SCMA Codebooks Optimization Based on Genetic Algorithm

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***Abstract*—Sparse code multiple access (SCMA) is a non-orthogonal multiple access scheme based on joint modulation and spread spectrum procedure. This scheme allows to increase the number of active users inside a given time-frequency resource. Design of SCMA codebooks is a challenging problem. The paper considers the design of SCMA codebooks based on Genetic Algorithm (GA). In general case, mother constellation is not required for GA, and optimization is performed directly on the codebooks. We present the obtained structured codebooks containing two antipodal codeword pairs. Optimization was carried out to improve SCMA signal performance in additive white Gaussian noise (AWGN) channel by constraining the average energy of codewords. The obtained codebooks have minimum Euclidean distance equal to 0.87 (at unit average power of SCMA signal) and outperform known codebooks in AWGN channel with both Maximum Likelihood (ML) receiver or Message Passing Algorithm (MPA) detection. The comparison of existing and proposed codebooks is performed using computer simulation and union bounds. The asymptotic gain over the best known codebooks is 0.8 dB. As a result of the simulation, proposed codebooks demonstrate similar performance for ML and MPA detection algorithms. The proposed method is suitable for codebook design for other non-orthogonal schemes, e. g., Pattern Division Multiple Access (PDMA).**

I. Introduction

Fifth generation (5G) wireless communication standard requires higher spectral efficiency, massive connectivity and lower latency. New standard is expected to be commercially deployed in 2020, consequently at this juncture a lot of research is being carried out. One of the main applications of this technology is the Internet of Things (IoT), which includes Machine-to-Machine and Device-to-Device communication. 5G systems should support 100 billion connections, data rate of several tens of megabits per second for thousands of users and 1 ms latency [1]. Non-orthogonal multiple access (NOMA) schemes [2] are possible solutions to increase the number of users inside a given time-frequency resource. Unlike conventional orthogonal multiple access techniques such as time or frequency division and code division multiple access, NOMA introduces some controllable interference to implement overloading at the cost of increased receiver complexity. As a result, higher spectral efficiency and massive connectivity can be achieved [3]. SCMA [4] is a scheme of code-domain multiplexing NOMA and a potential candidate of NOMA in new telecommunication standards. This system is a generalization of Low Density Signature (LDS) [5] scheme. Therefore, the LDS scheme below will also be called SCMA.

The conventional SCMA codebook design is based on multidimensional complex-valued mother constellation and special operators. The problem is to define J different K-dimensional constellations each containing M elements [4]. This problem requires brute force technique for the best solution and it is not implementable in practice. Therefore, sub-optimal methods are used. There are phase rotation, complex conjugate, dimension permutation of the constellation and layer power offset operators for design of codebooks [6]. The use of these operators over the mother constellation helps to reduce the computational complexity of the problem.

In [7], [8], [9], the SCMA codebooks are presented. They are based on different techniques and metrics. Optimization can be done either by maximizing the minimum Euclidean distance (or product distance in fading channels) and to maximize the channel capacity. Lattice theory is suitable for this optimization.

In AWGN channel, maximization of the minimum Euclidean distance of the SCMA signal set is required. We present a new method for such optimization, based on Genetic Algorithm [10]. In general case, it does not require mother constellation. Potentially, it is possible to obtain better performance due to the larger number of degrees of freedom. In this paper, codebooks are structured, thus the optimization problem is simplified. The obtained codebooks outperform known codebooks in bit error probability terms.

The article is structured as follows. The SCMA description is presented in Section II. The review of SCMA codebooks is presented in Section III. The GA optimization method is introduced in Section IV. Simulation results are shown in Section V. Section VI draws the conclusions.

II. SCMA Description

Here we introduce the basics concepts of SCMA. The encoding and detection procedures are considered below.

A. SCMA Encoding

An SCMA encoding procedure is defined as a mapping from m bits to a K-dimensional complex codebook of size M, where $M = 2^m$ [4]. K-dimensional complex codewords consist of $N < K$ non-zero elements. Each user j has a unique

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codebook from the set of J codebooks, i. e. J users (usually called layers) can transmit information over K orthogonal resources simultaneously. The overloading factor is defined as $\lambda = J/K$.

