Detection of SCMA Signal with Channel Estimation Error

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***Abstract*—Fifth generation wireless communication systems should support, among other things, very large number of simultaneous connections. To address this requirement, various schemes of non-orthogonal multiple access (NOMA) were proposed that allow to increase the number of simultaneously active users. One of NOMA schemes is sparse code multiple access (SCMA), where sparse multidimensional codewords allow to use iterative detecting algorithms with reasonable complexity. In the paper, SCMA detection is investigated in the presence of channel estimation error. Uncoded and turbo coded SCMA is analyzed. Uplink channel with Rayleigh flat block fading is assumed. Simulation results show that required accuracy of the channel estimation depends on the turbo code block length. For full utilization of turbo code error-correction capability with short blocks (40 bits) normalized variance of channel estimation error should be less than 10^{-3}, the same value applies to the case of uncoded SCMA. For turbo code with long blocks (1024 bits), estimation can be less accurate, with normalized variance up to 10^{-2}. With such channel estimation accuracy, power loss is about 0.6–0.7 dB compared with the case of perfect estimation. Two different types of codebooks have shown the same performance for coded SCMA, that leads to conclusion that codebook with more simple structure that provides less complexity of detection algorithm is a good candidate for use in SCMA schemes. The comparison with traditional orthogonal multiple access scheme with the same overall spectral efficiency is provided for both uncoded and coded SCMA systems. In case of coded system, SCMA scheme is shown to have smaller BER in the range of bit error probabilities below 10^{-4}–10^{-5} for long blocks. The power gain is 0.5–1 dB for long blocks and a few tenths of dB for short blocks.**

I. Introduction

Fifth generation (5G) wireless communication standard requires higher spectral efficiency, massive connectivity and lower latency. 5G is expected to be commercially deployed in 2020, therefore currently a lot of research is being carried out. One of the main applications of this technology is the Internet of Things (IoT). 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]. 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 frequency division, time 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]. NOMA is divided into two types: power-domain multiplexing (detection based on successive interference cancellation techniques) and code-domain multiplexing (detection based on Maximum Likelihood (ML) algorithm or Message Passing Algorithm (MPA)). SCMA [4] is a scheme of the second type and a possible candidate of NOMA for 5G. The main advantage of other NOMA techniques, e. g. Low Density Signature (LDS) [5] or Multi-User Shared Access (MUSA) [6] is some potential gain of multidimensional constellation shaping [2]. Another advantage of SCMA, along with other NOMA systems, is the ability to provide grant-free uplink (UL) data transmission that increases spectral efficiency of the system [7].

One of the problems with coherent signal detection is necessity of channel estimation. Only after obtaining channel state information it is possible to demodulate the received signal. For conventional digital communication schemes this issue is sufficiently studied, but the problems of SCMA system channel estimation are at an early stage of investigation. In [8], blind detection algorithms in UL are considered and two algorithms for channel estimation are presented. These methods are Focal Underdetermined System Solver and Expectation Maximization. Both are iterative algorithms to obtain a vector of channel coefficients. In [9], algorithm of channel estimation based on sparse Bayesian learning is presented.

In this paper, we investigated the effect of channel estimation error on bit error probability in Rayleigh flat fading channel for uncoded SCMA and SCMA with turbo coding. Channel estimation error is defined in terms of its variance, without relying on specific algorithms of channel estimation.

II. SCMA description

A. SCMA encoding

An SCMA encoding procedure is defined as a mapping from m bits to an 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 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 $\lambda = J/K$. An example of codebook set for $J = 6$ and $K = 4$ is presented below [10]:

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

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

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

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

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

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

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

The columns of codebooks are codewords, thus every user maps $m = 2$ bits to one of $M = 4$ four-dimensional codewords. Below, this codebooks set will be referred to as $\mathbf{CS1}$.

SCMA codewords are transmitted over K shared resource elements (RE), e. g. orthogonal frequency division multiple access subcarriers. Users' placement on REs (i. e., codebook sparsity) can be described by a factor graph (Fig. 1) [10]. This structure is equivalent to the structure of low density parity check codes (LDPC). Circles correspond to users, while rectangles correspond to REs.

B. SCMA detection

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

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

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 a channel coefficients vector of 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.

