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RESEARCH ARTICLE

Constellation Shaped 3D HQAM-DPSK Modulation for Single Wavelength Multi-Dimensional Optical Transmission

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ABSTRACT A novel concept for single wavelength high spectral-efficient multi-dimensional optical transmission with geometric and probabilistic constellation shaping and bit mapping technique is presented in this study. We propose a simultaneous Hexagonal RF-Quadrature Amplitude Modulation – Differential Phase Shift Keying(HQAM-DPSK) optical modulation for spectral efficient optical transmission. In order to mitigate signal distortion by inter-dimensional interference between intensity and phase, constellation shaping technique is applied to multi-dimensional optical transmission scheme. The validity of the proposed scheme is demonstrated by optical fiber transmission simulation.

INDEX TERMS Multi-dimensional optical transmission, hexagonal quadrature amplitude modulation with differential phase shift keying (HQAM-DPSK), optical constellation shaping.

I. INTRODUCTION

As traffic in the access network increases, there has been a growing body of research that explores how to increase transmission efficiency [1]. Previously, broad modulation bandwidth with high performance equipment and multiplexing was the efficient solution to increase capacity. However, saturation of evolution in equipment bandwidth performance and optical channel effects limit the expansion of modulation bandwidth. Also, multiplexing is difficult to use due to optical beating noise and its system complexity. Recent works suggest the multi-dimensional optical transmission as a solution to increasing spectral efficiency [2], [3], [4]. Multi-dimensional optical transmission is a signal transmission technique using orthogonal dimension sources such as intensity and phase of optical signal. HQAM-DPSK, which stands for Hexagonal Quadrature Amplitude Modulation – Differential Phase Shift Keying, is one example of a multi-dimensional modulation scheme. However, the proposed scheme has nonlinearity issue due to high frequency components in the modulation sequence. It limits the expansion of modulation level so that spectral efficiency cannot be enhanced very much. Interdimensional interference, which is recently introduced concept in multi-dimensional optical transmission, that occurs during direct phase detection also limits the level expansion and high-speed modulation [5].

In this paper, we propose probabilistic and geometric constellation shaping for HQAM-DPSK optical transmission in a direct detection based multi-dimensional optical transmission system. Probabilistic and geometric constellation shaping is attracting attention in high data rate optical transmission because of fine-grained rate adaptability and energy efficiency gains. [6] The aim of our research is to overcome nonlinear and inter-dimensional interference between two different modulation scheme so that higher spectral efficient optical transmission can be achievable.

II. TECHNICAL APPROACH

In this chapter, multilevel ASK-DPSK (Amplitude Shift Keying – Differential Phase Shift Keying) transmission scheme is described, followed by the theoretical analysis of constellation shaped QAM-DPSK optical transmission.

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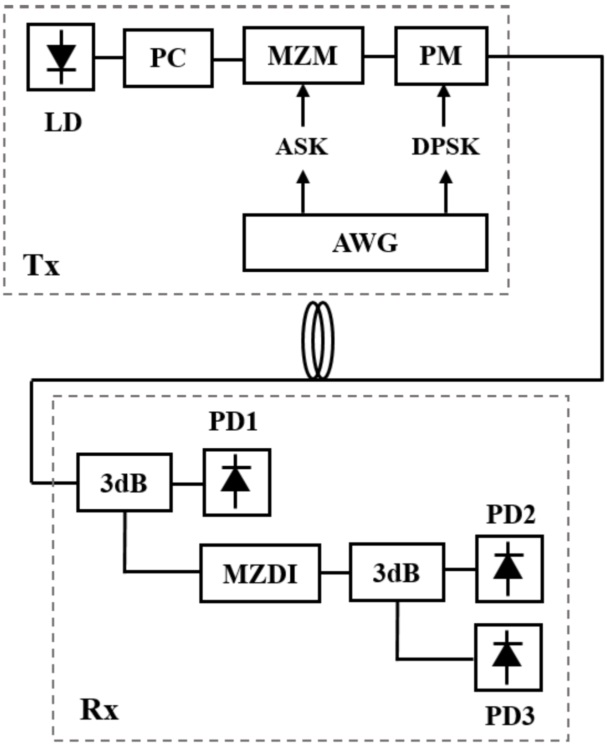

FIGURE 1. Transmission Link Schematic of ASK-DPSK single wavelength multi-dimensional optical modulation.

