Experimental Demonstration of Lloyd–Max Algorithm to Quantization Noise Reduction on a Power-Domain Non-Orthogonal Multiple Access based Coherent PON

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Abstract *This paper proposes the application of nonlinear quantization to a power-domain non-orthogonal multiple access (PD-NOMA-) passive optical network (PON) scheme. Experimental demonstration results indicate a gain of up to approximately 5 dB at a power ratio of 10 between two optical network units.*

Introduction

Wavelength division multiplexing (WDM) using a digital coherent technique in passive optical network (PON) systems has been previously studied to accommodate high-capacity, low-latency services needed for future radio access networks[1], [2]. An optical line terminal (OLT) allocates the various wavelengths to optical network units (ONUs) to guarantee low-latency transmission. However, the wavelength usage efficiency is low. Therefore, we have studied the use of a power domain non-orthogonal multiple access (PD-NOMA) scheme, which has been actively investigated in recent years[3], [4]. Figure 1 shows an example of a PD-NOMA-PON system. The PD-NOMA-PON system multiplexes the optical signals non-orthogonally in the power domain. Such a system can be expected to increase the number of ONUs in the WDM-PON link without incurring additional latency.

However, quantizers of analog-to-digital converters (ADCs) in the OLT and the ONU distort the signal by adding quantization noise depending on the power allocation ratio. This is because the OLT changes the ratio of the power allocation depending on the propagation distance and the optical splitter ratio between the multiplexed ONUs. This paper proposes applying the Lloyd–Max quantization (LMQ) algorithm[5] to a PD-NOMA-PON. We experimentally report that LMQ can reduce quantization noise, alleviating the optical signal-to-noise ratio (OSNR) penalty.

PD-NOMA-PON System

In our PD-NOMA scheme, we assume downstream transmission from the OLT to the ONUs.

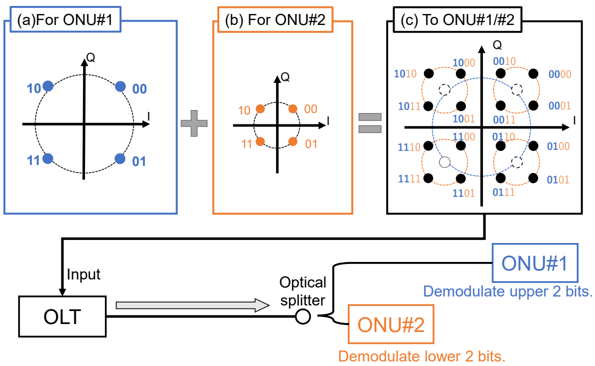

Fig. 1: Overview of PD-NOMA-PON system, (a)Signal for ONU#1, (b)Signal for ONU#2, (c) Signal to ONU#1/#2.

First, the OLT selects the pair of ONUs from among the accommodated multiple ONUs and allocates the disparate powers but the same wavelength to the pair of ONUs. Figure 1 shows the constellation maps of the signal of each ONU when the Quadrature Phase Shift Keying (QPSK) format is employed. In the PD-NOMA scheme, these two signals of disparate powers are linearly combined as shown in Figure 1 (c). The signal s multiplexed by the PD-NOMA scheme can be expressed as

$$s = \sqrt{P_1} s_1 + \sqrt{P_2} s_2, \tag{1}$$

where P_1 and P_2 ($P_1 > P_2$) are the average powers of the signals of the ONUs. The power ratio P_1/P_2 is determined by the link budget disparity users.

At the receiver side in Figure 1, the multiplexed signal is demodulated at ONU#1 as the normal QPSK signal. On the other hand, at ONU#2, there are two types of representative demodulation schemes. For one, the multiplexed signal is equalized and demodulated as QAM format.

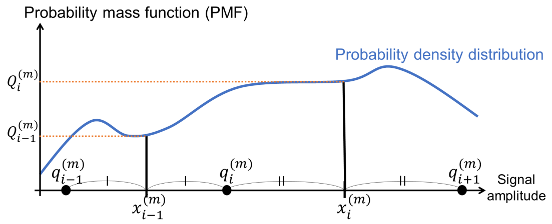

Fig. 2: Relation among $x_\nu^{(m)}$, $q_\alpha^{(m)}$, and $Q_\nu^{(m)}$.

The signals are then separated according to the bit allocation. This demodulation scheme is also known as a hierarchical modulation (HM)[4]. For the other method, a successive interference canceller with error correction is employed[6]. Our proposed nonlinear quantizer can be applied to both schemes.

In the PD-NOMA-PON system, the powers of the signals differ; here the link budget of ONU#2 is smaller than that of ONU#1. As the power ratio P_1/P_2 increases, the link budget of ONU#2 becomes relatively smaller and the link budget of ONU#1 becomes relatively larger. When the power ratio increases, the relatively small amplitude of ONU#2 is strongly affected by quantization noise in the DAC/ADC.

