The Impact of the Combined 8-QAM and QPSK Subcarrier Modulation for Coherent Optical OFDM

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Abstract: We investigated the optimized signal condition of the combined 8-QAM and QPSK subcarrier modulation for optical OFDM. The performance improvement was confirmed by WDM transmission experiments with the optimized power difference and subcarrier number.
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1. Introduction

In order to satisfy the demand for a further increase of data traffic in optical networks, a higher spectral efficiency is indispensable. To transmit higher bit-rate signal within the defined wavelength-division-multiplexed (WDM) channel spacing such as ITU-T grid, the use of multi-level modulation formats with a higher constellation size is indispensable. For example, 8-QAM is used to achieve a spectral efficiency of over 4.1 bit/s/Hz to transmit the net bit-rate of 104 Gbit/s within 25 GHz [1]. On the other side, the reachable distance can be extended with lower size of constellation because of the lower requirement for optical signal-to-noise ratio (OSNR). The issue is that the maximum spectral efficiency of each modulation becomes discrete because common consternation size is the power of two. For example, 8-QAM must be used to achieve 4.1 bit/s/Hz instead of QPSK because the maximum spectral efficiency of QPSK is 4 bit/s/Hz.

Orthogonal frequency division multiplexing (OFDM) has attracted attention as a promising technology for high capacity WDM optical communication systems due to its inherently low linear crosstalk and higher dispersion tolerance utilizing many subcarriers with lower symbol rate [2-8]. It can achieve arbitral spectral efficiency because the different kinds of subcarrier modulations can be applied to OFDM signal with arbitral ratio to utilize the WDM channel spacing [5,6]. However, the detailed studies on the optimization of signal condition with mixed subcarrier modulation haven't been conducted. In this paper, the optimization of the combined 8-QAM and QPSK subcarrier modulation is investigated keeping same spectral efficiency. The performance improvement compared to OFDM signal with all 8-QAM was confirmed by the 1680 km of SSMF transmission experiment at the spectral efficiency of 4.1 bit/s/Hz.

2. Concept of the combined subcarrier modulation

In this paper, we assume a WDM system with optical OFDM signals with 8-QAM subcarrier modulation where the WDM channel spacing is filled with the OFDM signal and guard-band. For the combined subcarrier modulation, some of 8-QAM subcarriers on the outside are changed to QPSK. 8-QAM and QPSK transmit 6 bit and 4 bit per symbol with polarization-division-multiplexing (PDM) respectively, therefore 2 subcarriers of 8-QAM are converted to 3 QPSK subcarriers to keep total bit-rate. The increased subcarriers are allocated to the side of OFDM signal. The ratio of subcarrier number of 8-QAM out of all the number of subcarriers can be determined arbitrarily. Additionally, the power ratio of subcarrier power from 8-QAM to QPSK can also be changed. With the constant power per WDM channel, the OSNR of QPSK and 8-QAM reduces and increases as the suppression ratio increases.

3. Experimental setup

Figure 1 shows the experimental setup. In this experiment, 2 ECL lasers and one fiber laser are aligned on a channel spacing of 6.25-GHz. The fiber laser has a linewidth of ~10 kHz and is used for the measured channel. For independent modulation of the measured and neighboring channels, two separate IQ modulators are used, which are driven by the in-phase (I) and quadrature (Q) components of OFDM baseband signal. The OFDM baseband waveforms produced by the arbitrary waveform generators (AWG) are calculated offline and outputted continuously. Two AWGs are used to produce two independent OFDM signals for decorrelation between measured and neighboring channels. At the outputs of the AWGs electrical lowpass filters (LPF) are used to suppress image-band products that are generated by the DACs of the AWG. The FFT size is 1024, from which 510 subcarriers carry data in 100 % 8-QAM modulation case, or 764 subcarriers carry data of 100 % QPSK modulation case. The cyclic prefix length is 10 samples (1.0 ns) per OFDM symbol. Together with the cyclic prefix, the OFDM symbol length and symbol rate are 103.4 ns and 9.67 MHz, respectively. After modulation, the measured and neighboring channels are combined with a polarization-maintaining optical coupler. Polarization multiplexing is emulated by splitting and recombining with exactly one OFDM symbol (103.4 ns) delay difference between the two paths.

The re-circulating loop consists of 3 spans of 80-km SSMF without optical dispersion compensation. The loss of every span is compensated for by a EDFA amplifier. At the receiver, the measured channel is selected with a 12.5-GHz FWHM optical bandpass filter (OBPF). After the OBPF, the signal is split into two random polarizations with a polarization beam splitter (PBS) and detected with a polarization-diverse 90 degrees optical hybrid. An ECL with ~100-kHz linewidth is used as a local oscillator (LO) and four single-ended 20-GHz PIN/TIA PD modules are employed for detection. A real-time digital storage oscilloscope with 16-GHz bandwidth and 50-GSa/s sampling speed is used to sample the four outputs of the optical hybrid. After detection, the data is post-processed off-line.