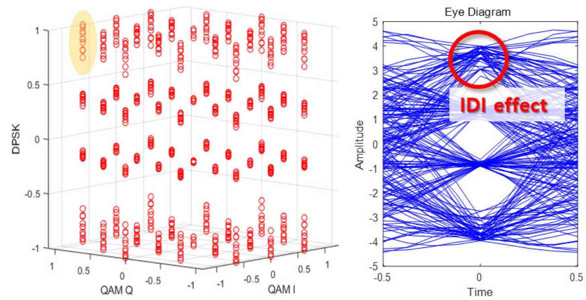

FIGURE 2. Effect of Interdimensional Interference of QAM-DPSK Transmission in 3D Constellation and Eye Diagram.

A. MULTIDIMENSIONAL OPTICAL TRANSMISSION

Multidimensional optical transmission is presented as a novel paradigm that can increase the transmission capacity by improving spectral efficiency in parallel to achieve multi-channel effect. Different resource, such as intensity and phase, of a single wavelength optical signal could be used simultaneously to achieve the similar effect as using multiple channels. Modulation teniques studied so far include two-dimensional OOK-DPSK modulating OOK in intensity dimension and DPSK in phase dimension. Also, three-dimensional QAM-DPSK using RF-QAM in intensity dimension and DPSK in phase dimension also proposed. Among them, we are focusing on direct detection based three-dimensional QAM-DPSK transmission. Before introducing proposed technique, traditional ASK-DPSK and QAM-DPSK multi-dimensional optical transmission schematics are needed to be discussed. Figure 2 illustrates the transmission link schematic of ASK-DPSK [6]. Here, we use the Mach-Zhender Modulator(MZM)-Phase Modulator(PM) cascading structure to avoid high frequency component issues of single modulator. The output of laser is a wave that has continuous intensity and phase over time with power P and center frequency ω_0. In above structure, the output signal of AM has a continuous phase. In other words, intensity modulation does not interfere in phase dimension. Similarly, intensity of the output signal of PM is equal to that of input signal of PM, i.e., phase modulation does not interfere in intensity dimension. We drive RF-QAM signal to AM with quadrature point operation. Optical signal from the transmitter is divided into two paths by a 3dB coupler. PD1 detects the intensity of one 3dB output signal. Another 3dB output passes through the Mach-Zehnder Delay Interferometer. Optical path length of the delay line is set to be an appropriate value so that T seconds are consumed passing through the MZDI delay line. This setup enables signal beating between optical signal arriving at a certain time t and that arriving at t-T. MZDI beating output optical signal is detected by a balanced photodetector (BPD). Then, the differential phase level can be decided with the same method of pulse amplitude modulation (PAM). Output electric field of multidimensional optical transmitter could be written as

$$E(t) = \sqrt{P}A(t)\exp\{j[\omega_0 t + \phi(t)]\} \tag{1}$$

where A(t) and ϕ(t) is QAM-modulated amplitude and DPSK-modulated phase. And since the receiver structure illustrated in figure 2 operates under direct-detection scheme, optical signal is detected as a form of photocurrent as equation

$$I_{PD1} = kR|E|^2 = \frac{1}{2}kI_0A_n^2 \tag{2}$$

$$I_{PD2} - I_{PD3} = \frac{1}{2}kI_0A_nA_{n-1}\cos(\phi_n - \phi_{n-1}) \tag{3}$$

Due to the direct detection property of photodetector, equation (2) does not include the phase information. It means that phase information does not affect intensity detection and symbol decision. However, the term related to amplitude A_n and A_{n-1} is included in the differential phase level decision path as equation (3). It means that intensity dimension data can interfere with phase dimension during phase detection. Equation (4) describes the sum of photocurrent of BPD within one symbol duration.

$$\int_0^T I(t)dt = \frac{1}{2}kI_0\cos(\phi_n(t) - \phi_{n-1}(t))\int_0^T A_n(t)A_(n-1)(t)dt \tag{4}$$

The integral part of the right side is an interdimensional interference (IDI) term by intensity. The variance of the IDI term directly affects the error performance of DPSK detection. Effect of IDI is depicted as figure 2. As IDI variance becomes larger, the thickness of one DPSK level is also increased. IDI variance depends on the swing intensity of the QAM symbol. In other words, the outer symbols of

