Non-Uniform Constellations for Broadcast and Multicast in 5G New Radio

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***Abstract*—5G New Radio (NR) is the wireless standard that will become the foundation for the next generation of mobile networks. NR implements different techniques that improve the performance in terms of data rate, coverage, reliability, latency or mobility. However, NR still has room for performance improvement in modulation, since it employs uniform Quadrature Amplitude Modulation (QAM) constellations to map information bits into complex symbols. Non-Uniform Constellations (NUC) are a practical solution to reduce the gap to Shannon. They are optimized by means of signal geometrical shaping for a specific signal-to-noise ratio (SNR) and channel model. Non-Uniform Constellations (NUCs) are presented in this paper as a potential technique to be implemented in future releases of 5G NR. A novel algorithm is also introduced for the design of NUCs for specific Modulation and Coding Schemes (MCS), which offer high performance gains compared to QAM. The optimized constellations provide gains up to 0.8 dB for AWGN channel.**

***Index Terms*—5G, New Radio, Non-Uniform Constellations, modulation, optimization.**

I. Introduction

MOBILE communications are experiencing a new era. In the last few years, media has evolved from downloading data on desktop computers and laptops to streaming on smartphones and tablets. Over 78% of the world's mobile data traffic is expected to be video by 2021 [1]. This increasing demand presents new challenges that may not be fulfilled when using cellular networks based on unicast. For this reason, the 3GPP standardization forum specified the use of broadcast in 4G Long Term Evolution (LTE) with the adoption of evolved Multimedia Broadcast Multicast Services (eMBMS) [2]. Unlike unicast, this service allows an infinite number of users to receive the same content simultaneously while using just a small amount of network resources. However, eMBMS has important limitations due to the reuse of LTE unicast networks and the lack of a flexible resource allocation [3].

5G New Radio (NR) is the wireless standard that will become the foundation for the next generation of mobile networks. It represents a key opportunity to deliver a seamless and integrated solution using unicast, broadcast and multicast. NR implements different techniques such as Long Density Parity Check (LDPC) and polar codes for performance improvement, scalable numerology with different Transmission Time Intervals (TTI) in order to reduce latency or the use of MIMO (Multiple-Input Multiple-Output) with a large number of antennas to deliver great capacities to users.

However, one of the significant limitations of 5G NR is the use of uniform Quadrature Amplitude Modulation (QAM) constellations to map information bits into complex symbols. QAM modulators employ a square shape with regularly spaced symbols in both in-phase (I) and quadrature (Q) components, permitting the use of a very simple demapping process. The receiver complexity is reduced but as main drawback the constraints imposed introduce a performance loss [4]. An important capacity increase in a future NR broadcast solution could be obtained by using Non-Uniform Constellations (NUC) instead [5]. In this case, constellation symbols are designed for a specific signal-to-noise ratio (SNR) by means of geometrical signal shaping and provide better performance than uniform QAM constellations. NUCs can also benefit from the uplink, which gives additional information on channel conditions. Two different types of NUC are considered in this paper, i.e. 1D- and 2D-NUC. 1D-NUCs have non-uniform distance between constellation symbols but keep the square shape to maintain demapping complexity. 2D-NUCs increase this complexity by relaxing the square shape constraint, but also providing better performance than both QAM and 1D-NUCs.

Previous work addressing the design and optimization of these constellations as well as the demapping complexity implications at the receiver can be found in the current literature. The non-uniform concept was first introduced in [6], which noted the capacity shortfall of uniform QAM and provided different constellations offering a capacity improvement. The concept of 1D-NUC was afterwards discussed in [7], and reference [5] optimized high-order 1D- and 2D-NUCs for an Additive White Gaussian Noise (AWGN) channel. In [8], high-order NUCs with constellation sizes of up to 4096 symbols are also investigated. At the receiver, sub-optimal demappers to reduce complexity with 2D-NUCs have been proposed in [9] and [10] for single and multiple antenna systems respectively.

