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RESEARCH ON UPLINK MIMO-SCMA COMMUNICATION SYSTEM

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Abstract. *Sparse code multiple access (SCMA) is a promising non-orthogonal multiple access scheme for future mobile communication. Combined with multiple input, multiple output (MIMO) technique, the spectrum efficiency of SCMA can be further improved. A joint factor graph method can be applied to the uplink MIMO-SCMA for more efficient signal detection. However, the corresponding decoding complexity of this system grows exponentially with the number of antennas and active users. To tackle this problem, a reduced complexity decoding scheme for the uplink MIMO-SCMA system is proposed by exploiting the unbalance feature of the uplink virtual codebook. Simulation result shows that the proposed algorithm has much lower complexity compared to existing complexity-reduced schemes with reasonable symbol error rate (SER).*

Keywords: MIMO, Sparse code multiple access (SCMA), Uplink transmission, Message passing algorithm

1. **Introduction.** To meet the requirement of massive connectivity, high throughput and low latency in future mobile communication, the non-orthogonal multiple access schemes such as power-domain non-orthogonal multiple access (p-NOMA) [1], sparse code multiple access (SCMA) [2], pattern division multiple access (PDMA) [3], multi-user shared access (MUSA) [4] have been developed [5]. The SCMA as a frequency and code domain non orthogonal multiple access scheme extended from LDS-CDMA [6], can achieve considerable balance between performance and complexity. By taking advantage of the sparse structure of SCMA codebook, the message passing algorithm (MPA) [7] is introduced to separate the non-orthogonal signal. However, the MPA is still suffered from exponential complexity by the number of the orthogonal resources allocated to each user.

Many efforts have been made to achieve a reasonable tradeoff between decoding accuracy and complexity for MPA. The max-log MPA proposed in [8] approximates the logarithm of exponential sum as max operation with Jacobian approximation in order to reduce computation complexity, while the Gaussian approximation is adopted in [9], where the original discrete messages are approximated as continuous Gaussian messages to avoid the complex marginalization operation. However, the above mentioned approximation schemes suffer from the BER performance loss. Other works focus on accelerating the converge rate of the MPA to avoid unnecessary iterations. The weighted MPA [10] accelerates the converge rate by assigning the weight factor for each probability value to change the probability distribution; however, it still suffers from decoding accuracy loss. The shuffled MPA in [11] accelerates the converge rate by using the updated information immediately in current iteration, which has negligible BER performance loss but it is difficult for parallel implementation since the message update order becomes asynchronous. On the other hand, the complexity can be reduced by stopping updating information when

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the specific condition is satisfied, such as the selective MPA [12] which stops updating the branches with high reliability.

A joint detection of downlink MIMO and SCMA signal was first proposed in [13], where the detection of MIMO and SCMA signal is done in one shot to avoid conventional inefficient minimum mean square error (MMSE) or zero forcing (ZF) detection procedures. However, the decoding complexity grows exponentially with the number of antennas on both sides, and the uplink scenario has not been investigated.

In this paper, we formulate the uplink MIMO-SCMA system model for the first time. Furthermore, to tackle the severe complexity problem in the joint MIMO-SCMA detection in uplink MIMO-SCMA system, the corresponding low complexity message passing algorithm is developed, in which the users with fast converge rate are decoded before the maximum number of iteration is reached and removed from the joint factor graph. We proposed a new criterion to remove users with fast converge rate under uplink virtual codebook structure. Simulation result shows that the proposed algorithm can achieve reasonable complexity without significant decoding accuracy loss.

The rest of the letter is organized as follows. Section 2 briefly introduces the basic concept of SCMA and formulates the uplink MIMO-SCMA system model. Section 3 presents the maximum likelihood (ML) detection method and conventional message passing algorithm for SCMA signal, and then proposes the sub-set based message passing algorithm with its complexity analysis. The simulation results are displayed and discussed in Section 4. Finally, the paper is concluded in Section 5.

