K-means assisted adaptively partitioned entropy loading for FBMC/OQAM system

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Abstract: We adopted K-means clustering to efficiently partition the subcarriers to reduce the complexity of PS-QAM on FBMC/OQAM system using KK receiver. The net data rate of 100 Gb/s is achieved after 125 km transmission. © 2020

1. Introduction

To approach the Shannon capacity, probabilistic shaping (PS) technologies eliminate the last stone in linear optical channels with powerful forward error correction (FEC) [1]. The combination of probabilistic amplitude shaping (PAS) and constant composition distribution matching (CCDM) elegantly realizes PS signals based on the conventional quadrature amplitude modulation (QAM) with soft-decision FEC (SD-FEC) [2]. In theory, PS-QAM signals can contribute 1.53 dB shaping gain in an additive white Gaussian noise (AWGN) channel compared to the conventional QAM signals [1]. However, in practical transmission systems, optical channels are generally in fading state due to the effect of the limited bandwidths, leading to a colored SNR distribution across the spectrum. Therefore, the total channel is no longer an AWGN channel, reducing the shaping gain of PS-QAM in single carrier systems. Fortunately, the multicarrier systems can refine this situation by slicing the spectrum. For example, the well-known orthogonal frequency division multiplexing (OFDM) signals equally divide the spectrum by hundreds of subcarriers. Therefore, each subcarrier exhibits nearly a flat channel response to emulate an AWGN channel, maximizing the shaping gains of PS-QAM signals. By loading the PS-QAM with specific entropy to each subcarrier, the Shannon capacity in a fading channel can be nearly achieved. The scheme is called entropy loading (EL) [3] referring to the classic bit and power loading (BPL). The EL efficiently enhances the performance of OFDM systems including coherent OFDM and discrete multi-tone (DMT). Recently, the EL of DMT breaks the record of data rate in single-lane intensity modulation and direct detection systems [4].

Generally, the conventional EL (CEL) scheme adapts to a channel by manipulating the entropy of every subcarrier, leading to an optimal performance but also a huge complexity. Each subcarrier consumes an individual distribution matchers (DM), which means that generally several hundred DMs are needed for CEL. By adaptively partitioning subcarriers into several precoding sets, the number of DM can be efficiently reduced to less than 4 while keeping the superior performance than BPL [5]. However, the partition process is based on the brute-force searching. With the increase of precoding sets, the complexity increases exponentially. Besides, to keep the orthogonality between subcarriers after optical fiber transmission, cyclic prefix (CP) and/or cyclic suffix (CS) should be inserted for DMT systems, which degrades the spectral efficiency (SE).

In this paper, we first perform the adaptively partitioned EL (APEL) on the filter bank multicarrier (FBMC) system using offset-QAM (OQAM) or staggered multi-tone (SMT) system [6]. By applying a prototype filter to each subcarrier, SMT completely removes CP/CS without inducing the inter-carrier interference (ICI) or inter-symbol interference (ISI) [6, 7]. And the Kramers-Kronig (KK) receiver is conducted to recover the optical field and enable chromatic dispersion compensation (CDC) [8]. Furthermore, we adopt the K-means clustering algorithm to solve the partition algorithm for APEL, of which complexity is dramatically reduced to a polynomial smoothed level [9] from the exponential level of brute-force searching. We demonstrate that the proposed low-complexity APEL achieves almost the same performance as the CEL by experiments.

2. K-means Assisted Adaptive Partitioned Entropy Loading

For EL, the loaded PS-QAM is determined based on the signal-to-noise ratio (SNR) of each subcarrier. Since the SNR of the subcarrier in conventional DMT systems varies individually, different PS-QAM is prepared for each subcarrier, leading to intolerable hundreds of different DMs. Fortunately, the SNR of subcarriers can be equalized by precoding, thus only one PS-QAM or DM is needed for each precoding set. As demonstrated in [10], the SNR equalization effect of precoding is also effective for SMT systems. Utilizing this effect, the PS-QAM can be loaded per precoding set instead of per subcarrier, substantially reducing complexities.

In [5], the subcarriers of DMT are partitioned to several precoding sets for the assignment of the suitable PS-QAM. To obtain the optimal pattern, brute-force searching is adopted, inducing relatively high complexity.

However, we found that the subcarriers in each optimally partitioned set have similar probe SNR, which can be abstracted to a clustering problem that the subcarriers are classified by their SNR. It can be efficiently solved by K-means algorithm. Since only one-dimension, SNR, is used, the complexity of the algorithm is low. And the number of precoding sets (NPS), K, just corresponds to the number of clustering. Therefore, the algorithm is simple and expressed in Fig. 1(a).

