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FUTURE NETWORKS: 5G AND BEYOND

An adaptive Uplink SCMA Scheme Based on Channel State Information

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Abstract:

The sparse code multiple access (SCMA) is one of the promoting candidate of code-domain non-orthogonal multiple access (CD-NOMA) for the upcoming generations of wireless communications systems, and it has been actively investigated in recent years. The key distinguishing feature of SCMA comes from the gain of its multi-dimensional sparse codebooks. Nevertheless, all users have not the same business requirements, and their physical layer needs depend on many factors such as the maximum allowed delay, the required rate and the targeted quality of service. In this paper, an adaptive SCMA scheme is proposed to tackle this problem. The idea is to divide users into different groups such as an adaptive designed codebook is allocated to each group. Unlike the traditional SCMA, the sparsity degree, the constellation size, and the allocated power per user, can be adapted to each group requirements in order to increase the overall performance of an uplink SCMA system. Simulation results show that the proposed scheme outperforms the traditional regular SCMA.

1 Introduction

Soon, the number of devices and connected users will be exceeding more than 50 billion of active hosts. As a result, a massive automatic data will be exchanged among huge number of connected devices. Among the fifth generation (5G) promises, when compared to fourth generation (4G), is to increase the user data rate by 10 to 100 (up to 10 Gbit/s), to reduce the latency by 10, to increase the connectivity density by 10. In order to meet the massive connectivity requirement of the upcoming future generations of wireless networks, innovative non-orthogonal multiple-access (NOMA) techniques were proposed and they are mainly divided into two categories: power-domain NOMA (PD-NOMA) and code-domain NOMA (CD-NOMA) [1]. PD-NOMA (which is traditionally called NOMA) exploits the power dimension to allow different users to access the same resources element (RE). Sparse code multiple access (SCMA) [2] is a multiple-carrier CD-NOMA technique which enjoys a good spectrum-efficiency thanks to the shaping gain of its multi-dimensional codebook [3]. The new radio (NR) study in 3GPP considered the SCMA among the multiple access techniques for 5G [4, 5].

SCMA can serve several users simultaneously by using a specific sparse codebook for each user such as bits are directly mapped to the multi-dimensional codewords, the inter-user interference is eliminated by employing the low-complexity message passing algorithm (MPA) or one of its variations [6]. Well designed multi-dimensional codebook plays a major factor in improving SCMA performance since it increases its shaping gain. Constellation with low projections [2], spherical codebooks [7], and star-QAM based multi-dimensional constellation [8] are among existing codebook designs. A comprehensive review of multi-dimensional constellations for SCMA systems is introduced in [3].

Most existing SCMA systems are based on regular structure where users are treated equally that is why they can not be adapted to users' business needs or conditions in the same scenario which is not realistic. So new irregular SCMA systems are needed to manage different requirements such as capacity, connectivity, and data rate, and to also exploit the knowledge of channel state information (CSI). Some existing work tried to solve this problem, for instance an irregular SCMA codebook design [9] was proposed to assign different codebooks with various dimensions according to different users' requirements. Simulations show that using an irregular codebook design does improve the system performance in terms of bit error rate (BER), however the authors did not take into consideration the impact of the correlation among users. Another irregular SCMA design was proposed in [10], the idea was to employ different rotated angles to design different codebooks for several user's needs, nevertheless the proposed codebooks are still far from optimization. The authors in [11] studied the resource allocation for different users in the same system by proposing a flexible resource scheduling scheme.

Other contribution in [12] proposed an energy-saving algorithm for a joint codebook design and assignment, and power allocation for both uplink and downlink SCMA scenarios.

Here, we propose two optimized adaptive codebooks for irregular SCMA structure by adapting either the constellation size or the sparsity degree of each codebook such as we can respectively adjust either the data rate or the quality of service of each user. The served users are divided into several groups such as each group has its specific characteristics of the designed codebook. The proposed codebook design extends the work in [8] to propose a joint optimization of the mother constellations and the rotation operators which are employed to generate the different codebooks. The log-domain MPA (Log-MPA) detctor is employed at the receiver. Simulation results demonstrate that the BER performance of the optimized adaptive codebooks is better than that of existing regular codebooks.

The rest of the paper is organized as follows. The SCMA system model is presented in section 2, the optimized codebooks are introduced in section 3. Simulation results are then provided in section 4. Finally, the conclusions of this research work are summarized in section 5.

