Non-Uniform Constellations for ATSC 3.0

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***Abstract*—This paper introduces the concept of a non-uniform constellation (NUC) in contrast to conventional uniform quadrature-amplitude modulation (QAM) constellations. Such constellations provide additional shaping gain, which allows reception at lower signal-to-noise ratios. ATSC3.0 will be the first major broadcasting standard, which completely uses NUCs due to their outstanding properties. We will consider different kinds of NUCs and describe their performance: 2-D NUCs provide more shaping gain at the cost of higher demapping complexity, while 1-D NUCs allow low-complexity demapping at slightly lower shaping gains. These NUCs are well suited for very large constellations sizes, such as 1k and 4k QAM.**

***Index Terms*—Non-uniform constellations, constellation shaping, QAM, ATSC3.0, terrestrial broadcast.**

I. Introduction

THE TRANSITION from first to second generation digital terrestrial broadcast systems, such as transition from DVB-T to DVB-T2 [1], offered a variety of new technologies and algorithms, which reduced the gap to the famous Shannon limits [2]. One major trend was the adoption of more powerful forward error correction (FEC) schemes. Cutting-edge low-density parity-check (LDPC) codes together with an outer BCH code replaced the long established combination of a convolutional code with an outer Reed-Solomon (RS) code. Similar data throughput was thus achieved at about 5dB less signal-to-noise ratio (SNR) [3]. Subsequent activities to further improve FEC schemes resulted in minor additional gains in the order of 0.01-0.3dB. Larger FEC gains were obtained at the price of higher complexity, e.g., by LDPC parity check matrices with higher density and or longer codeword lengths. Obviously, the new FEC schemes were already close to optimum. In order to further increase spectral efficiencies, the constellations had to be changed. While conventional quadrature-amplitude modulation (QAM) employed signal points on a regular orthogonal grid, so-called non-uniform constellations (NUCs) loosened this restriction.

Constellation shaping techniques have a long history: already in 1974, Foschini (now well known for his groundbreaking work on multi-antenna systems) and his colleagues proposed constellations, which minimize symbol error rates over an additive white Gaussian noise (AWGN) channel [4]. Ten years later, Forney et al. provided a mathematical proof of the ultimate shaping gain limit [5]. This limit however only applies to the so-called signal set capacity. A more realistic capacity limit is given by the bit interleaved coded modulation (BICM) capacity [7]. In [8], several known constellations (e.g., square or rectangular grids) were compared with respect to this BICM capacity. Other methods to obtain shaping gain tried to heuristically force the constellation to look Gaussian-like [9], however lacking a mathematical proof. The optimization of constellations in the 1-dimensional space with respect to BICM capacity was first described in [10]. In [11], constellations up to 32-QAM have been optimized in the 2-dimensional space to maximize BICM capacity for the AWGN channel and a range of SNR values. A summary of both optimized NUCs in both 1- and 2-dimensional space is given in [12], where constellations up to 1048576 points are examined.

In general, signal shaping can be classified into two groups: probabilistic shaping, which tackles the symbol probabilities by using a shaping encoder, and geometrical shaping by modifying the location of the constellation points. The former approach requires a shaping decoder at receiver side, which increases the overall complexity. The latter only requires to store a new set of constellation points and may require finer quantization in hardware implementations. This paper focuses only on geometrically shaped NUCs.

In March 2013, the Advanced Television Systems Committee announced a 'call for proposals' for the ATSC 3.0 physical layer, with one of the goals being to maximize spectral efficiencies [13]. It was thus not completely unexpected that the proposed technologies included both LDPC codes for FEC, and NUCs for constellations. ATSC3.0 may most likely become the first major broadcast system deploying such constellations.

This paper is structured as follows: Section II provides an introduction to the limits imposed by information theory, with focus on BICM capacity, which will be used as optimization criterion for NUCs, as discussed in Section III. Here, we will

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distinguish between 2-dimensional NUCs and low-complexity 1-dimensional NUCs. Simulation results are presented in Section IV, the conclusions are drawn in Section V.