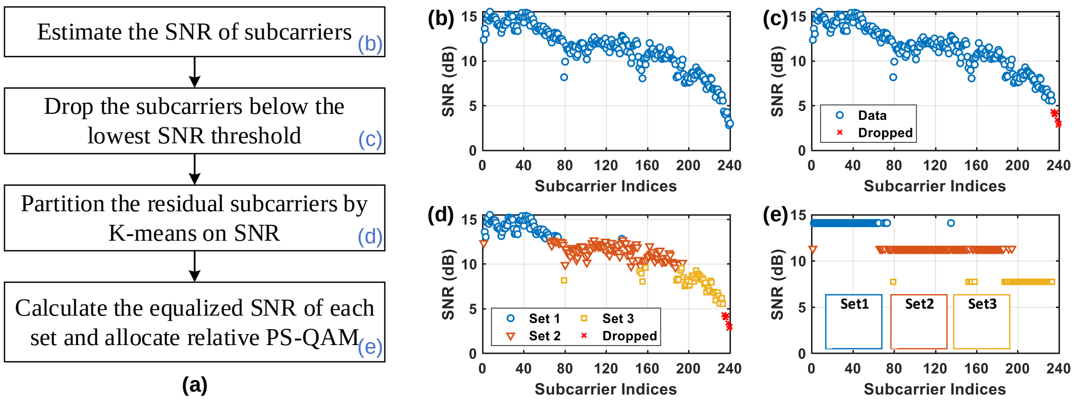
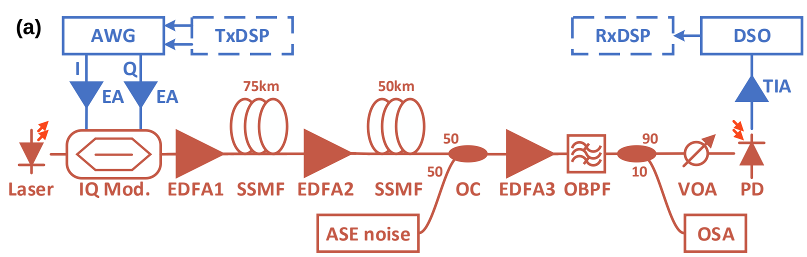


Fig. 1. K-means assisted APEL. (a) The flow diagram, (b), (c) and (e) the corresponding schematic diagrams

The first step is to estimate the SNR of each subcarriers by transmitting a probe signal (4QAM modulated SMT). One representative result is shown in Fig. 1(b). Then, the subcarriers with the SNR below the lowest SNR threshold are dropped in the second step, cf. Fig. 1(c). The lowest SNR threshold denotes the minimum SNR that can support the error-free transmission of 4QAM, identified by normalized generalized mutual information (NGMI). The detailed procedures to obtain the SNR thresholds of different PS-QAM can be found in [5]. In the third step, the K-means clustering algorithm is performed on the SNR in dB of the residual subcarriers. We take 3 as the NPS for example. As depicted in Fig. 1(d), the subcarriers with similar SNR are allocated into the same set. For each set, the noise power is expected to be equalized by precoding [11]. In addition to the water-filling criteria (The summation of noise power and signal power is a constant), the assigned signal power and equalized SNR is obtained. Finally, according to the relationship between SNR and optimal PS-QAM given in Fig. 1[5], the PS-QAM is assigned to each precoding set as shown in Fig. 1(e).

3. Experimental Results and Analysis



(b)

Tx DSP	Rx DSP
Serial to Parallel	Synchronization
CCDM	Serial to Parallel
Mapping	KK & CDC
Precoding	PPN Filtering
OQAM Modulation	FFT
IFFT	OQAM Demodulation
PPN Filtering	Channel Equalization
Parallel to Serial	NGMI & SNR Estimation

Fig. 2. (a) Experimental setup, (b) DSP blocks for transmitter (Tx) and receiver (Rx)

The proposed scheme is evaluated on the experimental setup shown in Fig. 2. In the transmitter, the serial pseudorandom data is generated by Mersenne Twister algorithm and converted to the parallel. Then, the parallel data in each precoding set are shaped by a CCDM and mapped to a QAM. After discrete Fourier transform (DFT) precoding operation, the signal performs OQAM modulation, of which detail refers to [6, 7]. After that, the data in frequency domain are transformed to the time domain by inverse fast Fourier transform (IFFT) with 512 points, where 240 subcarriers are loaded with data to generate single sideband (SSB) signal. The polyphase network (PPN) filtering adopts the PHYDYAS filter with the overlapping factor of 4 [7]. Then, the data is converted to the serial and loaded to an arbitrary waveform generator (AWG, Micram) with 70 GSa/s sampling rate. Subsequently, the baseband signal is amplified by two electrical amplifier (EAs) and modulated on the optical carrier (1550.12 nm center wavelength and 100 kHz linewidth) by an IQ modulator, of which bias voltage is tuned to optimize carrier to signal power ratio. The link consists of two spans of standard single mode fiber (SSMF) with the total length of 125 km. In the receiver, the signal is coupled with the amplified spontaneous emission (ASE) noise to control the optical signal to noise ratio (OSNR). Before detected by a photodetector (PD, 30 GHz bandwidth) equipped with a transimpedance amplifier (TIA), the out-of-band noise is filtered by an optical bandpass filter (OBPF) and a variable optical attenuator (VOA) keeps the received power constant at 0 dBm. Finally, the received signal is recorded by a digital storage oscilloscope (DSO, Keysight DSOX93304Q) with 80 GSa/s sampling rate. The DSP in the receiver is the inverse of that in the transmitter, where KK detection and CDC are performed to enhance the performance. The samples per symbol is set to 4 for KK detection. Hereafter, CDC is assumed to be conducted with KK detection. A SMT frame consists of 1 synchronization TS, 8 TSs for channel estimation, 1 null TS to divide other TSs with payload in time domain, and 160 payload SMT symbols. Besides, the CEL, the equally partitioned precoding (EPP) assisted EL and the BPL algorithm, Levin-Campello, are conducted as benchmarks. EPP divides subcarriers equally along the spectrum into each set.

