Spectral Efficiency of Uplink SCMA System with CSI Estimation

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Abstract—**Sparse code multiple access (SCMA) is a non-orthogonal multiple access scheme. This scheme allows to increase the number of active users inside a given time-frequency resource. The paper considers the spectral efficiency of coded uplink SCMA system in block fading channel with account for channel state information estimation quality. Two channel estimation schemes are investigated, one is based solely on pilot signals, another uses hard decisions after SCMA decoding to improve estimation quality. Orthogonal and non-orthogonal pilot signals are considered. Increasing the number of pilot signals improves channel state information, but, on the other hand, it reduces spectral efficiency of the communication system, so the number of pilots should be minimized. The simulation results are provided for different pilot signal lengths. Spectral efficiency obtained with channel estimation based on orthogonal pilot sequences is equivalent to it in the case of data-aided estimation with SCMA non-orthogonal pilots. For small number of pilot symbols, the energy gain of data-aided algorithm is approximately 1 dB as compared with an estimate based on pilot signals only. For the investigated SNR range (SNR $<$ 10 dB) and short non-orthogonal pilot signals, four iterations of Message Passing Algorithm are required for data-aided estimation and detection without decreasing spectral efficiency.**

I. INTRODUCTION

Fifth generation (5G) wireless communication standard requires higher spectral efficiency (SE), 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]. Sparse code multiple access (SCMA) [4] is a scheme of code-domain multiplexing NOMA and a potential candidate of NOMA in new telecommunication standards. This system is an improved version of Low-Density Signature (LDS) [5] scheme. The main advantage over LDS is some potential gain of multi-dimensional constellation shaping [2].

To implement coherent reception, channel state information (CSI) is required. In [6], [7], we investigated the effect of channel estimation error on bit error probability in Rayleigh flat fading channel for uplink SCMA with turbo coding, where channel estimation error was defined in terms of its variance, without relying on specific algorithms of channel estimation. In this paper, we investigate SCMA detection with CSI estimation. Such problem was studied in [8], [9], [10] with assumption that pilot signals occupy multiple resource blocks, and the number of *active users is much less* than their maximum number (usually 6 of 36). In these works, joint channel estimation and identification of active users are investigated. Unlike these publications, we consider channel estimation in the presence of *all the active users* in the resource block to analyze the dependence of spectral efficiency of such system on different CSI estimation techniques.

There are many methods of CSI estimation. Three main groups are pilot, data-aided (also called semi-blind) and blind estimation (see, for example, [11, Chapter 6]). The pilot signals may be either orthogonal or non-orthogonal. In this work, we investigate channel estimation based on different pilot signals, and also data-aided estimation with pilots. We use data-feedback-aided algorithm with hard decisions from SCMA detector. Orthogonal pilot signals provide smaller channel estimation error than non-orthogonal signals. However, as was described in [12], users with identical codebooks may use the same time-frequency resource. It is necessary to have many pilot signals for the separation of users. The ensemble of orthogonal signals is insufficient for this purpose. Thus, the use of non-orthogonal signals is needed. As such, we used pilot signals based on SCMA codewords. Also, the use of SCMA codewords as pilots leads to unification of signals' structure. Estimations based on orthogonal and SCMA pilot signals (these signals have relatively large cross-correlation) can be considered like boundaries. Orthogonal signals allow to obtain the best estimate of the channel state. On the other hand, estimate based on SCMA signals can be considered as the worst case. There are methods for design of good non-orthogonal pilots for Multiple Input–Multiple Output (MIMO) system [13], [14]. These methods can be adapted for design of pilots in SCMA scheme. Thus, the estimate obtained with these pilot signals will be located between the boundaries denoted above.

The SCMA description is presented in Section II. The channel model is described in Section III. The CSI estimation techniques are considered in Section IV. The definition of effective spectral efficiency is introduced in Section V. Simulation results are shown in Section VI. Section VII draws the conclusions.

II. SCMA DESCRIPTION

In this section, we introduce the basics concepts of SCMA. The encoding and detection procedures are considered below. SCMA codebooks, which are used in the work, are presented.

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 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 $J = 6$, $K = 4$ and $N = 2$ is presented below [15]:

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

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

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

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

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

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

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

Matrices are 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.

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) [15]. This structure is equivalent to the structure of low density parity check codes (LDPC). Circles correspond to users, while rectangles correspond to REs.