II. Ultimate Communication Limits

A. Channel Capacity

In his seminal work, Shannon defined the maximum possible throughput over any given channel as the *channel capacity* [2]. The channel is fully described by its transition probabilities $p(r_k|s_k = x_l)$, where we assume a memoryless channel. The index k denotes the discrete time index, s_k and r_k are transmitted and received symbols at time k, respectively. The particular transmit symbol x_l is taken from an alphabet $\mathbb{X}$, which may be finite or infinite. For an AWGN channel, $p(r_k|s_k = x_l)$ is simply a Gaussian distributed probability density function, centered around the transmitted symbol (assuming zero-mean noise), with noise variance according to SNR. Shannon's channel capacity is the maximum mutual information (MI) between channel input s_k and output r_k, where maximization is performed over the distribution of the input alphabet $\mathbb{X}$. To keep the amount of mathematical details to a minimum, the interested reader is referred to [14]. Here, we will simply explain MI between two random variables A and B as the amount of information, which can be gained about B by observing A (or vice versa, since MI is commutative). The receiver of a communication system has an uncertainty about the potentially transmitted symbols s_k. But luckily, it can observe the channel output r_k, which helps reducing this uncertainty, and this reduction is exactly the MI. For the AWGN channel, Shannon proved that the maximum MI can be achieved, if the transmit alphabet $\mathbb{X}$ is itself Gaussian distributed, resulting in the famous capacity of $C_C = \log_2(1+\text{SNR})$, given in bits/s/Hz. This serves as an ultimate limit for the channel itself, but can never be achieved by a practical system, since an infinite number of transmit symbols has to be realized.

B. Signal Set Capacity

Another capacity limit includes the particular modulation format, in general a QAM constellation with symbols from a finite alphabet $\mathbb{X}$. The number of symbols m, i.e., the cardinality of $\mathbb{X}$, is usually a power of 2, $M = \log_2(m)$ being the number of bits, which are mapped to a symbol via a bit labelling function μ. The resulting capacity C_S is called *signal set capacity* (or sometimes coded modulation (CM) or multilevel coding (MLC) capacity), and is given by the maximum MI between the input bits of the QAM mapper and the channel output, as indicated in Figure 1. We assume equiprobable symbols x_l, i.e., each symbol occurs with probability $p(x_l) = 1/m$. Thus, no maximization of MI has to be performed, assuming that the symbols are defined by a particular constellation (e.g., located on an equidistant uniform grid). No restriction has been made about the receiver of this system, so it is assumed that a perfect receiver is decoding the symbols r_k. This can be realized by a joint symbol detector and decoder, where demapping and FEC decoding are considered as a combined unit. Multilevel codes (MLC) are one way to approach this limit [15], with trellis coded modulation (TCM) [16] as a special form thereof. Another way to approach C_S is to use iterative demapping and decoding as deployed in BICM-ID schemes [17], [18].

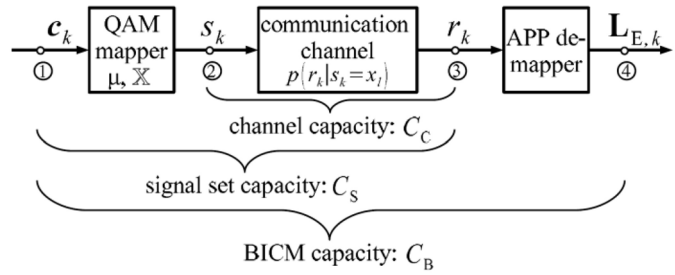

Fig. 1. Definition of channel, signal set and BICM capacity.

C. BICM Capacity

Finally, a more pragmatic communication system decouples symbol demapping from FEC decoding, and assumes that a QAM demapper computes soft values once, which will be forwarded to the subsequent FEC decoding stage. To fully decouple FEC encoding and mapping (especially for fading channels), an interleaver is placed between these blocks. The resulting system is thus called bit-interleaved coded modulation (BICM) [6], and the ultimate throughput limit is termed *BICM capacity* C_B [7], see Figure 1. An optimum demapper at receiver side computes a posteriori probabilities (APP) as soft values, typically in the form of (extrinsic) log-likelihood ratios (LLR), called $\mathbf{L}_{E,k}$ in Figure 1. This vector comprises all M LLRs for each of the M bits per symbol.

If C_B (in bits/s/Hz) is smaller than the overall FEC code rate, error free reception is not possible. Hence, C_B has to be large enough to provide the FEC decoder with LLRs exceeding a particular reliability level to provide low bit error rates. For a given channel realization, the only way to maximize C_B is to apply shaping to the constellations.