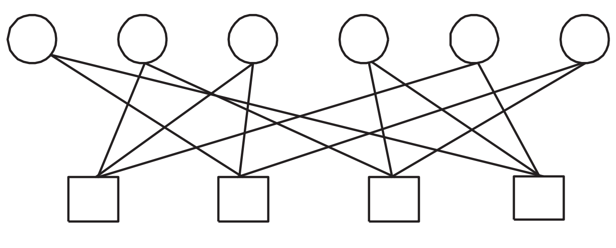

Fig. 1. Factor graph ($J = 6$, $K = 4$, $\lambda = 1.5$)

The signal (1) 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. Message Passing Algorithm (MPA) has complexity $O\left(M^{d_f}\right)$ per RE 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. Nevertheless, in UL case it is not critical because detection is performed at the base station, while encoding procedures at the mobile stations are not computationally intensive. The procedure of detection is similar to decoding of LDPC codes. The detailed description of the algorithms can be found, for example, in [11]. An additional reduction in the computational complexity can be obtained by choosing special codebook structure [12]. Decrease of the number of projections per RE (or complex dimension) reduces complexity. The MPA decoding of the following codebooks (subsequently called $\mathbf{CS2}$) from [13] has complexity $O(3^{d_f})$, because all codewords have only 3 possible values ($-a$, 0, a) for each RE:

$$\mathbf{CB}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ a & 0 & 0 & -a \\ 0 & 0 & 0 & 0 \\ 0 & a & -a & 0 \end{bmatrix}, \quad \mathbf{CB}_2 = \begin{bmatrix} a & 0 & 0 & -a \\ 0 & 0 & 0 & 0 \\ 0 & a & -a & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{CB}_3 = \begin{bmatrix} 0 & a & -a & 0 \\ a & 0 & 0 & -a \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{CB}_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ a & 0 & 0 & -a \\ 0 & a & -a & 0 \end{bmatrix},$$

$$\mathbf{CB}_5 = \begin{bmatrix} a & 0 & 0 & -a \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & a & -a & 0 \end{bmatrix}, \quad \mathbf{CB}_6 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ a & 0 & 0 & -a \\ 0 & a & -a & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

where $a = \sqrt{2/3}$, thus the average power of signal is equal to 1, as in the case of $\mathbf{CS1}$. In the general case, if M_p denotes the number of projections per complex dimension of M-ary constellation (codebook size), then detection complexity is $O\left(M_p^{d_f}\right)$ [4]. Penalty for this complexity reduction is some increase of bit error rate (BER). It is worth noting that codebooks like $\mathbf{CS2}$ can be used only in uplink with fading channels. In additive white Gaussian noise channel they have catastrophically high BER, because minimum Euclidean distance between codewords is small. In fading channels, due to random nature of gain phases, we can differentiate between codewords, unlike the case of additive white Gaussian noise channel.

III. CHANNEL MODEL

A. Block fading model

Detection in UL channel is considered. All users (in our examples, J = 6) are allocated in one resource block (RB). For normal cyclic prefix, RB has 7 orthogonal frequency-division multiplexing symbols and 12 subcarriers, similar to LTE standard [14]. The total number of REs in RB is 84. We assume that pilot signals are located on 12 REs. Thus data are located on 72 REs that correspond to 18 SCMA codewords. The pilot signals and one SCMA codeword are shown in

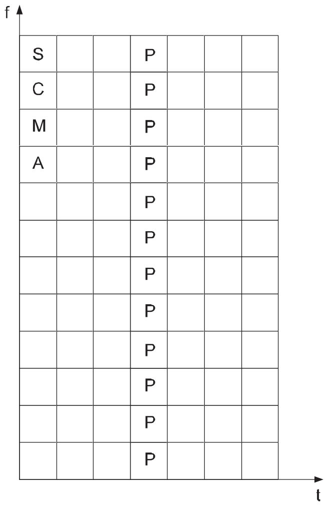

Fig. 2. Resource block with pilots and data allocation

Fig. 2. The block fading model is considered, i. e. the complex vector of channel gain $\mathbf{h}_j$ for each user in each fading block (RB) is assumed to be constant and vary independently among different fading blocks (RBs) [9]. In our case, 18 SCMA codewords in each RB have the same channel coefficients matrix.