2. System Model for Uplink MIMO-SCMA.

In this section, we briefly review the basic SCMA system model and demonstrate how it can be formulated into the uplink MIMO-SCMA model with joint factor graph representation. The basic SCMA system consists of N independent data streams and K orthogonal resources, e.g., OFDM subcarriers, with $N > K$ and defines the overload factor by $\lambda = N/K$ $(\lambda > 1)$. Each data stream (user/layer) is assigned with one unique code book $X_j \in \mathbb{C}^{K\times M}$, and every $\log_2(M)$ bits of each data stream are directly mapped into the corresponding codeword from the codebook.

2.1. MIMO-SCMA model.

We consider a MIMO-SCMA uplink communication system where J users simultaneously communicate with one base station (BS). Each user is equipped with N_U antennas and the base station is equipped with N_R antennas, with system diagram in Figure 1. For the n_u-th antenna of user j $(n_u = 1, 2, \ldots, N_U)$, every $\log_2(M)$ bits from the bit stream $b_j^{n_u}$ are directly mapped into a K-dimension complex codeword $\mathbf{x}_j^{n_u}$ from the code book assigned to the n_u-th antenna, with $\mathbf{x}_j^{n_u} \in \mathbb{C}^{K\times 1}$. The entire signal transmitted by user j can be given as $\mathbf{x}_j = \left[\left(\mathbf{x}_j^1\right)^T, \left(\mathbf{x}_j^2\right)^T, \ldots, \left(\mathbf{x}_j^{N_U}\right)^T\right]^T \in \mathbb{C}^{N_U K\times 1}$. The received signal at the base station can be given as

$$\mathbf{y} = \sum_{j=1}^{J} \mathbf{H}_j \mathbf{x}_j + \mathbf{n}_j, \tag{1}$$

where the MIMO channel $\mathbf{H}_j \in \mathbb{C}^{N_R K\times N_U K}$ is given as

$$\mathbf{H}_j = \begin{bmatrix} diag\left(\mathbf{h}_j^{1,1}\right) & diag\left(\mathbf{h}_j^{1,2}\right) & \cdots & diag\left(\mathbf{h}_j^{1,N_U}\right) \\ diag\left(\mathbf{h}_j^{2,1}\right) & diag\left(\mathbf{h}_j^{2,2}\right) & \cdots & diag\left(\mathbf{h}_j^{2,N_U}\right) \\ \vdots & \vdots & \ddots & \vdots \\ diag\left(\mathbf{h}_j^{N_R,1}\right) & diag\left(\mathbf{h}_j^{N_R,2}\right) & \cdots & diag\left(\mathbf{h}_j^{N_R,N_U}\right) \end{bmatrix}, \tag{2}$$

and the element $\mathbf{h}_j^{n_r,n_u}$ denotes the channel gain vector for K OFDM sub-carriers between the n_u-th antenna of user j and n_r-th antennas of BS, and $\mathbf{n}_j = \left[\left(\mathbf{n}_j^1\right)^T, \left(\mathbf{n}_j^2\right)^T, \ldots, \left(\mathbf{n}_j^{N_U}\right)^T\right]^T \in \mathbb{C}^{N_U K\times 1}$ denotes the additive complex Gaussian noise vector of the j-th user.