D. Capacity Comparisons

For the AWGN channel, the above three capacities are compared in Figure 2. The signal set capacity (here called CM capacity) and the BICM capacity are plotted for well-known uniform constellations with Gray labelling. In general $C_C > C_S \geq C_B$, but the difference between C_S and C_B is hardly visibly for Gray mappings. Both C_S and C_B converge towards M bits/s/Hz, when the SNR tends towards infinity. As can be observed, the C_B curve has a gap to the Shannon limit, which becomes larger, the bigger the constellation size is. This gap can be further reduced by using NUCs instead of conventional constellations, as described later.

While the signal set capacity is independent of the labelling function μ, the BICM capacity does depend on bit labelling. Usually, Gray labelling is deployed, where adjacent symbols differ in one bit only. It is interesting to note that constellations with more than 16 points do not have a unique class of Gray labellings, but allow for several kinds of Gray labellings, with

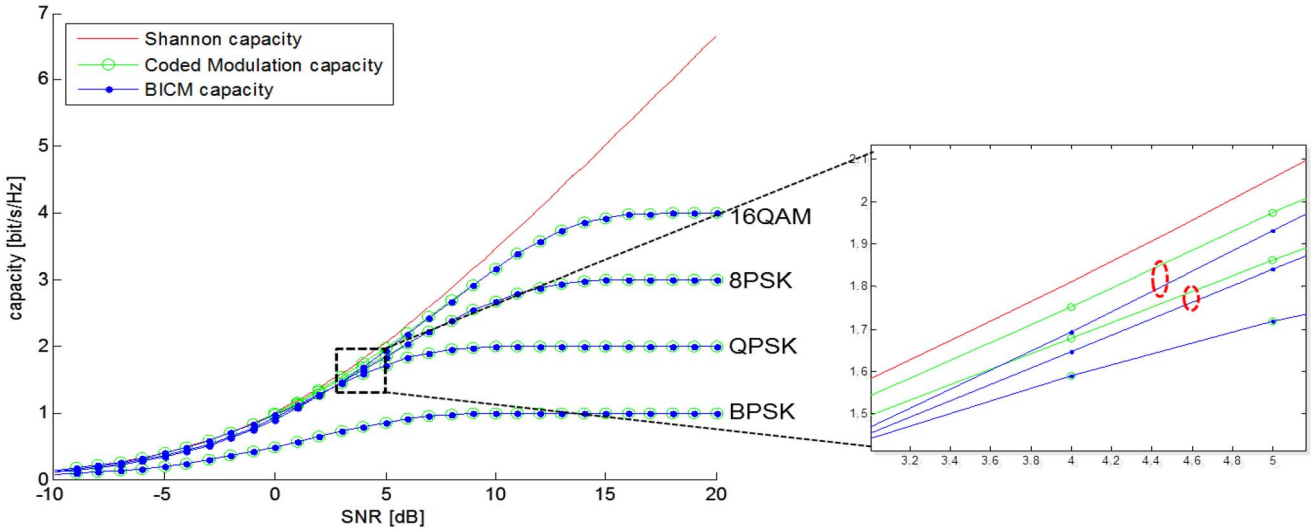

Fig. 2. Shannon's channel capacity, CM and BICM capacity.

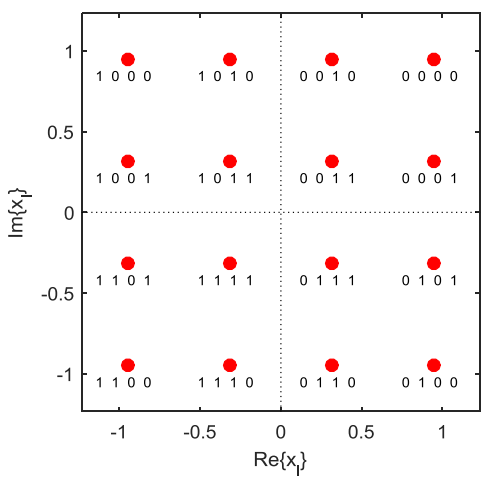

Fig. 3. Uniform 16QAM constellation with binary reflected Gray labeling.

the so-called binary reflected Gray labelling offering the maximum BICM capacity for a uniform constellation [19]. Figure 3 depicts such a labelling for a 16QAM constellation, which is deployed in systems like DVB-T or DVB-T2. The constellation points are uniformly located on an orthogonal grid with the same minimum Euclidean distance of points to their closest neighbours. Such constellations are called uniform constellations (UCs) in contrast to non-uniform constellations, which will be discussed in the following chapter.

