A Low Complexity Detection Algorithm for Fixed Up-Link SCMA System in Mission Critical Scenario

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***Abstract*—Sparse code multiple access (SCMA), as one of the most promising candidate techniques for the fifth generation communications system, is a nonorthogonal multiple access scheme which can provide large scale connections. Its philosophy is to map coded bits directly to multidimensional sparse codewords, and the message passing algorithm (MPA) is utilized to detect the multiuser signals. However, the relatively high computation of MPA detection may lower the performance when SCMA is implemented in practical applications. The partial marginalization MPA (PM-MPA) helps to reduce the computation of original MPA detection. In this paper, an improved detection scheme based on PM-MPA is proposed. Our analysis and simulation shows that compared with PM-MPA, the improved PM-MPA (IPM-MPA) can obtain a lower bit error ratio. Besides, the simulation also shows that, to achieve the same performance, the IPM-MPA is less complex than PM-MPA.**

***Index Terms*—Internet of Things (IoT), low complexity, message passing algorithm (MPA), sparse code multiple access (SCMA).**

I. INTRODUCTION

As a TYPICAL scenario in the fifth generation communication system, the Internet of Things (IoT) and the Internet of Mission Critical Things (IoMCT) motivate a wide range of applications in various fields, such as smart home, smart grids, smart city, public transportation monitoring, especially to the mission critical scenario [1]. However, the emerging IoT needs to meet high standards, such as low latency, massive connection, and better coverage [2]. Related works have been done to research the obstacles faced by IoT, including massive scaling, architecture and dependency, robustness and openness of IoT system [4]–[10]. The security and the privacy of IoT are also intensely investigated in recent years. Jia *et al.* [9] and Elbouanani *et al.* [10] investigated the need for security in IoT network and challenges that IoT network faces. To improve the privacy in IoT, Li *et al.* [11] proposed an RFID system in which the privacy protection can be turned on or off by validate authorities. Li *et al.* proposed a PREDICT project on privacy and security enhancing dynamic information collection and monitoring [6].

Among enormous research fields, there is no denying that multiple access is one of the most challenging problems since IoT and IoMCT require new approaches and low-complexity algorithms to meet massive connections. Some techniques are emerging to try to tackle the problem. With these potential candidates, nonorthogonal multiple access (NOMA) seems to be the most promising by providing the massive connection as well as increasing the throughput. NOMA which employs the linear superposition and elaborate coding system, allows the users share the same frequency-time domain in an overloaded way. Saito *et al.* [13] presented an NOMA concept for cellular future radio access toward the 2020s information society. NOMA superposes multiple users in the power domain although its basic signal waveform could be based on the orthogonal frequency division multiple (OFDM) access or the discrete Fourier transform-spread OFDM. Multiuser multiple access [14], [15], which is represented by Yuan *et al.* can obtain larger user capacity by employing nonorthogonal complex spread sequence to spread the symbols in the transmitted users. Dai *et al.* [16] proposed pattern defined multiple access, a method to realize multiple access by system signature matrix at the transmitter and the successive interference cancelation-based detector at the receiver. In addition, sparse code multiple access [17], which can be seen as a generalization of sparsely spread CDMA [18], offers an NOMA scheme. In SCMA, the constellation mapper and the spread procedure are merged together to turn coded binary bits into multidimensional codewords and then these codewords are modulated on the OFDM channels in a sparse way [19]. The SCMA allows for both overloaded users and low complexity.

To facilitate SCMA implemented in practical scenarios, numerous studies are also carried out. By combining SCMA with MIMO, Du *et al.* built a joint sparse graph combining the single graph of MIMO channels and SCMA codewords [20], which can obtain tolerant

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bit error ratio (BER) while maintaining low complexity. Zhang *et al.* [21] proposed a method integrating the message passing between SCMA detector and turbo decoder into the factor graph of the SCMA detector to construct a joint factor graph, the joint detection and decoding algorithm can get extra performance gain compared with the conventional iterative detection and decoding scheme. Dong *et al.* [22] discussed the energy efficiency in up-link SCMA system and conceive a novel method called cooperative coevolutionary particle swarm optimization to solve the energy efficiency maximization problem. Xiao *et al*. [23] proposed a novel iterative detection and decoding scheme for SCMA systems combined with low-density parity-check decoding. Xiao *et al.* provided a way to evaluate the performance of SCMA system in a system level [24].