SCMA codewords are transmitted over K shared resource elements (RE), e. g. orthogonal frequency division multiple access subcarriers. The SCMA sparsity scheme can be represented by a factor graph, where rows are orthogonal resources and columns are users. The example of such factor graph is presented below, where every user occupies two orthogonal resources (two ones in every column), so each orthoganal resource is shared by three users:

$$\mathbf{F} = \begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}. \tag{1}$$

B. SCMA Detection

After transmitting over channel, received signal is expressed by the following equation:

$$\mathbf{y} = \sum_{j=1}^{J} \operatorname{diag}(\mathbf{h}_j)\mathbf{x}_j + \mathbf{n}, \tag{2}$$

where $\mathbf{x}_j = (x_{1j}, \ldots, x_{Kj})^{\mathrm{T}}$ is the SCMA codeword of user j, $\mathbf{h}_j = (h_{1j}, \ldots, h_{Kj})^{\mathrm{T}}$ is the channel coefficients vector for user j, and $\mathbf{n}$ is a complex additive white Gaussian noise with zero mean and σ^2 variance, i. e. $\sigma^2/2$ per in-phase and quadrature components.

The signal (2) can be detected by ML algorithm, but it has very large complexity, $O(M^J)$, that increases exponentially with the number of users J and polynomially with the codebook size M [4]. For many users and/or large codebook size, ML detection is not feasible in real-time applications. Fortunately, there is an iterative suboptimal algorithm with a lower computational complexity. MPA has complexity $O\left(KM^{d_f}\right)$ per iteration, where d_f is the number of users contributing to every RE [4], however, the energy costs in the receiver are still significant. In factor graph (1), $d_f = 3$ (the number of ones in every row). The procedure of detection is similar to decoding of low-density parity-check (LDPC) codes.

III. SCMA Codebooks Overview

The codebooks from literature review are presented below.

This codebook set for $J = 6$, $K = 4$, and $N = 2$ is presented in [11]:

$$\mathbf{CB}_1 = \begin{bmatrix} 0 & -0.1815 - 0.1318j & 0 & 0.7851 \\ 0 & -0.6351 - 0.4615j & 0 & -0.2243 \\ 0 & 0.6351 + 0.4615j & 0 & 0.2243 \\ 0 & 0.1815 + 0.1318j & 0 & -0.7851 \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_2 = \begin{bmatrix} 0.7851 & 0 & -0.1815 - 0.1318j & 0 \\ -0.2243 & 0 & -0.6351 - 0.4615j & 0 \\ 0.2243 & 0 & 0.6351 + 0.4615j & 0 \\ -0.7851 & 0 & 0.1815 + 0.1318j & 0 \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_3 = \begin{bmatrix} -0.6351 + 0.4615j & 0.1392 - 0.1759j & 0 & 0 \\ 0.1815 - 0.1318j & 0.4873 - 0.6156j & 0 & 0 \\ -0.1815 + 0.1318j & -0.4873 + 0.6156j & 0 & 0 \\ 0.6351 - 0.4615j & -0.1392 + 0.1759j & 0 & 0 \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_4 = \begin{bmatrix} 0 & 0 & 0.7851 & -0.0055 - 0.2242j \\ 0 & 0 & -0.2243 & -0.0193 - 0.7848j \\ 0 & 0 & 0.2243 & 0.0193 + 0.7848j \\ 0 & 0 & -0.7851 & 0.0055 + 0.2242j \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_5 = \begin{bmatrix} -0.0055 - 0.2242j & 0 & 0 & -0.6351 + 0.4615j \\ -0.0193 - 0.7848j & 0 & 0 & 0.1815 - 0.1318j \\ 0.0193 + 0.7848j & 0 & 0 & -0.1815 + 0.1318j \\ 0.0055 + 0.2242j & 0 & 0 & 0.6351 - 0.4615j \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_6 = \begin{bmatrix} 0 & 0.7851 & 0.1392 - 0.1759j & 0 \\ 0 & -0.2243 & 0.4873 - 0.6156j & 0 \\ 0 & 0.2243 & -0.4873 + 0.6156j & 0 \\ 0 & -0.7851 & -0.1392 + 0.1759j & 0 \end{bmatrix}^{\mathrm{T}},$$

where $\mathbf{CB}_j$ is a codebook for user j.

