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Low-Complexity Non-uniform Constellation Demapping Algorithm for Broadcasting System

Chen Wang, Fang Wang, Mingqi Li, and Jinfeng Tian

***Abstract*—This paper presents a novel low-complexity soft demapping algorithm for two-dimensional non-uniform spaced constellations (2D-NUCs) and massive order one-dimensional NUCs (1D-NUCs). NUCs have been implemented in a wide range of new broadcasting systems to approach the Shannon limit further, such as DVB-NGH, ATSC 3.0 and NGB-W. However, the soft demapping complexity is extreme due to the substantial distance calculations. In the proposed scheme, the demapping process is classified into four cases based on different quadrants. To deal with the complexity problem, four groups of reduced subsets in terms of the quadrant for each bit are separately calculated and stored in advance. Analysis and simulation prove that the proposed demapper only introduces a small penalty under 0.02dB with respect to Max-Log-MAP demapper, whereas a significant complexity reduction ranging from 68.75% to 88.54% is obtained.**

***Keywords*—non-uniform constellation, soft demapping, complexity, QAM, NGB-W**

I. Introduction

SHANNON described the limit of channel capacity theoretically in his paper [1]. According to him, bit-interleaved coded modulation (BICM) is an efficient scheme to approach the theoretical limit with a reasonable receiver complexity. It is a flexible modulation/coding scheme which allows the designer to choose a modulation constellation independently of the coding rate depending on broadcasting communication scenarios. Besides, it is particularly well suited for fading channels [2]. Due to these favorable features, BICM has been regarded as a pragmatic yet powerful approach to achieve high data rates. It is employed in the state-of-the-art broadcasting standardizations such as DVB-T2 [3] and ATSC 3.0 [4]. In the next generation broadcasting-wireless (NGB-W) system in China [5], BICM with low density parity check (LDPC) [6] and BCH codes is also adopted.

High-order uniform Gray labeled quadrature amplitude modulation (QAM) is commonly applied combined with

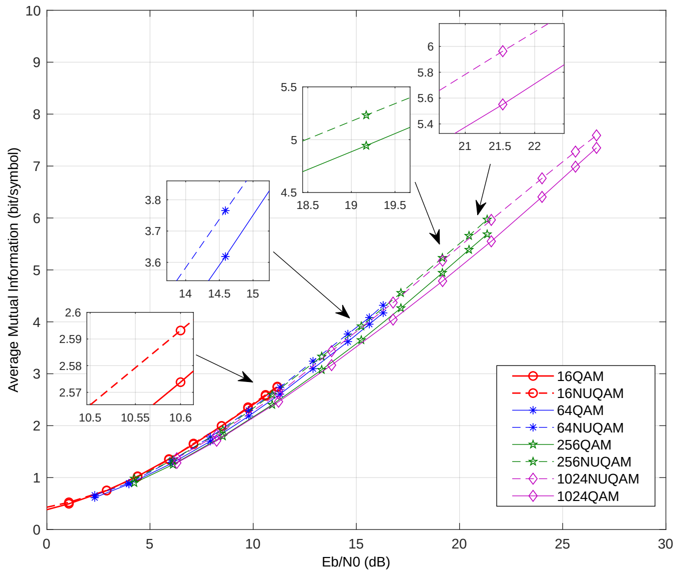

Fig. 1. AWGN channel capacity QAM vs. NU-QAM in NGB-W

BICM chain to increase spectral efficiency. Despite uniform constellations can get very close to the Shannon's channel capacity curve, there still exists a performance gap in higher SNR regions owing to the regular distribution of points [7]. Also, it becomes more apparent as the modulation order increases. Thus, uniform constellations are no longer sufficient. According to [8], shaping the constellation to follow a Gaussian distribution is a beneficial way to narrow this gap. One typical shaping method is to transmit uniform constellations with different probabilities; the other approach to get shaping gain is NUCs which have more points at low-power levels than high-power levels. According to the dimension of constellations, the NUCs are classified into 1D-NUCs and 2D-NUCs. The first ones have rectangular shaping while the second type of NUCs is designed without constraint on shape. Some advanced systems such as Digital Video Broadcasting - Next Generation Handheld (DVB-NGH) [9] and ATSC 3.0 [10] have adopted NUCs. Since 2D-NUCs take more freedoms into account, they can provide higher capacity gain than 1D-NUCs [11]. However, for massive order constellations (beyond 256 constellation points) the latency and demapping complexity involved in 2D-NUCs make their use unfeasible in the practical application. In this case, 1D-NUCs are the most appropriate solution [12]. Taking advantage of the capacity gain provided by NUCs, 2D-NUCs and massive order 1D-NUCs are adopted in NGB-W. As shown in Fig. 1, the M-

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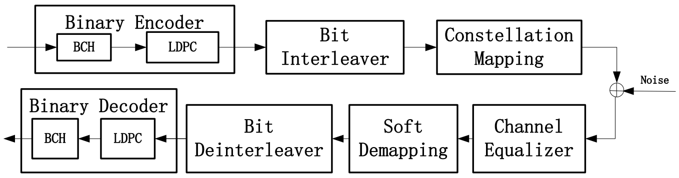


Fig. 2. BICM system in NGB-W

NUCs can provide up to 0.8dB shaping gain under the ideal condition without BICM process versus the traditional uniform constellations [13].