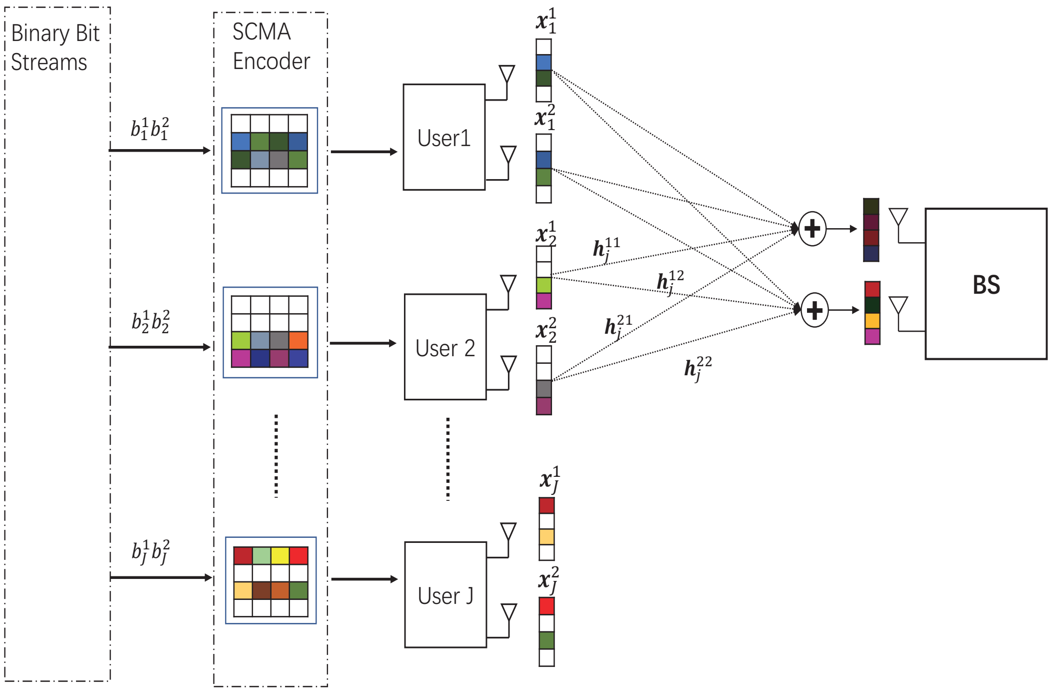

FIGURE 1. Uplink MIMO-SCMA system with $N_R = 2$, $N_U = 2$

By mathematical manipulation, we can reform (1) as

$$\mathbf{y} = \sum_{j=1}^{J}\sum_{n_u=1}^{N_U} diag\left(\mathbf{h}_j^{n_r}\right)\breve{\mathbf{x}}_j^{n_r} + \mathbf{n}_j, \tag{3}$$

where

$$\mathbf{h}_j^{n_r} = \left[\left(\mathbf{h}_j^{n_u,1}\right)^T, \left(\mathbf{h}_j^{n_u,2}\right)^T, \ldots, \left(\mathbf{h}_j^{n_u,N_R}\right)^T\right]^T \in \mathbb{C}^{N_R K\times 1},$$

and

$$\breve{\mathbf{x}}_j^{n_r} = [\underbrace{(\mathbf{x}_j^{n_u})^T, (\mathbf{x}_j^{n_u})^T, \ldots, (\mathbf{x}_j^{n_u})^T}_{N_R}]^T \in \mathbb{C}^{N_R K\times 1}.$$

In (3), the received signal $\mathbf{y}$ is the combination of $N_U \times J$ components with standard SCMA signal form, which can be treated as $N_U \times J$ virtual users. Thus, we define

$$\breve{\mathbf{\Gamma}}_{j'}^{n_r} = [\underbrace{(\mathbf{\Gamma}_{j'}^{n_u})^T, (\mathbf{\Gamma}_{j'}^{n_u})^T, \ldots, (\mathbf{\Gamma}_{j'}^{n_u})^T}_{N_R}]^T \in \mathbb{C}^{N_R K\times M}, \tag{4}$$

where $j' = J\times(n_u - 1) + j$, $(j = 1, 2, \ldots, J,\ n_u = 1, 2, \ldots, N_U)$ and $\mathbf{\Gamma}_{j'}^{n_u}$ $(j' = 1, 2, \ldots, N_U \times J)$ denotes the original codebook used by user j at n_u-th antenna. At BS, the virtual codebook can be constructed as

$$\breve{\mathbf{X}}_{j'} = diag\left(\mathbf{h}_j^{n_r}\right)\breve{\mathbf{\Gamma}}_{j'}^{nr} \in \mathbb{C}^{N_R K\times M}. \tag{5}$$

The joint factor graph of the MIMO-SCMA system can be given as

$$\mathbf{F} = \begin{bmatrix} \mathbf{F}^1 & \mathbf{F}^2 & \cdots & \mathbf{F}^{N_U} \\ \mathbf{F}^1 & \mathbf{F}^2 & \cdots & \mathbf{F}^{N_U} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{F}^1 & \mathbf{F}^2 & \cdots & \mathbf{F}^{N_U} \end{bmatrix} \in \mathbb{C}^{N_R K \times N_U J}, \tag{6}$$

which consists of $K' = N_R \times K$ function nodes (FNs) and $J' = N_U \times J$ variable nodes (VNs), corresponding to $K' = N_R \times K$ virtual orthogonal resources and $J' = N_U \times J$ virtual users. The transformation of MIMO-SCMA is illustrated by Figure 2.