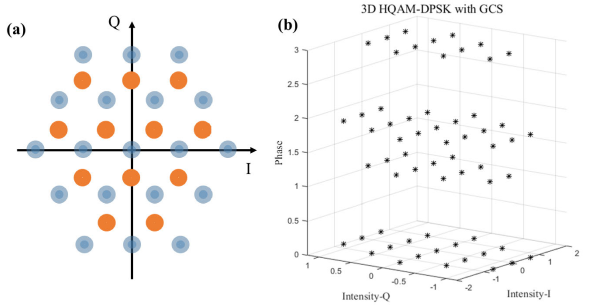

FIGURE 3. **Constellation of Shaped HQAM-DQPSK (a)Constellation of 19 HQAM (blue) and farthest 12 HQAM (orange) (b) 3D Constellation of Intensity-I, Intensity-Q, Phase.**

the constellation cause the large IDI variance. Therefore, in prior research, this IDI effect was controlled by setting the modulation range of the QAM signal as a small value to reduce variance of the IDI term. However, reducing the range of modulation limits the QAM error performance. This tradeoff relation bounds the bandwidth of modulation so that the spectral efficiency cannot be enlarged. Therefore, a more IDI-tolerant data transmission scheme should be introduced.

B. THEORETICAL ANALYSIS OF CONSTELLATION SHAPED HQAM-DPSK

Constellation shaping is mainly used to increase power efficiency. The proposed technique is different from the existing technique in view of the application target. Previous constellation shaping researches mainly focused on coherent optical transmission [7]. Traditional constellation shaping deals with the coordinate and distribution of the optical in-phase and quadrature component depending on the channel characteristic. What we propose is a technique that optimizes the constellation by calculating based on inter-dimensional interference issue in multi-dimensional optical transmitter and receiver structure, which differs from approaches of existing method. In this paper, we use in-phase and quadrature components of intensity, and phase level to construct a 3-dimensional constellation. We used Hexagonal-QAM(HQAM) as a scheme of geometric constellation shaping(GCS). HQAM is known as the energy-efficient signal transmission scheme compared to Square-QAM(SQAM) [8]. Symbol mapping based on honeycomb-like hexagon structure increases the density. The proposed constellation uses the basic structure of the hexagonal QAM to collocate intensity QAM symbols. Figure 3-(a) illustrates the 19-HQAM constellation with blue dots. The density of HQAM is larger than that of SQAM. This difference of constellation structure makes HQAM more spectrally efficient. Also, the peak power of HQAM symbol is less than that of SQAM with same average power. This can reduce the IDI variance slightly. Since QAM-DPSK is 3D modulation, we used multi-dimensional characteristic of proposed scheme. We can consider the additional hexagonal constellation that has a different phase level with the given 19-HQAM constellation. The orange dots of 3-(a) illustrate 12 hexagonal symbols which have the farthest distance with 19-QAM. Each 12 QAM symbols are placed at the incenter of triangle

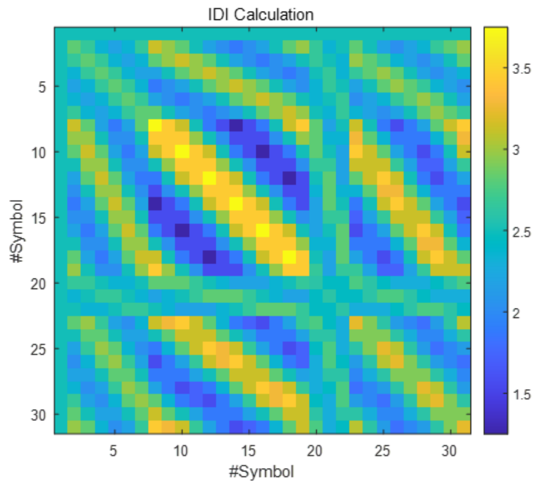

FIGURE 4. **Result of IDI Calculation with 19+12 HQAM Symbols.**

consisting of 19 QAM Symbols. Then, 19 QAM and 12 QAM alternately allocated to each phase layer. We used two groups of hexagons as the constellations of intensity dimension, with different phase levels, as figure 3-(b). Constellation depicted in figure 3-(b) contains 62 symbols, with 19 or 12 QAM symbols for each 4 phase layer. By using the farthest HQAM layer we can ensure the 3D symbol distance to be enough, therefore SER performance can be improved even if the level merging of DPSK caused by IDI is taking place. Of course, even in SQAM, SER performance can be improved by the same technique. However, the number of symbols available in the farthest layer is smaller than HQAM. To sum up, we used 3D HQAM constellation with sufficient 3D symbol distance to transmit multi-dimensional optical signals with high spectral efficiency and ensured transmission performance.

Although the error performance has been secured through GCS, it is still limited due to IDI. Figure 4 describes the effect of IDI with a calculation result of equation (4). Here, we can find that the variance of optical beating output still remains. Therefore, we additionally introduce probabilistic constellation shaping, which is know as energy-efficient transmission technique [9], [10], to reduce IDI effect. We know that the swing intensity of RF QAM affects DPSK signal to be spread. The keynote of proposed probabilistic constellation shaping(PCS) is reducing the probability of occurrence of symbols with large swing intensity. In other words, the outer symbols of HQAM constellation have less probability than inner symbols. This probabilistic operation results in decrement of overall variance of IDI, which leads to overall SER performance enhancement.

