

Joint Optimization of Processing Complexity and Rate Allocation through Entropy Tunability for 64-/256-QAM Based Radio Fronthauling with LDPC and PAS-OFDM

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Abstract: We experimentally demonstrate LDPC coded PAS-OFDM 64-/256-QAM signals in radio fronthauls. Through entropy allocation by adjusting the complexity and signal bandwidth, tunable power margins gain up to 3 dB and relaxed process latency are achieved.

OCIS codes: (060.2330) Fiber optics communications; (060.5625) Radio frequency photonics

1. Introduction

Research on probabilistic shaping (PS) based millimeter-wave (MMW) radio access network (RAN) has made substantial progress recently [1]. In orthogonal frequency division multiplexing (OFDM) based RAN, portion of subcarriers are subject to different levels of signal degradation due to either frequency selective power fading or local oscillator leakage [2]. However, in most cases, a uniform PS setting is commonly applied to all subcarriers where all subcarriers have the same entropy as shown in Fig. 1(a) [3]. Besides, the bit-loading technique is widely adopted to combat the uneven signal-to-noise-ratio (SNR) distribution over frequency. Nevertheless, such a technique only changes the entropy by integers, which cannot fully exploit the channel capacity. PS provides a continuous tuning of entropy to an arbitrary, non-integer value, which has been applied to each subcarrier to achieve maximum capacity [4]. However, as this scheme adjusts the entropy per subcarrier, it increases the network complexity and induce additional latency to meet precise distribution requirements. Therefore, we propose to divide the OFDM subcarriers into several PS units as shown in Fig. 1(b), and then tune the entropy per PS unit based on the channel SNR conditions (namely, rate allocation). In this case, we can track the SNR fluctuations per PS unit by utilizing different entropies. Grouping several subcarriers into one PS unit achieves two core properties: (i) we can relax the symbol length per subcarrier (which reduces latency requirement), and (ii) achieve flexible tuning of power margins while controlling the digital processing complexity. State-of-art constant composition distribution matcher (CCDM) combined with probabilistic amplitude shaping (PAS) can preserve the probability distribution from CCDM [5,6]. Fig. 1 illustrates the radio-based fronthaul link where we employ the proposed scheme. For the link between the distributed unit (DU) and remote radio unit (RRU), fiber covers most of the distance. While in the areas where fiber is too costly to be deployed or unavailable, a MMW based RRU is employed as a wireless relay for providing a Gbps data delivery.

In this paper, for the first time, we experimentally demonstrate the feasibility of using low-density parity-check (LDPC) coded PAS-OFDM to conduct the proposed PS unit-based rate allocation in a hybrid fiber/MMW radio fronthaul. Compared with the uniform QAM OFDM or PS OFDM with uniform setting, our rate allocation scheme has higher received power sensitivity and a smoother Normalized Generalized Mutual Information (NGMI) over subcarriers. We also achieve a balance between system complexity/latency and receiver performance by tuning the PS unit size. Power margin's tunability is enabled by adjusting the number of subcarriers per PS unit and total effective entropy. Post-FEC bit-error-rate (BER) is utilized to verify the pre-FEC performance gain.

2. Principle of operation and experimental setup

Three schemes are investigated by experimental demonstrations: (i) Uniform QAM distribution, (ii) PS QAM with the same rate per subcarrier in Fig. 1(a), and (iii) PS QAM aided adaptive rate allocation per PS unit as shown in Fig. 1(b). Assuming the OFDM signal has T subcarriers in total, we first divide the data into S PS units with T/S subcarriers per unit. We then optimize the rate per PS unit based on the pre-estimated SNR:

$$H_j = S \cdot H_{total} \cdot \log_2(1 + SNR_j) / \sum_{i=1}^M \log_2(1 + SNR_i), \quad (1)$$