The signal is extracted electronically by a digital filter. The polarization de-rotation can be realized through MIMO processing at the receiver [7]. RF-aided phase noise compensation is employed to compensate for the phase noise of the local oscillator [8]. For all reported BERs, 4 Mbits is evaluated per measurement. The nominal bit-rate is 29.8-Gbit/s, from which 6% is used for training symbols and 1% for a cyclic prefix. When a FEC with 7% overhead is assumed, a net bit-rate of 26.0 Gbit/s is obtained. This results in a net spectral efficiency of 4.1 bit/s/Hz for 6.25-GHz channel spacing.

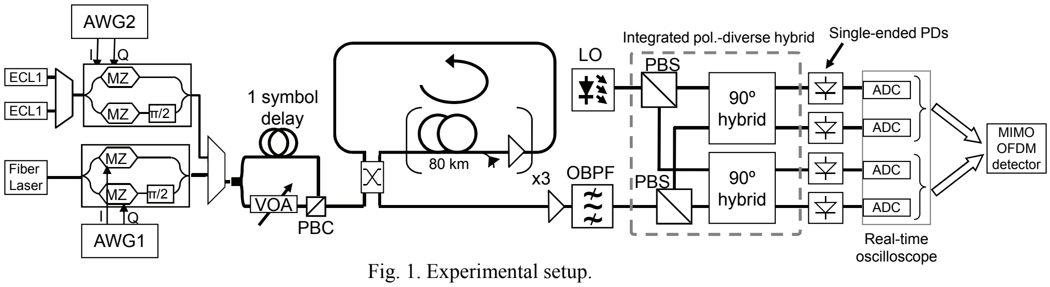

Fig. 1. Experimental setup.

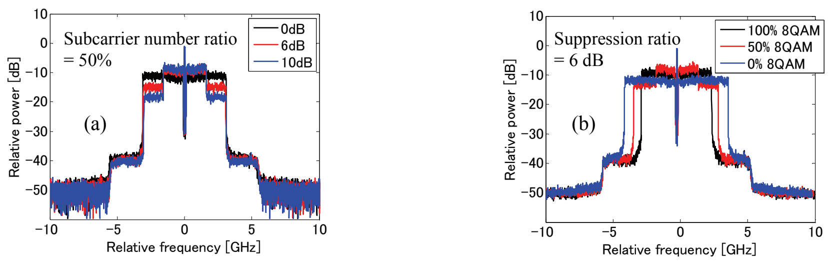

Fig. 2. The spectra of OFDM signal at Back-to-Back keeping same net bit-rate of 26.0 Gbit/s, a) with different suppression ratio for 50% 8QAM subcarrier modulation, b) The spectra of OFDM signal with different ratio of subcarrier number.

In this experiment, the subcarrier number ratio of 8-QAM from the total number of subcarriers is used as the parameters keeping the net bit-rate per WDM channel constant. The subcarrier number ratio is changed as 0, 14, 40, 50, 70 and 100 %. The suppression ratio is defined as the power of a 8-QAM subcarrier over a QPSK subcarrier expressed in dB, which is set to 0, 2, 4, 6, 10 dB in this experiment. The optical spectra with different suppression ratio and different subcarrier number ratio are shown in Fig. 2a and 2b, respectively.

4. Experimental results

To determine the optimum suppression ratio from 8-QAM to QPSK, the back-to-back BER performance as a function of OSNR sensitivity for single channel is measured with different suppression ratio. In this paper, the resolution bandwidth for OSNR measurement is set to 0.1 nm. The total signal power is kept same for all conditions. The subcarrier number ratio of 8-QAM is set to 50 %. Figure 3a shows the experimental results of the relationship between the suppression ratio and required OSNR for the BER of 1x 10^{-3}. For the detail, the required OSNR of 8-QAM and QPSK subcarriers in the each OFDM signal are also shown. From the result, the required OSNR of 8-QAM and QPSK become same around 6 dB of suppression ratio, where gives the lowest required OSNR.

The required OSNR for the BER of 1x 10^{-3} with different subcarrier number ratio is shown in Fig. 3b. The suppression ratio is set to 6 dB. The required OSNR for the BER of 1x 10^{-3} decreases as the subcarrier number ratio of 8-QAM decreases monotonously. The bandwidth of each subcarrier number ratio is also shown. For the spectral efficiency of 4.1 bit/s/Hz, the WDM channel spacing is set to be 6.25 GHz. With this criteria, the subcarrier number ratio of higher than 50 % is required. The improvement of required OSNR from 100 % to 50 % 8-QAM modulation is 0.4 dB. Figure 3c shows the BER in a single-channel transmission over 960 km as a function of the fiber launch power. The subcarrier number ratio is changed from 14 to 100 % with the suppression ratio of 6 dB keeping same net bit-rate. The optimized launch power is -3dBm/ch at the all of conditions. Especially, BER is improved at the subcarrier number ratio less than 50 %.