III. Optimization of Non-uniform Constellations

When optimizing NUCs of a given constellation size m for a transmission system using a BICM chain, we need to maximize the BICM capacity C_B. The only constraint on the constellation is that the average transmit power should be constant, usually normalized to unity, i.e., the transmit symbols need to fulfil the following power constraint

$$\mathcal{P}_x = \frac{1}{m}\sum_{l=0}^{m-1} |x_l|^2 \overset{!}{=} 1. \tag{1}$$

The task is to maximize C_B by modifying the QAM symbols x_l, considering constraint (1). Since C_B depends on the channel transition probabilities $p(r_k|s_k = x_l)$, this optimization has to be performed for each particular channel. In particular, a different optimum NUC may result for an AWGN channel for each SNR value. For modern FEC codes, such as LDPC, with their steep bit error rate (BER) curves as a function of the SNR, the target SNR of the NUC is easily selected according to the SNR of the code's waterfall region (the SNR where the BER curve drops by several orders of magnitude), i.e., for each code rate a different NUC is used [20]. This allows for optimum performance, independent of the SNR at each user's location. When a user suffers worse SNR than the target SNR of the FEC code (and the NUC), successful decoding is anyhow not possible due to the cliff behaviour of "all-or-nothing" FEC codes. In contrast, when the actual SNR is better than the target SNR, decoding is still possible even though the constellation may not be optimal for the actual SNR. NUCs for ATSC3.0 have been optimized both with respect to performance over flat AWGN channel and over independent and identically distributed Rayleigh fading with perfect side information at receiver side. To further optimize the combination of coding and modulation, the bit interleaver was carefully optimized as well for each combination of constellation size and code rate.

The degrees of freedom (DOF) for the optimization are the m complex symbols $x_l \in \mathbb{X}$. In the following, we will describe two different optimization approaches.

A. Two Dimensional NUCs

All m complex DOFs will be considered to optimize 2D NUCs, i.e., $2m$ real-valued DOFs have to be optimized. For a 16QAM, this results in 32 DOFs. To reduce the number of DOFs of 2D NUCs by a factor of four, quadrant symmetry can be assumed [12]. In general, one DOF can be fixed due to power constraint (1), but this depends on the way the optimization problem is solved. Since capacity functions are in general

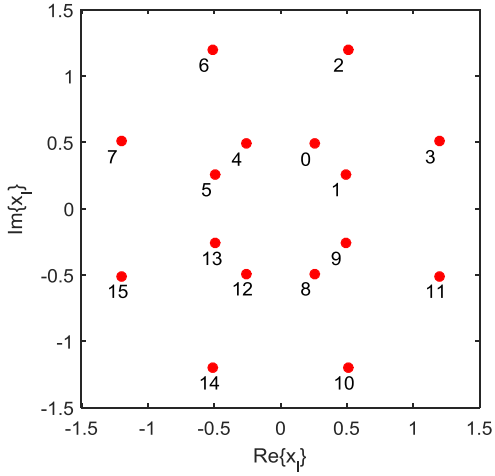

Fig. 4. Optimized 2D 16NUC for ATSC3.0 for LDPC of rate 7/15.

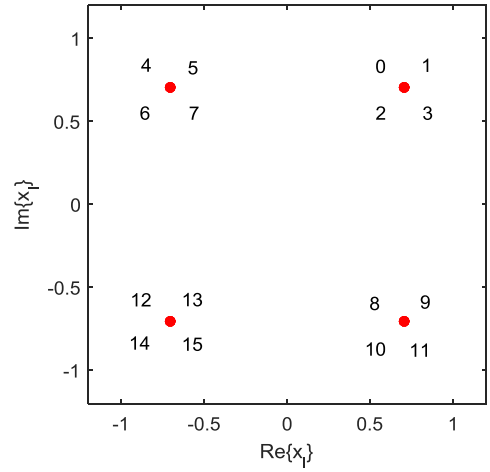

Fig. 5. Optimized 2D 16NUC for ATSC3.0 for LDPC of rate 2/15.

non-convex, optimization thereof relies on numerical tools such as non-linear gradient search algorithms. Some optimization methods consider a two-step approach of an unconstrained optimization followed by a radial contraction to comply the power constraint in a second step [4], others apply constrained quadratic programming methods [21] or yet other tools.