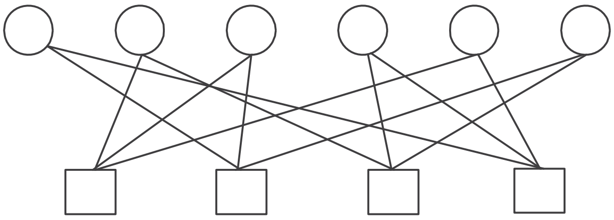

Fig. 1. Factor graph ($J = 6$, $K = 4$, $\lambda = 1.5$)

B. *SCMA detection*

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

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

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. Every channel coefficient h_{kj} (on kth RE for jth user) is a circularly-symmetric complex normal distributed value (zero mean and σ_h^2 variance, i. e. $\sigma_h^2/2$ per dimension). Below, we will assume that $\sigma_h^2 = 1$, without loss of generality.

The signal (1) can be detected by the maximum likelihood (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. The procedure of detection is similar to decoding of LDPC codes. The detailed description of the algorithms can be found, for example, in [16].

III. CHANNEL MODEL

In this paper, analysis of spectral efficiency in uplink (UL) Rayleigh flat fading channel is considered. All users are allocated in one resource block (RB), whose parameters are identical to RB from LTE standard [18]. The total number of REs in RB is R. We assume that pilot signals consume L REs. Thus, data are located on $(R-L)$ REs that corresponds to $Q = (R-L)/K$ SCMA codewords. The number L should be such that Q is an integer. The block fading model is considered, i. e. the complex vector of channel gains $\mathbf{h}_j$ for each user is assumed to be constant over each RB and vary independently among different RBs [19]. The size of fading block is equal to RB size. The block fading model has been applied previously at investigation of orthogonal frequency-division multiplexing (OFDM) systems. The details for the UL channel can be found in [20].

In the considered channel model, symbols of pilot signal and data can be arbitrary allocated within the RB.

In the block fading channel, Eq. (1) is transformed into the following equation:

$$\mathbf{y} = \mathbf{X}\mathbf{h} + \mathbf{n}, \tag{2}$$

where $\mathbf{X}$ is a matrix of SCMA codewords with size $K \times J$ and $\mathbf{h}$ is a vector of channel coefficients with size $J \times 1$.

In block fading model, Q SCMA codewords in each RB have the same channel coefficients vectors $\mathbf{h}$.

IV. CSI ESTIMATION TECHNIQUES

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, blind estimation, as well as their combinations. Blind channel estimation has high computational complexity, especially for SCMA systems. Thus, we investigated only two schemes: pilot-aided and data-feedback-aided estimation (semi-blind method).

A. Pilot-aided estimation

The number of REs for pilot symbols should be a multiple of K, because every SCMA codeword occupies K REs, also it should be not less than J.

We introduce the matrix $\mathbf{P}$ with size $L \times J$, which contains pilot signals with length L for J users. According to what was said in the previous section, L symbols of pilots can be allocated on different REs within RB (not necessarily sequentially), but identically for all users.

After transmitting over channel, received pilot signals are expressed by the following equation:

$$\mathbf{y}_{\mathrm{p}} = \mathbf{P}\mathbf{h} + \mathbf{n},$$

where $\mathbf{y}_{\mathrm{p}}$ are symbols of received pilot signals.

Channel estimate based on Least-square (LS) estimator (solution of an overdetermined system of linear equations, because $L > J$) is given by

$$\hat{\mathbf{h}} = \left(\mathbf{P}^H\mathbf{P}\right)^{-1}\mathbf{P}^H\mathbf{y}_{\mathrm{p}}, \tag{3}$$

where $\left(\mathbf{P}^H\mathbf{P}\right)^{-1}\mathbf{P}^H$ is called the Moore-Penrose pseudoinverse of matrix $\mathbf{P}$.

SCMA codewords are used as non-orthogonal pilot signals. The pilot signals used for simulations will be presented in Section VI.

Chu sequences [17] of even length were selected as the orthogonal pilot signals. This is similar to the use of Zadoff-Chu sequences in LTE [18]. The symbols of sequence are

$$p_k = \frac{\exp\left(\frac{i\pi k^2}{L}\right)}{\sqrt{J}}, \tag{4}$$

where $k = 0, 1, \ldots, L-1$ and $\sqrt{J}$ is a normalization for unit average power.