2 System model

We consider a synchronous uplink SCMA system with a base station and J separate users so-called layers and K orthogonal frequency-division multiplexing (OFDM) sub-carriers, so-called resource elements (REs). An SCMA transmitter encodes the data bits of user j and maps them into a K dimensional codeword, $\mathbf{x}_j$. The constellation function, associated for each user j, g_j, generates a constellation set with M_j alphabets of length N_j. Then, the mapping matrix V_j maps the N_j dimensional constellation points to SCMA codewords to form a distinct codebook $\mathbf{C}_j$. Each codebook presents the signature of the corresponding user. The codebooks are built based on multi-dimensional constellations whose shaping gain enables to outperform the traditional spread code based schemes [13]. As to the codewords of SCMA, they are sparse, i.e. only $N_j \ll K$ of their entries are non-zero, which is called *codebook sparsity degree*, and the rest are zeros. The sparsity key of SCMA that all codewords corresponding to the j^{th} SCMA layer have a unique location of non-zero entries at the same $(K-N_j)$ positions.

Figure 1 illustrates the SCMA system under three scenarios. A regular SCMA is presented in Fig.1(a) where all users are spread over two REs ($N=2$) and employs a codebook of size $M=4$. The system is described with the factor graph matrix $\mathbf{F}_{\text{ss}} = (\mathbf{f}_{\text{ss},1}, \cdots, \mathbf{f}_{\text{ss},J})$, it is obvious that all users have the same codebook sparsity degree. The same factor graph matrix is valid when each user employs his specific constellation size M_j as shown in Fig.1(b). This scenario allows to serve users at different data rates. On the other hand, different sparsity degrees can be used such as each user sends $\log_2(M)$ bits over a specific number of sub-carriers as depicted in Fig.1(c). An example of a factor graph with different sparsity degrees, $\mathbf{F}_{\text{ds}}$, is given in the following.

$$\mathbf{F}_{\text{ss}} = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix} \quad , \quad \mathbf{F}_{\text{ds}} = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{1}$$

The codewords of all layers are then superimposed and exchanged over the K REs. The K-dimensional received vector is given by,

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

where $\mathbf{h}_j$ is the $K \times 1$ channel gain vector and $\text{diag}(\mathbf{h}_j)$ is a diagonal matrix whose diagonal elements are the entries of $\mathbf{h}_j$. The $K \times 1$ vector $\mathbf{n}$ corresponds to the additive zero-mean white circularly complex Gaussian noise with variance N_0; i.e. $\mathbf{n} \backsim \mathcal{CN}(0, N_0\mathbf{I}_K)$, where $\mathbf{I}_K$ is the identity matrix of size K.

3 Adaptive SCMA Codebook Design

The SCMA codebook design problem involves finding the optimum user-to-RE spreading matrix $\mathcal{S}^*$, along with the optimum multi-dimensional constellation $\mathcal{X}^*$, and can be defined as:

$$\mathcal{S}^*, \mathcal{X}^* = \arg\max_{\mathcal{S},\mathcal{X}} D\left(\phi(\mathcal{S}, \mathcal{X}; J, \{M_j\}, \{N_j\}, K)\right) \tag{3}$$

where D is a design criterion and ϕ is the SCMA system as it was described in section 2. Also, $\mathcal{S} = \{\mathbf{S}_j, 1 \le j \le J\}$ where $\mathbf{S}_j$ is the spreading matrix of user j, it is worth noting that $\mathbf{f}_{\text{ss,j}} = \mathbf{S}_j\mathbf{S}_j^T$. Existing SCMA codebooks