B. Channel estimation

To detect the transmitted bits, the matrix of channel coefficients $\mathbf{h}$ should be estimated at the receiver. There are many different techniques for channel estimation: pilot-aided, semi-blind and blind estimation, and their combinations. In LTE UL, channel estimation is based on pilot signals. We assume that estimation in considered SCMA system is also based on pilot signals, but the specific structures of the pilots and algorithms for channel estimation are not determined.

The channel estimation error is defined as $e = \hat{h}_{ij} - h_{ij}$, where $\hat{h}_{ij}$ is the channel estimate for RE i of user j. Every channel coefficient h_{ij} is circularly-symmetric complex normal distributed value (zero mean and σ_h^2 variance, i. e. $\sigma_h^2/2$ per dimension). We assumed that the channel estimation error e and the channel estimate $\hat{h}_{ij}$ are also Gaussian distributed complex values with σ_e^2 and $\sigma_{\hat{h}}^2$ variances, correspondingly. The channel estimation error has zero mean. Finally, we assumed that the channel estimation error is orthogonal to the channel estimate [15], therefore

$$\sigma_e^2 = \sigma_{\hat{h}}^2 - \sigma_h^2.$$

Operating with error variance, we are not bound by specific pilots and algorithms for channel estimation. Our goal is to determine the required accuracy of estimation.

During the simulations, channel gain had unity variance ($\sigma_h^2 = 1$), hence channel estimation variance σ_e^2 is actually normalized to channel gain variance.

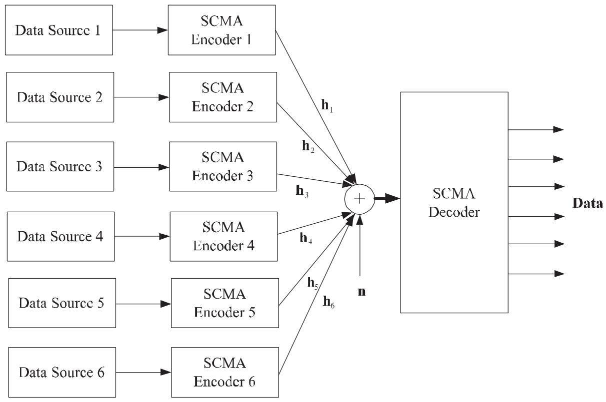

Fig. 3. Uncoded SCMA link

IV. System model

A. Uncoded SCMA

We investigated the UL SCMA system. The scheme of investigated system model is shown in Fig. 3. Six data streams from Data Sources are encoded independently by SCMA Encoders and transmitted through six independent Rayleigh flat fading channels $\mathbf{h}_j$. In the receiver of base station, SCMA Decoder detects signals (1) and forms six bit streams.

The parameters of SCMA scheme: $K = 4$, $N = 2$, $J = 6$ and $M = 4$. Both codebooks $\mathbf{CS1}$ and $\mathbf{CS2}$ will be used.

B. Coded SCMA

Turbo code with rate 1/3 from LTE standard [16] is used. Two block lengths are considered, short blocks of 40 bits and long blocks of 1024 bits. It should be noted that short blocks do not provide good spectral efficiency, but 5G systems should include support for transfer of small amounts of data from various sensors.

Data stream from each user is encoded by Turbo Encoder and then by SCMA Encoder. In the receiver of base station, signals (1) transmitted through six independent Rayleigh flat fading channels $\mathbf{h}_j$ are detected by SCMA Decoder, and then decoded by Turbo Decoders. The scheme of investigated system model is shown in Fig. 4.

The parameters of SCMA scheme are the same as in uncoded model.

Considered coded system do not contain channel interleaver. The choice of optimal interleaver for such a system is a special challenge.

C. Comparison with 8-PSK

The results obtained are compared with Gray-coded 8-ary phase shift keying (8-PSK) modulation. This modulation has the same spectral efficiency (3 bits per orthogonal resource in uncoded case) as considered SCMA system.