Matrices are shown transposed only to fit them into the column width of the paper. The columns of codebooks are codewords, thus every user maps $m = 2$ bits to one of $M = 4$ four-dimensional codewords. The average power of signal is equal to 1. Below, this codebooks set will be referred to as **CS1**.

The codebook set **CS2** is based on QPSK mother constellation with Gray code bit mapping. Those codebooks are obtained by multiplication of symbols from QPSK alphabet with complex exponents $e_1 = 1$, $e_2 = \exp(j\pi/6)$ and $e_3 = \exp(j\pi/3)$. Every column has two identical rotation factors as in a simple LDS system. The matrix with those exponents is given below:

$$\mathbf{S} = \begin{bmatrix} 0 & e_2 & e_3 & 0 & e_2 & 0 \\ e_1 & 0 & e_3 & 0 & 0 & e_1 \\ 0 & e_2 & 0 & e_3 & 0 & e_1 \\ e_1 & 0 & 0 & e_3 & e_2 & 0 \end{bmatrix}.$$

In terms of LDS, every column is a low-density signature and symbol from QPSK constellation is multiplied by it.

The codebook set **CS3** is from [7]. Those codebooks are based on PAM–4 constellation with different resource element mapping for each user. For maximization of channel capacity, the effect of phase rotation, angle θ, is used. It is mentioned in that paper that this angle can be different for codewords in different columns, and the analysis is left for future study. Unfortunately, codebooks themselves are not presented in that paper. Based on some of the results from paper, we provided optimization for maximization of minimum Euclidean distance, d_{min}. For this purpose, we have multiplied the second symbol of the codeword for an additional rotation factor, r. The matrix with rotation factors is given below (binary code bit mapping is used for PAM–4):

$$\mathbf{S} = \begin{bmatrix} e_1 & 0 & e_2 & 0 & e_3 & 0 \\ 0 & e_1 & e_2 r & 0 & 0 & e_3 \\ e_1 r & 0 & 0 & e_2 & 0 & e_3 r \\ 0 & e_1 r & 0 & e_2 r & e_3 r & 0 \end{bmatrix},$$

where $e_1 = 1$, $e_2 = \exp(j\theta)$, $e_3 = \exp(j2\theta)$ and $r = \exp(j\phi)$.

The optimum value $\theta_{opt} = \pi/3$ [7]. As a result of our optimization, angle ϕ can be arbitrary in the range from $\pi/3$ to π. For any ϕ in this range, $d_{\min} = 0.7303$. For the purpose of codebook sets comparison, $\phi = 87^\circ$ was assumed without loss of generality. The encoding procedure is similar to the previous codebook set.

The codebook set $\mathbf{CS4}$ is presented in [8]. Those codebooks are obtained by capacity maximization in AWGN channel. The optimization is provided by rotation of codeword symbols. Multidimensional mother constellation is obtained by combining one-dimensional constellation sets. Minimum Euclidean distance for those codebooks is $d_{\min} = 0.6690$.

The codebook set $\mathbf{CS5}$ presented in [9] is based on QPSK mother constellation and full search of rotation factors for the given factor graph structure. For those codebooks, $d_{\min} = 0.7924$. Codebooks from $\mathbf{CS4}$ and $\mathbf{CS5}$ are normalized, similarly to the codebooks from previous codebook sets, that average power of signal will be equal to 1.

IV. SCMA Codebooks Optimization

This section consists of three parts. In the first part, we present the formulation of the optimization problem. In the second part, the implementation of optimization procedure is described. The analysis of obtained codebooks is given in the third part. We provided optimization for SCMA codebooks in AWGN channel, but in the third part the comments about optimization in Rayleigh fading channel are also given.