As an example, Figure 4 shows a NUC with 16 constellation points (called 16NUC), which has been optimized for ATSC3.0 for a combination with an LDPC code of code rate 7/15. The bit labels are given as integer numbers, with 0000 corresponding to 0, 0001 to 1, and so on (least significant bit is the right-most label). The constellation resembles a 16APSK (amplitude phase shift keying), but a closer view reveals four different amplitudes, not only two. Nevertheless, all 2D NUCs from ATSC3.0 offer a symmetry with respect to the four quadrants, i.e., the complete constellation can be derived from the first quadrant by simple rotation rules. The target SNR for the AWGN channel of this NUC was about 5.3dB. At this SNR, the uniform 16QAM from Figure 3 offers a BICM capacity of C_B(5.3dB, 16QAM) = 2.00 bits/s/Hz. The optimized 16NUC from Figure 4 offers at the same SNR C_B(5.3dB, 16NUC) = 2.04 bit/s/Hz, i.e., 0.04 bits/s/Hz more, which corresponds to a theoretical SNR gain of about 0.16dB. In practice, the gain in bit error rates simulations was about 0.2dB.

To understand the outcome of an optimized NUC, let us focus on an extreme case, where the target SNR for the AWGN channel is chosen extremely low. The outcome can be seen in Figure 5, which is a 16NUC for code rate 2/15. This very low code rate allows receiving this constellation at about -2.6dB SNR. Only four points are visible, resembling the classical quadrature phase shift keying (QPSK) constellation, but in fact, these are four clusters consisting of four almost identical points. The reason why this constellation still works fine at very low SNR is that at least two out of $M = 4$ bit labels offer robust MI: the first two most significant bits (left-most labels) offer similar robustness as the two bit positions of a QPSK, which is optimum for four constellation points (maximizing Euclidean distance, while maintaining independent dimensions for each bit). The other two weaker bit levels are "sacrificed" for this purpose, since they cannot be resolved anymore from the (almost) overlapping points. The bit-wise MI of those weak bits is close to 0 and will remain so, even for very large SNR. In general, NUCs of all constellation sizes converge towards a "QPSK-like" constellation, if target SNR goes to very small values, i.e., four clusters will remain with $m/4$ overlapping points each.

As another extreme case, consider the application for very large code rates, i.e., very large target SNR. In such cases, the NUCs tend to become uniform QAM constellations, with the BICM capacity converging towards M bits/s/Hz. This implies that conventional uniform QAM constellations are only optimum for uncoded systems, if SNR is significantly large, but in combination with FEC coding, they are outperformed by NUCs.

Note from Figure 4 that the four bit levels cannot be demapped independently. A uniform QAM such as the one from Figure 3 on the other hand allows demapping half of the bits independently from the other half. In case of the depicted 16QAM, the first and third bit label are mapped to the real part of the constellation, while the second and forth bit label are mapped to the imaginary part. Thus, demapping can be split into two independent demappers for each dimension: effectively, only a real-valued pulse amplitude modulation (PAM) is demapped on each axis, resulting in much lower complexity.

B. One Dimensional NUCs

To exploit the properties of two independent dimensions as in uniform QAM constellations, the NUC is reduced to a one-dimensional PAM with non-uniform points. Both real and imaginary component of the NUC are formed by the same PAM. An m-ary complex constellation is thus reduced to $\sqrt{m}$ real-valued points. We may further assume symmetry to the origin, resulting in only $\sqrt{m}/2$ real-value points (again, one of these points may be normalized due to power constraint (1)). The resulting NUC will be called 1D NUC.