In order to detect the NUCs signal, a soft demapping algorithm such as Max-Log-MAP is typically implemented to obtain reliable soft information of the bit probabilities for FEC decoding in the receiver. It calculates the log-likelihood ratio (LLR) based on the Maximum Likelihood Principle. With 2D-NUCs, the I and Q components are dependent because of its circular shaping, and at the demapping stage, a 2-D constellation demapper is needed. That implies the complexity is $\mathrm{O}\left(2^{m+1}\right)$, where m is the number of mapping bit per symbol. As for massive order 1D-NUCs such as 1K-NUC, despite one detector can be decomposed into two independent non-uniform pulse amplitude modulation (PAM) detectors, reducing the number of Euclidean Distance (ED), there are still a considerable number of computations required in the demapping stage [14]. Consequently, the demapping complexity is one of the bottlenecks of 2D-NUCs and massive order 1D-NUCs implementation. It is necessary to research a low-complexity soft demapping algorithm for them.

A literature review shows that many works focus on the simplified demapper for Rotated Constellations (RCs) [15], [16]. According to [15], the I and Q components of an RC symbol are transmitted both in different carriers and different time slots, thus are affected by independent fadings. The 1D-demapper is not valid. Similar to 2D-NUCs, it also requires 2^m 2-D ED calculations. The concept of simplified demapper presented in [15], [16] is to reduce the area where Euclidean Distances are evaluated. Depending on the quadrant or subquadrant in which the received point lies in the complex plane, the 2-D distances are computed to a reduced subset of the entire constellation, decreasing the number of required operations and so the hardware complexity. These algorithms reduce the complexity by 25% up to 50% with variable performance degradation.

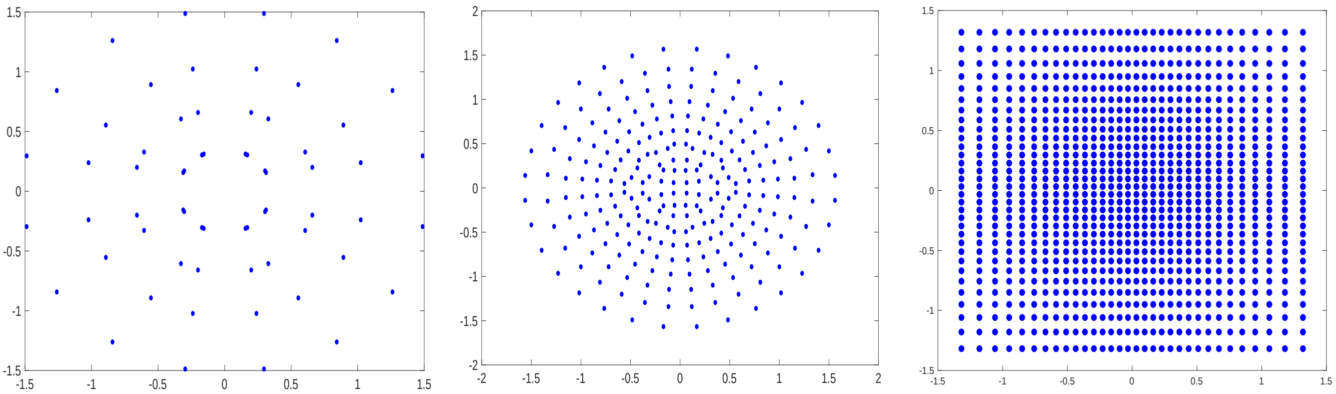
In the latest result [17], a low-complexity 2D-NUCs demapping strategy called Quadrant Search Reduction (QSR) is presented based on the previously shown demappers for RCs. It assumes that a symbol is received in the same quadrant that was transmitted. This assumption hampers the performance of QSR at low SNRs corresponding to low code rates (CRs). In order to overcome the drawback, the authors combine QSR with another type of simplified demapping strategy for NUCs, Condensed Symbols Reduction (CSR). CSR merges the closest points in the constellation diagram. This strategy exploiting the condensation of NUCs at low CRs was first proposed in [18]. Nevertheless, CSR is only valid for the condensed constellations. The NUCs in ATSC 3.0 become barely condensed as CR increases, and the complexity nearly does not decrease. In the combined strategy called QCSR, different algorithms are dominant according to different SNR ranges. By simulating, QCSR only performs at mid code rates. The number of constellation points selected decreases to some extent but with a 0.1dB performance loss.

This paper aims to reduce the demapping complexity for 2D-NUCs and massive order 1D-NUCs. We propose a generic scheme that can be applied to any code rate. It decreases the number of EDs to be computed almost without impact (under 0.02dB) on the system performance, compared with Max-Log-MAP demapper. In order to illustrate performance, simulations of our demapper and QSR algorithm are respectively conducted for the same constellations. According to the criterion of selecting the smallest possible N that ensures a performance loss smaller than 0.1dB at Bit-error-rate (BER) of 10^{-4} , our demapper has lower complexity than QSR. Moreover, the advantage is rather apparent for high CRs. In this paper, we provide simulation results of BER performance using the NUCs optimized for NGB-W. The demapping complexity could be reduced by 68.75% to 88.54% for different constellations which is beyond that of QSR. Also, the advantage becomes larger in terms of the modulation order. Furthermore, the novel demapper can also be combined with CSR strategy to get better performance in the further research.

The rest of the paper is organized as follows. Section II briefly introduces the BICM system in NGB-W including the designed M-NUCs and the channel model. Section III is a description of the traditional soft demapping process and the previous QSR algorithm for NUCs. Section IV mainly presents the proposed low-complexity demapping algorithm. Also, its demapping complexity for different NUCs is addressed and compared with that of the traditional algorithm. In Section V, simulation results of the proposed algorithm, QSR and the traditional algorithm for 2D-NUCs are presented and analyzed. Besides, the extension to 1D-1KNUC is also carried out. Eventually, the main contributions of the work are summarized in Section VI.