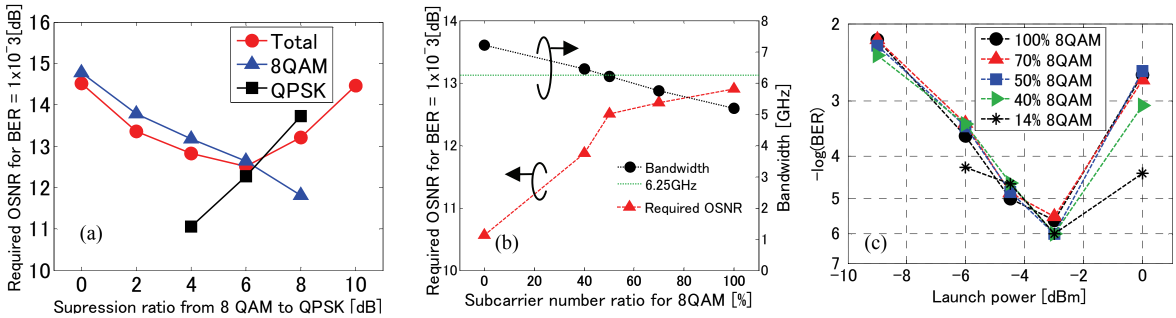

Fig. 3. The signal performances of OFDM signal at Back-to-Back keeping same bit-rate of 26.0 Gbit/s, a) the relationship between the suppression ratio and the required OSNR with 50 % subcarrier number ratio for 8-QAM, b) OSNR sensitivity with different subcarrier number ratio with the 6 dB suppression ratio, c) the BER as a function of the fiber launch power for single channel over 960 km.

Based on the experimental results in single channel transmission, the 6 dB for suppression ratio and 50 % for subcarrier number ratio are chosen for WDM experiment. Figure 4a shows the optical spectra in WDM condition with 100 and 50 % of subcarrier number ratio. The center optical sig nal is the measured channel and two signals on the left and right side of the measured channel are neighboring channels located in 6.25 GHz WDM channel spacing. Figure 4b shows the Back-to-Back OSNR sensitivity of 100 % and 50 % subcarrier number ratio with and without neighboring channels, respectively. From the comparison between the single channel and WDM case, the increment of required OSNR is estimated to be 0.5 and 0.3 dB for 100 and 50 % subcarrier number ratio, respectively. It means that the inter-channel linear crosstalk of 50 % subcarrier number ratio is smaller than 100 % subcarrier ratio case. Figure 4c shows the transmission performance of the 100 % and 50 % of subcarrier number ratio as a function of transmission distance with the optimum launch power of -4.5 dBm/ch, which is reduced from the single-channel transmission. With the threshold of a concatenated FEC code with 7% overhead (2.3 x 10^{-3}), 50 % subcarrier number ratio can extend the reachable distance up to 1680 km and 0.6 dB of Q-factor improvement converted from BER is observed after 1680-km transmission. It is confirmed that the combined subcarrier modulation technique is effective to extend the reachable distance.

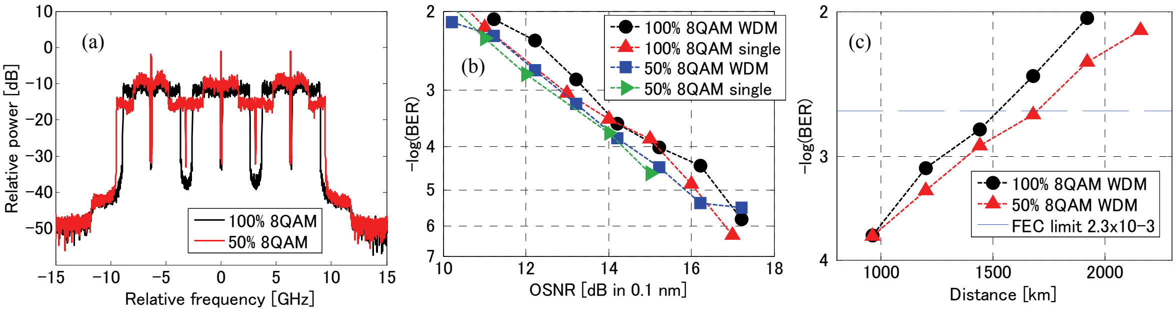

Fig. 4. Optical OFDM signal in WDM condition, a) the optical spectra with the ratio of 100% and 50% 8QAM modulation, b) the OSNR sensitivity curves of 100 % and 50 % subcarrier number ratio in single and WDM cases, c) the transmission performance of as a function of transmission distance.

5. Conclusion

The feasibility studies of combined subcarrier modulation technique are demonstrated in the condition of constant bit-rate and WDM channel spacing whose spectral efficiency is 4.1 bit/s/Hz. It is confirmed that the reachable distance of 3 x 29.8 Gbit/s WDM signals in 6.25 GHz channel spacing is extended up to 1680 km using 50% of QPSK subcarrier modulation instead of 8QAM with 6 dB of suppression ratio.

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