Lloyd–Max algorothm

A typical ADC quantizes the signal at uniform resolution. However, such a quantization is not suitable for the PD-NOMA-PON system because the signal of smaller allocated power cannot be properly demodulated due to the coarse resolution. Therefore, we employ the well-known LMQ as a representative nonlinear quantization for the PD-NOMA-PON system.

The LMQ algorithm searches the delimiter and rounding values that minimize quantization noise according to the amplitude distribution of the signal. Let D_m and N be the m-th training signal sequence and the number of quantization bits, respectively. m denotes the training sequence number $\{m = 1, 2, \cdots, M \in \mathbb{N}_+\}$. $x_\nu^{(m)}$ $(\nu = 1, 2, \cdots, 2^N - 1 \in \mathbb{N}_+)$ and $q_\alpha^{(m)}$ $(\alpha = 1, 2, \cdots, 2^N \in \mathbb{N}_+)$ denote the partition and the value of the quantization threshold, respectively. Here, $Q_\nu^{(m)}$ denotes the probability mass function (PMF) of the amplitude distribution of the signal. Figure 2 shows the relation among $x_\nu^{(m)}$, $q_\alpha^{(m)}$, and $Q_\nu^{(m)}$.

The goal of the LMQ algorithm is the calculation of the partition $x_\nu^{(m)}$. When $m = 1$, the linear quantizer is employed. For the next iteration $m+1$, $q_i^{(m+1)}$ is updated as

$$q_1^{(m+1)} = \mathbb{E}[\{q_\alpha^{(m)} | q_\alpha^{(m)} < x_1^{(m)}\}], \qquad (2)$$

$$q_i^{(m+1)} = \frac{x_{i-1}^{(m)} Q_{i-1}^{(m)} + x_i^{(m)} Q_i^{(m)}}{Q_{i-1}^{(m)} + Q_i^{(m)}}, \qquad (3)$$

$$q_{2^N}^{(m+1)} = \mathbb{E}[\{q_\alpha^{(m)} | q_\alpha^{(m)} > x_{2^N}^{(m)}\}], \qquad (4)$$

where $i = \{2, 3, \cdots, 2^N - 1 \in \mathbb{N}_+\}$. Here, $\mathbb{E}[\cdot]$ denotes the average value. For $m > 1$, the partition $x_\nu^{(m)}$ is calculated as

$$x_\nu^{(m+1)} = \frac{1}{2}\left(q_\nu^{(m+1)} + q_{\nu+1}^{(m+1)}\right). \qquad (5)$$

The process is repeated M times. Finally, we obtain the set of partitions $x_\nu^{(M)}$. In general, the partitions should be adaptively changed. However, optical access networks present the advantage of optical channel stability, so that the signal amplitude does not rapidly change. For this reason, the OLT need not update the partitions frequently.

Experimental setup

We evaluated the feasibility of employing the LMQ on the PD-NOMA-PON system. Figure 3 shows an experimental setup for measuring the bit error rate (BER) for various OSNR values. First, the QPSK signals were generated with the PRBSs $2^{15} - 1$ and linearly multiplexed. Here, we inserted the pilot signal of the QPSK format into the multiplexed signal in order to perform symbol synchronization at the receiver. The multiplexed signal passed through a root raised cosine (RRC) filter with a roll-off factor of 0.25. Afterwards, the multiplexed signal was input into an arbitrary waveform generator (AWG). A 20-Gbaud electrical analog multiplexed signal was generated. Note that the multiplexed signal was pre-equalized to suppress the frequency characteristics in the AWG. A laser diode (LD) of 100 kHz linewidth was used to convert the electrical analog signal to an optical signal. OSNR was adjusted by adding amplified spontaneous emission noise to the signal using an erbium doped fiber amplifier (EDFA).

At the receiver side, the optical signal was detected by a coherent receiver with a local oscillator of 1 kHz linewidth of 1 kHz. A digital signal oscilloscope (DSO) performed the ADC with an 8-bit linear quantizer at a sampling rate of 160 GHz. The 160-GHz sampled signal was downsampled fourfold offline using an anti-aliasing filter. Afterwards, the signal was quantized using a 4-bit linear quantizer or LMQ.