For comparison purposes, we considered the following resource allocation scheme for 8-PSK. One RB is divided into 6 six smaller RBs. The size of each small RB is 12 REs (36 bits are transmitted by every user). The number of transmitted

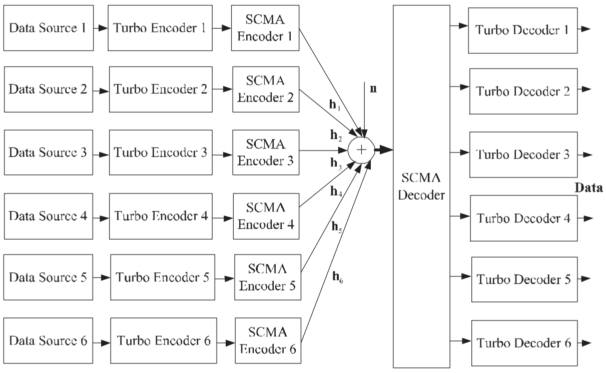

Fig. 4. Coded SCMA link

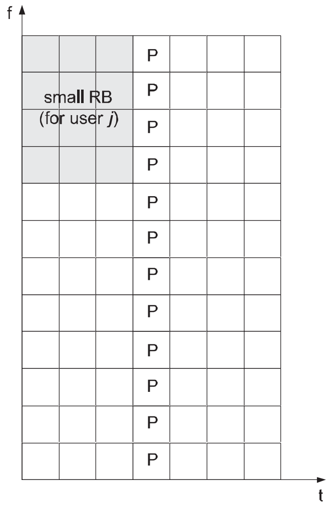

Fig. 5. Data allocation for orthogonal system

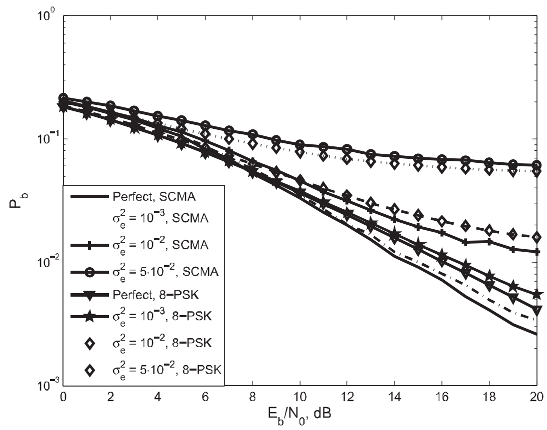

Fig. 6. Bit error probability vs. E_b/N_0: uncoded systems: **CS1** codebooks and 8-PSK

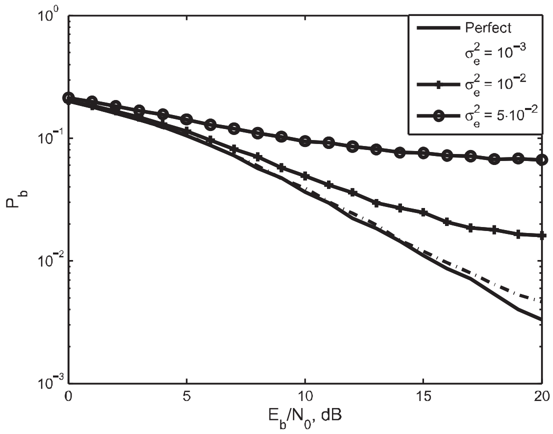

Fig. 7. Bit error probability vs. E_b/N_0: uncoded system, **CS2** codebooks

bits by every user in the small block is equal to that for SCMA scheme. The same Rayleigh block fading model is used. The model with one small RB for user j is shown in Fig. 5.

V. Simulation results

Computer simulation was carried out for uncoded and turbo coded UL SCMA single-input single-output system in Rayleigh flat fading channel. Perfect time, frequency and phase synchronization was assumed. We also assumed that all users always transmit data, i. e. they are always active. The problem of active users detection is not considered. The results for SCMA are compared with results for 8-PSK results, obtained under the same assumptions about the channel and synchronization. As a measure of signal-to-noise ratio (SNR), we used SNR per bit (E_b/N_0) for a single user:

$$E_b/N_0 \;= \mathrm{SNR} - 10\log_{10}(3)\ \mathrm{dB},$$

where SNR is a power signal-to-noise ratio, and 3 bits per orthogonal resource is a spectral efficiency for **CS1** and **CS2** (12 bits per 4 REs) and 8-PSK.

As we consider fading channels, all E_b/N_0 values are mean values averaged over channel states.