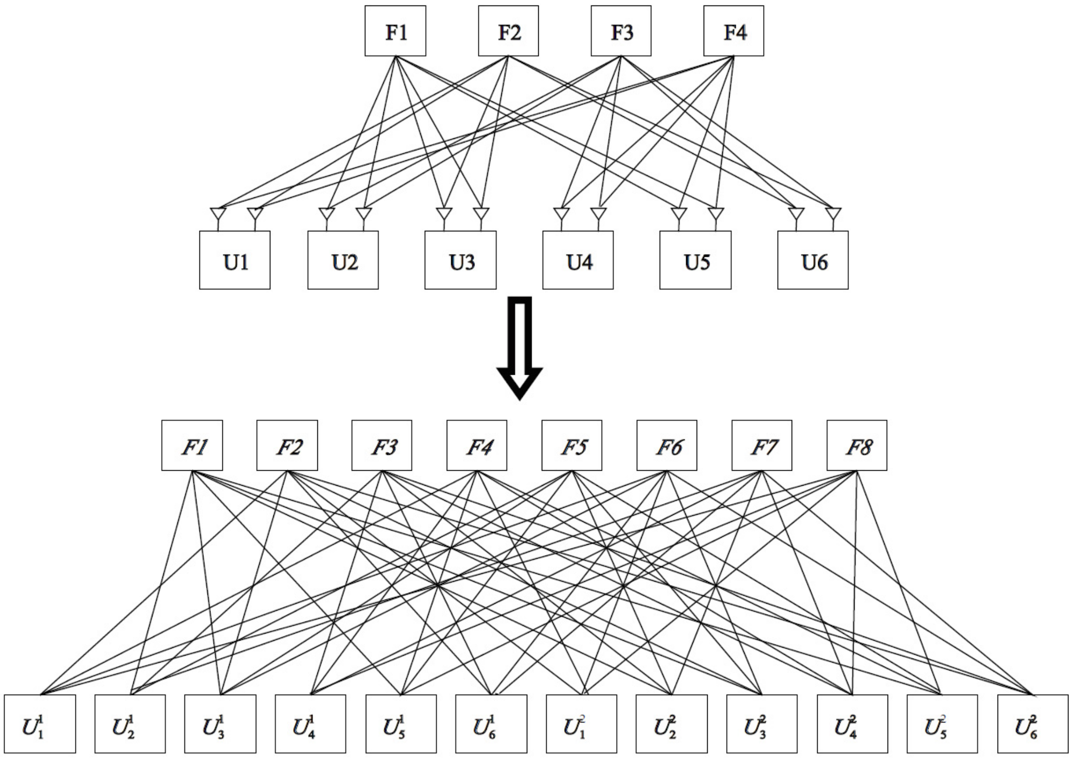

FIGURE 2. Joint factor graph repersentation of uplink MIMO-SCMA

3. MIMO-SCMA Signal Decoding.

3.1. **Optimal detection.** We denote the codeword selected from virtual codebook $\breve{\mathbf{X}}_{j'}$ as $\chi_{j'}$. When given the received signal $\mathbf{y}$ and virtual codebooks $\breve{\mathbf{X}} = \left\{\breve{\mathbf{X}}_1, \breve{\mathbf{X}}_2, \ldots, \breve{\mathbf{X}}_{J'}\right\}$, the optimum detection of codewords $\hat{\chi} = \{\hat{\chi}_1, \hat{\chi}_2, \ldots, \hat{\chi}_{J'}\}$ that maximizes the joint a posteriori probability can be written as [6]

$$\hat{\chi} = \arg\max_{\chi \in \breve{\mathbf{X}}} \prod_{j'=1}^{J'} p(\chi_{j'}) p(\mathbf{y}|\chi_{j'}). \tag{7}$$

If all the codewords are transmitted with equal probability, it can be transformed into

$$\hat{\chi} = \arg\min_{\chi \in \breve{\mathbf{X}}} \left\| \mathbf{y} - \sum_{j'}^{J'} \chi_{j'} \right\|^2. \tag{8}$$

However, the complexity of the maximum likelihood (ML) detection grows exponentially with $N_R \times K$ and $N_U \times J$, which makes this detection method not practical.

