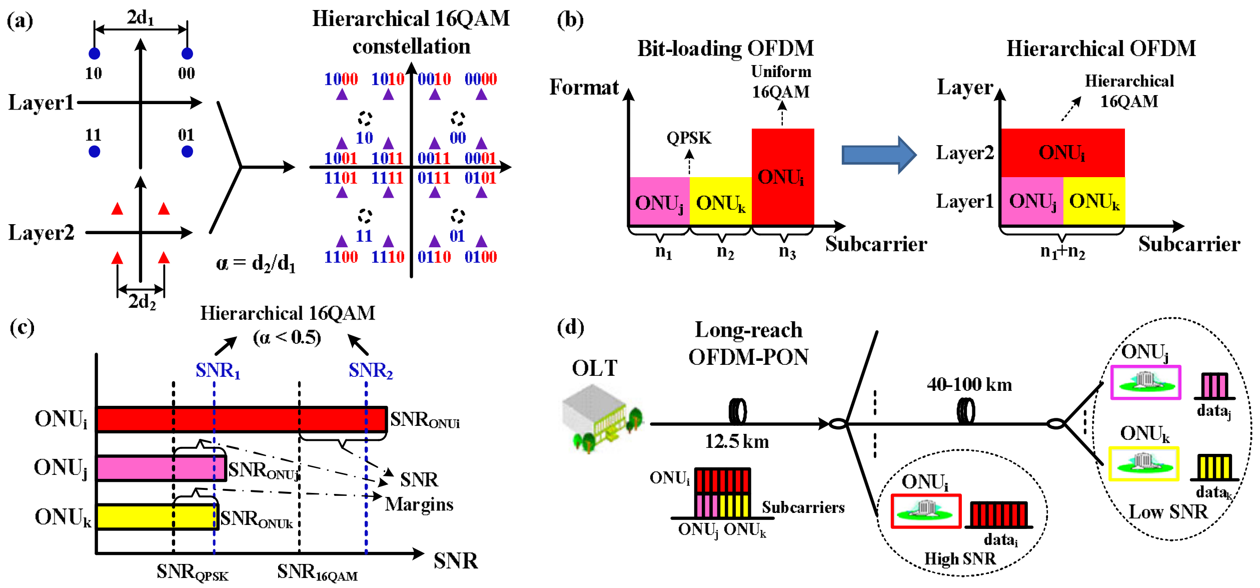

Fig. 1. (a) 16QAM hierarchical modulation. (b) Comparison between bit-loading OFDM and hierarchical OFDM. (c) Received SNRs in different ONUs and required SNRs for different formats to achieve error-free transmission. (d) Schematic diagram of long-reach OFDM-PON with hierarchical modulation.

respectively. The minimum distances between points in two QPSK constellations are denoted by $2d_1$ and $2d_2$. Subsequently, the two QPSK symbols are superimposed together to form a hierarchical 16QAM symbol. The mapping of information bits in hierarchical 16QAM is indicated in Fig. 1(a) with a Karnaugh map style Gray mapping, where the first two bits (blue numbers) represent the information bits of $data_1$ and the two remaining bits (red numbers) represent the information bits of $data_2$. Here, we define a hierarchical parameter α as the ratio of d_2 to d_1 ($\alpha = d_2/d_1$). If α = 0.5, it is the uniform 16QAM, which has been widely used in optical communications. However, we are only interested in the case with α < 0.5, where the constellation is truly hierarchical. It is observed in the Fig. 1(a) that the points in the same quadrant have the same information bits of the $layer_1$. For example, any point in the first quadrant, (the ones labeled 0000, 0010, 0001, 0011), is treated as point 00 for $layer_1$. When α < 0.5, the distances between the four points in each quadrant become small, thus the constellation looks like a "cloud". If one wants to extract the information bits of $layer_2$, the points in the "cloud" should be distinguished from each other at the receiver. Obviously, the bit error rate (BER) performance of data in the $layer_1$ is better than that of data in the $layer_2$. We define SNR_1, SNR_2, SNR_{QPSK}, and SNR_{16QAM} as the required minimum SNRs to achieve error-free transmission for $data_1$ and $data_2$ in hierarchical 16QAM signal, QPSK signal, and uniform 16QAM signal, respectively. Based on the analysis in Ref. [5], an inequality $SNR_2 \geq SNR_{16QAM} \geq SNR_1 \geq SNR_{QPSK}$ can be obtained. As α becomes smaller, SNR_1 decreases at the cost of the increase of SNR_2.