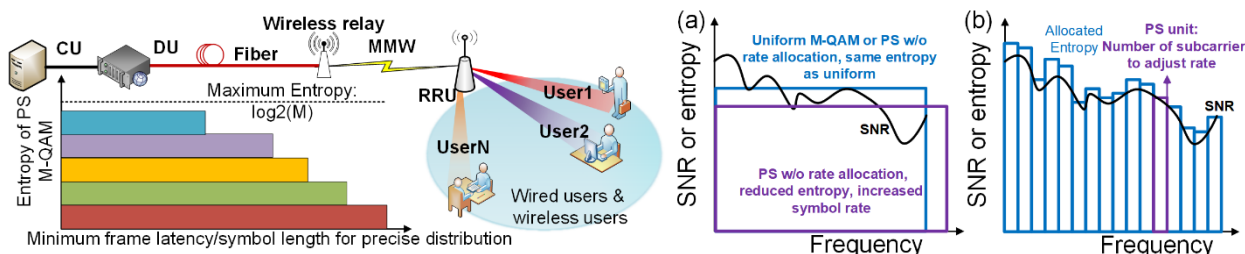


Fig 1. Fiber-wireless converged mobile fronthaul. (a) and (b): Principle of the adaptive rate allocation using PS based on measured channel SNR.

where $j \in [1, S]$, H_j and SNR_j denote allocated bits/symbol and pre-measured SNR of the j_{th} PS unit, respectively. H_{total} is the target bits/symbol of the whole data frame. Eq (1) ensures that the averaged entropy of the PS units corresponds to H_{total} . Since the distribution matcher rate loss increases with the decrement of symbol length and T/S ratio, the allocated entropy per unit is better in tracking the SNR fluctuation at the cost of higher complexity and extra latency [5]. In the case of lower H_j , frame latency must be increased, as shown in Fig.1, to ensure low rate loss. We also consider two different application scenarios. The first scenario is in bandwidth-limited systems, wherein a PS signal with a higher-order QAM is employed to achieve the same bits/symbol and same data rate as the uniform lower-order QAM. For instance, we compare the PS 64-/256-QAM with uniform 16-/64-QAM based on the same bits/symbol, and within the same bandwidth. In the second scenario, the available QAM level is fixed with an additional bandwidth being allocated for PS signals to achieve X bits/symbol. To keep the same bit rate, bandwidth of the PS signal will be increased by $\log_2(M)/X$ more than the uniform QAM scheme as shown in Fig. 1(i).

Fig. 2 depicts experimental setup of the proposed scheme. In the transmitter DSP, a pseudorandom binary sequence (PRBS) is split into two sequences, namely, sequence 1 and sequence 2 as shown in Fig. 2. Sequence 1 is divided into several PS units and loaded to CCDM block to generate the desired probability of symbol amplitude, which obeys Maxwell-Boltzmann (MB) distribution, as shown in Fig. 2(a). To combine PS with LDPC code, only half of amplitude levels are generated after the CCDM block, e.g., four levels (1,3,5,7) for 64-QAM and eight levels (1,3,5,7,9,11,13,15) for 256-QAM. After binary labeling the CCDM output amplitude to bits sequence, the bits sequence is combined with Sequence 2 from the original PRBS to perform encoding using the LDPC parity matrix (PM) with an overhead of 25%. Then we apply the β operation to the FEC encoding result and the second part of PRBS to generate a sequence with the same length of the output amplitude from CCDM, which can be used for the sign of the amplitude. Note that $\beta(1)=1$, $\beta(0)=-1$. QAM signal can be assembled from the amplitude and sign, which is followed by OFDM modulation and up-conversion. Consequently, the target distribution from CCDM is preserved without distortion after LDPC encoding [6]. Fig. 2(b) presents the probability distribution of the PS-5.75 64QAM signal and PS-7.8 256 QAM signal with 2-D MB distribution. The LDPC and PS encoded OFDM signal is generated through a digital to analog converter (DAC) and amplified via a power amplifier (PA) before it is loaded to a 10-GHz bandwidth Mach-Zehnder Modulator (MZM). After an optical boost of Erbium-doped fiber amplifier (EDFA), the signal is delivered through a 15-km single mode fiber (SMF) and then detected by a photodetector (PD). After O/E conversion, an electrical mixer directly upconverts the electrical signal to a 60-GHz MMW signal using an RF source and a frequency quadrupler. After 1.5-m MMW transmission, an envelope detector (ED) is utilized to detect and down-convert the signal. In the receiver DSP, after down-conversion, synchronization and equalization, and OFDM demodulation, we do inverse QAM assembling, which separates the sign and magnitude of the I and Q signal. Then we do FEC decoding and CCDM decoding to get the post-FEC BER.

