Probabilistic Amplitude Shaping to Enhance ARoF Fronthaul Capacity for Mm-Wave 5G/6G Systems

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Abstract—Analog radio-over-fiber (ARoF) technology has proven to be a promising solution to part of the future millimeter-wave (mm-wave) 5G/6G architecture due to its attractive benefits such as simplified remote antenna units (RAUs), low-power consumption, and low cost. However, ARoF channels present hefty drawbacks, such as phase noise and nonlinear effects, that need to be addressed. The probabilistic amplitude shaping (PAS) technique is able to reduce the impact of such drawbacks, allowing a fine optimization of channel capacity usage. In particular, enumerative sphere shaping (ESS) implementation stands out as an excellent PAS approach because of its energy-efficiency and low complexity for short blocklengths. In this work, for the first time to the best of our knowledge, an ESS scheme is evaluated in an experimental bidirectional mm-wave ARoF setup oriented towards 5G communications. Furthermore, a novel soft ESS demapping algorithm is proposed and explained. The experimental results confirm the ESS technique, together with the proposed algorithm, as a convenient solution to enhance the channel capacity use of mm-wave ARoF systems for the 5G/6G fronthaul.

Keywords—5G, 6G, ARoF, fronthaul, mm-wave, ESS, probabilistic shaping, OFDM, PAS, soft demapping.

I. INTRODUCTION

The emergence of new types of services such as virtual reality, 4K/8K video streaming, or Internet of things (IoT) demands a substantial enhancement in mobile networks. Improvements in terms of data rate, latency, number of connected devices, energy consumption, and reliability are crucial key performance indicators (KPIs) to guarantee a good user experience [1]. The fifth generation of mobile networks (5G) aims to upgrade the mentioned KPIs. The ongoing deployment of the 5G network is mainly focused on the usage of sub-6 GHz bands. Nonetheless, sub-6 GHz bands are congested and, thus, bandwidth limitation is a major impediment to increase the mobile network data rate. Since millimeter-wave (mm-wave) bands are the next operational frequencies to be exploited, one of the next steps for future mobile networks as 5G-advanced and 6G consists of the utilization of mm-wave signals. However, the employment of higher frequencies brings with it an increase in free-space path loss (FSPL), which consequently reduces the coverage radius of mobile cells. Thereby, the number of mobile cells will enormously increase compared to current mobile networks to cover the same area [2], making simplicity of the remote antenna unit (RAU) as an essential requirement to accomplish a scalable mm-wave 5G/6G network [3].

Analog radio-over-fiber (ARoF) raises as a suitable solution to simplify the complexity of the RAU, since radio frequency (RF) upconversion, digital-to-analog converters (DAC), and analog-to-digital converters (ADC) are not required in the RAU. Moreover, ARoF brings other attractive benefits such as large bandwidth, low latency, and high spectral efficiency [3], [4]. However, phase noise is considered a high limiting factor in mm-wave 5G/6G scenarios due to the relatively low subcarrier spacing of the orthogonal frequency-division multiplexing (OFDM) signals established in the 3rd Generation Partnership Project (3GPP) standardization [5], [6]. In addition, additive white Gaussian noise (AWGN) and nonlinear effects are also two of the other main impairments in OFDM ARoF systems [4]. In conclusion, ARoF channels are complex to the level that simple bit-loading schemes cannot fully exploit the maximum capacity. Therefore, rate adaptability methods are highly recommended to optimize the final performance in ARoF systems [7], [8]. Conventional modulation and coding schemes (MCSs) use uniform quadrature amplitude modulation (QAM) with variable forward error correction (FEC) rates. Nevertheless, according to [9] and [10], probabilistic amplitude shaping (PAS) QAM with a fixed FEC rate outperforms the mentioned MCSs in terms of rate adaptability and performance in optical fiber communications. Furthermore, the works carried out in [7] and [8] experimentally demonstrate that PAS-OFDM is a method of great rate adaptability to achieve the maximum capacity in ARoF fronthauls.