II. System Model

BICM was first introduced by Zehavi in [19] and considered as the dominant technique for coded modulation of broadcasting system in fading channel. It consists of a forward error correction code (FEC), a bit-wise interleaver and a symbol mapper. Fig. 2 illustrates the BICM scheme in NGB-W. As the outer code, BCH code is used to retain Bit Error Rate (BER) floor lower than 10^{-11} for fixed scenarios and 10^{-7} for mobile scenarios. It aims at increasing the error correction capability of the system. From another viewpoint, LDPC code regarded as the inner code are applied after BCH to achieve high throughput. It makes the channel capacity curve close to the Shannon limit at the waterfall region with low complexity. Afterward, one encoded bit is interleaved with respect to the other by a bit interleaver which is a serial concatenation of sub-block interleaver and row-column interleaver. In this way, the output of the channel encoder and the input to the modulator are separated, providing some flexibility.



(a) 64 NU-QAM for CR = 1/2 (b) 256 NU-QAM for CR = 4/5 (c) 1024 NU-QAM for CR = 5/6

Fig. 3. 2-D NU-QAMs and high-order 1-D NU-QAM for different code rates in NGB-W

With regard to the mapper, high-order NUCs are implemented to increase spectral efficiency and get closer to the capacity limit, including 16 NU-QAM, 64 NU-QAM, 256 NU-QAM, and 1024 NU-QAM. Unlike uniform constellations, NUCs are optimized with respect to the average mutual information (AMI) which is the expression of BICM capacity for AWGN and Rayleigh identically and independently distributed (i.i.d.) channels [20]. In particular, different NUCs are optimized for different target SNRs, i.e., each NUC pattern matches with a specific code rate. Taking the complexity into account, we adopts 1D-NUC for 1024-QAM and 2D-NUC for 16, 64 and 256-QAM in the system. As an example, the representative designed NU-QAMs for low code rate(1/4), relatively intermediate code rate(1/2) and the less robust code rate(4/5, 5/6) are depicted in Fig. 3 and Fig. 4. However, the proposed algorithm is valid for any other NUCs.

Based on the previous BICM scheme, we can get the channel model. If x is the transmitted signal, then the received symbol y can be described as

$$y = hx + n \tag{1}$$

where h is a memoryless channel fading coefficient, and n denotes an additive white Gaussian noise (AWGN) with variance N_0.

III. Soft Demapping Algorithm For NUCs

A. Max-Log-MAP Algorithm

In the soft demapper, log-likelihood ration (LLR) metrics are calculated as the soft information of the bit probability for FEC decoding. Owing to the low demapping complexity, Max-Log-MAP algorithm is extensively employed. However, the number of EDs to calculate is the same as the ML algorithm. According to [21], for a received signal y, the equation of computing LLR value on the i-th bit b_i is given by

$$\begin{aligned}\mathrm{LLR}\left(b_i\right) &= \log\frac{Pr\left(b_i=0|y\right)}{Pr\left(b_i=1|y\right)}\\ &= \log\frac{\sum_{x\in\chi_i^0}\exp\left(-\frac{|y-|h|x|^2}{N_0}\right)}{\sum_{x\in\chi_i^1}\exp\left(-\frac{|y-|h|x|^2}{N_0}\right)}\\ &\approx\frac{1}{N_0}\left[\min_{x\in\chi_i^1}\left|y-|h|\,x\right|^2-\min_{x\in\chi_i^0}\left|y-|h|\,x\right|^2\right]\end{aligned} \tag{2}$$

where χ_i^0 denotes the constellation set in which $b_i = 0$ and χ_i^1 is the constellation set in which $b_i = 1$. Approximation Eq.(3) is utilized to avoid the complex exponential and logarithmic operations while maintaining a fairly accurate result.

$$\ln\sum_j e^{-x_j}\approx\max_j\left(-x_j\right)\approx\min_j\left(x_j\right) \tag{3}$$

In the receiver, both channel equalization and signal demodulation are carried out in the frequency domain. With an ideal channel estimation, considering a zero force equalization process, the received signal can be modified as follows.

$$y=\frac{hx+n}{\hat{h}}=x+\frac{n}{\hat{h}} \tag{4}$$

where $\hat{h}$ represents the estimated channel frequency response. Then substitute Eq.(4) into Eq.(2). Equation (2) generates to

$$\begin{aligned}LLR(b_i) &= \frac{|\hat{h}|^2}{N_0}\left[\min_{x\in\chi_i^1}|y-x|^2-\min_{x\in\chi_i^0}|y-x|^2\right]\\ &=\alpha\left[\min_{x\in\chi_i^1}|y-x|^2-\min_{x\in\chi_i^0}|y-x|^2\right]\\ &=\alpha\left[\min_{x\in\chi_i^1}\left((I_y-I_x)^2+(Q_y-Q_x)^2\right)-\right.\\ &\qquad\left.\min_{x\in\chi_i^0}\left((I_y-I_x)^2+(Q_y-Q_x)^2\right)\right]\end{aligned} \tag{5}$$

where $\alpha = \frac{|\hat{h}|^2}{N_0}$ is related to each subcarrier. The value of i ranges from 0 to $(B-1)$, with B as the number of bits that affect each dimension of a constellation [17]. For 1D-NUCs and 2D-UCs, B is the half of the total number of bits in a cell, i.e., $B = m/2$. Only 1-D distances require to be computed. In the case, the demapping complexity is $O(2^{\frac{m}{2}})$ in one dimension. The formula of LLR metric calculation can be described as:

$$
\begin{aligned}
LLR(b_j) &= \alpha\left[\min_{x\in\chi_j^1}(I_y - I_x)^2 - \min_{x\in\chi_j^0}(I_y - I_x)^2\right] \\
LLR(b_f) &= \alpha\left[\min_{x\in\chi_f^1}(Q_y - Q_x)^2 - \min_{x\in\chi_f^0}(Q_y - Q_x)^2\right] \qquad (6) \\
N(j) &= N(f) = B \quad N(j) + N(f) = m
\end{aligned}
$$

where N denotes the number of the variable. However, with 2D-NUCs, the correlation between I and Q components causes that B equals to m and 2-D distances must be considered, which implies the demapping complexity of $O(2^{m+1})$. The complexity order becomes especially high for high-order 2D-NUCs and massive order 1D-NUCs. For example, considering 2D-256NUC and 1D-1024NUC, for each LLR value 1024 multiplications and 2048 multiplications are respectively required.