3. Experimental results

Fig. 3 (a) illustrates the result of PS unit size sweeping using PS-4.0 64QAM versus uniform 16QAM with the same occupied bandwidth. There are 400 subcarriers and each of them has 54 symbols. The subcarrier spacing is 1.5MHz. Since the channel fluctuation is relatively flat, 400, 200, and 100 subcarriers per PS unit show similar performance. With fine adjustment, the sensitivity gain significantly increases with the decreasing of the number of subcarriers per PS unit block. However, when the PS unit size is reduced to 10 subcarriers, the performance becomes worse. This is

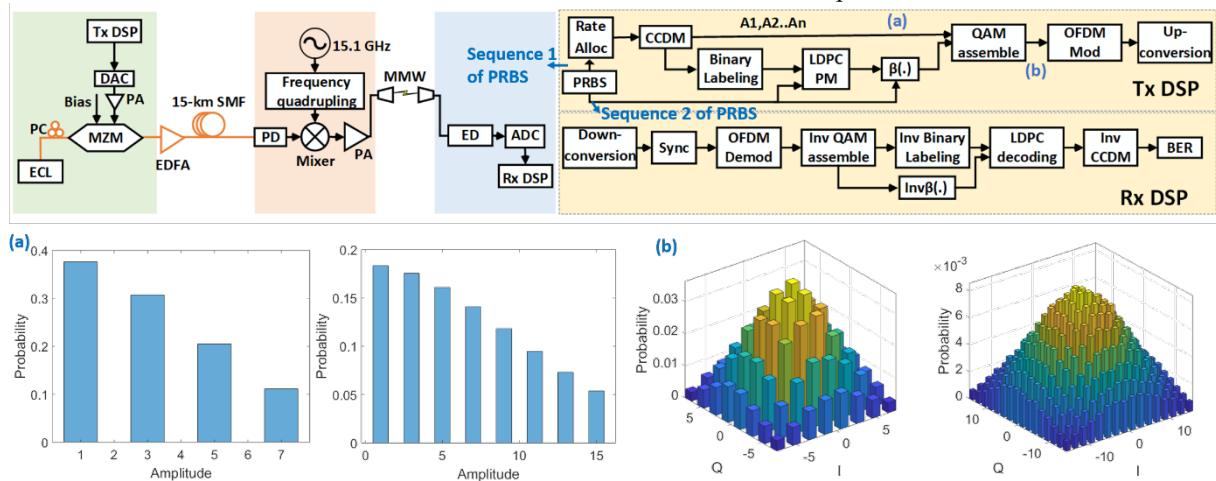


Fig 2. Experimental setup and DSP diagram., ECL: external cavity laser, ADC: analog to digital converter, sync: synchronization. (a) The probability distribution of the output of CCDM for PS 5.75 64QAM and PS 7.8 256QAM. (b) The probability distribution of the assembled PS 5.75 64QAM and PS 7.8 256QAM symbols.