Constant composition distribution matching (CCDM) is the most evaluated and investigated architecture to reach PAS in the communication system literature due to its low complexity [11]. However, CCDM is inefficient in terms of rate loss and energy-efficiency for short blocklengths [12], [13]. Long PAS blocks imply a severe inconvenience in wireless communications since PAS frames are encapsulated in OFDM symbols. Thus, if the PAS blocks are excessively long, they are contained in more than one OFDM symbol, increasing the overall delay. This issue becomes more dramatic in mm-wave scenarios as shorter OFDM symbol durations are selected to handle the high phase noise associated with mm-wave signals [5]. Hence, CCDM is not a preferred solution for mm-wave 5G/6G wireless applications where latency is a critical factor. The enumerative sphere shaping (ESS) realization proposed in [12] is an excellent solution for performing PAS-QAM in fiber wireless communications due to its high energy-efficiency, low rate loss, and low computational complexity for short blocklengths [13], [14].
By taking advance of the shaping redundancy employed in the PAS signals, soft PAS demapping can be performed and, thus, the bit error rate (BER) can be reduced [14]. In this work, for the first time (to the best of the authors’ knowledge), an algorithm for softly demapping ESS blocks is presented and explained. The concept of this algorithm can be extrapolated to other PAS solutions. Moreover, for the first time, an ESS scheme is experimentally evaluated on a mm-wave bidirectional ARoF fronthaul adhered to the 5G numerology [6]. Additionally, hard and soft ESS demapping methods are compared in the experimental setup, showing a slightly improvement in performance when soft demapping is applied. Finally, the experimental ESS results show a substantial enhancement over the bit-loading technique, highlighting PAS implementation, and ESS in particular, as a promising candidate for optimizing channel capacity use in mm-wave 5G/6G ARoF fronthauls.

II. PROBABILISTIC AMPLITUDE SHAPING FOR THE ARoF 5G/6G FRONTHAUL

As mentioned above, ARoF is an excellent solution to deploy the future mm-wave 5G/6G fronthaul. However, the utilization of ARoF technology brings several drawbacks and these are the following:

**Phase noise:** according to the phase noise model of Leeon, the phase noise level is proportional to the carrier frequency [15]. Thus, mm-wave RF sources offer higher phase noise than other lower frequency bands. In addition, transporting mm-wave signals in ARoF links implies an increment of the final phase noise [16]. Furthermore, 5G New Radio (NR) signals are not robust in phase noise channels, as the OFDM subcarrier spacing values (15 to 240 kHz) are relatively low [5], [6]. Therefore, mm-wave OFDM ARoF systems are highly limited by phase noise.

**AWGN:** since high FSPL is inherently related to mm-wave wireless communications, a low-power signal is received when the user is relatively far from the RAU. Moreover, in an ARoF system, the AWGN noise floor is augmented by the devices involved in the system, such as lasers, RF amplifiers, or photodiodes (PD). Thereby, mm-wave ARoF channels are limited in terms of signal-to-noise ratio (SNR).

**Nonlinear effects:** signals transmitted through ARoF channels suffer from distortion. This distortion effect originates from components such as DACs, ADCs, RF amplifiers, Mach-Zehnder modulators (MZMs), and optical fibers due to their nonlinear transfer functions or finite resolutions. The distortion effect of these components increases for higher input signal powers, delimiting a distortion region and consequently reducing the dynamic range of the system [17].

The impacts of the three drawbacks explained above are gradually reduced by employing different PAS configurations on the data subcarriers of the transmitted OFDM signal. This fact is because the SNR and signal-to-interference ratio (SIR), caused by phase noise and nonlinear effects, increase when the low-power QAM symbols are more frequent [8], [18]. Therefore, applying PAS in mm-wave OFDM ARoF scenarios is a well-suited solution to maximize channel capacity utilization [7], [8]. As mentioned in Section I, ESS algorithms provide an excellent trade-off between energy-efficiency, rate loss, computational complexity, and blocklength compared to other solutions such as CCDM [12], [14]. In the following subsections, the concept of ESS and the proposed soft ESS demapping method will be presented and explained.