III. SIMULATION ANALYSIS

The simulation is designed and performed to evaluate the benefits of the proposed geometric and constellation shaping. We compared the performance by symbol error rate (SER) of non-shaped SQAM-based multi-dimensional optical signal with proposed geometric and geometric-probabilistic shaped optical signal with 1Gbps bit rate as proof of concept. Considering the fiber channel-induced distortion and

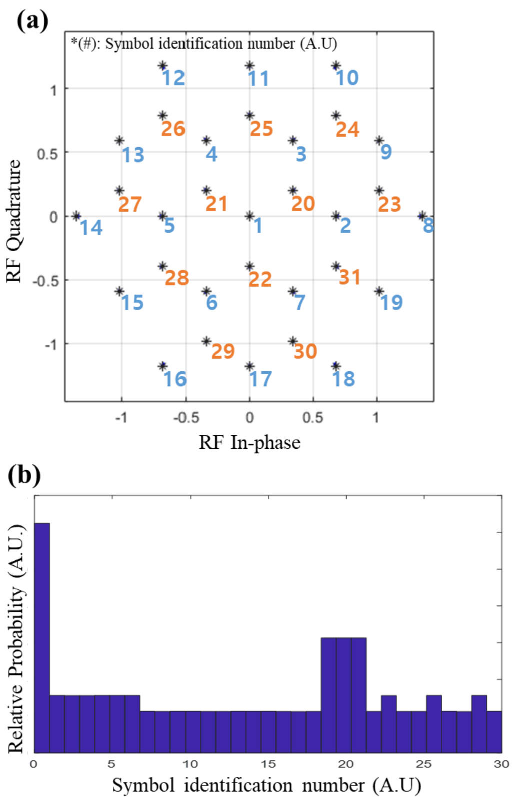

FIGURE 5. Constellation of (a) 19 HQAM (blue) and farthest 12 HQAM (orange) with symbol identification number (#symbol) (b) Probabilistic Shaping Rule in 19-12 HQAM.

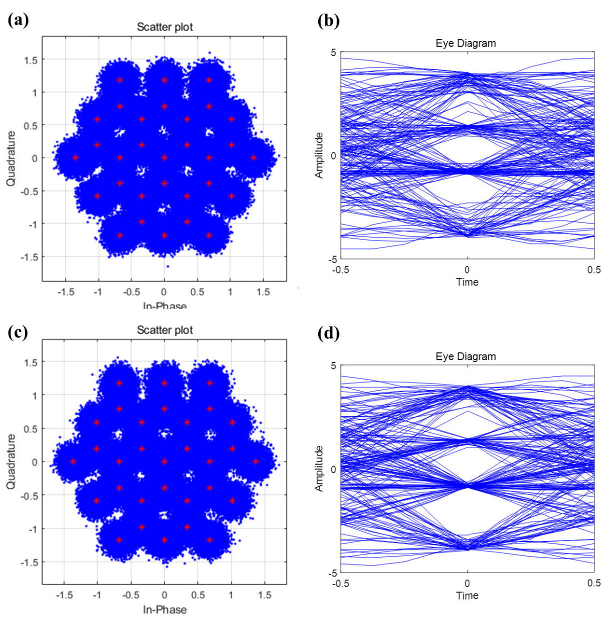

FIGURE 6. Received optical signal (a) GCS constellation (b) GCS DPSK eye diagram (c) G-PCS constellation (d) G-PCS DPSK eye diagram.

optical power attenuation, tested modulation level is set as 16SQAM-4DPSK and 19HQAM-4DPSK. Here, 16SQAM-4DPSK has non-shaped constellation. Equivalent 16-square QAM is assigned to four layer of phase according to the differential level. The total number of transmitted symbol of

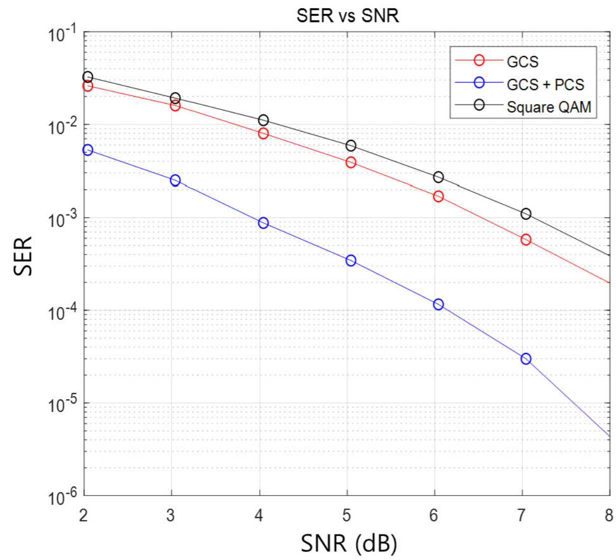

FIGURE 7. SER vs SNR performance analysis of SQAM, proposed GCS-HQAM and proposed G-PCS HQAM.