Fig. 1(b) shows the principles of the bit-loading OFDM and the proposed hierarchical OFDM. In a long-reach OFDM-PON, the received SNRs in different ONUs are not the same due to various factors, such as fiber transmission length and receiver performance. We assume that the received SNRs of ONUs in the long-reach OFDM-PON (Fig. 1(d)) meet the inequality $SNR_{ONUi} \geq SNR_{16QAM} \geq SNR_{ONUj,k} \geq SNR_{QPSK}$. Thus, by employing bit-loading OFDM technique, n_1 and n_2 subcarriers with QPSK format are allocated to ONU_j and ONU_k, while n_3 subcarriers with uniform 16QAM format are assigned to ONU_i. However, the ONUs still have some remaining SNR margins as illustrated in Fig. 1(c), which are not enough to increase the modulation order in the subcarriers. In this case, if the received SNRs in the ONUs satisfy the inequality:

$$SNR_{ONUi} \geq SNR_2 \geq SNR_{16QAM} \geq SNR_{ONUj,k} \geq SNR_1 \geq SNR_{QPSK} \tag{1}$$

a hierarchical 16QAM with α < 0.5 can be used in the n_1+n_2 QPSK-modulated subcarriers with $layer_1$ and $layer_2$ transmitting the data from $ONU_{j,k}$ and ONU_i as depicted in Fig. 1(b). By properly choosing the hierarchical parameter α, one can adaptively adjust SNR_1 and SNR_2 to meet the inequality (1). Thus, the spectral efficiencies in the first n_1+n_2 subcarriers are improved and n_3 subcarriers originally allocated to ONU_i can be re-assigned to other newly deployed ONUs. Therefore, the capacity of OFDM Tx with limited bandwidth can be greatly increased by using the proposed hierarchical modulation in the long-reach OFDM-PON. Note that the hierarchical modulation formats and the hierarchical parameter α can be appropriately adjusted to optimize the system performance according to the practical network conditions.

Experimental Setup and Results

The experimental setup of the long-reach OFDM-PON using the proposed hierarchical OFDM scheme is shown in Fig. 2. The OFDM Tx in the OLT consists of a distributed feedback (DFB) laser, a polarization controller (PC), a Mach-Zehnder modulator (MZM), an arbitrary waveform generator (Tektronix AWG 7122C), an erbium doped fiber amplifier (EDFA), and a tunable optical filter (TOF). We assume that the available bandwidth provided by the OFDM Tx is limited to 5 GHz and the data rates of ONU_1, ONU_2, and ONU_3 are 5 Gb/s, 2.5 Gb/s, and 2.5 Gb/s, respectively. In the OLT, a continuous wave (CW) light at 1557.2 nm from the DFB laser is fed into the single-driver MZM and modulated by an electrical OFDM signal. The OFDM data is generated offline by Matlab. The total number of OFDM subcarriers is 256, in which 128 subcarriers are used to transmit data for ONUs and other subcarriers are set to zero as guard band. In the mapping process, two kinds of modulation formats, uniform 16QAM and hierarchical 16QAM, are used. To reduce the cost and complexity of the OFDM-PON, Hermitian symmetry is implemented to provide real numerical output data. Since the sampling rate of the AWG is 10 GSample/s and only 128 out of 256 subcarriers carry data, the generated electrical OFDM signal has a bandwidth of 5 GHz. Through the E/O conversion in the MZM, the optical OFDM signal is fed into the EDFA and TOF. At the output port of OLT, the optical OFDM signal with a power of 9 dBm is launched into a 12.5-km standard single mode fiber (SSMF). After

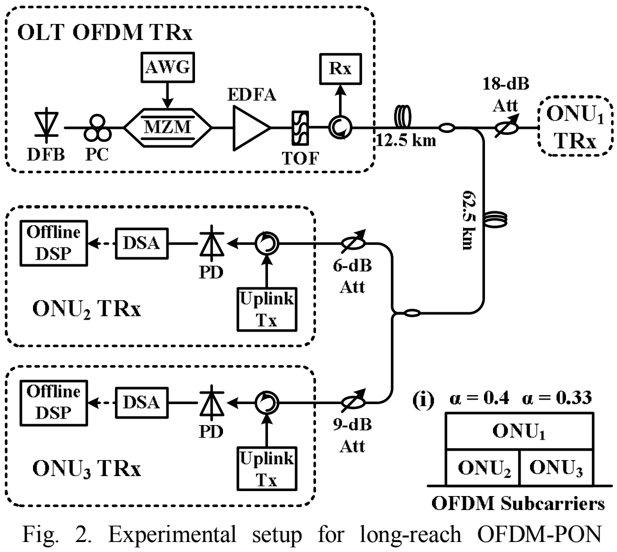

Fig. 2. Experimental setup for long-reach OFDM-PON using the proposed hierarchical OFDM modulation scheme.

fiber transmission, the optical signal is split into two parts by a 3-dB optical coupler. One part is routed to ONU_1 and the other is delivered to ONU_2 and ONU_3 by a 62.5-km SSMF and another 3-dB optical coupler. At the ONU side, three attenuators are used to emulate 1:64, 1:4 and 1:8 optical splitters. The received optical powers in ONUs (P_1, P_2, and P_3) are -15.5 dBm, -19 dBm, and -22 dBm, respectively. The optical OFDM signal is detected by a 10-GHz PD and sampled by a real-time oscilloscope (Tektronix DSA 70804) with a sampling rate of 25 Gsample/s. The sampled data are processed offline and the data required by the end users are retrieved.