According to Eq.(5), the essential question of a NUCs demapper is to find the closest points. Apparently, using an approximation for the calculation of EDs [18] and decreasing the number of mathematical operations [15], [16] are two different approaches to reduce the complexity. In this paper, we only focus on the later.

B. QSR Algorithm Analysis

QSR algorithm [17] is based on the quadrant-symmetric constellations. It reduces the size of the searching range during the LLR calculation of one bit from 2^m to N symbols. The algorithm can be separated into two main steps. In the first step, the probability of each symbol transmitted from one particular quadrant is calculated off-line. These symbols are stored by probability order in a look-up table for the following LLR calculation. The second step decides the minimum number N of distances that ensures a performance loss smaller than 0.1dB.

The critical issue of QSR algorithm is its assumption which is a symbol received in the same quadrant that was transmitted. At low SNRs, high noise power causes a high probability of selecting an erroneous quadrant. That means more symbols have to be included in the reduced subsets to ensure performance loss smaller than 0.1 dB. Therefore, QSR provides negligible complexity reduction at low SNRs. In addition, only one subset for all LLR metric computations of B bits is not efficient since the number of closest points for different bits is not identical. In the next section, a new scheme is presented to avoid these problems.

IV. Proposed Demapper

In this work, a simplified algorithm is raised for NUCs demapping. Depending on the quadrant in which the received symbol lies, distances are computed to the different group of reduced subsets. It can be not only used for 2D-NUCs

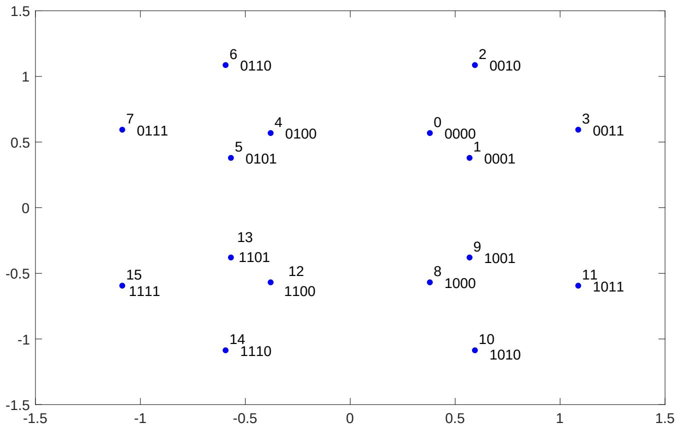


Fig. 4. 16 NU-QAM designed for CR = 1/4

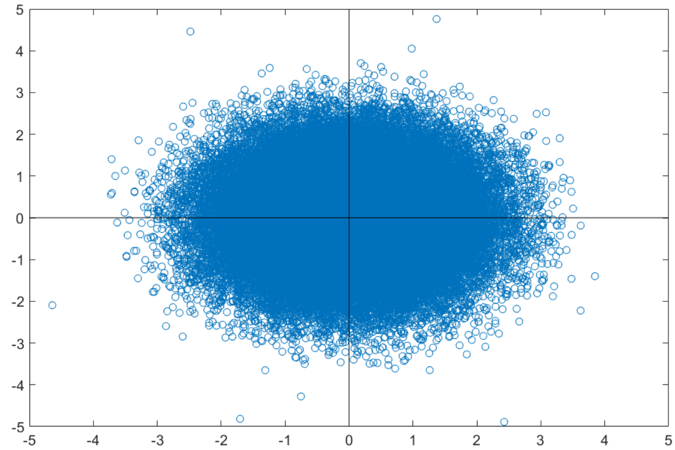


Fig. 5. 10^6 received points of 16 NU-QAM (CR = 1/4) over an i.i.d. Rayleigh channel for SNR = 8.08dB

but also 1D-NUCs. The number of required operations is considerably decreased. Moreover, the new scheme can obtain more complexity reductions without performance loss increment compared with QSR algorithm.

A. Simplified Soft Demapper

The reduced subsets are readily determined by analyzing the minimum 1-D or 2-D distances between y and the constellation symbols in the original sets. Groups of subsets corresponding to the four falling quadrants are independent on each other. Therefore, they can be computed separately. Regarding the quadrant-symmetric constellations, subsets for the other three quadrants can be derived from these for a particular quadrant. Otherwise, the following calculation steps need to be implemented four times. It does not result in extra complexity since this process can be done off-line.

