A low-complexity 64QAM-based probabilistically shaped OFDM for W-band RoF system

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Abstract: We experimentally demonstrated a low-complexity probabilistic shaping (PS) 64QAM-OFDM in an IM-DD-based W-band RoF System. After 45-km SSMF and 4-m wireless transmission, the experimental results show that its receiver sensitivity is better than that of uniformly distributed-OFDM (UD-OFDM).

1. Introduction

Radio-over-fiber (RoF) is a prospective mobile fronthaul technology with rising need for high bandwidth and mobility of wireless communication. It also functions as a radio access network, connecting base band equipment to remote radio heads. W-band (75~110 GHz) radio, in particular, has great accuracy and minimal air attenuation. As a result, a W-band RoF system can improve the transmission range and capacity of wireless services [1]. However, the majority of millimeter-wave RoF (MMW-RoF) methods now in use rely on expensive and complicated coherent receivers to transmit signals [2]. In addition to avoiding complicated and pricey high-speed mixers, millimeter-wave local oscillators, and high-speed DACs in order to save equipment costs, the intensity modulation and direct detection (IM-DD) schemes using envelope detectors also prevent frequency drift in the photon-assisted MMW system [3]. Additionally, the probabilistically shaped (PS) constellation may be used for rate adaptation and is seen as a viable method to overcome Shannon's limit [4]. Recently, the Gallager many-to-one mapping (MTO), the hierarchical distribution matcher (HiDM), the constant composition distribution matcher (CCDM), the bit-weighted distribution matching (BWDM), and the prefix-free code distribution matching (PCDM) are a few PS approaches that have been presented [5–7]. Field-programmable gate array (FPGA) implementations have only been made for PCDM, BWDM, and HiDM [8–10]. In order to use the MTO shaping approach, the receiver must implement an iterative strategy that applies both inner and outer iterations to the LDPC decoder and the PS decode. This shows that the method is expensive in terms of compute time, memory utilization, and power consumption, as well as hardware implementation complexity. Additionally, the CCDM necessitates division and multiplication operations that are highly resource-intensive [6]. In [7], a low-complexity PS-16QAM scheme based on BWDM for DMT symbols in an IM-DD system. And L. Zhang et al. conducted experimental verification on it in a high-speed real-time system [10]. The experimental results shows the scheme does not require complex multiplication and division operations, and it has less computational and hardware complexity. However, the limitation of this approach is that it cannot be directly applied to other order QAMs.

In this work, a low-complexity PS-64QAM-OFDM based on two-stage bit weight distribution matching (TS-BWDM) is proposed and experimentally demonstrated for IM-DD-based W-band RoF system. 28.13 Gb/s PS-64QAM-OFDM signals transmission is achieved with the BER under 3.8×10^{-3} after 45-km SSMF and 4-m wireless.

2. The Principle of PS-64QAM Based on TS-BWDM

The process of TS-BWDM in detail is depicted in Fig. 1(a). Firstly, the original input bit stream is divided into three parallel data streams, U_1, U_2 and U_3 with the matching bit length of n_1, n_2 and n_3 following the serial to parallel conversion. Here, U_1-path performs flag bit insertion, U_2-path mainly realizes two-stage bit-weighted inversion, and U_3-path performs the judgment of the second bit-weighted inversion to realize approximate Gaussian distribution (GD). The three parallel data streams can be expressed as

$$U_i = \left\{D_{i,1},\ D_{i,2},\ ...,\ D_{i,n_i}\right\} \tag{1}$$

where $D \in \left\{0,1\right\}$ and i is the index of the parallel bit streams. The U_2 is then subjected to the two-stage bit-weighted inversion processing procedure, which is a crucial component of TS-BWDM. In the two-stage bit-weighted inversion, U_2 is bitwise separated into a number of sets, each of which contains k bits, and one flag bit, the newly added most significant bit (MSB), is added to U_1 set via weight computation based on the original k elements of U_2. The constellation labeling design with Gray mapping rules for PS-PAM8 is shown in Fig. 1(c). The red marked bit represents the symbol bit. It is obvious that the PS can be achieved by increasing the probability of '1' in the inner circle of U_2. After the weight calculation, if the probability of '1' is greater than k/2, the corresponding MSB is defined as '1'. If not, the MSB is set to '0' and the k bits of the set undergo a bit negation operation. Fig.1 (d) shows the probability distribution of PS-PAM8 symbols for k=3 after 1st stage inversion. To achieve the PS-PAM8 signals following approximate GD, similarly, the U_3 is divided into several sets according to the flag bits inserted by the first bit-weighted reversion operation, and each set also includes k bits. After calculating the weight of the subset in U_3, the bits in the subset of U_2 corresponding to '1' in the subset of U_3 are subject to the bit inversion operation if the probability of '1' is greater than $k/2$. If not, these bits remain unchanged. It is worth noting that the two-stage bit-weighted inversion here are performed on U_2, and only one-stage flag bit insertion operation is performed on U_1.