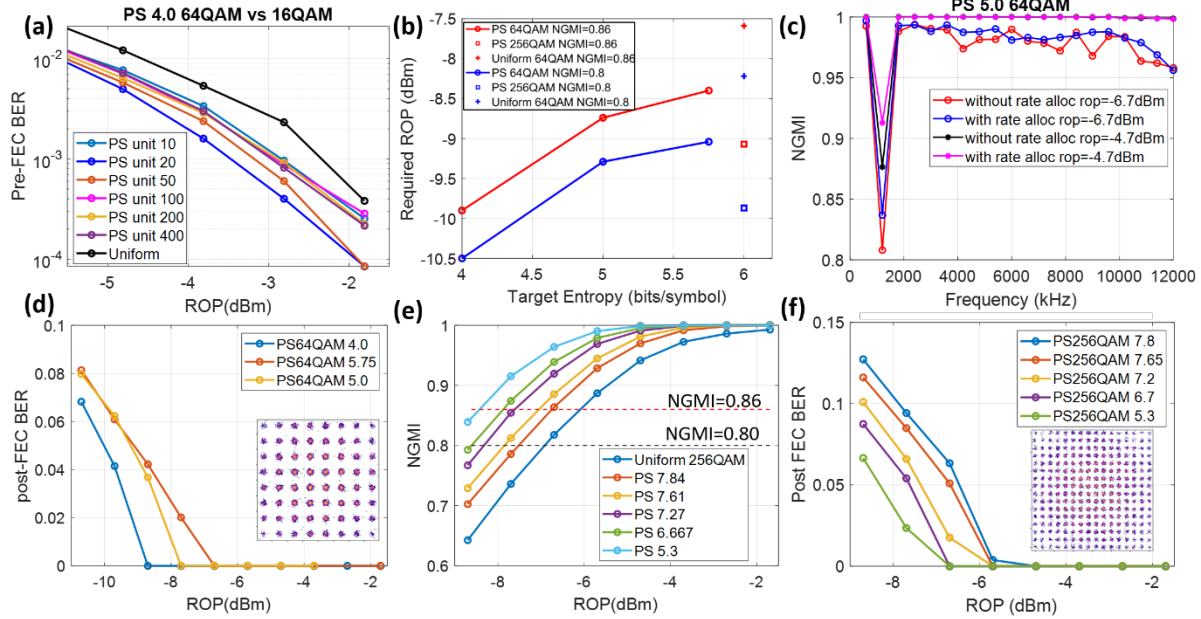


Fig 3. Experimental results. (a) Pre-FEC BER versus ROP of uniform 16QAM and PS 4.0 64QAM using different sizes of PS units. (b) Required ROP versus target entropy with certain NGMIs. (c) NGMI versus signal frequency with and without adaptive rate allocation. (d) Post-FEC BER versus ROP of PS 64QAM symbols. (e) NGMI versus ROP of PS 256QAM symbols (f) Post-FEC BER versus ROP of PS 256QAM symbols.

due to insufficient symbol length per PS unit for an accurate distribution matching and SNR estimation fluctuations. The issue can be solved by increasing the symbols per subcarrier to ensure sufficient symbol length for PS but it will increase the complexity and frame duration. In the following experiment, we utilize the optimized PS unit size of 20 for PS signal. Fig. 3(b)-(d) present the case of PS 64-QAM versus uniform 64-QAM. The signal consists of 400 subcarriers and 400×54 symbols with a subcarrier spacing of 500 kHz. To keep the same data rate, the bandwidth of the PS signal would be slightly increased to $6/\text{Entropy}$ of PS signal times the original bandwidth of uniform 64-QAM. Fig.3 (b) illustrates the required received optical power (ROP) for $\text{NGMI} = 0.86$ and 0.8 in different cases. Compared with uniform 64QAM, with slightly increased bandwidth, PS-5.75 shows around 0.8-dB sensitivity gain. PS-4.0 shows highest ROP gain (~ 2.4 dB) but needs 20% extra bandwidth to compensate for the lower entropy. Therefore, when the bandwidth is strictly limited, PS-6.0 256-QAM as indicated in the square box is the better choice, which shows 1.55-dB ROP improvement. Fig. 3(c) compares the performance of PS-5.0 64-QAM signal without rate adaptation and with rate adaptation, respectively. By allocating rate dynamically using a PS unit of 20 subcarriers per block, the NGMI over frequency domain is optimized and becomes smoother. Fig.3 (d) presents the post-FEC BER result, which verifies the gain presented by NGMI and pre-FEC BER. The inset is the recovered PS-5.75 64-QAM constellation at a ROP of -1.7 dBm. Fig.3 (e) and (f) show the results of PS 256-QAM with increased bandwidth versus uniform 256-QAM. The increased bandwidth of the PS signal with an entropy of X bits/symbol is increased to $8/X$ times the original bandwidth. There are 200 subcarriers and 200×81 symbols with a subcarrier spacing of 500 kHz. Fig. 3(e) illustrates that when the system has enough bandwidth, ROP gain increases with the decreasing of target entropy. The system shows up to 3-dB power margin gain regarding NGMI threshold of 0.86. Compared with PS 64-QAM signal, higher order QAM can achieve more improvement by using PS. Similarly, we present the post-FEC BER of the signal and the trend aligns with the NGMI performance in Fig. 3(e). PS signal with reduced target entropy shows better performance in post-FEC BER. Inset is the PS-7.8 256-QAM constellation at the ROP of -1.7 dBm.

4. Conclusion

We propose and experimentally demonstrate an rate allocation scheme based on PS unit in a LDPC coded PAS-OFDM radio based fronthaul. The scheme relaxes the latency requirement by grouping several subcarriers into one PS unit for entropy tuning. Optimal PS unit size with 20 subcarriers selected from PS unit size ranging from 10 subcarriers to 400 subcarriers can achieve a balance between the required sensitivity performance and precise distribution matching. PS unit size and total effective entropy tunability achieve a flexible adjustment of power margins gain from 0.8 dB to 3 dB with consideration about available bandwidth and processing complexity.

5. References

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