The first step is to get the distribution range and generate the received points. As shown in Eq.(5), the LLR values only correlate to the closest points to the received symbol wherever y comes from. Hence, it is not necessary to consider the transmitted quadrant, that is, the assumption of QSR is not required. Totally 10^6 constellation symbols are transmitted

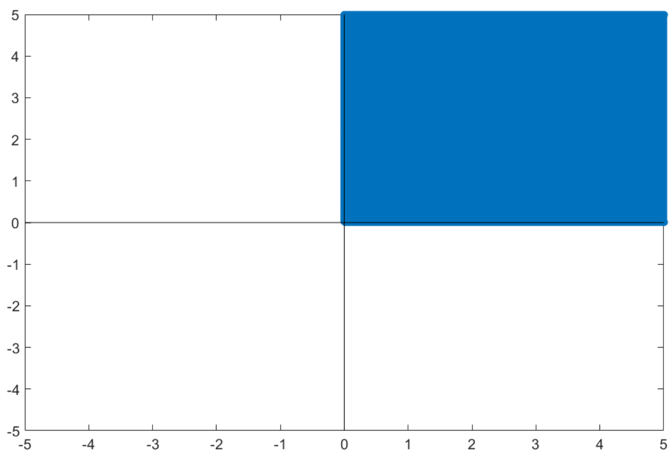


Fig. 6. Simulate 10^9 received symbols in the first quadrant

over i.i.d. Rayleigh channel at the target SNR in order to get the maximum boundary. Afterward, 10^9 points are randomly generated with equal probability in this square as the received symbols. This number is confirmed in [16] and ensures to fill up the square as possible. The second step is to calculate EDs. Due to no intersection between sets χ_i^0 and χ_i^1, they are calculated by separate. Besides, the closest constellation point subsets in LLR computations of different bits of the symbol received are not same. In consequence, 1-D or 2-D EDs between each received symbol and the constellation points in χ_i^0 and χ_i^1 $(i = 0, ..., B-1)$ are computed. By comparing these distances, it is found out that the closest point sets are almost fixed. Based on this, all unrepeatable points with the minimum EDs are chosen to compose the reduced subsets S_i^0 and S_i^1 $(i = 0, ..., B-1)$. For 1D-NUCs, subsets of one-half of bits can be derived from the other half as a result of its constellation shape. Finally, all m reduced subsets are stored in a look-up table by their labels. The entire process can be done off-line without adding additional complexity.

With these reduced subsets, the formula of LLR value computation for 2D-NUCs and 1D-NUCs are respectively changed to Eq.(7) and Eq.(8). The novel demapping algorithm for a NUC symbol is described in Algorithm 1. Step 5, 6 and 9, 10 are executed via the two equations.

$$LLR\,(b_i) = \alpha\Bigg[\min_{x\in S_i^1}\left((I_y - I_x)^2 + (Q_y - Q_x)^2\right) - \min_{x\in S_i^0}\left((I_y - I_x)^2 + (Q_y - Q_x)^2\right)\Bigg] \tag{7}$$

$$\begin{aligned} LLR(b_j) &= \alpha\left[\min_{x\in S_j^1}(I_y - I_x)^2 - \min_{x\in S_j^0}(I_y - I_x)^2\right] \\ LLR(b_f) &= \alpha\left[\min_{x\in S_f^1}(Q_y - Q_x)^2 - \min_{x\in S_f^0}(Q_y - Q_x)^2\right] \end{aligned} \tag{8}$$

Fig. 4 presents an example of 16 NU-QAM designed for code rate of $1/4$ in NGB-W. It is a quadrant-symmetric 2-D NUC. All constellation points are labeled as shown in the figure. It is optimized for AWGN channel for SNR of 5.92 dB and i.i.d. Rayleigh channel for SNR of 8.08 dB. Fig. 5 depicts 10^6 constellation points transmitted over an i.i.d. Rayleigh channel. It can be seen that the absolute values of the I/Q components never exceed 5. That is, the receiving range in the first quadrant is $[0, 5]$. As Fig. 6 shows, we generate 10^9 points within this range as the received symbols which ensures as many locations covered as possible. Then the reduced subsets

TABLE I
REDUCED SUBSETS FOR 16 NU-QAM OF 1/4 CODE RATE

b_i	Quadrant	$x \in S_i^0$	$x \in S_i^1$
b_3	1	0 1 2 3	9 11
	2	4 5 6 7	13 15
	3	5 7	12 13 14 15
	4	1 3	8 9 10 11
b_2	1	0 1 2 3	4 6
	2	0 2	4 5 6 7
	3	8 10	12 13 14 15
	4	8 9 10 11	12 14
b_1	1	0 1	2 3
	2	4 5	6 7
	3	12 13	14 15
	4	8 9	10 11
b_0	1	0 2	1 3
	2	4 6	5 7
	3	12 14	13 15
	4	8 10	9 11

Algorithm 1 Proposed Demapping Algorithm For NUCs

Initialization: y: received symbol, R: code rate, T_M^R: the look-up table of M-QAM with a code rate of R, $\hat{h}$: estimated channel coefficient, N_0: noise power spectral density, B: the number of bits affecting each dimension

Demapping:

1: Judge the quadrant in which y lies according to the sign of its I/Q components.
2: Look up the table T_M^R to get S_i^0 and S_i^1, $i = 0, ..., m-1$ for this quadrant
3: **for** each $i \in [0, B-1]$ **do**
4: **if** y is a 2D-NUC **then**
5: Calculate the 2-D distances between y and the constellation points in S_i^0 and S_i^1
6: Choose one point in each subset of S_i^0 and S_i^1 with the minimum distance
7: **end if**
8: **if** y is a 1D-NUC **then**
9: Calculate the 1-D distances between y and the constellation points in S_{2i}^0, S_{2i}^1, S_{2i+1}^0, S_{2i+1}^1
10: Choose one point in each subset of S_{2i}^0, S_{2i}^1, S_{2i+1}^0, S_{2i+1}^1 with the minimum distance
11: **end if**
12: **end for**
13: **for** each $j \in [0, m-1]$ **do**
13: Calculate $LLR(b_j)$
14: **end for**

S_i^0 and S_i^1, $i = 0, 1, 2, 3$ for the first quadrant are calculated. The other subsets are derived by symmetry. Assuming y demapped into $b_3b_2b_1b_0$, the total 32 reduced subsets are shown in Table I. As shown in Fig. 4, when the received symbol falls into the first quadrant, the initial search ranges of $LLR(b_3)$ are set χ_3^0 including points $\{0, 1, 2, 3, 4, 5, 6, 7\}$ and set χ_3^1 including points $\{8, 9, 10, 11, 12, 13, 14, 15\}$. From Table I, the reduced subsets S_3^0 consists of points $\{0, 1, 2, 3\}$ and S_3^1 only includes points $\{9, 11\}$ which is 1/4 of χ_3^1. The total number of EDs to compute in b_3 demapping process is 6. It implies the demapping complexity is significantly declined by 62.5%.