A. Optimization Problem

The objective function for optimization by genetic algorithm is $D(\boldsymbol{\gamma}, \boldsymbol{\varphi})$. This function returns the minimum Euclidean distance $d_{\min}$, calculating $M^J(M^J - 1)/2$ mutual distances between M^J SCMA signals. Our goal is to maximize $d_{\min}$. For optimization procedure, we introduce the following notation:

$$\alpha_j^2 + {\beta_j}^2 = E, \tag{3}$$

$$\alpha_j^2/\beta_j^2 = \gamma_j, \tag{4}$$

where E is the energy of codeword, α_j and β_j are magnitudes of codeword symbols, and γ_j is power variation in the codewords (the ratio between energies of symbols in codeword), and $j = 1, 2, \dots, J$. Different γ_j for different codebooks provide power variation on orthogonal resources. This has a positive effect on the convergence of MPA detector [4].

From (3) and (4),

$$\alpha_j(\gamma_j) = \sqrt{E\gamma_j/(\gamma_j + 1)},$$

$$\beta_j(\gamma_j) = \sqrt{E/(\gamma_j + 1)}.$$

All codebooks in the designed set has similar structure, the example of this structure for $j > 1$ is presented below:

$$\mathbf{CB}_j = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \alpha_j e^{j\varphi_i} & -\beta_j e^{j\varphi_i} & \beta_j e^{j\varphi_i} & -\alpha_j e^{j\varphi_i} \\ -\beta_j e^{j\varphi_{i+1}} & -\alpha_j e^{j\varphi_{i+1}} & \alpha_j e^{j\varphi_{i+1}} & \beta_j e^{j\varphi_{i+1}} \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

where $i = 2k, k = 1, 2, \dots, J - 1$.

Every non-zero row of codebook is multiplied by $\exp(j\varphi_i)$, except the first nonzero row of $\mathbf{CB}_1$ that is not multiplied by the complex exponent. Designed codebooks have two pairs of antipodal codewords, so the low-complexity SCMA detector based on solving overdetermined systems of linear equations [12], that outperforms Max-Log-MPA algorithm in terms of computational complexity for $M = 4$ and $J = 6$, can be applied for SCMA detection in AWGN or downlink fading channels.

Thus, vector parameters for objective function has the forms

$$\boldsymbol{\gamma} = (\gamma_1, \gamma_2, \dots, \gamma_J) \tag{5}$$

and

$$\boldsymbol{\varphi} = (\varphi_1, \varphi_2, \dots, \varphi_{JN-1}). \tag{6}$$

The total number of real-valued variables for optimization is equal to $(J(N + 1) - 1)$.

B. Implementation

We used genetic algorithm implementation from MATLAB Global Optimization Toolbox [13]. The function **ga** finds minimum of fitness function (in our case, $D(\boldsymbol{\gamma}, \boldsymbol{\varphi})$). Therefore, we minimize negative minimum Euclidean distance. The detailed description of this function can be found in [14]. We mostly used default values for the parameters of this function, the only exceptions are maximum number of iterations of algorithm and the bounds for optimization variables:

$$0.01 \leqslant \gamma_j \leqslant 40, \ j = 1, 2, \dots, J,$$

$$0 \leqslant \varphi_i < 2\pi, \ i = 1, 2, \dots, (JN - 1).$$

The maximum number of iterations before the algorithm halts is equal to 15. The algorithm stops if the average relative change in the best fitness function value is less than or equal to 10^{-6} [13]. If after 15 iterations this condition was not fulfilled, then the algorithm was started again (initial population is a solution from the previous step). Initial population for the first step is a set of values randomly drawn from the range between lower and upper bounds. The whole optimization procedure required no more than 100 iterations. For unit SCMA signal power, $E = 2/3$.

To further refine the solution, the interior point methods (class of algorithms that solve convex optimization problems) can be used. For this second step, we used MATLAB function **fmincon** that finds minimum of constrained nonlinear multivariable function [15].