A. Enumerative sphere shaping for PAS approach

The PAS approach aims to optimize the communication channel capacity use by altering the probabilistic distribution of the M-QAM symbols. To achieve this, PAS algorithms increase the probability of low-power M-QAM symbols in respect to high-power symbols, moving from a uniform distribution to a Maxwell-Boltzmann distribution [12]. The way to perform this distribution conversion consists of including PAS redundancy and, hence, the throughput is reduced. In order to have higher probabilities on the lower power M-QAM symbols or, in other words, to reach a more confined Maxwell-Boltzmann distribution, it is necessary to add more PAS redundancy. Thus, the M-QAM signal can gradually adapt to the channel conditions by correctly choosing the most fitted PAS configuration. The most studied and investigated PAS architecture is CCDM due to its low computational complexity [11]. However, sphere shaping (SS) is a more preferred solution than CCDM. This preference is because SS is able to use all the sequences inside of the sphere while CCDM utilizes some of the sequences located on the surface of the sphere (see Fig. 1) [12]. Therefore, SS solutions offer more energy-efficient PAS blocks than by using CCDM and, thus, the rate loss is lower [12].

The ESS algorithms proposed in [12] employ the SS architecture and lexicographical ordering. These algorithms are computationally less complex than other SS solutions such as shell mapping (SM) [14]. Thereby, the benefits of

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Fig. 1. Comparison between the sequences utilized by CCDM (left) and SS (right) architectures. Each circle corresponds to an N-dimensional shell where the radius is proportional to the PAS block energy. The colored segments refer to the sequence used in the respective PAS approach.

Fig. 2. Block diagram for generating PAS-OFDM signals using ESS.
using SS architectures to perform PAS with low complexity can be realized by using the ESS algorithms of [12]. Specifically, these ESS algorithms are two: the enumerative shaping algorithm whose goal consists of transforming the uniform distribution of the input pulse amplitude modulation (PAM) symbols into a Maxwell-Boltzmann distribution; the enumerative deshaping algorithm realizes an inverse process to obtain the initial PAM symbols. To realize PAS-QAM, the enumerative shaping algorithm is applied independently for in-phase and quadrature PAM symbols and the signals of the M-QAM symbols are included, as shown in Fig. 2. For a PAS-OFDM implementation, the enumerative shaping algorithm is employed on the data M-QAM subcarriers before OFDM modulation on the transmitter side, as illustrated in Fig. 2. On the receiver side, Fig. 3 shows the inverse procedure for decoding the received PAS-OFDM blocks. Observing Fig. 3, a hard PAM demapping block is needed before the enumerative deshaping algorithm. Furthermore, in this work, a novel soft ESS demapping algorithm is proposed to improve final yields by taking advantage of PAS redundancy. The soft ESS demapping process is included in the block diagram of Fig. 3 and will be explained in the next subsection.

B. Soft ESS demapping

The PAS redundancy included during the ESS shaping can be used to determine if the received ESS block belongs to the ESS codebook. A simple way to identify an ESS non-codeword is to check if the energy of the received ESS block is located inside of the ESS sphere (see Fig. 1). The flowchart of Fig. 4 classifies the different types of ESS blocks received with errors. An errored ESS block means that the transmitted and received ESS blocks differ by one or more PAM symbols. The worst case occurs when the received ESS block belongs to the ESS codebook. In this case, the error detection is not feasible to realize using only PAS redundancy. On the contrary, when the errored ESS block is a non-codeword, this can be classified in terms of energy: non-codewords with more energy than the ESS external shell -type A error-; and non-codewords with energy inside of the ESS shell -type B error-.

Algorithm 1 Soft ESS demapping algorithm

Given \( r_1, r_2, \ldots, r_N \) and \( R_1, R_2, \ldots, R_N \):

1. Calculate hard demapped ESS block energy as
   \[
   E_r = \sum_{k=1}^{N} | R_k |^2
   \]

2. Exit the algorithm if \( E_r \) is inside of the ESS shell
   \[\text{if } (E_r \leq E_{\text{max}}) \text{ then}
   \text{Exit algorithm}
   \]