For example, a 1024QAM (also called 1k QAM) has 2048 real-valued DOFs for 2D NUCs, but only 16 DOFs for 1D NUCs. The optimization process itself is greatly eased by

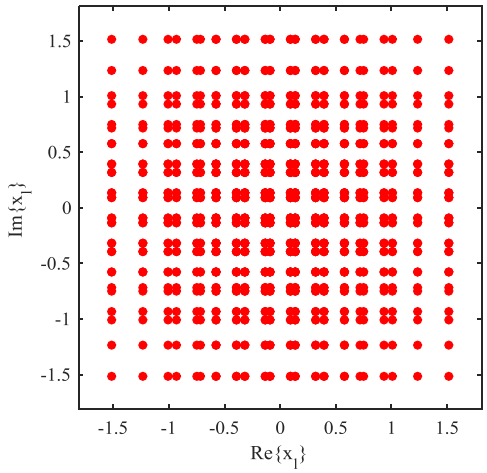

Fig. 6. Optimized 1D 1k NUC for ATSC3.0 for LDPC of rate 7/15.

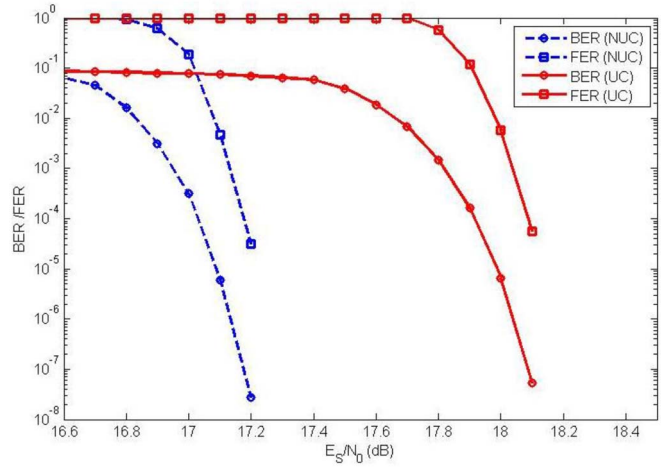

Fig. 7. Shaping gain of conventional uniform constellation (UC) versus NUC for 256QAM and 64k LDPC of rate 10/15 over AWGN channel.

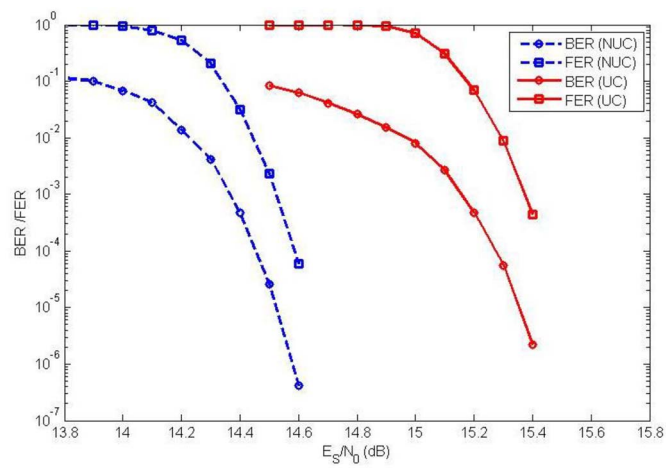

Fig. 8. Shaping gain of conventional uniform constellation (UC) versus NUC for 256QAM and 64k LDPC of rate 7/15 over Rayleigh i.i.d. channel.

this limitation, but mostly, the complexity reduction for the demapper is an important feature. Maximum likelihood (ML) demapping of a 2D NUC has to consider all m constellation points for APP computation, but only $2 \cdot \sqrt{m}$ candidates for 1D NUCs (the factor 2 arises from 2 independent PAM demapping processes).

For ATSC3.0, 16QAM, 64QAM and 256QAM have been optimized as 2D NUCs, but for 1k and 4k constellations, lower complexity 1D NUCs have been proposed. The drawback of 1D NUCs is that the restriction of DOFs results in slightly smaller shaping gains compared with the 2D variants. Figure 6 shows as an example a 1D NUC with 1024 constellation points (1k NUC), optimized for an LDPC of rate 7/15. Both real and imaginary component apply the same 32PAM, and half of the bit labels (not shown in the figure) are mapped independent of the other half to each dimension.

It can be shown empirically (not shown here) that 2D NUCs offer about 0.2-0.3dB more shaping gain compared with 1D NUCs of the same constellation size due to the larger number of DOFs for NUC optimization.