3.2. **Conventional message passing algorithm.** Since different user's codewords across different orthogonal resources are coupled with each other, the MPA can be used to separate the codewords by iteratively calculating a series of marginal probabilities [7].

It is assumed the set of all virtual users that connect to orthogonal resource k' as $\eta_{k'}$, the set of all orthogonal resources that connect to user j' as $\xi_{j'}$, and the set of all possible combination of symbols of $\eta_{k'}$ as $\mathbb{M}_{\eta_{k'}} = \{\{m_{11}, m_{21}, \ldots, m_{|\eta_{k'}|1}\}, \{m_{12}, m_{22}, \ldots, m_{|\eta_{k'}|2}\}, \ldots, \{m_{1M}, m_{2M}, \ldots, m_{|\eta_{k'}|M}\}\}$, where $\mathbb{M}_{\eta_{k'}}(j, m)$ denotes the subset of $\mathbb{M}_{\eta_{k'}}$ and user j''s symbol is fixed to m. The detailed procedures of MPA are given as follows.

First, we calculate the initial value as follows

$$p\left(\mathbf{y}_{k'}|\mathbb{M}_{\eta_{k'}}\right) = \frac{1}{\sqrt{2\pi}N_0}\exp\left[-\frac{1}{2N_0}\left(\mathbf{y}_{k'} - \sum_{j'\in\eta_{k'}}^{|\eta_{k'}|}\breve{\mathbf{X}}_{j'}(k', m)\right)\right], \tag{9}$$

$\forall k' \in \{1, 2, \ldots, K'\}$ and $m \in \{1, 2, \ldots, M\}$, where $\breve{\mathbf{X}}_{j'}(k', m)$ denotes the k'-th orthogonal resource and the m-th code word (k'-th row and m-th column) of user j''s codebook $\breve{\mathbf{X}}_{j'}$.

In the t-th step, we calculate

$$I_{k'\to v}^{(t)}(m) = \sum_{m'\in\mathbb{M}_{\eta_{k'}}(v,m)} p\left(\mathbf{y}_{k'}|\mathbb{M}_{\eta_{k'}}(v, m)\right) \times \prod_{v'\in\eta_{k'}/v} I_{v'\to k'}^{(t-1)}(m'), \tag{10}$$

$$I_{j'\to g}^{(t)}(m) = normalize\left(\prod_{g'\in\xi_{j'}/g}^{|\xi_{j'}|} I_{g'\to j'}^{(t-1)}(m)\right), \tag{11}$$

$\forall j' = 1, 2, \ldots, J'$, $m \in \{1, 2, \ldots, M\}$ and $g \in \xi_{j'}$, where the normalized term is defined as

$$I_{j'\to g}^{(t)}(m) = \frac{I_{j'\to g}^{(t)}(m)}{\sum_{m'=1}^{M} I_{j'\to g}^{(t)}(m')}, \quad \forall m \in 1, 2, \ldots, M.$$

After the iterative procedure, the final decision of user j''s symbol can be given as

$$\hat{m}_{j'} = \arg\max_{m}\prod_{g\in\xi_{j'}}^{|\xi_{j'}|} I_{g\to j'}^{(t)}(m). \tag{12}$$

Due to the sparsity of SCMA codebook, the computational complexity can be decreased to exponentially with $|\eta_{k'}|$ and $|\xi_{j'}|$ by using the MPA. However, the complexity is still too high when the number of the antennas becomes large.

3.3. **Proposed sub-set based message passing algorithm.** The virtual codebook constructed by uplink channel side information is irregular, which means that the virtual user comes from the transmit antennas with better channel condition, would have a stronger codebook than others, and converges within a few MPA iterations with a much faster convergence rate, leading to a huge computational redundancy in the rest of iterations.

The key idea of the proposed algorithm is that if the users with fast convergence rate can be decoded in advance and removed from the non-orthogonal signal in the future iterations under the specific criterion, the computational complexity for the future iteration can be decreased dramatically. More specifically, for every user that is removed, the computation burden for $|\xi_j|$ FNs that connect to the removed user can be decreased to $1/M$ when the extrinsic information is updated to other VNs.