The vital part of SCMA concentrates on the codebook and receiver design. The encoder of SCMA system infuses the QAM and spread process together, so a good shaping gain of codebook in SCMA system is of essential importance.

Multidimensional codebook design has been investigated in different aspects. Kschischang *et al.* [31] provided a generalized method to design a codebook of SCMA system. Yu *et al*. [25] devised an improved method based on star-QAM signaling constellations to construct the codebook. This method can improve BER performance without sacrificing the low detection complexity. Cai *et al.* [26] proposed a multidimensional SCMA codebook design based on constellation rotation and interleaving, which can obtain lower BER than the low density signature in down-link Rayleigh fading channels. A spherical code method, which can efficiently improve the system performance, to build mother multidimensional codebook is investigated in [27].

Since SCMA was proposed, numerous researches have been carried out to reduce the complexity of SCMA detectors to fulfill IoMCT requirements about computation. The detection can be realized by finding the maximum joint posterior probability of all users' transmitted symbols. But the tremendous computation hampers practical implementation. So, the message passing algorithm (MPA) [28], which is used in LDS [29], [30] based on the sum-product algorithm [31] is employed in the SCMA detector to reduce computation. To further lower the complexity, some studies are conduct. Liu *et al.* [32] designed a framework for fixed-point implementation of the log-domain MPA to reduce the complexity of receivers of SCMA system. Xiao *et al.* [33] proposed two improved receiver algorithms, which cannot only simplify the detection structure but also curtail exponent operations quantitatively in logarithm domain. Bayesteh *et al.* [34] investigated a way to reduce complexity by designing codebooks providing low complexity of detections and low complexity detection structure due to the codebooks.

Mu *et al.* [35] proposed a simplified detector based on partial marginalization, in which the complexity is reduced by fixing the t codewords in the mth iteration. An improved partial marginalization MPA (IPM-MPA) detector for the fixed up-link SCMA system is proposed in this paper. The simulation results show that compared with the method in [35], the improved one can obtain a lower BER while maintaining the same level of computation. Besides, the analytical results also shows that, to achieve the same performance, IPM-MPA is more computational efficient than PM-MPA.

Though SCMA can be used in the scenarios with a massive number of users, the codebooks need to be designed specifically, which is beyond the scope in this paper. In this paper, we will use a simple codebook presented in [36] to analyze the performance of the method proposed in this paper.

The rest of this paper is arranged as follows. Section II describes a universal model of SCMA. The original MPA detection, the PM-MPA detection, and the improved MP-MPA detection are depicted in Section III. The computation analysis and the simulation results will be given in Sections IV and V, respectively. A concise conclusion is drawn in Section VI.

In this paper, we use notations $\mathbb{B}$ and $\mathbb{C}$ to represent the complex field and binary field. Scalar, vector, and matrix are denoted as x, $\mathbf{x}$, and $\mathbf{X}$, respectively. The element in ith row and jth column of kth is $\mathbf{X}_{i,j}$ and the kth element of $\mathbf{x}$ is x_k.