For instance, an area already implementing NUCs is digital terrestrial broadcasting. The state-of-the-art specification ATSC 3.0 (Advanced Television Systems Committee - Third Generation) [11] includes both 1D and 2D-NUCs as a mandatory technology for the delivery of media services. Specific NUCs were designed for each coding rate (CR) and modulation order according to the SNR of the waterfall region. The same process can be applied to 5G. This work presents a set of NUCs designed for 5G NR and specific Modula-

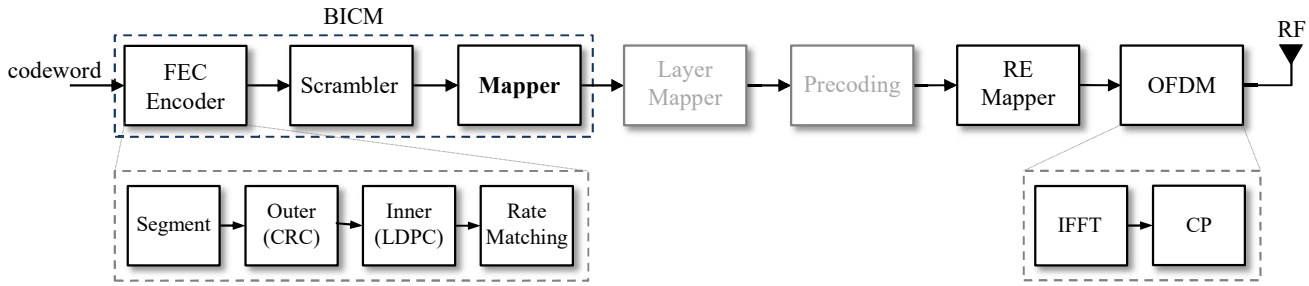

Fig. 1. Generic 5G New Radio physical layer transmitter block diagram considered for single antenna communications.

tion and Coding Schemes (MCS). Each MCS index uses a different constellation order and coding rate (CR), therefore requiring for a specific symbol distribution that performs under particular SNR values. These constellations could be used for a terrestrial 5G broadcast mode using a specific physical channel. Another possibility is to include them as part of a mixed broadcast/unicast mode in future 5G releases [12] [13]. Note that the design in both cases is equivalent, since the SNR target does not change, and would provide significant advantages with use cases where high capacities are required, such as Media and Entertainment (M&E) [14]. The optimized constellations provide up to 0.8 dB of gain for AWGN channel.

The rest of this paper is structured as follows. Section II briefly introduces the physical layer of 5G NR. In Section III, NUCs are designed for a wide range of MCS indexes. Section IV presents both capacity and performance analysis, where obtained gains are also shown. Finally, the main findings of the work are summarized in Section V.

II. 5G New Radio: Physical Layer Overview

An initial 3GPP NR Release-15 was delivered in December 2017 and the final version is expected to be published in June 2018. Fig. 1 shows the physical layer transmitter block diagram specified in [15] and [16]. For simplicity, only a single antenna configuration is considered in this paper. A transport block (TB) with data bits is inserted to the Bit-Interleaved Coded Modulation (BICM) chain and encoded using a combination of error detection, error correcting and rate matching. First Cyclic Redundancy Check (CRC) bit sequence is attached to the TB. If the TB size is larger than the maximum code block (CB) size, the input data bit sequence is then segmented and an additional bit sequence is attached to each CB. The bit sequence for a given CB is then coded using a Low-Density Parity-Check (LDPC) matrix. The rate matching for coded data then consists of the selection and pruning or repetition of bits and a bit interleaver. Bits generated are then scrambled and split into groups of bits depending on the modulation order and mapped to constellation symbols. Complex modulated symbols are then passed to the layer mapper and precoder. Since this works only considers the use of a single antenna, these two blocks are not needed. Instead, the complex symbols are just located in the resource elements available in the corresponding subframe and modulated to transmit using an Orthogonal Frequency-Division Multiplexing (OFDM) signal. Finally, a cyclic prefix (CP) with specific duration is inserted.