The matrix $\mathbf{P}$ with size $L \times J$ is a concatenation of J vectors $\mathbf{p}_j$ with size $L \times 1$, i. e.

$$\mathbf{P} = [\mathbf{p}_1 \quad \mathbf{p}_2 \quad \ldots \quad \mathbf{p}_J]. \tag{5}$$

Pilot sequences $\mathbf{p}_j$ $(j \neq 1)$ are cyclic shifts of $\mathbf{p}_1 = \{p_k\}$, $k = 0, 1, \ldots, L-1$. Due to the properties of Chu sequences, all $\mathbf{p}_j$ sequences are orthogonal.

In our investigation, both orthogonal and non-orthogonal pilot signals occupy the same number of REs. Non-orthogonal pilots have nonzero cross-correlation, but their ensemble can be larger than with orthogonal pilot signals.

B. Data-aided estimation

Data-aided estimation allows to improve channel estimate and thus to reduce block error rate (BLER), which in turn increases the actual spectral efficiency. This technique can also be called data-feedback-aided estimation, because it uses decisions of data symbols for further channel re-estimation. Algorithm has five stages.

Algorithm 1 Data-aided channel estimation and detection

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1: Channel estimation by pilot-aided method. Pilot signals are used for channel estimation. According to Eq. (3), channel estimate $\hat{\mathbf{h}}$ is obtained;
2: Data detection. MPA detection is performed based on obtained channel estimate;
3: Data reconstruction. Reconstruction of transmitted data symbols after detection of received signal is performed;
4: Channel re-estimation. Both pilots and reconstructed data symbols are used;
5: Final data detection. MPA detection is performed based on improved channel estimate.
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Stages 2–4 can be iteratively repeated for improvement of channel estimate.

In SCMA system, iterative MPA algorithm is used for data symbols detection. On stage 2 and stage 5, different numbers of MPA iterations can be used. The number of iterations on stage 2 affects the quality of the estimation. The number of iterations on stage 5 affects the final bit error probability. From a practical standpoint (to minimize computational complexity), it is of interest to determine the number of iterations, after which a performance improvement does not occur.

The decoder and encoder of turbo code are not included into Algorithm 1 (stage 2 and stage 3, respectively) in our work. According to [21, Chapter 17.4], there is potential error propagation, where the erroneous data decisions result in erroneous channel estimation, which inflicts further precipitated data decision errors, etc. Due to the convolutional structure of turbo code, even one erroneously decoded bit can lead to the incorrect block at re-encoding procedure (especially critical case is when the erroneous bit occurs at the beginning of the block).

Notations for this channel estimation method are presented below.

The received signal (2) can be represented as

$$\mathbf{y} = \begin{bmatrix}\mathbf{y}_p \\ \mathbf{y}_d\end{bmatrix} = \begin{bmatrix}\mathbf{P} \\ \mathbf{D}\end{bmatrix}\mathbf{h} + \mathbf{n},$$

where $\mathbf{y}$ is an $R \times 1$ vector with all received symbols from RB, $\mathbf{y}_p$ and $\mathbf{y}_d$ are vectors with pilot and data received symbols with size $L\times 1$ and $(R-L)\times 1$, consequently, and $\mathbf{D}$ is a matrix of SCMA codewords (data signal) with size $(R-L)\times J$. Thus channel estimate (3) is expressed by the following equation:

$$\hat{\mathbf{h}} = \left(\begin{bmatrix} \mathbf{P} \\ \hat{\mathbf{D}} \end{bmatrix}^H \begin{bmatrix} \mathbf{P} \\ \hat{\mathbf{D}} \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{P} \\ \hat{\mathbf{D}} \end{bmatrix}^H \begin{bmatrix} \mathbf{y}_p \\ \mathbf{y}_d \end{bmatrix},$$

where $\hat{\mathbf{D}}$ is a matrix of reconstructed SCMA codewords after demodulation with size $(R-L)\times J$.

V. SPECTRAL EFFICIENCY

In digital communication systems, spectral efficiency, η, is defined as

$$\eta = \frac{C}{W} \text{ bit/s/Hz},$$

where C is the channel capacity (in [bits/s]) and W is the channel bandwidth (in [Hz]).

In practice, there are definitions of spectral efficiency that differ from classic Shannon's Capacity Theorem [22]. Among them is effective spectral efficiency SE_{eff}, that for coded communication systems is expressed by the following equation [23]:

$$\text{SE}_{\text{eff}} = (1 - \text{BLER})S,$$

where S is a *nominal* spectral efficiency taking into account pilot signals and redundancy of error correction coding, i. e. the ideal spectral efficiency without transmission bit errors. This value is defined as

$$S = B/R_{\text{RE}}, \tag{6}$$

where B is a number of information bits in code block and R_{RE} is a number of REs with data and pilots for transmitting of one code block.