By the first stage bit-weighted inversion processing procedure, the probabilities of '1' and '0' in the U'_2 can be written as

$$P(U'_2)=\begin{cases}\frac{1}{2^k}\left(\sum_{x=\lceil k/2\rceil}^{k}\frac{x+1}{k+1}C_k^x+\sum_{x=\lfloor k/2\rfloor+1}^{k}\frac{x}{k+1}C_k^x\right), & U'_2=1\\ 1-\frac{1}{2^k}\left(\sum_{x=\lceil k/2\rceil}^{k}\frac{x+1}{k+1}C_k^x+\sum_{x=\lfloor k/2\rfloor+1}^{k}\frac{x}{k+1}C_k^x\right), & U'_2=0\end{cases} \tag{5}$$

where $\lceil\cdot\rceil$ means the operation for the minimal integer larger than the value inside it. $\lfloor\cdot\rfloor$ indicates the opposite operation.

The key to the second stage bit-weighted reversion is to re-reverse the subset in U'_2 according to the distribution of '1'and '0' in U'_3, which includes three steps:

- Step 1: The flag bits added by the initial bit-weighted reversion operation are used to partition the U'_3 into a number of sets, each of which also contains k bits.
- Step 2: Calculate the weight of the subset in U'_3.
- Step 3: Find the bits in the subset of U'_2 corresponding to '1' in the subset of U'_3, if Z is greater than $k/2$, and these found bits is re-reversed. If not, these bits remain unchanged.

The probability distribution of PS-PAM8 symbols for k=3 after 2[st] stage inversion is shown in Fig. 1(e). After PS-64QAM mapping operation, the generated PS-64QAM constellation is shown in Fig. 1(f).

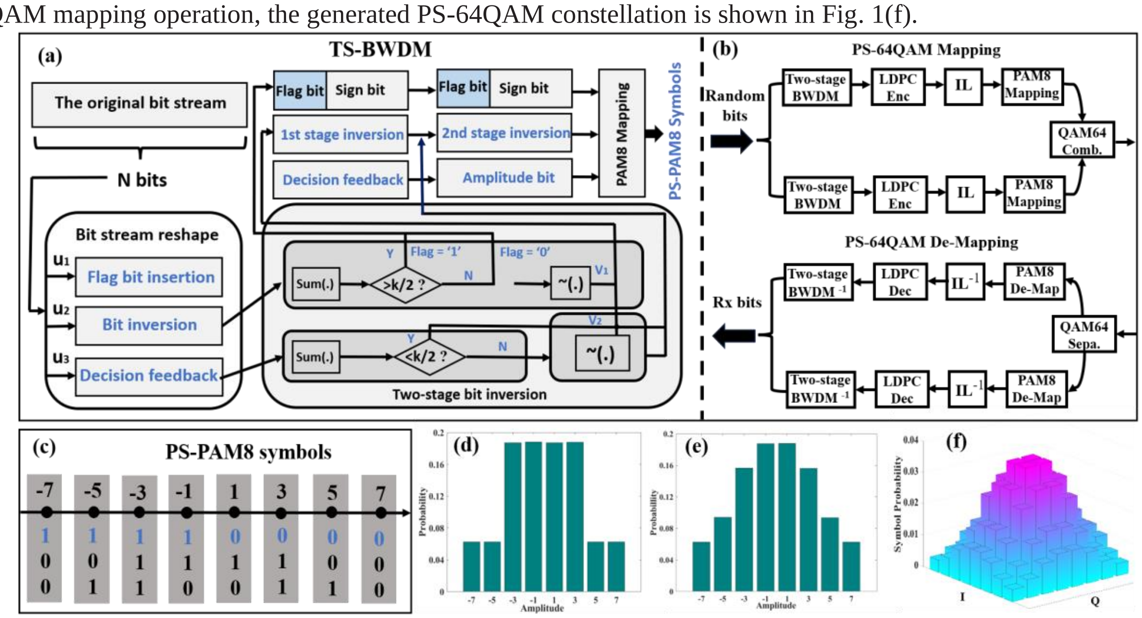


Fig. 1. Principle flowchart. (a) TS-BWDM, (b) PS-64QAM Mapping/De-Mapping, (c) PS-PAM8 with Gray mapping, (d) and (e)Probability distribution constellation example of k = 3 for 1[st] stage inversion and 2[st] stage inversion, (f) The probability distribution of PS-64QAM symbols.