It is important to note that the CR and modulation combination provides the BICM spectral efficiency that this technology can achieve. Unlike 4G, the target CR is predefined. Both the modulation order and CR are given by the MCS [17]. The TB size and therefore the input bits to transmit may change, but the optimum constellation designed for a specific MCS index will remain always the same, as next sections show.

III. Non-Uniform Constellations Design

The theoretical approach given by Shannon indicates that the best capacity for an AWGN channel is only obtained if the received signal has a Gaussian distribution [18]. However, mobile communications have traditionally used QAM constellations, which imply received signals with nearly rectangular shape. The use of discrete symbol distributions clearly affects the transmitted signal. The idea under NUCs is to adapt this distribution to the channel and maximize the BICM capacity.

Let x denote the transmitted signal and y the received signal. Given a wireless communication system with channel h, the received signal is calculated as $y = hx$. From reference [19], BICM systems can be modelled as a set of m parallel binary-input channels, which are connected to the encoder output by a switch modelling an ideal interleaver. Each channel m corresponds to a position in the signal label of the constellation χ. Hence, the BICM capacity (in a single antenna system) can be calculated as follows:

$$C = m - \sum_{l=1}^{m} E_{x,y,h} \left[\log_2 \frac{\sum\limits_{x' \in \chi} p(y|x',h)}{\sum\limits_{x' \in \chi_l^b} p(y|x',h)} \right] \tag{1}$$

where $E_{x,y,h}$ denotes expectation with respect to x, y and h, $b \in \{0,1\}$ is equiprobable, and χ_l^b denotes the set of symbols in the constellation χ for which the code bit c_l equals b. This expression holds in general for all signal sets χ, and for all memoryless vector channels such as AWGN, Rice or Rayleigh. This formula is the basis of the optimization algorithm used, which is explained next.

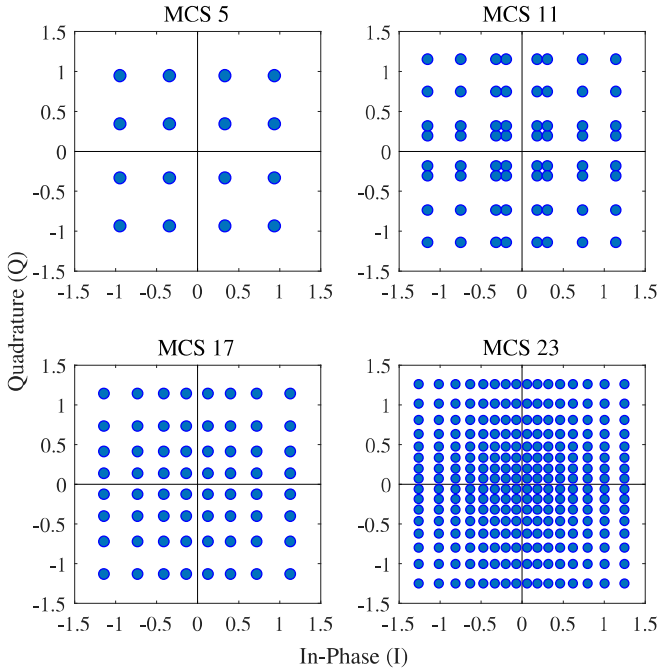

Fig. 2. Examples of 1D-NUC optimized for different constellation orders and specific MCS 5, 11, 17 and 23.