The flexibility of the set $\eta_{k'}$, $\xi_{j'}$ and $p\left(\mathbf{y}_{k'}|\mathbb{M}_{\eta_{k'}}\right)$ becomes the main difference between the conventional MPA and the proposed algorithm. In the conventional MPA, $\eta_{k'}$ and $\xi_{j'}$ remain unchanged during the entire iteration procedure until the maximum number of iteration is reached. In the proposed algorithm, we assume that the virtual user with

$\max_m \prod_{g\in\xi_{j'}}^{|\xi_{j'}|} I_{g\to j'}^{(t)}(m) > 1 - \beta N_0/E_b$, $\forall m = 1,2,\ldots,M$, can be decoded in advance and removed from the upcoming iteration. Consequently, when one user j' is decoded and removed, corresponding VN node can be removed from the factor graph; therefore, $\eta_{k'} = \eta_{k'}/j'$ for all $k' \in \xi_{j'}$. Since user j' is removed, a subset of $\Phi_{\eta_k}^{(t)} = p(\mathbf{y}_{k'}|\mathbb{M}_{\eta_{k'}})$ for these FNs where the symbol for j' is $\hat{m}$, can be taken for the upcoming iterations.

It is very difficult to give the analytical form of the proposed reduced complexity MPA algorithm because its complexity not only depends on the size of the set of pre-decoded users Ψ, but also depends on the factor graph structure. We show some worst case complexity under different $|\Psi|$ with system parameter of $N_U = 2$, $N_R = 2$, where d_r, d_c are the number of users that connect to one orthogonal resource and number of resources that allocated one user by the original code book assigned to every transmit antenna respectively. The details are given in Table 1, where N denotes the number of rest iterations.

Algorithm 1 Pseudocode for proposed algorithm

Input: received signal $\mathbf{y}$, channel information $\mathbf{h}$, codebook $\mathbf{CB}$, max number of iteration T, parameter β

Output: estimate symbols of all $N_U \times J$ data streams $\hat{M} = \{\hat{m}_1, \hat{m}_2, \ldots, \hat{m}_{N_U\cdot J}\}$

STEP 1:Initialization:

construct the virtual codebook $\breve{\mathbf{X}}$ according to (5)
calculate $\eta_{k'}$ and $\xi_{j'}$ according to $\breve{\mathbf{X}}$
set iteration index $t = 1$
set $I_{j'\to g}^{(0)} = 1/M$, $\forall j' = 1,2,\ldots,J'$ and $g \in \xi_{j'}$
initialize the set of decoded users $\Psi = \emptyset$
calculate $\Phi_{\eta_k}^{(0)} = p(\mathbf{y}_{k'}|\mathbb{M}_{\eta_{k'}})$ using (9)

STEP 2:Iteration:

while $t < T$:
update $I_{k'\to v}^{(t)} \forall k' = 1,2,\ldots,K'$ with $\Phi_{k'}^{(t)}$ and $\eta_{k'}$ using (10)
update $I_{j'\to g}^{(t)} \forall j' = 1,2,\ldots,J'$ with $\xi_{j'}$ $\forall j' \notin \Psi$ using (11)
if $\max_m \prod_{g\in\xi_{j'}}^{|\xi_{j'}|} I_{g\to j'}^{(t)}(m) > 1 - \beta N_0/E_b$, $\forall j' \in 1,2,\ldots,J'$
    add j' to Ψ
    set $\eta_k^{(t+1)} = \eta_k^{(t)}/j'$, $\forall k' \in \xi_{j'}$
    set $\Phi_{k'}^{(t+1)} = \Phi_{k'}^{(t)}(j', \hat{m}_{j'})$, $\forall k' \in \xi_{j'}$
$t = t + 1$

STEP 3:Final output:

Calculate $\hat{M}$ using (12)