B. Computation Complexity Analysis

The simplified demapper is not limited to the symmetry of constellation pattern and the non-uniform dimension. Since almost all possible nearest points are included in the reduced subsets, the performance is hardly degraded. Meanwhile, compared with the traditional Max-Log-MAP algorithm, our proposed scheme dramatically reduce the search range during the process of LLR calculation, decreasing the number of required mathematical operations and so the demapping complexity.

In this paper, the demapping complexity is measured by the total number of EDs for all LLRs. For example, concerning the NU-16QAM in Table I, it becomes evident that the number of distance to calculate for b_3, b_2, b_1 and b_0 are respectively 6, 6, 4 and 4. Therefore, total 20 2-D distances to be calculated is only 31.25% of that needed in the traditional Max-Log-MAP algorithm. The complexity and percentage of the EDs reduction between the proposed and Max-Log-MAP demappers are computed for all NUCs with 10 CRs including 1/5, 1/4, 1/3, 5/12, 1/2, 7/12, 2/3, 3/4 and 4/5 in NGB-W. For the sake of simplicity, only the maximum value and the minimum value for each kind of modulation are presented in Table II. As shown, the maximum complexity reduction for NUCs in NGB-W is 88.54% in the case of NU-64QAM with 1/5 CR. The proposed demapper presents more substantial demapping complexity reduction at low code rates in both 1-D and 2-D NUCs.

V. Simulation Results

In this section, we evaluate the system performance of the proposed algorithm compared with the traditional Max-Log-MAP and QSR from the demapping complexity and BER point of view. Since the size of the reduced subset for each bit is different in our demapper, the average number of EDs required to compute is considered as N in QSR. These simulations were conducted with the BICM chain introduced in part II, with a LDPC code length of 19200 bits for 2D-NUCs and 57600 bits for 1D-NUCs, over an i.i.d. Rayleigh channel. Besides, time and frequency interleavers and Orthogonal Frequency-Division Multiplexing (OFDM) technology were also utilized. All these NUC constellations are optimized for NGB-W. A total number of 10^4 FEC blocks were transmitted for SNRs in the waterfall region. All results in this brief have been measured at a BER of 10^{-4} with a performance loss smaller than 0.1dB.

A. Performance Comparision with QSR

In common, FEC with high code rate is combined with high-order modulation to improve system capacity. To compare the performance of the proposed and QSR algorithms, we perform a set of simulations for 2D-NUCs including 16-QAM with a low CR 1/4, 64-QAM with a relative medium CR 1/2 and 256-QAM with a high CR 4/5.

Fig. 7 displays the BER performances of the proposed algorithm and QSR strategy for a 16 NU-QAM. The results for the ideal Max-Log-MAP demapper are also shown for comparison purposes. As shown, the smallest N in QSR is 9 according to the selected criterion. Nevertheless, it is only 5 in our algorithm according to Table II. It illustrates there is an extra 25% reduction. Moreover, the performance degradation of our system is almost zero, while that of QSR with $N = 6$ is over 0.15dB.

Fig. 8 shows the results for 64-QAM. It can be seen that the BER curve of Max-Log-MAP nearly overlaps that of the proposed algorithm. Owing to the same reduced subsets, 1/2 CR has the same complexity as 1/5 CR, a total 44 number of EDs for all LLRs. On the other hand, QSR strategy leads to an approximate 0.8dB performance penalty, with slightly higher complexity of $N = 18$.

In Fig. 9, the BER curves of three demappers for 256-QAM are shown. At the waterfall region, the BER curve of QSR algorithm with $N = 68$ (total 544 EDs) descends very lowly which causes substantial performance degradation. On the other hand, there is only an imperceptible (below 0.02dB) performance gap between the traditional Max-Log-MAP algorithm and the proposed algorithm with a relatively lower complexity (total 532 EDs). As explained, compared to QSR algorithm, the performance gain of the proposed system is over 1.5dB which is more significant than that for 64-QAM.

In conclusion, the novel demapper provides considerable complexity reduction while the system performance degradation can be ignored. Besides, it outperforms the previously known QSR algorithm and the performance gain increases with the increment of CR.

B. Extension to 1D-1KNUC

In this part, we extend the new demapping algorithm to the 1D-1KNUC in NGB-W. Similarly, with 2D-NUCs, the main restriction of massive order 1D-NUCs is the number of computations required in the demapping stage [12]. Hence, our algorithm is also appropriate for 1D-1KNUC. It has been presented in Fig. 10 that two BER curves for 1D-1KNUC with a code rate 5/6, one for the ideal Max-Log-MAP demapper and one for our proposed scheme. From the figure, it can be seen that the performance loss of our scheme is almost zero.