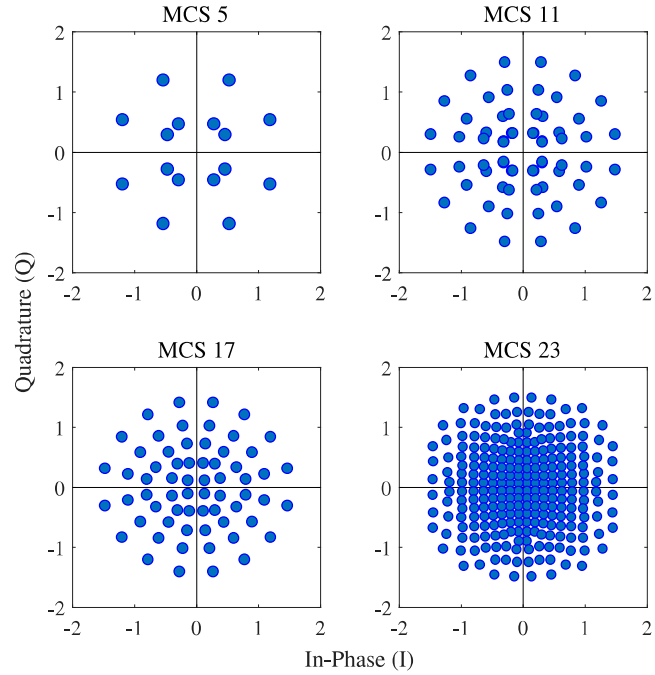

Fig. 3. Examples of 2D-NUC optimized for different constellation orders and specific MCS 5, 11, 17 and 23.

A. Optimization Process

Two types of NUC are addressed in this paper, depending on the number of dimensions considered in the optimization, i.e. 1D and 2D-NUC. The optimization burden is drastically reduced when defining just the first quadrant of the constellation. With 2D-NUCs, real and imaginary parts are the variables to optimize, and the total number of parameters is $M/2$, where M is the number of constellation symbols. The number of parameters with 1D-NUCs is reduced to $\sqrt{M}/2$, since only the positions in a single I/Q component need to be optimized. Note that there is no possible optimization with QPSK.

In the case of high-order constellations, an exhaustive search across all parameters is infeasible. It is hence desired to use an algorithm with low complexity and high computational efficiency that provides an optimum result. In this work, we use an iterative algorithm to gradually modify symbol positions. Let $\mathbf{x}$ be a set of input constellations and C the capacity obtained using (1). On first run, the algorithm is passed the first constellation of $\mathbf{x}$ and iteratively modifies the symbol positions until it converges to a local minimum. Once this initial run identifies a new optimum constellation, it is stored and the next in $\mathbf{x}$ is tested. This process is repeated iteratively until all constellations in $\mathbf{x}$ are exhausted. Finally, the stored constellation with highest capacity is returned. Examples of initial constellations may be QAM or NUCs obtained previously for a similar MCS.

B. Designed Constellations

Constellations have been designed for MCS indexes defined in 3GPP for 5G NR. In this paper, we use indexes from 5 to 27, as defined in [17] (Table 5.1.3.1-2). Note that there are two possible tables to determine the modulation order and CR associated to an MCS index. For simplicity, only the table considering the highest constellation order specified in NR, i.e. 256QAM, is selected. Indexes from 0 to 4 are used with QPSK and therefore are out of the scope of this work. The SNR is selected for each MCS as the value that provides a block error rate (BLER) of 1% with QAM. The bandwidth is 10 MHz and the numerology employed is $\mu = 0$, i.e. 15 kHz of carrier spacing. Fig. 2 and Fig. 3 depict several examples of 1D- and 2D-NUCs designed for MCS 5, 11, 17 and 23. At low MCS indexes, constellations tend to group some symbols in clusters and they evolve towards Gaussian shapes as the MCS increases.

The overall performance can be improved by using these constellations in future 5G broadcast and multicast solutions. In fact, since the constellation design is not very sensitive to a specific SNR under evaluation, the use of NUCs can provide capacity improvements even when the constellation was not originally designed for that SNR. Following this approach, in this paper we also design and evaluate a single NUC that maximizes the average BICM capacity for a whole range of SNRs associated to all MCS indexes used for a particular constellation order. Gains are not optimum in this case, but receivers only have to store a single constellation, maintaining memory requirements. Complexity-wise, the optimum case is the use of a single 1D-NUC that keeps not only QAM memory requirements but also the demapping complexity. This constellation provides a performance gain in all cases, if the constellation order is high enough, as shown in next section.