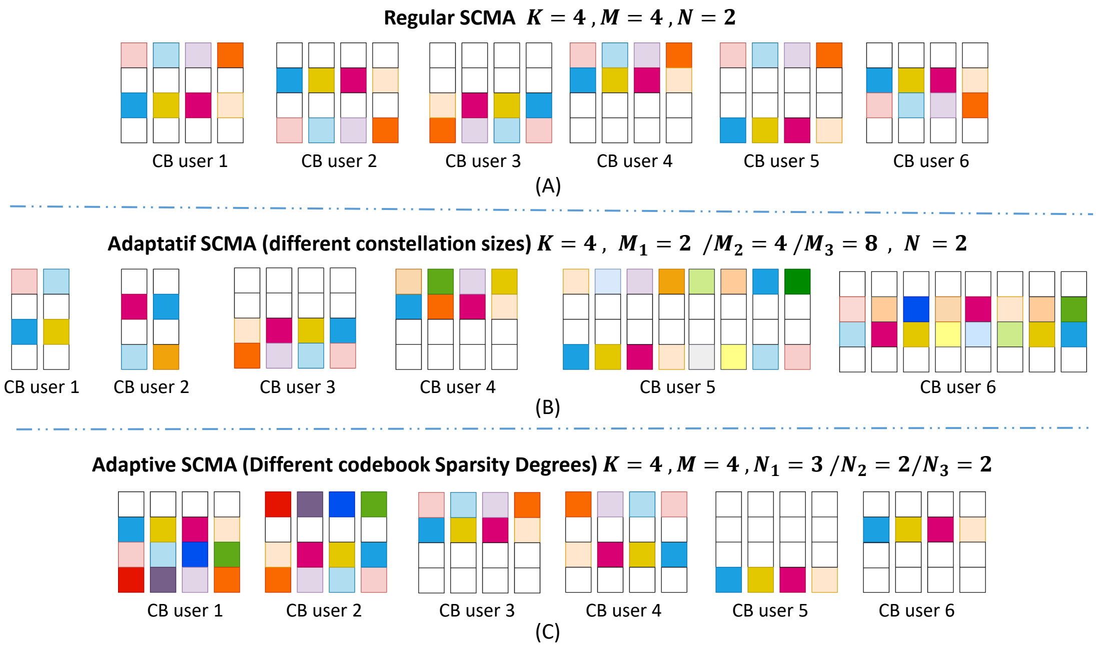

Figure 1 – Presentation of the SCMA encoder for (a) regular system (b) adaptive system with different codebook sparsity degrees (b) adaptive system with different constellation sizes.

designs simplified this optimization problem into a sub-optimal multi-stage approach [3], such as the design of SCMA codebook is performed in three main steps : Firstly a mother constellation, $\mathbf{X}_m$, is designed, then a user-specific rotation matrices, $\triangle_j$, are used to generate user-specific multi-dimensional constellations which are finally spread to generate the J codebooks. Hence, the optimization problem in (3) is reformulated as follows,

$$\{\triangle_j\}, \mathbf{X}_m^* = \arg \max_{\{\triangle_j\}, \mathbf{X}_m} D\left(\phi(\mathcal{S}^*, \{\triangle_j \mathbf{X}_m\}; J, \{M_j\}, \{N_j\}, K)\right) \tag{4}$$

such as the j^{th} codebook is calculated by,

$$\mathbf{C}_j = \mathbf{S}_j^* \triangle_j^* \mathbf{X}_m^*. \tag{5}$$

In the following subsections, the design of mother constellations and rotation matrices will be introduced.

3.1 Mother constellation design

The $N \times M$ mother constellation consists of N vector or dimension of size M, that is the N rows of $\mathbf{X}_m$. The proposed design is inspired by the work in [8] and extends it to the case of adaptive SCMA. We have two distinct cases, namely systems with different codebook sparsity degrees and those with different constellation sizes.

For the former case, we need to design a constellation matrix $\mathbf{X}_m$ of size $N = \max(N_1, \cdots, N_J)$ such as only N_j dimension are used to generate the codebook $\mathbf{C}_j$. Each dimension is generated from the previous one by adding an interleaving and power scaling effect such as inter-layer interference can be eliminated more easily. Here, we will study an SCMA system with three distinct groups of users that is $N_1 = 3, N_2 = 2, N_3 = 1, M = 4$ where the factor graph matrix $\mathbf{F}_{\text{ds}}$ as defined in (1) is adopted. The employed mother constellation is expressed as,

$$\mathbf{X}_m = \begin{bmatrix} \alpha R_1 & R_1 & -R_1 & -\alpha R_1 \\ -R_2 & \alpha R_2 & -\alpha R_2 & R_2 \\ \alpha R_3 & R_3 & -R_3 & -\alpha R_3 \end{bmatrix} \tag{6}$$

where $R_2 = \beta R_1$ and $R_3 = \beta R_2$. The optimization approach in this paper is more powerful since we consider $\alpha, \beta \in \mathbb{C}$ in contrast to [8] which allows to have some inter- and intra-dimensional rotations in addition to the power variation. The optimization consists of finding the values of α and β which maximizes the codebook design criterion.