3. Calculate the Euclidean distance for each PAM symbol of the received ESS block as
   \[
   d_k = R_k - r_k
   \]

4.Modify \( R \) in order to obtain a demapped ESS block energy inside of the ESS shell
   \[
   k = 1
   \]
   \[
   \tilde{R} = R
   \]
   \[
   E_{\text{diff}} = E_r - E_{\text{max}}
   \]
   \[
   d_k' = d_k
   \]
   \[
   \text{while } [(E_{\text{diff}} > 0) \text{ and } (k \leq N)] \text{ do}
   \]
   \[
   n = \text{argmax}(d_k')
   \]
   \[
   m = \text{argmax}(\mathcal{A}_k = R_n)
   \]
   \[
   \text{if } m > 1 \text{ then}
   \]
   \[
   R_n = \mathcal{A}_{m-1}
   \]
   \[
   E_{\text{diff}} = E_{\text{diff}} - |\mathcal{A}_m - \mathcal{A}_{m-1}|^2
   \]
   \[
   \text{end if}
   \]
   \[
   d_m' = -\infty
   \]
   \[
   k = k + 1
   \]
   \[
   \text{end while}
   \]

The ESS blocks with type A error are very simple to detect and most non-codewords fall into this category. Concerning the type B error, since the lexicographical ordering is utilized, some non-codewords are inside of the ESS shell and, thus, the ESS deshaping algorithm must be employed to identify them. Fortunately, the number of ESS blocks with type A error is significantly larger than those with type B error because only a few internal shell combinations are non-codewords [12]. Therefore, for an appropriate trade-off between performance and complexity, the proposed soft ESS demapping algorithm focuses on the detection and correction of received ESS blocks with type A error.

Algorithm 1 describes the proposed soft ESS demapping method where \( R, \tilde{R}, N, \) and \( E_{\text{max}} \) are the hard and soft demapped symbols, the ESS blocklength, and the maximum energy of the ESS codebook, respectively. This algorithm is applied for each received ESS block \( r \) (see Fig. 3). Furthermore, in algorithm 1, \( \mathcal{A} \) refers to the PAM alphabet \{1, 3, 5, 7, . . .\} [12]. The proposed algorithm is composed of four steps: the first two steps aim to identify if the received ESS block is a non-codeword with type A error; the third step calculates the Euclidean distance which is used as a figure of merit to determine the less reliable PAM symbols to modify; the fourth step modifies the less reliable PAM symbols of the hard demapped ESS block \( R \). The intention of this fourth step is to correct the wrong PAM symbols of the hard demapped ESS
Fig. 5. Experimental setup to realize a bidirectional mm-wave 5G fronthaul based on ARoF.

### TABLE I. ESS CONFIGURATION PARAMETERS.

| Config. | A | B | C | D | E | F | G | H | I | J | K | L |
|---------|---|---|---|---|---|---|---|---|---|---|---|---|
| M-QAM   | 16| 16| 16| 16| 16| 16| 64| 64| 64| 64| 64| 64|
| Uniform | No| No| No| No| Yes| No| No| No| No| No| No| Yes|
| N       | 10| 10| 10| 10| 10| - | 18| 18| 18| 18| 18| - |
| L       | 8 | 7 | 6 | 5 | 4 | - | 19| 16| 14| 12| 10| - |
| OH PAS [%] | 33.3| 23.5| 16.3| 12.4| 8.7 | - | 29.9| 25| 20.5| 14.9| 11.1| - |
| Effective bits/symbol | 3 | 3.24| 3.44| 3.56| 3.68 | 4 | 4.62| 4.8 | 4.98| 5.22| 5.4 | 6 |

block. To achieve this, the fourth step attempts to modify the less reliable symbols of the hard demapped ESS block to obtain an ESS block energy within the ESS sphere. This modification consists of replacing the selected symbol by the previous PAM symbol of the alphabet $\mathcal{A}$ (e.g., $3 \rightarrow 1$ or $5 \rightarrow 3$) and, then, $E_{\text{diff}}$ is diminished. In addition, the reliability of the PAM symbols is indicated by the Euclidean distance. In algorithm 1, the maximum value of $d'$ is set to $-\infty$ to ensure that the selected PAS symbol is not considered in subsequent iterations. Lastly, it is important to highlight that the correction success of algorithm 1 is inversely proportional to the number of erroneous PAM symbols within the hard demapped ESS block.