C. Analysis of the Obtained Codebooks

The obtained codebook set $\mathbf{CS6}$ with is presented below:

$$\mathbf{CB}_1 = \begin{bmatrix} 0 & 0.7660 & 0 & 0.1346 - 0.2485j \\ 0 & -0.2826 & 0 & 0.3649 - 0.6735j \\ 0 & 0.2826 & 0 & -0.3649 + 0.6735j \\ 0 & -0.7660 & 0 & -0.1346 + 0.2485j \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_2 = \begin{bmatrix} 0.2646-0.6446j & 0 & 0.4168-0.0865j & 0 \\ -0.1617+0.3938j & 0 & 0.6822-0.1416j & 0 \\ 0.1617-0.3938j & 0 & -0.6822+0.1416j & 0 \\ -0.2646+0.6446j & 0 & -0.4168+0.0865j & 0 \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_3 = \begin{bmatrix} 0.6994+0.3766j & -0.1355+0.1316j & 0 & 0 \\ -0.1663-0.0895j & -0.5697+0.5535j & 0 & 0 \\ 0.1663+0.0895j & 0.5697-0.5535j & 0 & 0 \\ -0.6994-0.3766j & 0.1355-0.1316j & 0 & 0 \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_4 = \begin{bmatrix} 0 & 0 & -0.3644-0.4552j & 0.3550+0.4480j \\ 0 & 0 & 0.3572+0.4462j & 0.3621+0.4570j \\ 0 & 0 & -0.3572-0.4462j & -0.3621-0.4570j \\ 0 & 0 & 0.3644+0.4552j & -0.3550-0.4480j \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_5 = \begin{bmatrix} 0.6227-0.4960j & 0 & 0 & -0.1708-0.0611j \\ -0.1419+0.1130j & 0 & 0 & -0.7496-0.2680j \\ 0.1419-0.1130j & 0 & 0 & 0.7496+0.2680j \\ -0.6227+0.4960j & 0 & 0 & 0.1708+0.0611j \end{bmatrix}^{\mathrm{T}},$$

$$\mathbf{CB}_6 = \begin{bmatrix} 0 & 0.7441+0.2835j & -0.1347+0.1202j & 0 \\ 0 & -0.1687-0.0643j & -0.5942+0.5301j & 0 \\ 0 & 0.1687+0.0643j & 0.5942-0.5301j & 0 \\ 0 & -0.7441-0.2835j & 0.1347-0.1202j & 0 \end{bmatrix}^{\mathrm{T}}.$$

For this set of codebooks,

$$\boldsymbol{\gamma} = (7.35, 2.68, 17.69, 1.04, 19.25, 19.45)$$

and

$$\boldsymbol{\varphi} = (2.07, 5.10, 2.94, 0.49, 5.51, \ldots \\ 4.04, 4.04, 5.61, 0.34, 0.36, 5.55).$$

Using only the genetic algorithm, $d_{\text{min}} = 0.8567$. Applying the interior point method (with default values for the parameters of **fmincon** function) and using the solution of the genetic algorithm as a starting point, we got $d_{\text{min}} = 0.8660$. Thus, the gain of additional optimization was about 1 %.

Table I shows the minimum Euclidean distances for all codebook sets from Sections III and IV.

TABLE I
MINIMUM EUCLIDEAN DISTANCE FOR CODEBOOK SETS

CS	CS1	CS2	CS3	CS4	CS5	CS6
d_{min}	0.4581	0.5977	0.7303	0.6690	0.7924	0.8660

As can be seen, the 4th user has practically no power variations, and both its rotation angles are identical. In this case, the codewords are almost one-dimensional. Thus, the diversity effect is absent. In an uplink (UL) Rayleigh fading channel with diversity (when users have independent channel gains on their orthogonal resources), this user would have bad performance. For this channel, codebooks with better power variation and/or different rotation factors are more suitable. An example of such codebooks is the codebook set **CS7**. The parameters for those codebooks are

$$\boldsymbol{\gamma} = (23.88, 3.32, 17.23, 39.99, 6.32, 3.46)$$

and

$$\boldsymbol{\varphi} = (2.12, 5.41, 1.49, 4.32, 2.06, \ldots \\ 6.01, 4.27, 0.66, 6.06, 4.36, 3.37).$$