This paper compared 4-bit linear quantization with 4-bit nonlinear quantization using the Lloyd–Max algorithm with the required OSNR at the FEC

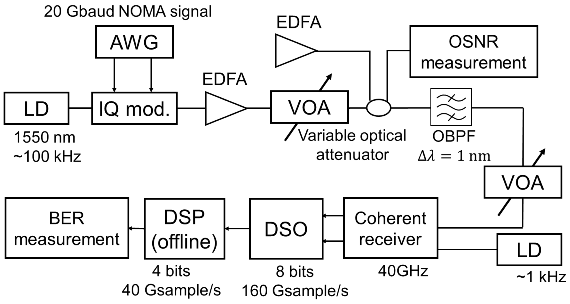

Fig. 3: Experimental setup

limit (3.8×10^{-3}). The Lloyd–Max algorithm requires training data, so we transmitted the multiplexed signals of 100 shots, using the first shot as the training data to implement the Lloyd–Max algorithm.

Next, we designed the PMF of the amplitude for both I- and Q-channels using the first shot signal. In this case, the first shot signal was linearly 4-bit quantized. We estimated the amplitude distribution by fitting the quantized signal to a mixed Gaussian distribution. The number of clusters in the mixed Gaussian distribution was set to 5. We employed an expectation-maximization algorithm[7] to estimate the mixed Gaussian distribution.

For the digital signal processing (DSP), an FFT-based compensator first coarsely eliminated the carrier frequency offset (CFO)[8]. Next, the signal passed through the RRC filter. Afterwards, an adaptive equalizer (AEQ) was applied in time domain. The equalization algorithm was a decision-directed least mean square (DD-LMS) algorithm. The number of AEQ taps was 9 and the step size was 4×10^{-4}. After performing the AEQ, the BER was measured.

Experimental results

Figure 4 shows the BER curves of the signals for ONU#2 at a low power allocation. We adjusted the power ratio P_1/P_2 to value of 4, 6, and 10. The results indicate that the LMQ enabled the OSNR penalties to be reduced for all cases compared with the linear quantizer. Figure 5 shows the BER curves of the signal for ONU#1 at a higher power allocation. Here again, the OSNR penalties were reduced. Figure 6 shows the required OSNR at the FEC limit for each quantization method of the signals to ONU#2. We obtained a larger gain by increasing the power ratio. In particular, at a power ratio of 10, a gain of approximately 5 dB was obtained.

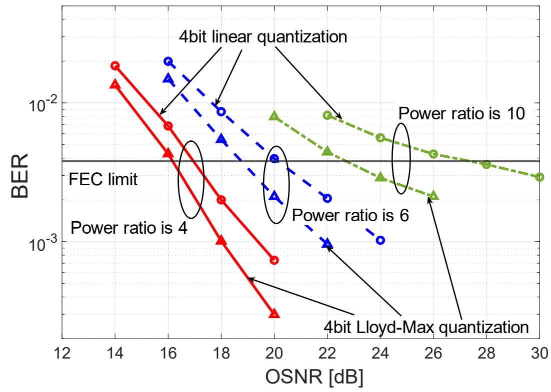

Fig. 4: BER curves of signals at low power allocations.

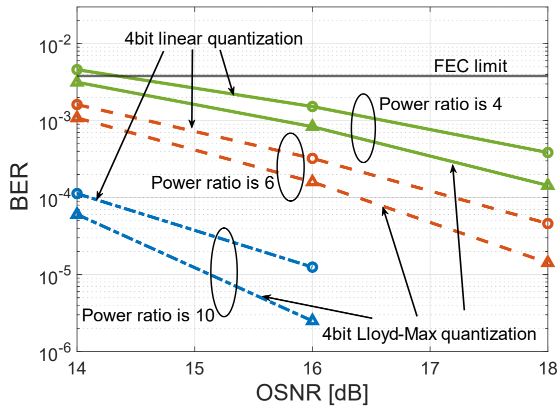

Fig. 5: BER curves of signals at high power allocations.

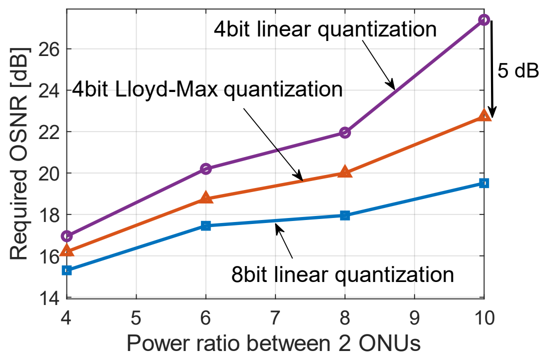

Fig. 6: Required OSNRs.

Conclusions

This paper proposed the application of the LMQ to a PD-NOMA-PON system via digital coherent technology. We experimentally demonstrated an LMQ-based PD-NOMA-PON with a 20-Gbaud signal. The results showed improvement of the OSNR penalty at every examined power ratio: 4, 6, and 10. At a power ratio of 10, the OSNR penalty decreased by approximately 5 dB.

Acknowledgements

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