For SCMA systems with different constellation sizes, the same approach is used but it must be adapted such as we have a distinct mother constellation for each value of M, that is $\mathbf{X}_{m,1} \in \mathbb{C}^{N \times M_1}, \mathbf{X}_{m,2} \in \mathbb{C}^{N \times M_2}, \mathbf{X}_{m,3} \in$

$\mathbb{C}^{N\times M_3}$. These matrices are given by,

$$\mathbf{X}_{m,1} = \begin{bmatrix} R_1 & -R_1 \\ -R_3 & R_3 \end{bmatrix}$$

$$\mathbf{X}_{m,2} = \begin{bmatrix} \alpha R_1 & R_1 & -R_1 & -\alpha R_1 \\ -R_2 & \alpha R_2 & -\alpha R_2 & R_2 \end{bmatrix} \tag{7}$$

$$\mathbf{X}_{m,3} = \begin{bmatrix} \alpha R_3 & \alpha R_1 & R_3 & R_1 & -R_1 & -R_3 & -\alpha R_1 & -\alpha R_3 \\ -R_4 & -R_2 & \alpha R_4 & \alpha R_2 & -\alpha R_2 & -\alpha R_4 & R_2 & R_4 \end{bmatrix}$$

Based on that the codebooks are designed for $J = 6$ users belonging to three distinct groups such as $N = 2, M_1 = 1, M_2 = 2, M_3 = 3$, and the factor graph matrix $\mathbf{F}_{\text{ss}}$ as defined in (1) is used.

One essential key to optimize the codebooks is to chose the best design criterion. Exiting design criteria including Euclidean distance, Euclidean kissing number, product distance, modulation diversity order and others are reviewed in [3]. The authors in [8] showed that the pairwise error probability between two transmitted vectors $\mathbf{x}_a, \mathbf{x}_b \in \mathcal{M}$ is given by,

$$\mathbb{P}(\mathbf{x}_a, \mathbf{x}_b|\mathbf{H}) = Q\left(\sqrt{\frac{\|\mathbf{H}\left(\mathbf{x}_a - \mathbf{x}_b\right)\|^2}{2N_0}}\right) \tag{8}$$

where $\mathcal{M}$ is the combination constellation. Hence, the optimization objective is to find α, β values that maximize the minimum square Euclidean distance of the combination constellation $\mathcal{M}$. A numerical search algorithm is employed for this objective. Obviously, codebooks for all users must be calculated to find $\mathcal{M}$.

3.2 Rotation matrix design

The last step of the codebook design is to find the optimal rotation angles. All existing works employ the typical rotation angles in [2, 10]. In this paper, we propose an optimized set of user-specific rotation matrices. The n^{th} entry of the $N_j \times N_j$ diagonal rotation matrix for user j is defined as,

$$\left[\triangle_j\right]_{n,n} = e^{j\theta_{j,n}}, \tag{9}$$

where $\theta_{j,n} \in [0, \pi[$ since the different dimensions of each mother constellation are symmetric. In order to simplify the optimization, quantized angles can be employed to represent the semi-circle, i.e. $\theta_{j,n}$ can be obtained from a uniform grid as following,

$$\theta = \left\{\frac{i\pi}{N_\theta}; 0 \leqslant i \leqslant N_\theta - 1\right\} \tag{10}$$

when N_θ is a design parameter. It is worth mentioning that for the system proposed in Fig.1(c), a total number of distinct rotation angles of $N_1 + N_2 + N_3$ is needed. However, for the system with different constellation sizes, we assign two rotation angles for each dimension with eight constellation points which is considered as a combination of two vectors with four constellation points. This makes the total number of distinct rotation angles of $M_1 + M_2 + 2M_3$.

A numerical search algorithm is employed to assign the optimal rotation angle for each dimension of each user. This requires to find the optimal values of α and β first which itself requires to know the rotation matrices. To solve this problem the rotation angles are assigned successively in the first step, α and β are optimized before optimizing the rotation angles in the second step.

4 Simulation Results

In this section, we will present the simulation results to highlight the performance of the proposed adaptive SCMA when compared with the SCMA proposed in [2] which will be denoted as regular SCMA. The simulation parameters are listed in Table 1. All results are based on Monte Carlo trials, for each realization the channel is assumed to follow a Rayleigh distribution and a random AWGN is added. SCMA system performance is evaluated through the BER for different values of E_b/N_0.