II. SYSTEM MODEL

A. Codebook and Encoder

Fig. 1 shows a block diagram of a fixed up-link SCMA system. There are J user layers in this system. The signal of each user layer is spread into K orthogonal recourse layers (OFDM channels, as a rule). SCMA system promises the signals are transmitted in an overloaded manner, i.e., $J > K$. Input binary bits are mapped into multidimensional codewords and each codewords is sent by one channel. The codewords mapped by input bits correspond to the codebook of the user layer and different users own different codebooks. Take jth user layer for example, $\log_2 |M|$ input binary bits $\mathbf{b}_j$ conforming its unique codebook $\chi_j \subset \mathbb{C}^K$ with cardinality $|\chi_j| = M$ are mapped into a K-dimensional codewords $\mathbf{x}_j$. To prevent the signals of different users from colliding drastically, the spread procedure is conducted in a sparse way, which means that $N$of the K-dimensional codewords are zero. In this paper, we use $\mathbf{D}_j = \{\mathbf{d}_{j1}, \mathbf{d}_{j2}, \ldots, \mathbf{d}_{jM}\}$ to represent all M N-dimensional codewords of jth user layer. So the whole procedure of the SCMA encoder can be seen as a two-step process.

1) Binary bits $\mathbf{b}_j$ will be first modulated into a N-dimensional none-zero constellation $\mathbf{d}_j = [d_1 d_2 \ldots d_N]^T$. We use g_j to describe the modulation, which can be formulated as

$$\mathbf{d}_j = g_j\big(\mathbf{b}_j\big). \tag{1}$$

2) $K - N$ zeroes will mapped into a K-dimensional codewords $\mathbf{x}_j$ with mapping matrix $\mathbf{V}_j \in \mathbb{B}^{K*N}$, which can be written as

$$\mathbf{x}_j = \mathbf{V}_j\big(\mathbf{d}_j\big). \tag{2}$$

So, the encoder of SCMA system can be modeled as

$$\mathbf{x}_j = \mathbf{V}_j g_j\big(\mathbf{b}_j\big). \tag{3}$$

Denote $\mathcal{V} = [\mathbf{V}_j]_{j=1}^J$ and $\mathcal{G} = [g_j]_{j=1}^J$ the codebook design can be represented as $\mathcal{S}(\mathcal{V}, \mathcal{G}; J, M, N, K)$.

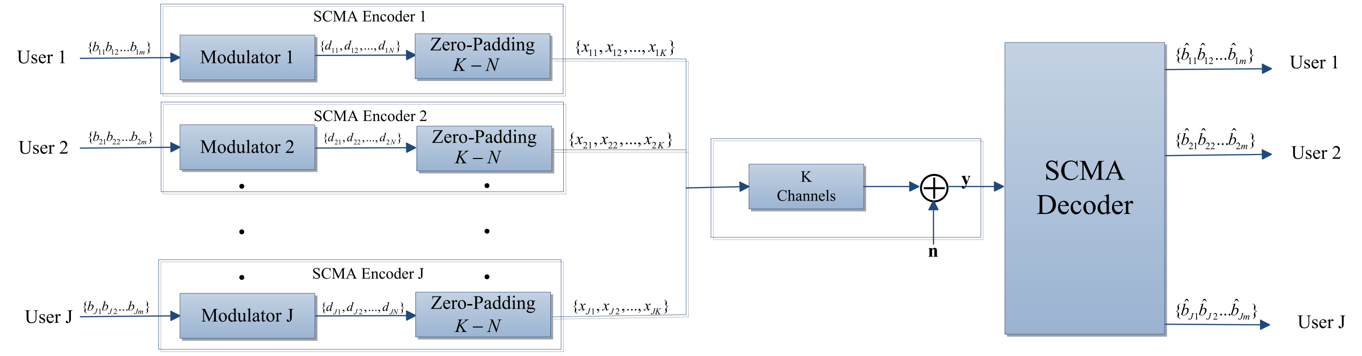

Fig. 1. Fixed up-link SCMA system model.

Based on [19], the optimal codebook design can be defined as

$$\mathcal{V}*, \mathcal{G}* = \arg\max_{\mathcal{V},\mathcal{G}}(\mathfrak{m}(\mathcal{S}(\mathcal{V}, \mathcal{G}; J, M, N, K))) \tag{4}$$

where $\mathfrak{m}$ is a criterion to evaluate the performance of codebook and encoder. The design can be decomposed as two parts.