Logarithmic Message Passing Algorithm (Log-MPA) with 5 iterations was used for SCMA detection. Turbo code decoding was performed by logarithmic maximum a posteriori Algorithm (Log-MAP) with 4 iterations.

The simulation was executed until reaching either 500 errors or 10^7 processed bits (for every user).

A. Uncoded SCMA

Firstly, dependence of BER on E_b/N_0 for uncoded SCMA was analyzed. The results at different channel estimation variances are shown in Fig. 6 and Fig. 7 for **CS1** and **CS2**, respectively. The Fig. 6 contains also curves for 8-PSK.

The perfect curve corresponds to estimation without error. In all figures below, bit error probability is shown averaged over six users (BER values for all individual users are practically identical). From simulation results, it can be concluded that required variance of estimation error for both codebooks sets is 10^{-3}. For $\sigma_e^2 = 10^{-2}$, loss in E_b/N_0 is very large (more than 6 dB at $P_b = 10^{-2}$). The bit error probability for **CS1** is slightly smaller than for **CS2** because of better product distance properties [12].

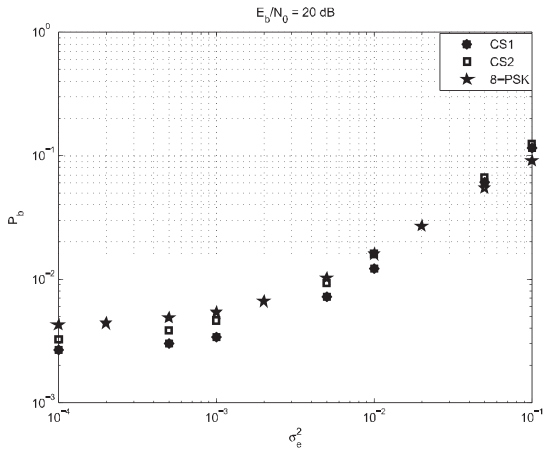

Fig. 8. Bit error probability vs. variance of channel estimation error: uncoded SCMA and uncoded 8-PSK

To get more detailed results, dependence of BER on the variance of channel estimation error at fixed $E_b/N_0 = 20$ dB was analyzed. The results for **CS1** and **CS2** are shown in Fig. 8.

The bit error probability for **CS1** and **CS2** is practically the same for all analyzed variances of channel estimation error.

The dependence of BER on E_b/N_0 for uncoded 8-PSK is shown in Fig. 6. It can be concluded that SCMA (both **CS1** and **CS2**) outperform 8-PSK when channel estimation error variance is small. This can be explained by product distance properties of the considered systems. Furthermore, **CS1** has additional gain due to multi-dimensional constellation shaping.

The properties of uncoded 8-PSK at fixed E_b/N_0 (see Fig. 8) differ from those of SCMA for different channel estimation error variances. For small σ_e^2, probability of error for SCMA is slightly less, but at high σ_e^2 (more than 10^{-2}) results become swapped. This behavior can be caused by additional noise (interference) from other users in SCMA system.

B. Turbo coded SCMA

Dependences of bit error probability on E_b/N_0 for turbo coded SCMA at different channel estimation variances are shown in Fig. 9–Fig. 12. For short code block (40 bits) required variance of estimation error is 10^{-3} for full utilization of turbo code error-correction capability. The loss in E_b/N_0 is no more than 0.5 dB at $P_b = 10^{-4}$ for **CS1** and **CS2** (see Fig. 9 and Fig. 10). Nevertheless, even at $\sigma_e^2 = 10^{-2}$ power gain over uncoded SCMA case with perfect channel estimation is approximately 7 dB. For long code block (1024 bits) required variance of estimation error is 10^{-2}. In this case, the power loss compared to a perfect estimate is about 0.6–0.7 dB at $P_b = 10^{-5}$ (see Fig. 11 and Fig. 12). Thus turbo coded SCMA with longer blocks shows lower demand for accuracy of channel estimate.

For 8-PSK such dependences are shown in Fig. 9 and Fig. 11. For short blocks, perfect estimation and $\sigma_e^2 = 10^{-3}$ 8-PSK insignificantly outperforms SCMA, but at high channel estimation error variances and $E_b/N_0 > 15$ dB SCMA properties are slightly better. For long blocks situation is similar, only the boundary E_b/N_0 is about 8–8.5 dB.