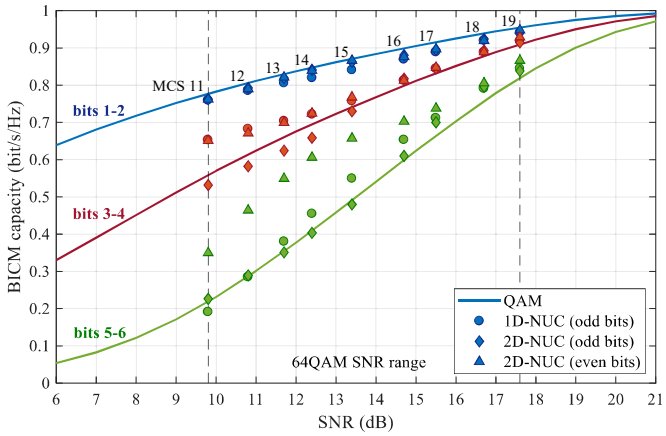

Fig. 4. Bit-level BICM capacities with 64NUC and 64QAM. MCS from 11 to 19.

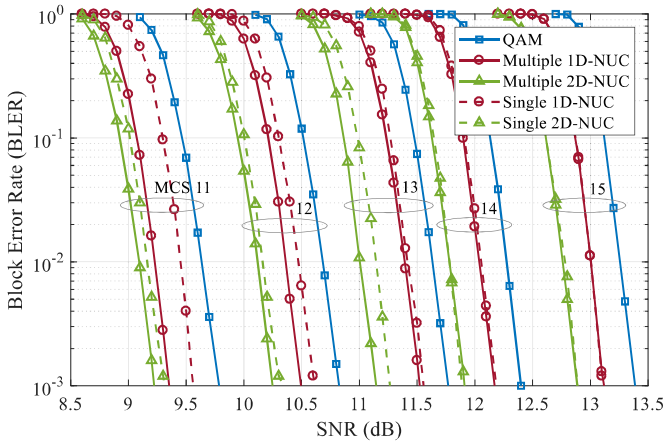

Fig. 5. SNR performance vs. block error rate of different types of constellation: 64QAM, 1D-64NUC and 2D-64NUC, for MCS from 11 to 15, AWGN channel.

IV. Performance Analysis

A. BICM Capacity Improvements

Fig. 4 depicts the bit-level capacities calculated for a Gray-coded 64QAM constellation, for a complete SNR range from 6 to 21 dB. It also shows 1D/2D-64NUCs optimized for specific SNRs and MCS indexes from 11 to 19 [17]. For the sake of simplicity, only odd bits are shown with 1D and QAM (I component), since the capacity for even bits is almost identical due to the square shape. As Fig. 4 shows, in every case the bit-level capacity for QAM reaches an asymptotic value of 1 bit/s/Hz, when the SNR is sufficiently high. The highest improvement with NUCs is achieved for low MCS indexes and the capacities become similar to QAM as the SNR increases. It is also important to highlight that NUCs sacrifice some capacity for the most significant bits at the expense of a very high increase in the rest of bits.