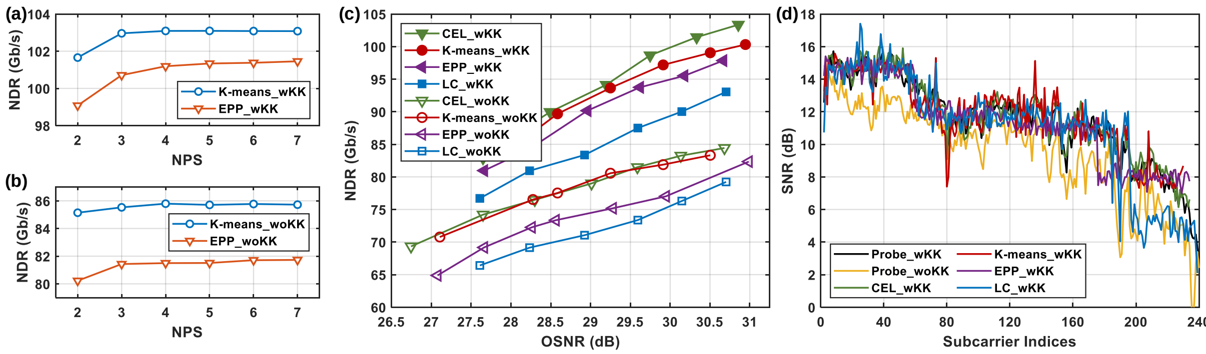


Fig. 3. Experimental results: The relationship between NDR and NPS (a) with KK detection and (b) without KK detection, (c) the NDR versus OSNR, (d) the SNR variation

We first investigated the impact of NPS on net data rate (NDR) which excludes all the redundancy. As shown in Fig. 3(a) and 3(b), the NDR increases with NPS but tends to be stable when NPS is larger than 3 for all the schemes with and without KK detection, which is similar to [5]. When NPS is set to 4, we measured the NDR by varying the OSNR. The comparisons of NDR for different adaptive loading algorithms are shown in Fig. 3(c), where all the measured points just meet the FEC limit indicted by NGMI. Without KK detection, the proposed K-means scheme almost achieves the same NDR as the optimal CEL. Lacking the optimization of precoding sets, the EPP scheme cannot compete with K-means scheme but still outperforms traditional LC scheme. Notably, KK detection improves the performance of all the schemes but does not change their relative relationship. The SNR variation of probe signal shown in Fig. 3(d) intuitively presents the SNR enhancement by KK detection. The SNR variation of CEL matches the probe SNR best, followed by that of K-means scheme thanks to its intrinsic clustering effect. While the EPP and LC could not deal with the fast SNR fading in high-frequency region. Though the CEL always achieves the optimal NDR, it maximally requires 240 DMs while the K-means and EPP only consume 4 DMs. Besides, the DM potentially requires long symbols to reduce the shaping rate loss. The subcarrier-wise allocation of PS-QAM suffers from large rate loss due to limited symbol length (160), making CEL hard to reach the expected NDR in practice. While the allocation per precoding set adopted by APEL, K-means and EPP, ensures sufficiently long symbol length (>5×10^3) to eliminate the rate loss.

4. Conclusions

In this paper, we proposed to use K-means clustering for the partition of precoding set to reduce the complexity of EL while keeping outstanding performance in practice. The algorithm is evaluated on the KK receiver assisted FBMC/OQAM or SMT system, which improves spectral efficiency compared to DMT system. Compared to the optimal CEL scheme, the K-means scheme achieves almost the same NDR with much less complexity. The NDR of 100 Gb/s is achieved by the proposed scheme after 125 km SSMF transmission. In addition, the first application of CEL and APEL on the FBMC based multicarrier system other than OFDM proves the wide feasibility of EL.

Acknowledgements

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