The dependences of BER on variance of channel estimation error at fixed $E_b/N_0 = 20$ dB for short blocks and at $Eb/N0 = 9$ dB for long blocks are shown in Fig. 13 and Fig. 14, respectively.

Similar to the case of uncoded SCMA, bit error probability for **CS1** and **CS2** is practically the same for all analyzed variances of channel estimation error.

For both short and long blocks the performance of SCMA is improved (probability of error becomes lower than for 8-PSK) with increase of E_b/N_0. At E_b/N_0 smaller than 15 dB for short blocks and 8–8.5 dB for long blocks, 8-PSK outperforms SCMA. This can be explained by smaller number of REs in RB for 8-PSK compared to SCMA (12 REs vs. 18 REs to transmit 36 bits by every user). Thus 8-PSK has less correlated channel, because the number of repeated channel coefficients is smaller than for SCMA. At high E_b/N_0 distance properties dominate, and, since they are better for SCMA (this was shown in the uncoded case), SCMA has less probability of bit error.

VI. CONCLUSION

The results obtained allow to conclude that required variance of channel estimation error for uncoded SCMA should be less or equal to 10^{-3}. Turbo coded SCMA with short blocks (40 bits) requires the same accuracy for full utilization of turbo code error-correction capability. Turbo coded SCMA with long blocks (1024 bits) can tolerate higher variance of channel estimation error: 10^{-2} or a little more. Furthermore, in this case there is a sufficient coding gain (more than 10 dB) compared to the case of short blocks.

Both codebooks sets **CS1** and **CS2** have practically the same performance. Consequently, the use of **CS2** is preferable because of lower computational complexity of SCMA decoder, especially for large M and/or d_f.

Comparing SCMA with conventional orthogonal multiple access scheme with 8-PSK modulation, we can conclude that uncoded SCMA outperforms 8-PSK in the range of acceptable values of channel estimation variance ($\sigma_e^2 < 10^{-2}$) for successful detection. Turbo coded SCMA scheme has less probability of bit error at high E_b/N_0 (when $P_b < 10^{-4}$–10^{-5}) and power gain is about 0.5–1 dB for long blocks and a few tenths of dB for short blocks.

The use of channel interleaver can reduce the required accuracy of channel estimation. This problem calls for additional investigation.

Possible direction of future work is investigation of channel error estimation in SCMA system with spreading codewords over the 4 RBs. In this case we will have diversity effect for **CS1** and, as a consequence, BER improvement. The investigation of channel error estimation in Multiple-Input Multiple-Output systems is also interesting.

Another possible field of investigation is design of pilot signal structure and algorithms of channel estimation for minimization of channel estimation error variance.

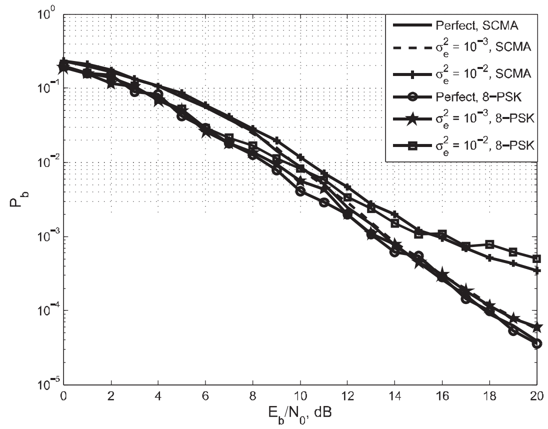

Fig. 9. Bit error probability vs. E_b/N_0: turbo coded SCMA **CS1** and 8-PSK, 40 bit blocks

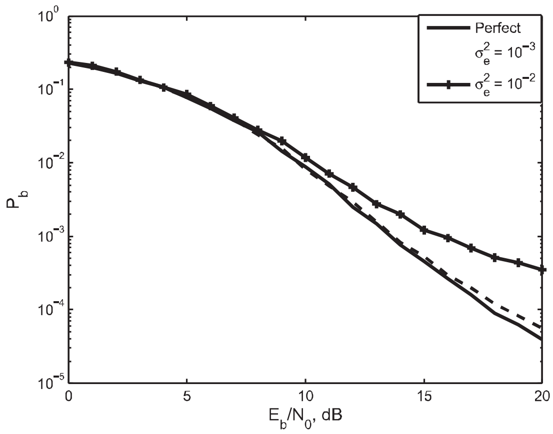

Fig. 10. Bit error probability vs. E_b/N_0: turbo coded SCMA, 40-bit blocks, **CS2**