Codebooks from **CS7** were obtained by maximization of minimum Euclidean distance (it is equal to 0.8329), but they have good distance properties for Rayleigh channel too. Genetic optimization was used for design those codebooks without the second refining step. This set of codebooks is one of "underoptimized" sets obtained during design of codebooks from **CS6**. For this codebook set, simulation in UL Rayleigh fading channel with diversity will be provided in Section V. It is worth noting that for codebook set **CS7** in AWGN channel bit error rate (BER) degradation is insignificant compared with **CS6** ($d^2_{\text{min,CB7}}/d^2_{\text{min,CB6}} = 1.08 \approx 0.3$ dB). Constraint on power variation γ (it should not be close to unity) is needed for codebook design in Rayleigh fading channel with diversity. Also the upper bound for the average symbol error rate (SER) in Rayleigh channel [16] can be used as the objective function (fitness function for GA optimization). In the general case, both maximization of minimum Euclidean distance and minimization of SER should be included in the fitness function. The study of these criteria is for future work.

V. SIMULATION RESULTS

Computer simulation was carried out for uncoded SCMA in AWGN channel. As a measure of signal-to-noise ratio (SNR), we used SNR per bit (E_b/N_0) for a single user:

$$E_b/N_0 = \text{SNR} - 10\log_{10}\left(\log_2\left(M\right)\lambda\right) \text{ dB},$$

where $(\log_2(M)\lambda)$ is a spectral efficiency of uncoded SCMA system (in our case, 3 bits per orthogonal resource). ML and Log-MPA with 5 iterations were simulated. The simulation was executed until reaching either 1000 errors or 10^7 processed bits (for every user).

BER averaged over all J users for Log-MPA detector is shown in Fig. 1. The proposed codebook set **CS6** outperforms other sets. Power gain is about 1.5 dB compared to **CS4** at BER $= 10^{-6}$. In Fig. 2, the bit error probability based on union bound [17] is shown. The curves confirm the energy gain of **CS6** over **CS5** equal to $d^2_{\text{min,CB6}}/d^2_{\text{min,CB5}} = 1.2 = 0.8$ dB. The comparison of ML and Log-MPA detectors is shown in Fig. 3 for **CS5** and **CS6**. Codebooks from **CS5** have no power variation on orthogonal resources, so MPA algorithm has bad performance for them. Compared with the ML algorithm, power loss is about 2 dB. So, potentially good codebooks would not achieve their performance bounds in real-world applications. The proposed codebooks do not suffer from this drawback, ML and Log-MPA with 5 iterations provide the same performance.

BER performance of SCMA systems can be different among users. In Fig. 4, BER for the best and the worst users are shown for different codebook sets. For **CS4**, all users have practically the same performance. For **CS5**, the difference between the best and the worst users does not exceed 0.6–0.7 dB. For

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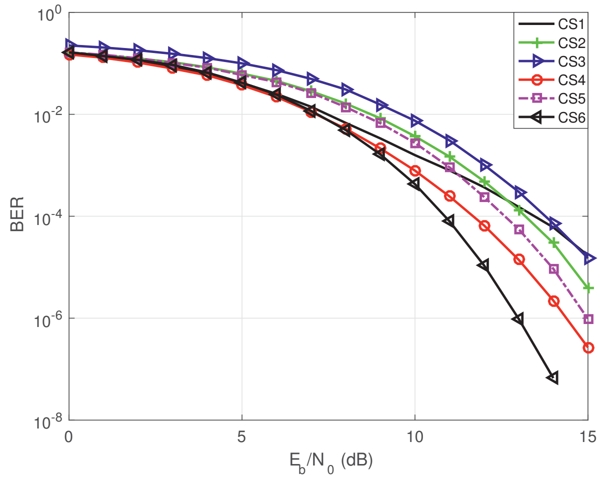