Table 1. Complexity comparison

Scheme	Complexity
Conventional MPA	$N(KN_R(N_Ud_r)(N_Ud_r-1)M^{N_Ud_r} + (N_UJ)(d_cN_R)(d_cN_R-1)M)$
Proposed $\|\Psi\| = 1$	$N((KN_R-N_Rd_c)(N_Ud_r)(N_Ud_r-1)M^{N_Ud_r}+N_Rd_c(N_Ud_r-1)(N_Ud_r-2)M^{N_Ud_r-1} + (N_UJ-1)(d_cN_R)(d_cN_R-1)M)$
Proposed $\|\Psi\| = 2$	$N((KN_R-N_Rd_c)(N_Ud_r)(N_Ud_r-1)M^{N_Ud_r}+N_Rd_c(N_Ud_r-2)(N_Ud_r-3)M^{N_Ud_r-2} + (N_UJ-2)(d_cN_R)(d_cN_R-1)M)$

4. **Numerical Results.** In this section, we evaluate the proposed algorithm in uplink MIMO-SCMA system, under the configuration that is $J = 6$, $K = 4$, $M = 4$, $N_U = 2$, $N_R = 2$. Without loss of generality, we assume that each antenna equipped by the same user is assigned with the same codebook, and the results are averaged from 10^5 times of independent realization of Rayleigh fading channel.

Figure 3 depicts the symbol error rate (SER) performance of the original MPA, the selective MPA [12], and the proposed algorithm. The parameters are set as follows, the selective MPA with $\alpha = 1, 5$ and the proposed algorithm with parameter $\beta = 0, 0.01, 0.1$. It can be seen that when $\beta = 0$, the SER performance of the proposed algorithm is exactly the same as the conventional MPA; it proved that the performance is not degraded by removing the users with normalized belief values 1. When β goes up to 0.1, the performance loss of the proposed algorithm is about 0.5dB, which is close to the selective MPA.

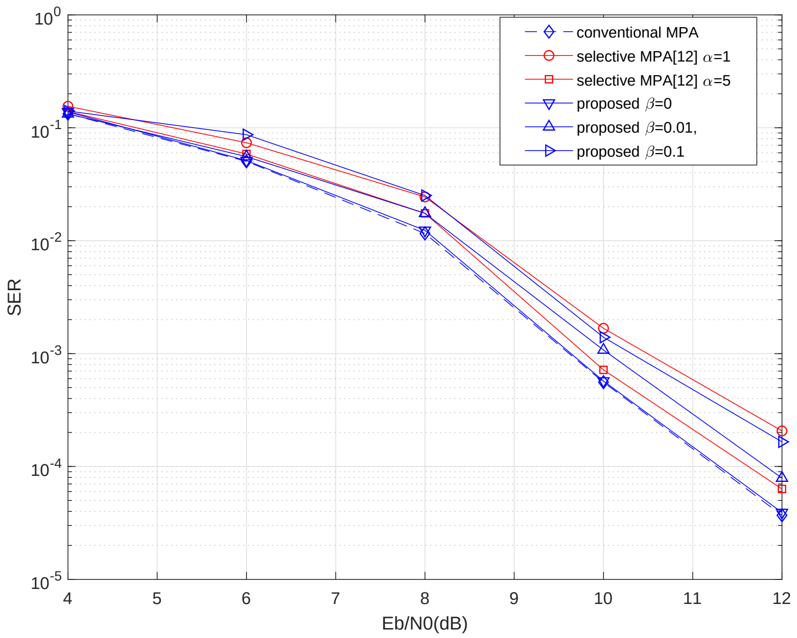

Figure 3. Average symbol error rate among different decoding schemes

Next, we investigate the complexity ratio of three algorithms, which are derived numerically by counting the executed operations. We define the complexity of the conventional MPA with 10 iterations as the baseline with complexity ratio of 1. Consequently, the conventional MPA with 8, 6, 4, 2 iterations has the complexity ratio of 0.8, 0.6, 0.4, 0.2, respectively. In Figure 4, under the most strict condition with $\beta = 0$, the proposed algorithm has a relatively high complexity compared to the selective MPA at low SNR region, but its complexity decreases significantly as E_b/N_0 becomes larger, and outperforms the selective MPA especially when E_b/N_0 is higher than 12dB. Under the less strict conditions, such as $\beta = 0.01$ and $\beta = 0.1$, the complexity ratios are continuously lower than the selective MPA.