4.1 The impact of different channel conditions on the performance of regular SCMA

All existing SCMA research works assume that all the users have the same channel conditions which is not exact. Here, we will study the SCMA performance when users have different channel states. We suppose that

Table 1 – Simulation Parameters for adaptive SCMA

Parameter	**Value**
SCMA Constellation Type	Optimized
Number of Monte Carlo trials	10000
Maximum number of symbol	1e7
Maximum number of bit errors	100
Number of MPA iterations	5
Number of sub-carrier	4
Number of users	6
Overload factor	1.5
Channel type	Rayleigh fading

the $J = 6$ users can be classified into three groups such as the average signal-to-noise ratio (SNR) varies from one group to another. The SNR level fluctuation (in dB) among the groups is denoted by δ such as when the average SNR for all users is γ then the average SNR per groups is either $\gamma - \delta, \gamma$ or $\gamma + \delta$. A performance evaluation of regular SCMA for different values of SNR level fluctuation is shown in Fig.2. Obviously, the BER increases when δ increases, for instance the BER is 5 and 50 times higher for $^{E_b}/_{N_0} = 15$dB when $\delta = 2$ and $\delta = 4$. Hence, it is recommended to design adaptive SCMA codebooks which take into consideration the variable nature of the channel state of each user. For the rest of simulation results, we will consider $\delta = 2$.

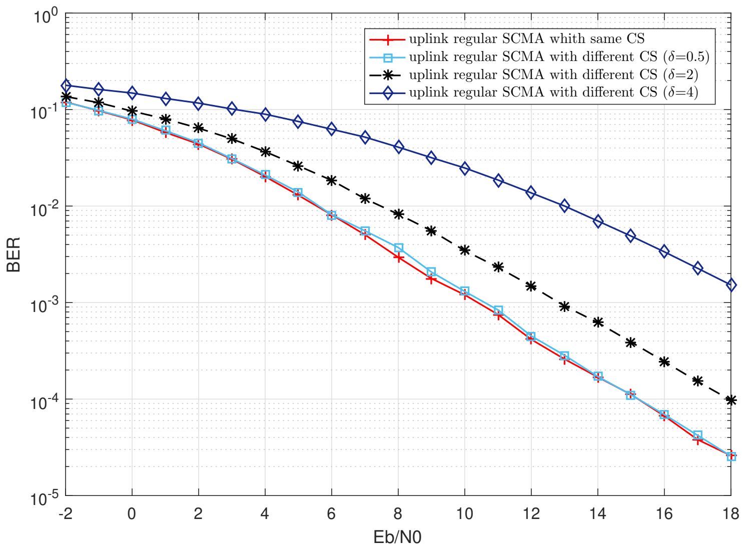

Figure 2 – Performance evaluation of uplink SCMA in [2] when users have different channel states for different values of SNR level fluctuation $\delta = 0.5, \delta = 2, \delta = 4$

4.2 Performance of adaptive SCMA with $N_1 = 3, N_2 = 2, N_3 = 1$ and $M = 4$

Fig.3 compares the performance of regular SCMA with SCMA based on the optimized codebook as proposed in this paper. Despite the fact that regular uplink SCMA outperforms the proposed adaptive SCMA when all users have the same channel state, it is the opposite when different channel states are taken into consideration, that is the performance of regular SCMA degrades and that of the adaptive SCMA becomes better. Clearly, the BER performance of the optimized adaptive SCMA codebook is better than that of regular uplink SCMA through Rayleigh fading channels, e.g. for a BER of 10^{-4}, a gain of almost 3 dB is achieved. This can be explained by the fact that we allocate more RE ($N_1 = 3$) for the users with the worst channel conditions.