Fig. 1. Average BER in AWGN channel

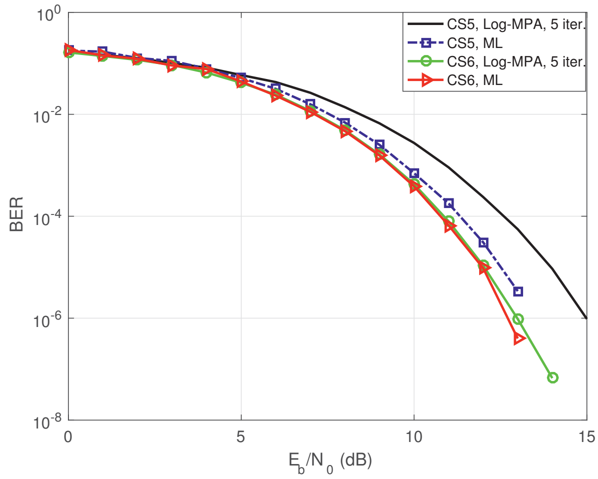

Fig. 3. Log-MPA and ML performance comparison for **CS5** and **CS6**

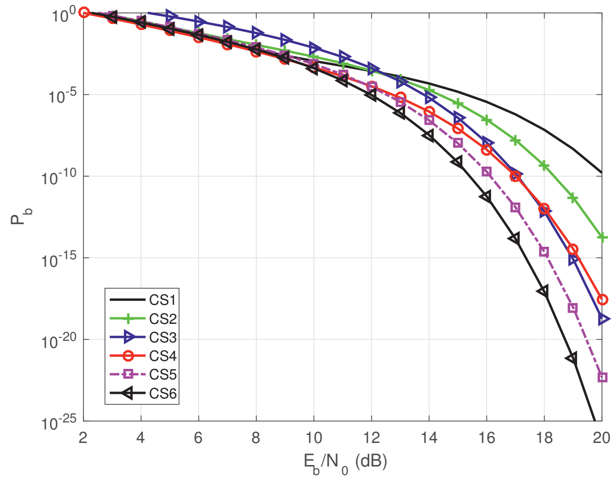

Fig. 2. Bit error probability, union bound

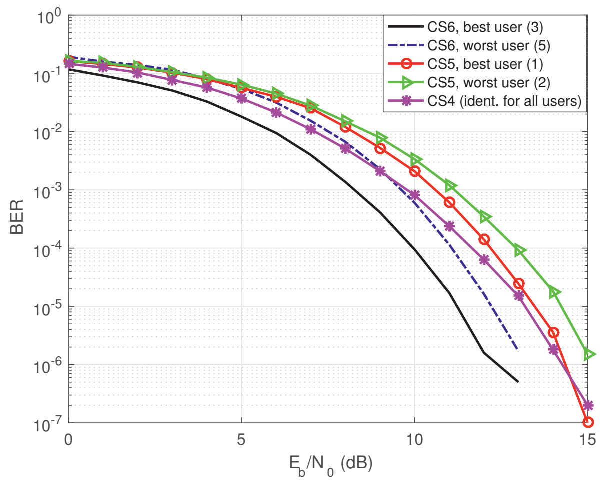

Fig. 4. Best and worst users for **CS4**, **CS5** and **CS6**, Log-MPA detector

CS6, the best and the worst users differ by about 1 dB. At $E_b/N_0 > 9$ dB, even a worst user from **CS6** outperforms all other codebook sets. The BER curves for all users from **CS6** in AWGN channel are shown in Fig. 5. The 3rd user has the best performance, while other users have identical performance with power loss about 1 dB.

The BER curves for all users from **CS6** in UL Rayleigh channel with diversity are shown in Fig. 6. Average BER curves in UL Rayleigh fading channel with and without diversity are shown in Fig. 7. In UL channel without diversity, **CS3** is the worst codebook set and **CS6** has performance similar to all other codebook sets. For UL channel with diversity, codebook set **CS7** is used instead of **CS6**, because the latter has very bad performance in this channel. For those codebooks, power loss is about 1–2 dB compared to other codebook sets.