IV. Simulation Results

ATSC3.0 offers a large variety of modulation and coding combinations, called MODCODs [22]: LDPC codes have either 64800 or 16200 bits as codeword lengths (64k or 16k codes, respectively), with code rates ranging from 2/15 to 13/15, in steps of 1/15 [23]. 64k codes have better performance than their shorter counterparts, but require more memory for decoding and have some impact on latency and power consumption. Constellations in ATSC3.0 range from very robust QPSK modulation over 16NUC to 4096NUC, each constellation carefully optimized for the LDPC code rate. The same constellation is used for both 16k and 64k LDPC, since the LDPC performance difference is rather small (less than 0.5dB on average) and to reduce the amount of different constellations.

Figure 7 depicts bit and frame error rates (BER and ER, resp.) over the AWGN channel, when using a 64k LDPC of rate 10/15 and an outer BCH code together with a traditional uniform 256QAM, in comparison with the optimized 256NUC from ATSC3.0 for this MODCOD. At FER = 10^{-4}, the NUC constellation allows reception at SNR level (here E_s/N_0) being 0.91dB lower than that for the uniform counterpart.

As pointed out before, ATSC3.0 NUCs have been designed considered both AWGN and Rayleigh fading channels. Figure 8 demonstrates the performance of a 256NUC, using 64k LDPC of lower rate 7/15. The channel is a passive one-tap Rayleigh fading channel, with fading coefficients being independent identically distributed (i.i.d.), which models a fully interleaved fading channel. Compared with the state-of-the-art uniform constellation, the SNR gain at FER = 10^{-4} is 0.9dB.

Such SNR gains, also called shaping gains, in dB, are summarized in Figure 9 for 64k codes of rates 2/15 until 13/15 for the AWGN channel of NUCs proposed for ATSC3.0 versus conventional uniform constellations of the same size. As a rule-of-thumb, shaping gains tend towards 0 for extremely small or large code rates ("(almost) all constellations are equally bad or good, respectively"), with a maximum shaping gain for rates around 7/15. However, for lower constellation sizes, such as 16QAM and 64QAM, an impressive gain is still

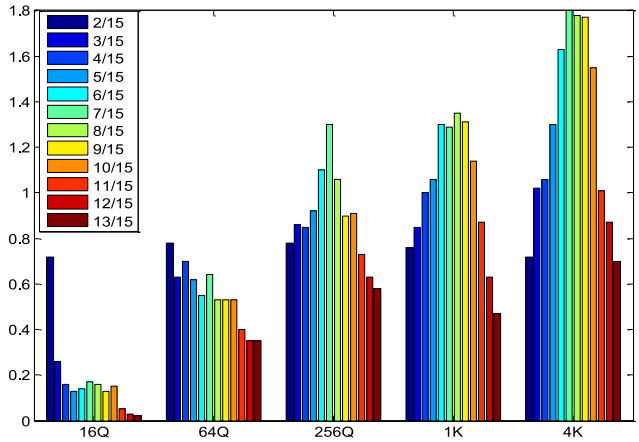

Fig. 9. Performance gains in dB of ATSC3.0 NUCs versus uniform constellations over AWGN channel.

possible also for low code rates like 2/15. Further, shaping gains become larger the larger the constellation size is. The reasons are that more DOFs are available for optimization, but also that larger uniform constellations result in a bigger gap to the Shannon limit, as shown in Figure 2. For 16NUC, only 0.2dB gains can be expected for 2D NUCs (almost no gain for 1D NUCs – not shown), while 256NUCs already exceed 1dB of shaping gains. For 1k and larger NUCs, up to 1.8dB are possible, which is well above the famous shaping gain limit of 1.53dB derived in [5]. However, this limit holds only for NUCs optimized with respect to signal set capacity C_S. The ultimate shaping gain limit with respect to BICM capacity C_B is still to be derived.

V. Conclusion

In this paper, we presented non-uniform constellations (NUCs), carefully designed for the ATSC3.0 physical layer. The design considered different channel realizations, and took the combination of LDPC code and bit interleaver into account. Results showed that shaping gains of more than 1.5dB are possible, which can be seen as a major step towards the ultimate limits of communications and which qualifies ATSC3.0 to become a future-proof cutting-edge terrestrial broadcast standard.

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