VI. Conclusion

In this paper, we present a novel low-complexity soft demapper for NUCs. It can be applied to both 1D-NUCs and 2D-NUCs and not limited to the shape of the constellation. In order to obtain LLR values, it needs to calculate distances between each constellation point and the received symbol. The proposed algorithm divides the demapping process into four

TABLE II
COMPUTATION COMPLEXITY COMPARISON BETWEEN SIMPLIFIED SOFT DEMAPPER AND THE TRADITIONAL ALGORITHM

Modulation	B	N(Euclidean Distances)/bit	Total Number of Euclidean Distances Required		
			Max-Log-MAP Algorithm	Simplified Algorithm	Reduction Percentage
2D NU-16QAM	4	16	64	20	68.75%
2D NU-64QAM	6	64	384	(R = 1/5) 44 (R = 5/6) 106	(R = 1/5) 88.54% (R = 5/6) 72.40%
2D NU-256QAM	8	256	2048	(R = 1/5) 350 (R = 5/6) 532	(R = 1/5) 82.91% (R = 5/6) 74.02%
1D NU-1024QAM	5	1024	5120	(R = 1/5) 727 (R = 7/12) 1293	(R = 1/5) 85.80% (R = 7/12) 74.75%

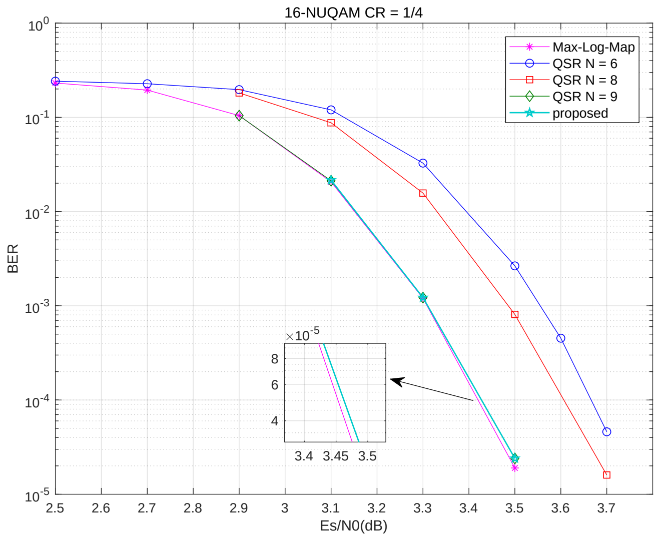


Fig. 7. BER performance comparison of Max-Log-MAP, QSR and the simplified demappers for the 16 NU-QAM with 1/4 code rate

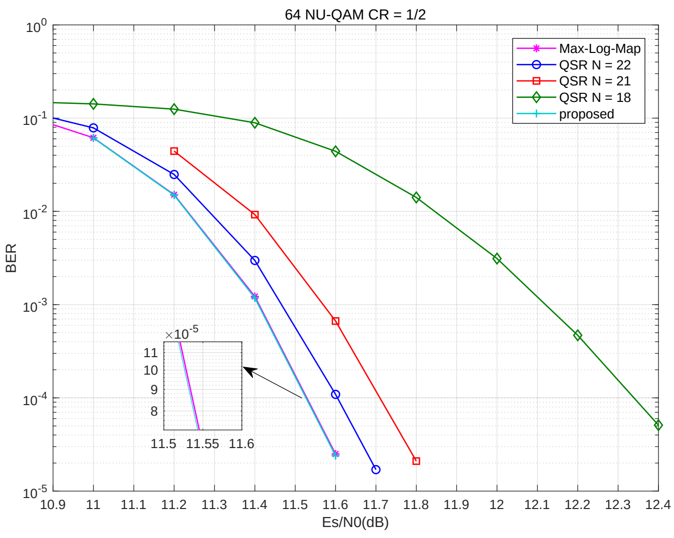


Fig. 8. BER performance comparison of Max-Log-MAP, QSR and the simplified demappers for the 64 NU-QAM with 1/2 code rate

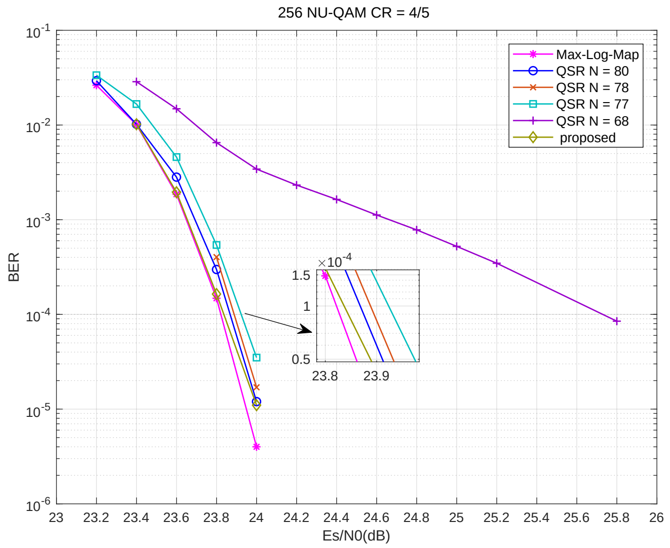


Fig. 9. BER performance comparison of Max-Log-MAP, QSR and the simplified demappers for the 256 NU-QAM with 4/5 code rate

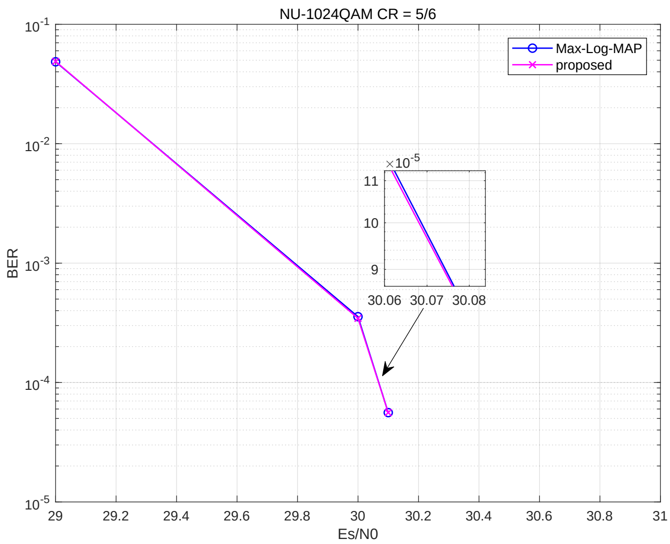


Fig. 10. BER performance comparison of Max-Log-MAP and the simplified demappers for the 1024 NU-QAM with 5/6 code rate