VI. SIMULATION RESULTS

A. System model

We investigated the UL SCMA system with codebooks from Section II. RB has 7 orthogonal frequency-division multiplexing symbols and 12 subcarriers, i. e. $R = 84$.

Turbo code with rate 1/3 from LTE standard [24] is used. The block length $B = 1024$ bits.

Data stream from each user is encoded by turbo encoder and then by SCMA encoder. We used random interleaver which rearranges the elements of coded block using a random permutation, interleaver size is equal to the length of bit block after turbo coding. In the receiver of base station, signals (1) transmitted through J independent Rayleigh flat fading channels $\mathbf{h}_j$ are detected by SCMA decoder, and then decoded by turbo decoders.

Non-orthogonal SCMA pilot signals which are used in simulations are presented below. We investigated pilot signals with three different number of symbols (8, 12, and 24) based on limitations described in Section IV.

The combinations of codewords to use as pilots were selected by brute force search to minimize the mean square error of channel estimation and to level bit error rate for all users.

For $L = 8$, pilot symbols are

$$\mathbf{P} = \begin{bmatrix} \mathbf{CB}_1(3) & \mathbf{CB}_2(2) & \mathbf{CB}_3(4) & \mathbf{CB}_4(3) & \mathbf{CB}_5(4) & \mathbf{CB}_6(2) \\ \mathbf{CB}_1(2) & \mathbf{CB}_2(4) & \mathbf{CB}_3(3) & \mathbf{CB}_4(1) & \mathbf{CB}_5(4) & \mathbf{CB}_6(4) \end{bmatrix},$$

where $\mathbf{CB}_j(n)$ is the codeword n of user j.

For $L = 12$, pilot symbols are

$$\mathbf{P} = \begin{bmatrix} \mathbf{CB}_1(1) & \mathbf{CB}_2(1) & \mathbf{CB}_3(1) & \mathbf{CB}_4(1) & \mathbf{CB}_5(1) & \mathbf{CB}_6(1) \\ \mathbf{CB}_1(3) & \mathbf{CB}_2(1) & \mathbf{CB}_3(4) & \mathbf{CB}_4(2) & \mathbf{CB}_5(2) & \mathbf{CB}_6(3) \\ \mathbf{CB}_1(2) & \mathbf{CB}_2(4) & \mathbf{CB}_3(3) & \mathbf{CB}_4(1) & \mathbf{CB}_5(4) & \mathbf{CB}_6(4) \end{bmatrix}.$$

Finally, for $L = 24$, pilot symbols are

$$\mathbf{P} = \begin{bmatrix} \mathbf{CB}_1(1) & \mathbf{CB}_2(1) & \mathbf{CB}_3(1) & \mathbf{CB}_4(1) & \mathbf{CB}_5(1) & \mathbf{CB}_6(1) \\ \mathbf{CB}_1(3) & \mathbf{CB}_2(1) & \mathbf{CB}_3(4) & \mathbf{CB}_4(2) & \mathbf{CB}_5(2) & \mathbf{CB}_6(3) \\ \mathbf{CB}_1(2) & \mathbf{CB}_2(4) & \mathbf{CB}_3(3) & \mathbf{CB}_4(1) & \mathbf{CB}_5(4) & \mathbf{CB}_6(4) \\ \mathbf{CB}_1(3) & \mathbf{CB}_2(1) & \mathbf{CB}_3(2) & \mathbf{CB}_4(4) & \mathbf{CB}_5(2) & \mathbf{CB}_6(2) \\ \mathbf{CB}_1(2) & \mathbf{CB}_2(2) & \mathbf{CB}_3(2) & \mathbf{CB}_4(3) & \mathbf{CB}_5(3) & \mathbf{CB}_6(3) \\ \mathbf{CB}_1(4) & \mathbf{CB}_2(4) & \mathbf{CB}_3(1) & \mathbf{CB}_4(3) & \mathbf{CB}_5(2) & \mathbf{CB}_6(2) \end{bmatrix}.$$

For orthogonal pilot signals, Chu sequences with identical L are obtained from Eqs. (4) and (5).

B. Simulations

Computer simulation was carried out for 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.