1) Design the optimal mapping matrix $\mathcal{V}*$. As referred, mapping matrix is a binary matrix with K rows and N columns. The design of mapping matrix is significant since it determines the sparsity of signals and the way that symbols overlapped in one channel. Actually, $\mathbf{V}$ can be constructed by inserting $K-N$ zero row into a K-dimensional unit matrix. In addition, the detection algorithm in receiver end also needs $\mathbf{V}_i \neq \mathbf{V}_j (i \neq j)$. So with certain K and N , a full $\mathcal{V}$ involving all possible $\mathbf{V}$ can be uniquely determined.
2) Once $\mathcal{V}*$ has be settled, the optimal problem can be written as

$$\mathcal{G}* = \arg\max_{\mathcal{V},\mathcal{G}}(\mathfrak{m}(\mathcal{S}(\mathcal{V}*, \mathcal{G}; J, M, N, K))). \tag{5}$$

The goal in this problem can be seen as to seek the optimal N-dimensional complex constellation with M points for all J user layers. The constellations with brilliant shaping gain-which means small Euclidean metric, small product distance, small average symbol energy, and small PAPR can reduce the complexity of detection algorithm and increase the throughput of SCMA system. Taherzadeh *et al.* [19] proposed a systematic approach to construct constellations. The idea is to find a mother constellation g^+ first and find J different constellation operators Δ_j, then g_i can be obtained via $g_i = \Delta_j(g^+)$. So, the optimization problem can be turned into

$$\begin{aligned} &g^+, \left[\Delta_j^+\right] \\ &= \arg\max_{g,\Delta_j}\Big(\mathfrak{m}\Big(\mathcal{S}\Big(\mathcal{V}*, \mathcal{G} = \Big[\Delta_j(g)_{j=1}^J\Big] J, M, N, K\Big)\Big)\Big). \end{aligned} \tag{6}$$

B. Multiplex Signal

In this paper, we use $\mathbf{x}_j = [x_{j1}x_{j2}\ldots x_{jK}]^T$ to denote the transmitted symbols of the jth layer and $\mathbf{X} = [\mathbf{x}_1\mathbf{x}_2\ldots\mathbf{x}_J]$. When the user layers send data conforming the rules of SCMA system, the received signal can be expressed as follows:

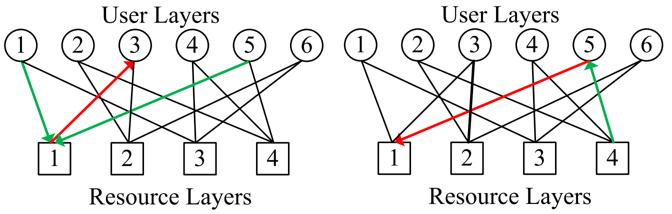

Fig. 2. Factor graph with $J = 6$ and $K = 4$.

$$\mathbf{y} = \sum_{j=1}^{J} \operatorname{diag}(\mathbf{h}_j)\mathbf{x}_j + \mathbf{n} \tag{7}$$

where $\mathbf{h}_j = [h_{j1}h_{j2}\ldots h_{jK}]^T$ denotes the channel gain of the jth user. The $\operatorname{diag}(\mathbf{h}_j)$ represents the diagonal matrix where the nth diagonal element is $h_{jn} \cdot \mathbf{n} = [n_1n_2\ldots n_K]^T$ is the noise vector whose elements are independent random variables following the Gaussian distribution with mean zero and variance σ^2. The fixed up-link implies that $\mathbf{h}_1 = \mathbf{h}_2 = \cdots = \mathbf{h}_J$. So, (1) can be further simplified as follows:

$$\mathbf{y} = \mathbf{h}\sum_{j=1}^{J} \mathbf{x}_j + \mathbf{n}. \tag{8}$$

In this paper, the factor graph and indicator matrix are assisted to illustrate the SCMA system comprehensively.