It is possible then to affirm that each NUC performs better at its design SNR than its uniform variant. At low SNRs, both 1D- and 2D-NUCs give similar gains due to the

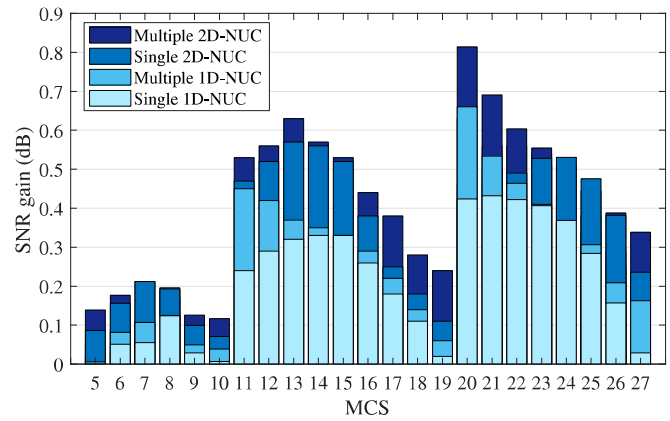

Fig. 6. NUC performance gain for AWGN channel. Constellations for all considered MCS indexes.

grouped symbols, reaching the same result independently on the parameters optimized, i.e. a QPSK constellation. However, that is not the case in 5G, where the MCS range only requires SNRs from 9.8 to 17.6 dB.

B. Link-Level Simulations

In the following section, the gains of different NUCs designed for 5G are presented, for AWGN channel. A simulation platform that comprises the NR specification as denoted in references [15] and [16] and shown in Fig. 1 is used. An optimum ML demapper with ideal channel estimation is employed in all cases. Regarding the stopping criterion, for each SNR a maximum number of 10^5 subframes and a minimum number of 500 erroneous subframes are simulated. The selected quality of service for comparison is a BLER lower than 0.1%.

Fig. 5 presents the SNR gain of different NUCs optimized in Section III for MCS indexes from 11 to 15. 64 symbols are used and QAM is also shown for comparison. On the other hand, Fig. 6 summarizes the performance gains for all constellations. The use of multiple NUCs, i.e. the use of different constellations per MCS index, is compared to the use of a single NUC per constellation order. Gains are computed as the difference in dB between QAM and the considered NUC.

Larger gains are achieved when using higher constellation orders and 2D-NUCs always obtain better gains than 1D-NUCs, due to the higher degrees of freedom in the design process. An MCS index 7 gives the highest SNR gain for 16NUC and lowest MCS indexes are the best option otherwise. The maximum gain achieved is 0.8 dB for MCS 20, which uses 256NUC. Gains obtained for 5G NR in this work and ATSC 3.0 in [4] are very similar. The main advantage in ATSC 3.0 comes from a wider optimization flexibility, where very low CRs are used for every constellation, therefore obtaining higher gains at low SNRs that are not considered in 5G. However, NUC gains provided by equivalent CRs in 5G and ATSC 3.0 follow the same trend. For instance, the gain in ATSC 3.0 for 256NUC and CR 2/3 (equivalent to MCS 20) is 0.9 dB [4], similar to the gain in Fig. 6. NUCs designed in this paper also allow the system to transmit higher MCS indexes

(increased data rate) while keeping very similar performance. For example, the difference in minimum SNR required when using MCS 14 with NUC and MCS 13 with QAM is 0.1 dB, as Fig. 5 shows. With 256 symbols this situation is even better, needing lower SNRs while using higher MCS indexes.

The use of a single 1D or 2D-NUC for every MCS index also provides gains in all cases, if 64 or 256 symbols are used. The best result is obtained for a medium MCS, since the average SNR for the whole range is similar. For low and high MCS indexes the difference to the optimum constellation is increased, and therefore the performance gain is reduced, as Fig. 6 shows. This behaviour is observed for both 1D and 2D-NUCs.

V. Conclusion

In this manuscript, both 1D and 2D-NUCs have been designed up to 256 symbols, which is the highest modulation order in 5G New Radio. The overall system performance can be improved by using these NUCs in future 5G releases, being very useful for the use of broadcast and multicast. The highest gain obtained is 0.8 dB for a 2D-NUC with MCS index 20, for an AWGN channel. The use of a single NUC for every MCS index also improves the system performance compared to QAM. Complexity-wise, the optimum case is the use of a single 1D-NUC that keeps not only QAM memory requirements but also demapping complexity.

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