Relation between power signal-to-noise ratio (SNR) and SNR per bit (E_b/N_0) for a single user, without account for power loss due to pilot insertion, is

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

where $(\log_2(M)\,\lambda)$ is a spectral efficiency of uncoded SCMA system (in our case, 3 bits per orthogonal resource) and r is a code rate. In accordance with the notations in Eq. (1), $\text{SNR} = \sigma_h^2/\sigma^2$.

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

The turbo code block length is $B = 1024$ bits and exact code rate $r = B/(3B+t)$, where $t = 12$ is a number of zero bits used for trellis termination. So, S from (6) for system with J users in our case can be expressed as

$$S = \frac{JB}{KT + \left\lceil \frac{KT}{R-L} \right\rceil L},$$

where $T = \frac{3B+t}{\log_2(M)}$, and $\lceil \ldots \rceil$ denotes rounding to the next larger integer.

Table I shows the spectral efficiency, S, for different values of L.

TABLE I. SPECTRAL EFFICIENCY

L, REs	S (total), bit/s/Hz	S (per user), bit/s/Hz
8	0.9004	0.1501
12	0.8533	0.1422
24	0.7111	0.1185

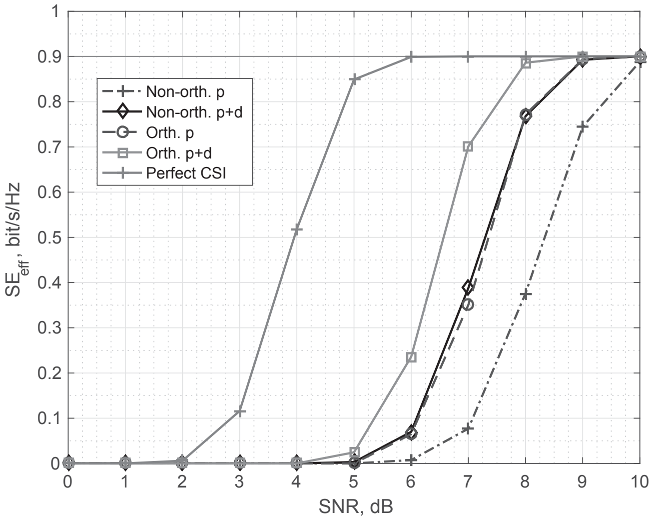

Fig. 2. $\mathrm{SE}_{\mathrm{eff}}$ vs. SNR for $L = 8$

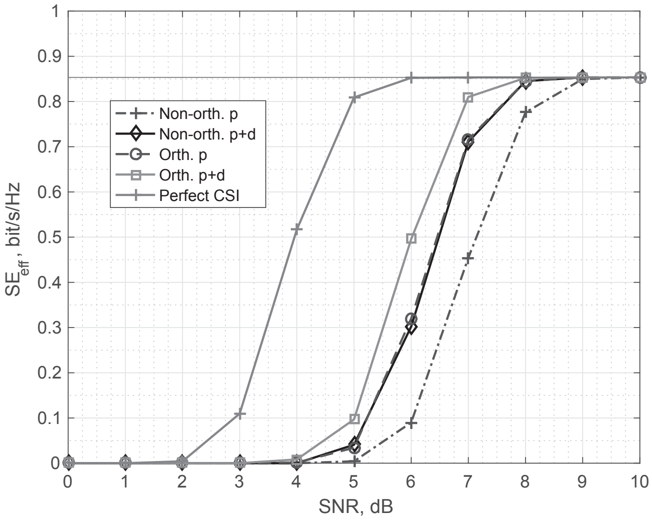

Fig. 3. $\mathrm{SE}_{\mathrm{eff}}$ vs. SNR for $L = 12$

Turbo code decoding was performed by logarithmic maximum a posteriori Algorithm (Log-MAP) with 4 iterations.

The simulation was executed until reaching either 100 block errors or 10^4 processed code blocks (for every user).