cases regarding the quadrant in which the received point lies. The constant closest point sets S_i^0 and S_i^1 for the i-th bit are calculated separately according to the minimum EDs. As for quadrant-symmetric constellations, the other three groups of subsets can be derived from one. Using reduced subsets S^0 and S^1 as the narrowed searching range to calculate LLR values can decrease the demapping complexity up to 88.54% depending on the code rate and type of modulation. For 2D-NUCs, the less the code rate is, the more the complexity reduction is. Moreover, simulation results verify that there is nearly no performance gap (below 0.02dB) between the proposed and the traditional Max-Log-MAP demappers.

The proposed demapper has a better performance than QSR demapping algorithm. On the one hand, under the condition of similar complexity, QSR algorithm causes more performance loss. That is to say, the new system has a performance gain of QSR. and it becomes rather obvious for high code rates. On the other hand, selecting the smallest N with a performance penalty less than 0.1dB, QSR provides less complexity reduction compared to the new demapper.

REFERENCES

[1] C. E. Shannon, "A mathematical theory of communication," *Bell Labs System Journal*, vol. 27, Jul., Oct. 1948

[2] Alvarado A . On Bit-interleaved Coded Modulation with QAM Constellations[J]. 2008.

[3] ETSI EN 302 755 V1.4.1(07/15) Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system(DVB-T2), *European Telecommunications Standards Institue*. Geneva, July 2015.

[4] Fay, Luke, et al. "An Overview of the ATSC 3.0 Physical Layer Specification." IEEE Transactions on Broadcasting 62.1(2016):159-171.

[5] Feng Songlin, Xie Wei. "Next-Generation Broadcast Network Wireless Systems." *Zte Technology Journal*, vol. 17, no. 4, pp. 14-18, August, 2011.

[6] Richardson, T. J., M. A. Shokrollahi, and R. L. Urbanke. "Design of capacity-approaching irregular low-density parity-check codes." IEEE Transactions on Information Theory 47.2(2002):619-637.

[7] J. Zoellner and N. Loghin. "Optimization of high-order non-uniform QAM constellations." in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, London, U.K., Jun. 2013, pp. 1-6.

[8] Loghin, Nabil Svenh, et al. "Non-Uniform Constellations for ATSC 3.0." *IEEE Transactions on Broadcasting* vol. 62, no. 1, pp.197-203, 2016.

[9] Gmez-Barquero, David, et al. "DVB-NGH: The Next Generation of Digital Broadcast Services to Handheld Devices." *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 246-257, 2014.

[10] L. Michael and D. Gmez-Barquero. "Bit-Interleaved Coded Modulation (BICM) for ATSC 3.0."*IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 181-188, 2016.

[11] J.Morgade, D. Ansorregui, B. Mouhouche, H. Jeong and H. Lee, "Improving the DVB-T2 BICM performance by newly optimized Two-Dimensional Non-Uniform Constellations," 2014 IEEE Fourth International Conference on Consumer Electronics Berlin (ICCE-Berlin), Berlin, 2014, pp. 96-100.

[12] J. Barrueco, J. Montalban, P. Angueira, C. A. Nour and C. Douillard, "Low-Complexity Lattice Reduction Demapper for Massive Order One-Dimensional Non-Uniform Constellations," 2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Valencia, 2018, pp. 1-5.

[13] Kou Y, Wang F, Tian J,et al. "Terrestrial broadcast technologies for next generation broadcast wireless systems." in *Proc. IEEE International Conference on Communication Workshop. (ICC)*, London, UK, Jun. 2015, pp. 2578-2582.

[14] C. Douillard, and C. A. Nour. "Bit-Interleaved Coded Modulation in Next-Generation Mobile Broadcast Standard DVB-NGH." in *Next Generation Mobile Broadcasting*, D. Gomez-Barquero, Ed.Boca Raton, FL, USA: CRC Press, 2013, pp. 321-354.

[15] Pérez-Calderón, D, et al. "Rotated constellation demapper for DVB-T2." Electronics Letters 47.1(2011):31-32.

[16] Perez-Calderon, Daro, et al. "Simplified Rotated Constellation Demapper for Second Generation Terrestrial Digital Video Broadcasting." IEEE Transactions on Broadcasting 59.1(2013):160-167.

[17] Fuentes, Manuel, D. Vargas, and D. Gmez-Barquero. "Low-Complexity Demapping Algorithm for Two-Dimensional Non-Uniform Constellations." *IEEE Transactions on Broadcasting*, vol. 62, no. 2, pp. 375-383, 2016.

[18] S. Kwon et al. "Simplified non-uniform constellation demapping scheme for the next broadcasting system." in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Ghent, Belgium, Jun. 2015, pp. 1-3.

[19] Ephraim Zehavi. "8-PSK Trellis Codes for a Rayleigh Channel." *IEEE Transactions on Communications*, vol. 40, no. 5, pp. 873-884, May 1992.

[20] Barrueco, Jon, et al. "Constellation Design for Bit-Interleaved Coded Modulation (BICM) Systems in Advanced Broadcast Standards." *IEEE Transactions on Broadcasting*, vol. 63, no. 4, pp. 603-614, Dec. 2017.

[21] Tao, Yuting, et al. "Low Complexity Switched Soft Demapper for Rotated QAM Constellations." IEEE Transactions on Broadcasting 62.3(2016):532-539.