III. EXPERIMENTAL SETUP

Fig. 5 shows the bidirectional experimental setup to perform a 5G mm-wave fronthaul based on ARoF [4]. This experimental setup is the same as presented in [4] with the difference that an RF switch and variable optical attenuator (VOA) are used after the end-user antenna and before the multicores fiber (MCF) of the downlink path, respectively. The gray boxes in Fig. 5 delimit the different segments involved in the 5G fronthaul: central office (CO), RAU, and end-user. The configuration of the setup is according to the mm-wave 5G standard [6]: OFDM as modulation format; 240 kHz of subcarrier spacing; time-division duplexing (TDD) as multiplexing scheme; 26 GHz is the carrier frequency (center of n258 band); and 245.76 MHz of bandwidth. One of the objectives of this bidirectional setup consists of sharing the vector signal generators (VSGs) between both directions, reducing complexity, cost, and power consumption [4]. More details about the experimental setup can be found in [4]. Additionally, the spectrum shapes for various points of the experimental setup are illustrated at the bottom of Fig. 5.

In the CO of the downlink part, first, an external cavity laser (ECL) emits an optical carrier at C-band. Then, the generated optical carrier is modulated with an RF carrier of 11.5 GHz using a null-biased MZM. In this way, two optical tones are produced with a separation of 23 GHz (Fig. 5 (A)). Next, the two optical tones are boosted and modulated with the OFDM signal by employing an erbium-doped fiber amplifier (EDFA) and a second MZM, respectively (Fig. 5 (B)). Subsequently, the modulated optical signal passes through a 10 km MCF. In the downlink RAU side, the optical signal beats on a PD, amplifying a modulated RF signal at 26 GHz (Fig. 5 (C)). Then, the RF signal is boosted by a medium power amplifier (MPA) and sent over a 9 m wireless link with a horn antenna. The end-user antenna catches the downlink transmitted signal. Consequently, RF amplification, downconversion, and filtering processes are performed (Fig. 5 (D)). Lastly, the resulting signal is sampled with a digital phosphor oscilloscope (DPO).

In the uplink path of the end-user, the OFDM signal is generated with an arbitrary waveform generator (AWG). Next, the signal is upconverted and boosted (Fig. 5 (E)). After that, the mm-wave signals pass through the wireless link. The second horn antenna of the RAU side receives the uplink transmitted signal at 26 GHz. Then, the RF signal is amplified with a low noise amplifier (LNA), downconverted, and filtered with a low-pass filter (LPF) (Fig. 5 (F)). The resulting RF signal is used to modulate an optical carrier generated by a second ECL. Hence, the uplink modulated optical signal passes through the MCF on a different core than the downlink. At the CO, a second PD is used to convert the optical signal into the electrical domain. Finally, the resulting electrical signal is captured and sampled by a second DPO.
Since the end-user only disposes of one horn antenna and both directions use the same frequency band, an RF switch is required. The commutation of this RF switch is determined by the slot time of each direction according to the TDD schedule. A Raspberry Pi is employed to control the RF switch. For a proper TDD implementation, the AWGs and DPOs of each direction, and the Raspberry Pi must be synchronized. For simplicity, this synchronization is carried out in the controller setup where a central computer sends the commands to each instrument (see green box in Fig. 5). Furthermore, in order to evaluate the ESS solution in a mm-wave 5G fronthaul, different ESS configurations are transmitted in the presented setup. Table I shows the main parameters of these ESS configurations, where $M$ is the modulation order, $N$ is the number of PAM symbols per ESS block, $L$ is the number of energy levels at the last stage of the ESS trellis [12], and OH PAS is the overhead in percentage introduced by the PAS process. It can be observed that the ESS scheme under evaluation permits a gradual entropy (effective bits/symbol) adaptation. Moreover, to evaluate the performance of the ESS signals transmitted in the experimental setup under different SNR conditions, a power sweep is realized on the downlink and uplink paths by tuning the VOA voltage and the power of the end-user VSG, respectively.