We performed main SE simulations for three lengths of pilot signals ($L = 8, 12, 24$) with the following CSI estimation methods (corresponding legend entries used on the graphs are shown in parentheses):

- perfect CSI (Perfect CSI);
- CSI estimation with non-orthogonal pilot signals (Non-orth. p);
- CSI estimation with orthogonal pilot signals (Orth. p);
- Data-aided CSI estimation with non-orthogonal pilot signals (Non-orth. p+d);

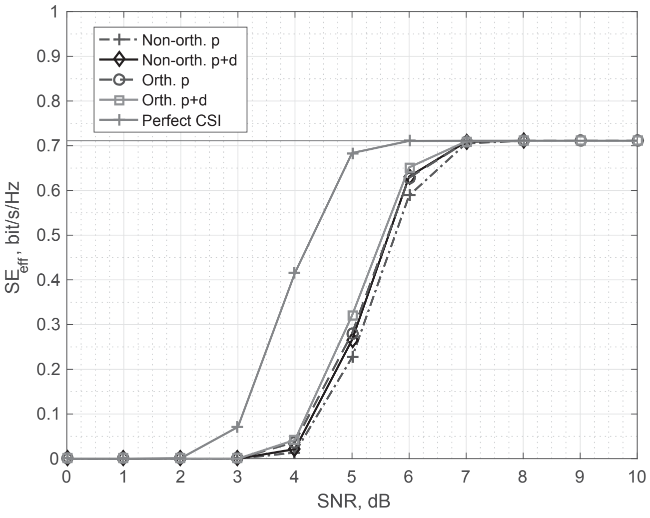

Fig. 4. $\mathrm{SE}_{\mathrm{eff}}$ vs. SNR for $L = 24$

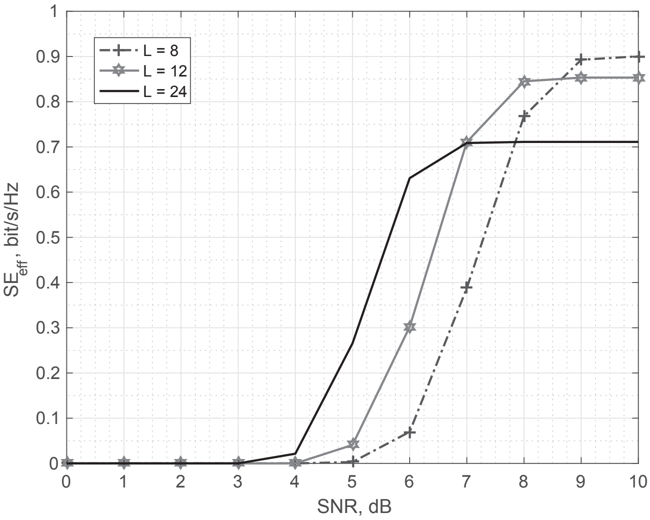

Fig. 5. $\mathrm{SE}_{\mathrm{eff}}$ vs. SNR for different length of non-orthogonal pilots

- Data-aided CSI estimation with orthogonal pilot signals (Orth. p+d).

To regenerate data symbols needed for data-aided estimation, hard decisions based on soft output of MPA detector are used. Logarithmic Message Passing Algorithm (Log-MPA) with 5 iterations was used for SCMA detection.

The obtained results are shown in Fig. 2–Fig. 4, where horizontal line is a nominal spectral efficiency S. For all values of L, spectral efficiency obtained with channel estimation based on orthogonal (Chu) pilot sequences is equivalent to it in the case of data-aided estimation with SCMA non-orthogonal pilots. For non-orthogonal sequences, energy gain of the data-aided estimation as compared with pilot-only estimation is about 1 dB for $L = 8$, 0.5–0.6 dB for $L = 12$, and 0.15–0.2 dB for $L = 24$. So, the use of data-aided estimation allows to increase the spectral efficiency.

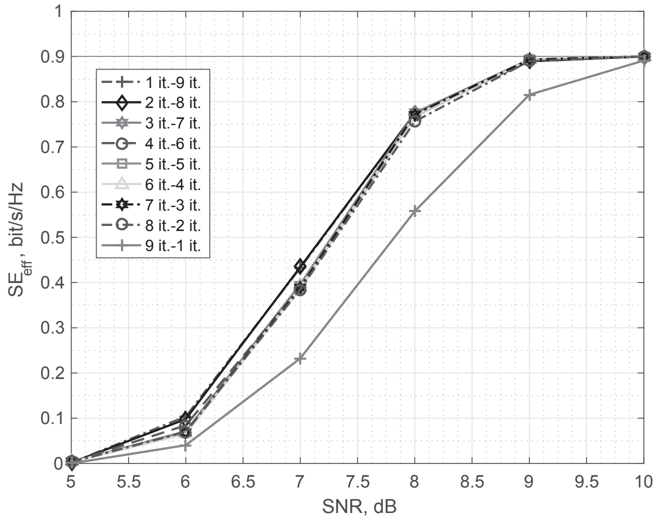

Fig. 6. SE_{eff} vs. SNR for different distributions of iterations between first and second detection stages

Fig. 5 shows results of SE simulation for different length of SCMA pilots (data-aided estimation). For SNR below 7 dB, long pilots are preferable, while for SNR above 9 dB the highest SE is obtained with short pilots.