VI. Conclusion

We presented a new method for SCMA codebooks design based on GA. In the general case, this technique does not require a mother constellation, but we designed structured codebooks with two pairs of antipodal codewords. Thus, the search for a good multidimensional complex constellation is not required. The result of the genetic algorithm can be used as a starting point for other optimization algorithms. The obtained codebooks outperform other known codebooks in AWGN channel. This codebook set have minimum Euclidean distance equal to 0.87 (at unit average power of SCMA signal). The asymptotic gain in comparison with the best known codebooks is 0.8 dB. The proposed codebooks demonstrate identical performance for ML and MPA detection algorithms. Codebooks have performance comparable with other codebooks in UL Rayleigh channel without diversity, but in UL Rayleigh channel with diversity their performance is not good. For this

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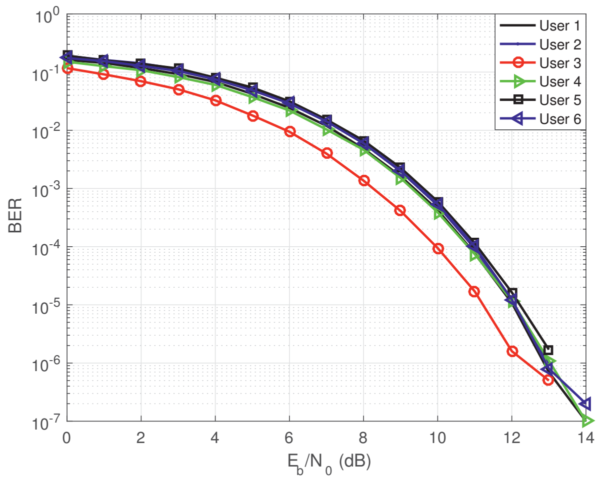

Fig. 5. BER for all users, AWGN channel, **CS6**

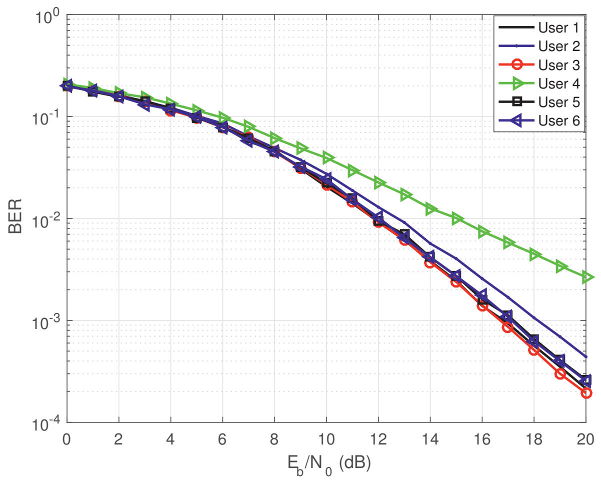

Fig. 6. BER for all users, Uplink Rayleigh channel with diversity, **CS6**

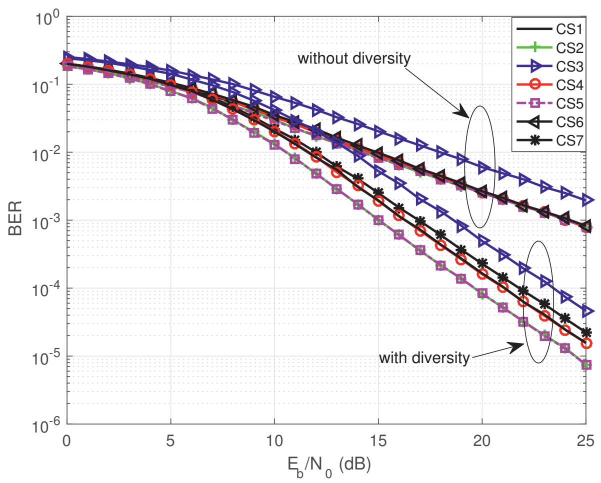

Fig. 7. Average BER in Uplink Rayleigh channel

case, we designed codebooks that have power loss about 1–2 dB relative to others, and retain very good performance (0.3 dB loss to the optimized version) in AWGN channel.

The proposed algorithm can be used for codebook design for other non-orthogonal systems, e. g., PDMA [18]. Also, by changing objective function of GA, codebooks optimized for other channel models can be obtained. For example, we can expect improved results for UL Rayleigh channel. Also the promising direction is joint codebook optimization to get good performance in both AWGN and Rayleigh channels.

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