### IV. EXPERIMENTAL RESULTS

Fig. 6 depicts the BER results as a function of the SNR by employing some configurations of Table I in the experimental setup explained in Section III. The top graph refers to the uplink direction, while the bottom one concerns the downlink. Furthermore, the 25% and 7% overhead (OH) FEC thresholds are also illustrated in Fig. 6 as dotted gray lines. These thresholds represent the maximum input BER when the output BER target is $10^{-9}$ for FEC configurations of 25% and 7% OH, respectively [19]. In addition, the dotted and continuous BER results refer to when the soft ESS demapping algorithm is applied or not, respectively. In this way, the yields of the proposed soft ESS demapping method can be appraised. Examining Fig. 6, it can be noticed that the uplink BER results perform better under the same SNR conditions. This difference in performance between both directions is due to the fact that the signal transmitted through the downlink path suffers from more nonlinearities. Most of these nonlinearities are caused by signal compression in devices such as RF amplifiers and MZMs. Moreover, by inspecting Fig. 6, a gap between 16-QAM and 64-QAM BER results can be detected for both directions. This gap is because PAS 64-QAM configurations have smaller spacing between constellation points and, hence, the BER increases substantially. Nevertheless, it can be noticed a gradual decrease in BER in the 16-QAM and 64-QAM regions when using the different ESS configurations.
The configuration with maximum entropy (effective bits/symbol) of Table I is estimated when its BER value is below the 7% or 25% OH FEC thresholds in Fig. 6. This process is done by an SNR step size of 0.01 dB. To achieve this SNR granularity, a linear interpolation of the SNR results of Fig. 6 is realized. With this procedure, the entropy results of Fig. 7 are obtained. The bit-loading solution is also displayed along with the soft and hard ESS implementations. The striped colored areas of Fig. 7 refer to the entropy improvement when using hard ESS implementation relative to the bit-loading method. Observing both graphs in Fig. 7, there is a significant enhancement when using the ESS implementation since the bit-loading technique offers large entropy steps ($\log_2(M)$ bits/symbol) while ESS allows for a more gradual entropy range. Therefore, the ESS scheme under evaluation conceives intermediate entropy values between bit-loading steps, approaching the channel capacity utilization to the Shannon limit. In addition, respecting the bit-loading technique, the ESS enhancement of Fig. 7 is greater in the downlink results because there are more nonlinearities in this direction and PAS-OFDM can be greater harnessed. In conclusion, the presented ESS scheme is highly recommended in mm-wave AROF fronthaul systems that suffer from severe nonlinearities.

The flat colored areas in Fig. 7 correspond to the increase in entropy when applying the soft ESS demapping with respect to the hard method. In this case, the entropy improvement is small, but appreciable. Nevertheless, the proposed algorithm 1 has low computational complexity and hence even small gains may justify its application. In addition, for future works, the reliability of the soft ESS demapped block can be quantified with a figure of merit. This figure of merit determines the reliability of the received ESS block respecting the ESS codebook. Thus, in combination with channel coding, such a figure of merit can be employed in an iterative decoding scheme as turbo codes do. In such a manner, the final BER can be substantially reduced.

V. CONCLUSIONS

In this work, firstly, the advantages of using PAS for mm-wave AROF fronthaul are presented. In particular, ESS algorithms are highlighted as a suitable solution to implement PAS due to their low rate loss and high energy-efficiency. Next, a novel soft ESS demapping algorithm is explained and presented. Then, a specific ESS scheme is experimentally evaluated in a bidirectional mm-wave AROF setup attached to the 5G standard with 9 m of wireless link. Respecting the bit-loading technique, the experimental results show a significant improvement in terms of channel capacity utilization when using the under-test ESS scheme. Moreover, the proposed soft ESS demapping algorithm outperforms the hard solution, marking it as an adequate complement for ESS implementations. Furthermore, by comparing the results of the different directions, it is experimentally proven that ESS is especially useful in channels with nonlinearities as it can help overcome their effects. Finally, as a remarkable conclusion, the experimental results validate the PAS solution and, in particular ESS, as an excellent method to optimize the channel capacity use in mm-wave OFDM AROF systems for 5G/6G communications.

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