Fixing the total number of iterations of Log-MPA (10 iterations), we performed simulations with different variants of their distribution between stages 2 and 5 of the algorithm. The obtained results are shown in Fig. 6 (non-orthogonal pilot signals, $L = 8$). In the legend, the first number refers to the stage 2 and the second number refers to the stage 5. It can be concluded that one iteration of Log-MPA is sufficient for the first round of data detection for given SNR range (SNR < 10 dB). The remaining iterations should be used for the final procedure of SCMA decoding, but after 3 iterations results do not improve, so we can choose this value as a reasonable trade-off between complexity and quality. At SNR < 9 dB, where effective spectral efficiency is less than 99% of nominal, this reduction of iterations practically does not worsen spectral efficiency of the system.

In addition, we conducted a simulation for Algorithm 1 with multiple iterations (2 and 3 iterations of whole data-aided estimation and detection algorithm) for orthogonal sequences with $L = 12$. In this case, we have no gain as compared with a single iteration, since for low SNR symbol error probability is high and re-estimations are not able to improve it. In this case, as described above, error propagation can happen. Turbo code corrects these errors, and spectral efficiency remains the same as for one iteration of the Algorithm 1. There are different techniques for mitigating this effect, one of them can be found in [21]. In the future, it is planned to investigate various methods to improve the quality of CSI.

VII. CONCLUSION

We investigated effect of channel estimation quality on the spectral efficiency of UL turbo coded SCMA scheme. By estimating BLER, we calculated the effective spectral efficiency of the system. For channel estimation, we used pilot-based and data-aided algorithms. By comparing the estimates obtained with orthogonal and non-orthogonal pilot signals, it can be concluded that energy gain in the first case is more than 0.2–1 dB depending on the number of pilot symbols. Identification of a large number of users requires a lot of pilot signals, that could not be orthogonal with a limited number of REs allocated to them. Thus, there is the only option of using non-orthogonal pilot signals. The data-aided algorithm can improve the quality of channel estimate, and consequently, increase the spectral efficiency, especially at low SNR values. As shown by the simulation results, spectral efficiency with channel estimation based on orthogonal (Chu) pilot sequences is equivalent to it in the case of data-aided estimation with SCMA non-orthogonal pilots.

We have defined the required minimum number of iterations (4 it.) of Log-MPA for data-aided estimation and detection without decreasing spectral efficiency.

Increase of spectral efficiency by 26.6% (from 0.71 bit/s/Hz to 0.9 bit/s/Hz) requires SNR to be increased by 2 dB.

Possible direction of future work is investigation of weight function for channel estimates obtained by pilots and data. It can potentially improve the channel estimate. The investigation of possible usage of log-likelihood ratios distribution of received bits for CSI estimation is also interesting.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of this work by the Ministry of the Education and Science of the Russian Federation (basic state assignment No. 8.7130.2017).

REFERENCES

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, “What will 5G be?”, *IEEE J. on Selected Areas in Communications*, vol.32 (6), June 2014, pp. 1065–1082.

[2] L. Dai, B. Wang, Y. Yuan, S. Han, C. I and Z. Wang, “Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends”, *IEEE Commun. Mag.*, vol.53 (9), Sept. 2015, pp. 74–81.

[3] B. Wang, K. Wang, Z. Lu, T. Xie and J. Quan, “Comparison study of non-orthogonal multiple access schemes for 5G”, *BMSB*, Jun. 2015, pp. 1–5.

[4] H. Nikopour and H. Baligh, “Sparse code multiple access”, *Proc. IEEE PIMRC 2013*, Sept. 2013, pp. 332–336.

[5] R. Hoshyar, F.P. Wathan and R. Tafazolli, “Novel low-density signature for synchronous CDMA systems over AWGN channel”, *IEEE Trans. Signal Proc.*, vol.56 (4), Apr. 2008, pp. 1616–1626.

[6] V. P. Klimentyev and A. B. Sergienko, “Detection of SCMA signal with channel estimation error”, *2016 18th Conference of Open Innovations Association and Seminar on Information Security and Protection of Information Technology (FRUCT-ISPIT)*, St. Petersburg, 2016, pp. 106–112.