3. Experimental Setup

Fig. 2 shows the experimental setup of the PS-64QAM OFDM for IM-DD-based W-band RoF system. At the transmitter, two external cavity lasers (ECLs) output continuous wave light waves spaced by 87 GHz. The baseband signal is loaded into an AWG to drive the Mach Zehnder modulator (MZM) via intensity modulation. The light waves are combined by the polarization-maintaining optical coupler (PM-OC) with optical spectrum in Fig. 2(b). After 45-km standard single-mode fiber (SSMF) transmission, the total optical power is adjusted by a variable optical attenuator (VOA). The coupled light wave is heterodyne beat in a 70-GHz photodiode (PD) to generate the 87-GHz W-band signal. It is boosted by an electrical amplifier (EA) and then beamed by a horn antenna (HA). After 4-m wireless transmission, the signal is received by another HA. After low noise amplifier (LNA), the envelope detector (ED) implements down-conversion to yield the baseband signal. It is boosted by an EA and captured by an oscilloscope (OSC). Fig. 2(c) illustrates the electrical spectrum of the PA-64QAM OFDM signal. Figs. 2(a) and 2(d) show the DSP at the transmitter and the receiver, respectively. The IFFT size is 1024 and 400 subcarriers are loaded with data. The length of both the cyclic prefix and suffix is 32. One DMT frame comprises of 9 TSs and 243 data-carrying DMT symbols. The bandwidths of LDPC-coded UD-64QAM, PS-64QAM OFDM signal (k=9) and that of k=3 are about 4.18 GHz, 4.34 GHz and 4.69 GHz, respectively. The LDPC code rate is 3/4 in our experiment.

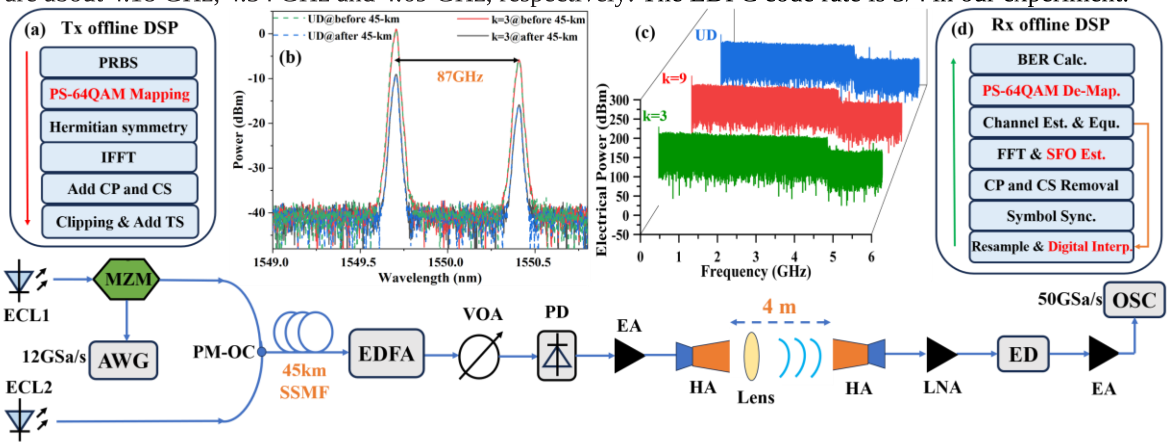
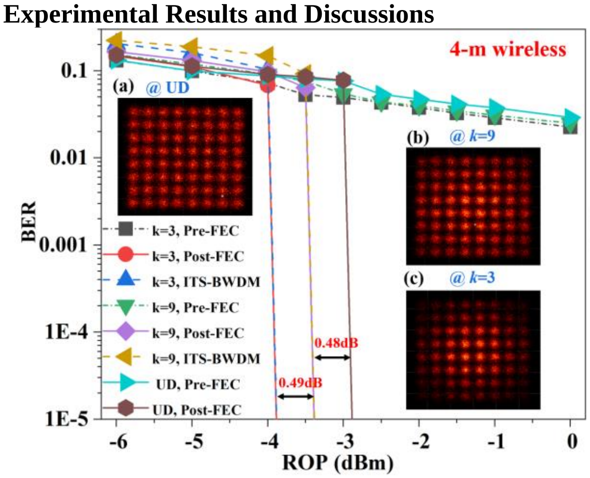