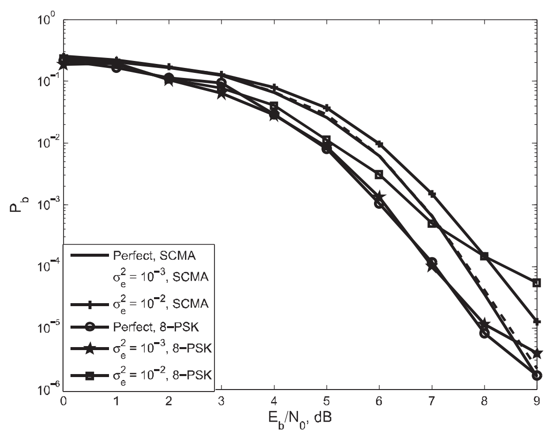

Fig. 11. Bit error probability vs. E_b/N_0: turbo coded SCMA **CS1** and 8-PSK, 1024-bit blocks

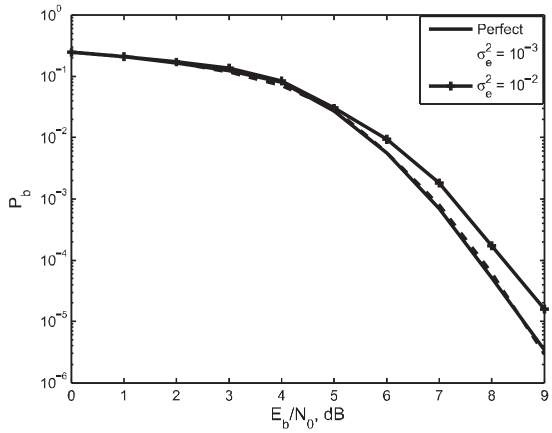

Fig. 12. Bit error probability vs. E_b/N_0: turbo coded SCMA, 1024-bit blocks, **CS2**

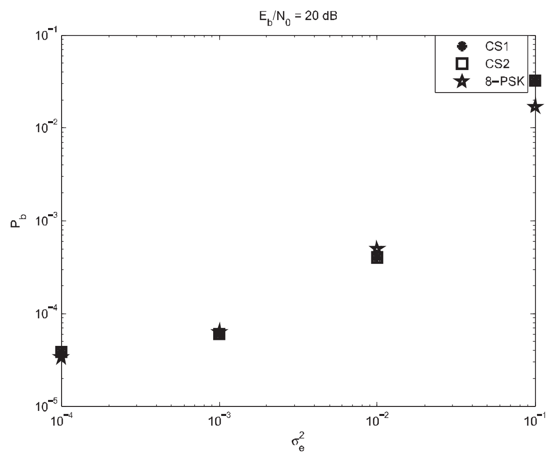

Fig. 13. Bit error probability vs. variance of channel estimation error: turbo coded SCMA and 8-PSK, short blocks

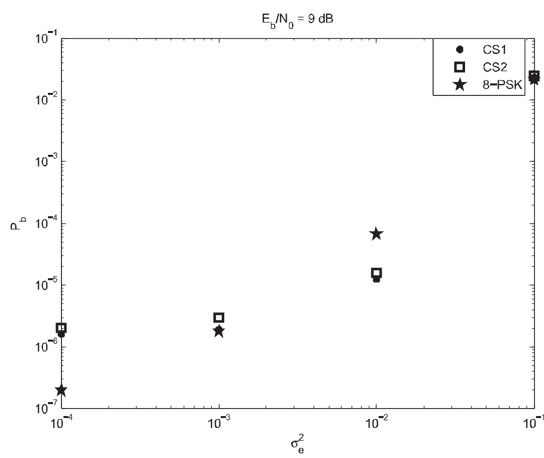

Fig. 14. Bit error probability vs. variance of channel estimation error: turbo coded SCMA and 8-PSK, long blocks

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