In a PON system, the received power can be used to evaluate the BER performance instead of SNR. Fig. 3 shows the BER curves of uniform 16QAM and hierarchical 16QAM signals after 12.5-km and 75-km fiber transmissions. The FEC threshold is set to be 2×10-3. The cross points A-E and A'-E' denote the required minimum received powers (P_A-P_E, $P_{A'}$-$P_{E'}$) to achieve a BER of 2×10^{-3} for uniform 16QAM signal and two layers of hierarchical 16QAM signal, respectively. It is assumed that at these points error-free transmission can be realized taking into account the use of FEC module. As shown in Figs. 3(a) and 3(b), P_1 is higher than P_A while $P_{2,3}$ is lower than $P_{A'}$. Therefore, uniform 16QAM and QPSK formats can be respectively employed in ONU_1 and $ONU_{2,3}$ if one utilizes the bit-loading OFDM scheme. Considering the data rates of ONUs, 64 subcarriers with uniform 16QAM format are assigned to ONU_1 and other 64 subcarriers with QPSK format are allocated to ONU_2. For ONU_3, there is no available bandwidth in the OFDM Tx to transmit data for it and therefore congestion happens. The total capacity of the OFDM Tx is about 7.5 Gb/s when bit-loading OFDM scheme is employed. However, there are some power margins for the three ONUs as shown in Fig. 3. Since P_1 is higher than P_E and P_2 is higher than $P_{D'}$, a hierarchical 16QAM format with α = 0.4 can be used in the first 64 data subcarriers with $layer_1$ and $layer_2$ delivering data for ONU_2 and ONU_1 respectively. It is observed that P_3 is lower than $P_{D'}$ but higher than $P_{B'}$, and P_1 is higher than P_C in Fig. 3. So the hierarchical 16QAM format with α = 0.33 is adopted to transmit data for ONU_3 and ONU_1 in the remaining 64 data subcarriers. By this means, all data of ONUs are successfully transmitted with BER values below the FEC threshold. Therefore, the capacity of OFDM Tx increases to 10 Gb/s by using the hierarchical modulation.

Conclusions

We have proposed a novel scheme of hierarchical modulation to increase the capacity of OFDM Tx in the OLT of long-reach OFDM-PON. A proof-of-concept experiment was conducted, and the transmission capacity of a 75-km long-reach OFDM-PON increased from 7.5 Gb/s to 10 Gb/s by using our proposal. In practical network operation, the hierarchical modulation formats and hierarchical parameter can be flexibly adjusted to maximize the capacity of the OFDM PON.

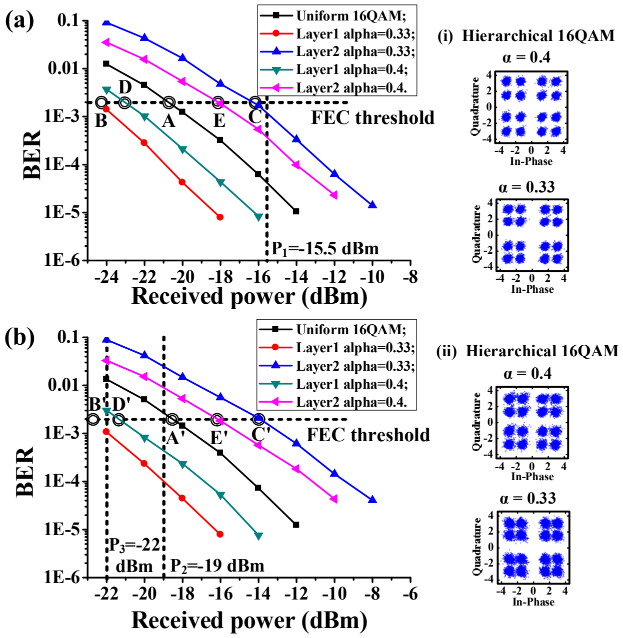

Fig. 3. BER curves for uniform 16QAM signal and hierarchical 16QAM signal after (a) 12.5-km fiber transmission. (b) 75-km fiber transmission.

Acknowledgments

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