Fig. 2. Experimental setup. Insets (a) The DSP with PS-64QAM OFDM at the transmitter, (b) The measured optical spectrum after the OC processing, (c) The electrical spectra for PS -64QAM OFDM, (d) The DSP with PS-64QAM OFDM at the receiver.

4. Experimental Results and Discussions



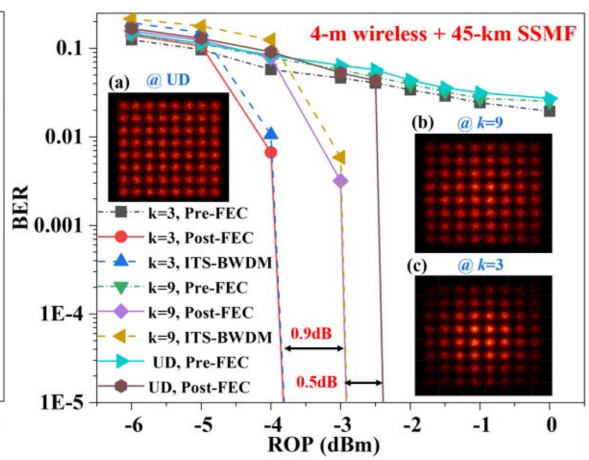


Fig. 3. BER versus ROP at 4-m wireless transmission. Fig. 4. BER versus ROP at 45-km SSMF + 4-m wireless transmission.

Figs. 3 and 4 show the BER of PS-OFDM in the case of 4-m wireless and 45-km SSMF + 4-m wireless under different received optical power, respectively. We can see that, in the 4-m wireless case, compared to UD-OFDM, about 0.97 and 0.48-dB receiver power sensitivity improvement can evidently be achieved for the PS-OFDM under k=3 and k=9, respectively. The constellations of UD-OFDM and PS-OFDM with the ROP of 0 dBm are shown in the insets of Fig. 3. In the 45-kmSSMF and 4-m wireless case, compared to UD-OFDM, about 1.4 and 0.5-dB receiver power sensitivity improvement can be achieved for the PS-OFDM under k=3 and k=9, respectively. The constellations after 45-km SSMF + 4-m wireless transmission with the ROP of 0 dBm are shown in the insets of Fig. 4. It clear that, after 45-km SSMF and 4-m wireless transmission, the receiver sensitivity of PS-OFDM is better than that of UD-OFDM.

5. Conclusions

In this paper, we proposed and experimentally demonstrated a low-complexity PS-64QAM OFDM for W-band RoF system. The experimental results show that the TS-SBWDM-based PS-64QAM scheme with k=3 can achieve 0.97dB and 1.4dB receiver sensitivity gain compared with UD-OFDM for 4-m wireless transmission and 45-km SSMF + 4-m wireless transmission, respectively. *This work was partially supported by National Natural Science Foundation of China (No. 62305067, No. 61935005, and No. 61835002, No. 62375219, No. 62331004).*

6. References

[1] C. Lim et al, J. Lightwave Technol. 2019, 1647-1656.
[2] K. Wang et al. OFC, 2021, pp. 1-3.
[3] J. He et al. OFC, 2022, Th2A.30.
[4] B. Fred, et al. J. Lightwave Technol. 2016, 1599-1609.
[5] X. Wu et al., Opt. Express., 2019, 9821-9828.
[6] T. Yoshida et al., J. Lightw.Technol, 2019, 1579-1589.
[7] Z. Dong et. al., J. Lightw. Technol, 2021, 98-104.
[8] Q. Yu, et al. J., Lightw. Technol., 2021, 1072–1080,
[9] L. Zhang et al., J. Lightw. Technol., 2022, 1339-1345.
[10] L. Zhang et al., OFC, 2023, W2B.10.