16SQAM-4DPSK is 64 while propose technique has 62 symbols. This difference is converted during the error probability calculation process. Dispersion coefficient is set by 17 ps/km·nm. In our target optical access network, transmission distance is set as 20km. Simulation is conducted with 10Gbits/s. Based on the preset transmission parameter, effect of dispersion is modeled and applied to simulation. The effect of power attenuation is calculated with received optical power −10 to −2dBm and converted to SNR(dB) value. All simulation parameters are set based on our previous study and experiment in [5]. Figure 5-(a) shows the geometric shaped HQAM constellation with symbol identification number mapping. Based on the equation (4) and figure 4, the distortion of DPSK level is proportional to the square of optical intensity signal. Therefore, symbol appearance probability is set as the inversely proportional to the swing intensity of QAM symbol. Overall distribution is described in figure 5-(b). Here, the number of symbol was assigned based on the swing intensity of QAM symbol.

Figure 6 shows the received intensity and phase signal of multidimensional optical transmission simulation. Figures 6-(a) and 6-(c) demonstrates the QAM signal constellation regardless of DPSK level. In those figures, it may be expected not to be detected because the QAM symbols in constellation seems to be overlapped with short symbol distance. However, since we allocated symbol as the 19 hexagon and 12 hexagons with farthest distance based on the phase level, as figure 5, 3D symbol distance was acquired so that there isn't any problem on QAM symbol detection. Comparing Figs 6-(a) and 6-(c), since we sent the same peak optical power the constellation of received signal shows almost same error vector magnitude. However, the eye diagrams 6-(b) and 6-(d) shows the large difference. Especially, the level merging effect by inter-dimensional interference is reduced with proposed probabilistic shaping scheme. It can be shown as the thickness of high-DPSK level eye pattern is greatly reduced.

We numerically compared the error performance as the symbol error rate (SER) of each modulation scheme as shown in figure 7. As described in figure, geometric and probabilistic shaped signal shows much better performance than the geometric shaped HQAM, and there was not much difference between SQAM and geometric shaped HQAM. In the transmission simulation, the modulation index of QAM symbol condition is set to be small value to acquire sufficient DPSK symbol power. So that effect of geometric shaping is not so much large. SER difference between SQAM and HQAM is caused by the reduced total number of symbol. In the actual transmission link, phase detecting receiver part is unstable so that maximum phase modulation level is up to 3 [4]. Considering that there are difficulties on phase detection due to instability and offset of MZDI receiving structure, proposed hexagon and farthest-hexagon geometric shaping can provide sufficient effect of acquiring sufficient symbol distance so that probability of burst bit error is reduced.

If we set the target SER of optical transmission link as $2*10^{-3}$ SER, which is considered as FEC limit in communication system, constellation shaped HQAM-DPSK could get 3dB of SNR gain compared to non-shaped SQAM symbol, with only 2 symbol loss. The calculation result of actual throughput can be considered. In this simulation, geometric constellation shaping reduced two symbols so that we can transmit total 62 symbol. It could be converted as 5.9542 bits per symbol, while the non-shaped SQAM-DPSK has 64 symbol so that it has 6 bits per symbol. In the real transmission system, acquiring additional SNR needs a complex technology such as sophisticated equalizing. Therefore, 3dB gain with modulation scheme only with 2 symbol loss could be helpful in power-limited optical transmission environment.

IV. CONCLUSION

We proposed HQAM-DPSK 3D geometric and probabilistic constellation shaping for multi-dimensional optical transmission. The proposed technique ensures performance by reducing the effect of inter-dimensional interference. By comparing with square QAM-DPSK. An enhancement of the signal transmission performance of proposed technique was numerically demonstrated. The symbol error performance of proposed scheme was two times smaller than that of well-known SQAM-based multidimensional optical transmission. Thus, the proposed 3D HQAM-DPSK could be helpful to increase spectral efficiency in direct detection based optical transmission systems.

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