4.3 Performance of adaptive SCMA codebooks with $M_1 = 2, M_2 = 4, M_3 = 8$ and $N = 2$

The idea of codebooks with different constellation sizes was inspired from the adaptive digital modulation where the size of the constellation increases when the channel is better and vice versa. Here, we have three groups of users with three different channel states, hence the two codebooks with 8 codewords are assigned to the group

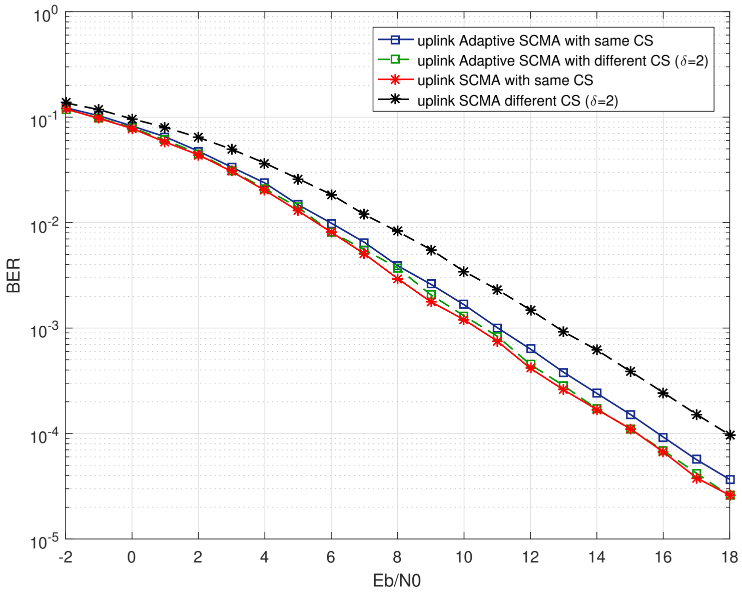

Figure 3 – Performance comparison between regular uplink SCMA and adaptive uplink SCMA with different sparsity degrees ($N_1 = 3, N_2 = 2, N_3 = 1$) when the different channel states are taken into consideration.

with the better channel conditions, and the two codebooks with 2 codewords are assigned to the group with the worst ones. BER performance of the proposed adaptive SCMA with different constellation sizes is compared to the regular SCMA is Fig.4. Our proposal provides better performance, for instance a gain of 2 dB is achieved when BER is of 10^{-4}.

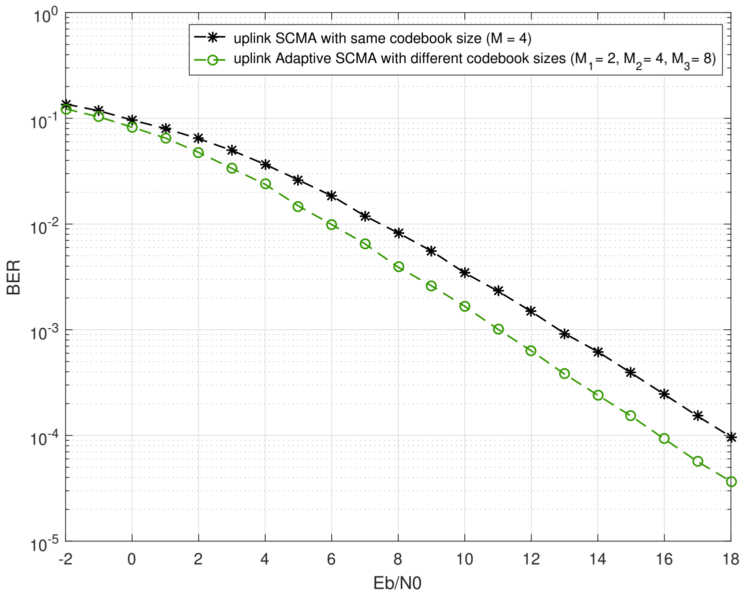

Figure 4 – Performance comparison between regular uplink SCMA and adaptive uplink SCMA with different constellation sizes ($M_1 = 2, M_2 = 4, M_3 = 8$) when the different channel states are taken into consideration.

5 Conclusions

In this paper, we discussed how to adapt the SCMA system according to user business requirements or his environment conditions such as his channel state for example. The proposed adaptive SCMA scheme divides users into groups and assigns to them either different codebook sparsity degrees or different constellation sizes. We introduced an enhanced method to optimize the mother constellations and the rotation matrices in the two cases. The total performance of the system is adjusted according to users' channel conditions by either allocating more REs to the users with the worst channel conditions, or by assigning largest codebook size to users with the best channel conditions. The performance of our proposed adaptive SCMA was evaluated through link-level simulations and it was compared to that of the conventional regular SCMA. Simulation results show that the optimized adaptive SCMA system provides better performance in terms of BER in the two cases.

6 References

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