Last but not the least, we investigate the impact of channel estimation error on the uplink MIMO-SCMA system. The channel estimation error model is defined as $\mathbf{h} = \hat{\mathbf{h}} + \Delta\mathbf{h}$, where $\Delta\mathbf{h} \sim \mathcal{CN}(0, \sigma_{ce}^2)$ and σ_{ce}^2 denotes the variance of channel estimation error. The result is given by Figure 5. It shows that the robustness of the proposed algorithm is the same as the conventional MPA, and the performance gap between the conventional MPA and the proposed algorithm narrows down when the channel estimation error becomes larger.

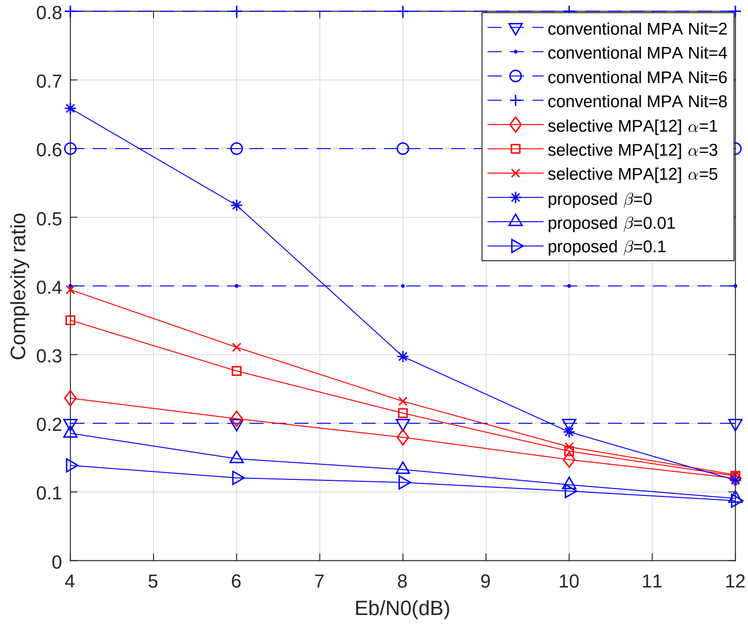

FIGURE 4. Complexity ratio among different decoding schemes

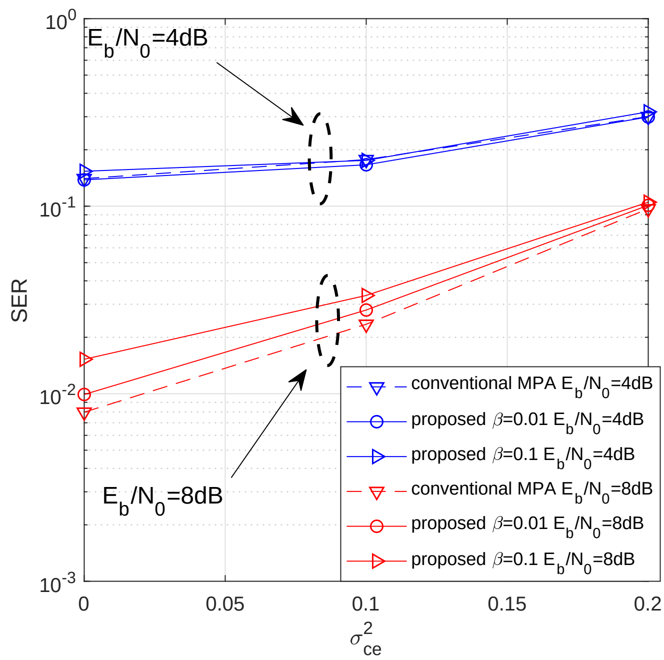

FIGURE 5. SER performance under imperfect channel

5. **Conclusion.** This paper formulates the uplink MIMO-SCMA system and proposes the corresponding low complexity decoding algorithm, and the computation complexity under proposed criteria is significantly reduced compared to the conventional MPA and the existing reduced complexity MPA decoding schemes. It should be noted that for the MIMO-SCMA system, when the number of receive antennas becomes large, the redundant received message can be exploited to further reduce the decoding complexity, which is left for future work.

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