[7] A. B. Sergienko and V. P. Klimentyev, “SCMA detection with channel estimation error and resource block diversity”, *2016 International Siberian Conference on Control and Communications (SIBCON)*, Moscow, Russia, 2016, pp. 1–5.

[8] Y. Wang, S. Zhou, L. Xiao, X. Zhang and J. Lian, “Sparse Bayesian learning based user detection and channel estimation for SCMA uplink systems”, *2015 International Conference on Wireless Communications & Signal Processing (WCSP)*, Nanjing, Oct. 2015, pp. 1–5.

[9] Y. Wang, X. Zhang, S. Zhou, J. Lian and L. Xiao, "User detection and channel estimation for SCMA uplink system in dispersive channel", *2016 IEEE International Conference on Communication Systems (ICCS)*, Shenzhen, China, Dec. 2016, pp. 1–5.

[10] K. Struminsky, S. Kruglik, D. Vetrov and I. Oseledets, "A new approach for sparse Bayesian channel estimation in SCMA uplink systems", *2016 8th International Conference on Wireless Communications & Signal Processing (WCSP)*, Yangzhou, Oct. 2016, pp. 1–5.

[11] Y. S. Cho, J. Kim, W. Y. Yang and C. G. Kang, *"MIMO-OFDM wireless communication with MATLAB",* Wiley, 2010.

[12] A. Bayesteh, E. Yi, H. Nikopour and H. Baligh, "Blind detection of SCMA for uplink grant-free multiple-access", *IEEE Int. Symp. on Wireless Commun. Systems*, Aug. 2014, pp. 853–857.

[13] Z. Xiujun, C. Xiang, Z. Shidong and W. Jing, "Non-orthogonal pilot design and analysis for CoMP systems", *2011 International Conference on Wireless Communications and Signal Processing (WCSP)*, Nanjing, Nov. 2011, pp. 1–5.

[14] H. Wang, W. Zhang, Y. Liu, Q. Xu and P. Pan, "On design of non-orthogonal pilot signals for a multi-cell massive MIMO system", *IEEE Wireless Communications Letters*, vol.4, no. 2, Apr. 2015, pp. 129–132.

[15] Altera Innovate Asia website, Presentation "1st 5G Algorithm Innovation Competition-ENV1.0-SCMA", Web: http://www.innovateasia.com/5g/en/gp2.html.

[16] K. Xiao, B. Xiao, S. Zhang, Z. Chen and B. Xia, "Simplified multiuser detection for SCMA with sum-product algorithm", Web: http://arxiv.org/abs/1508.00679.

[17] D. Chu, "Polyphase codes with good periodic correlation properties (Corresp.)", *IEEE Transactions on Information Theory*, vol.18 (4), Jul. 1972, pp. 531–532.

[18] 3rd Generation partnership Project: Technical Specification Group Radio Access Network, "Evolved universal terrestrial radio access (E-UTRA)", Physical Channels and Modulation, Release 10, 2010–2012, TS 36.211, Vol. 10.0.0.

[19] Y. Wang, S. Zhou, L. Xiao and X. Zhang, "Sparse Bayesian learning based user detection and channel estimation for SCMA uplink systems", *WCSP*, Oct. 2015, pp. 1–5.

[20] Teng-Han Tsai, Xiang Chen, Chong-Yung Chi, Wing-Kin Ma, Shidong Zhou and Yan Yao, "A subcarrier average based block-by-block blind channel estimation algorithm for multi-user OFDM systems", *2007 IEEE 8th Workshop on Signal Processing Advances in Wireless Communications*, Helsinki, Jun. 2007, pp. 1–5.

[21] L. Hanzo, Y. Akhtman, L. Wang, *"MIMO-OFDM for LTE, WiFi, and WiMAX: coherent versus non-coherent and cooperative turbo-transceivers",* John Wiley & Sons, 2011.

[22] C. E. Shannon, "Communication in the presence of noise", *Proc. IRE*, vol.37, Jan. 1949, pp. 10–21.

[23] G. Aiyetoro, G. Giambene, and F. Takawira, "Link adaptation in satellite LTE networks", *Journal of Advances in Information Technology*, vol.5 (1), Feb. 2014, pp. 37–43.

[24] 3rd Generation Partnership Project: Technical Specification Group Radio Access Network, "Evolved universal terrestrial radio access (E-UTRA)", Multiplexing and channel coding, Release 10, 2010–2012, TS 36.212, Vol. 10.0.0.