C. Factor Graph Representation

The factor graph is used to describe the relationship between user layers and resource layers in the SCMA system. Fig. 2 gives an example where the system contains four resource layers and six user layers, that is, $J = 6$ and $K = 4$. In this paper, we denote $\varepsilon_{k,j}$ the edges that link jth user layer and kth resource layer, which means that the signal will transmit to corresponding layers. The factor graph reveals the sparse spread procedure clearly. We can see in Fig. 2 that there are only two resource layers that links to each user layer.

D. Indicator Matrix

The indicator matrix describes the factor graph in a mathematical way. Indicator matrix corporates the spread patterns of all the user layers. The matrix contains J columns and K rows, which denotes the number of user layers and recourse layers, respectively. $\mathbf{F}$ only contains 1 and 0 , $\mathbf{F}_{k,j} = 1$ represents the signal will be transmitted from the jth user layer to the kth recourse layer while jth user will not transmit signal through kth recourse if $\mathbf{F}_{k,j} = 0$. We use $d_{vj} (j = 1, 2, \ldots, J)$ and $d_{ck} (k = 1, 2, \ldots, K)$ to respectively represent the weight of column j and the weight of row k, which means the number of 1 in each row or column. In this paper, we suppose that $d_{v1} = d_{v2} = \cdots = d_{vJ} = d_v$ and $d_{c1} = \cdots = d_{cK} = d_c$. Besides, the index vectors are represented as $\boldsymbol{\varepsilon}_j = \{k|\mathbf{F}_{k,j} = 1\}(j = 1, 2, \ldots, J)$ and $\boldsymbol{\eta}_k = \{k|\mathbf{F}_{k,j} = 1\}(k = 1, 2, \ldots, K)$. $\boldsymbol{\varepsilon}_j$ contains all resource layers connected to jth user layer and $\boldsymbol{\eta}_k$ contains all user layers connected to kth resource layer.

III. DETECTION SCHEME

A. Original MPA and PM-MPA

The classical method to detect signal and determine the transmitted symbols with observation $\mathbf{y}$ and channel information $\mathbf{h}$ is Most a posterior (MAP) Algorithm. The MPA will estimate the codeword $\tilde{\mathbf{x}}$ by maximizing the posterior probability $P(\mathbf{x}|\mathbf{y})$, which can be represented as

$$\tilde{\mathbf{x}} = \arg\max_{\mathbf{x}\in\chi} P(\mathbf{x}|\mathbf{y}). \tag{9}$$

We can estimate the transmitted symbols of the jth layer by maximizing a joint posterior probability mass function (pmf)

$$\tilde{\mathbf{x}}_j = \arg\max_{\mathbf{x}'\in\chi} \sum_{\substack{\mathbf{x}_i \in \chi,\, i \neq j \\ \mathbf{x}_j = \mathbf{x}'}} P(\mathbf{x}|\mathbf{y}). \tag{10}$$

With Bayes rule

$$P(\mathbf{x})P(\mathbf{y}|\mathbf{x}) = P(\mathbf{y})P(\mathbf{x}|\mathbf{y}). \tag{11}$$

We can draw the following conclusion by combining (9) and (11):

$$\begin{aligned}\tilde{\mathbf{x}}_j &= \arg\max_{\mathbf{x}'\in\chi} \sum_{\substack{\mathbf{x}_i \in \chi,\, i \neq j \\ \mathbf{x}_j = \mathbf{x}'}} P(\mathbf{x}_i|\mathbf{y}) \\ &\propto \arg\max_{\mathbf{x}'\in\chi} \sum_{\substack{\mathbf{x}_i \in \chi,\, i \neq j \\ \mathbf{x}_j = \mathbf{x}'}} P(\mathbf{y}|\mathbf{x}_i)P(\mathbf{x}_i)\end{aligned} \tag{12}$$

where $P(\mathbf{x}_i)$ is *a priori* pmf of jth user. In this paper, we assume that the priori pmf of all users are independent to each other.

In addition, the complex signals $\mathbf{y}$ are independent in different channel because of the noncorrelation of noise. So, $P(\mathbf{y}|\mathbf{x}_i)$ can be furtherly written as

$$P(\mathbf{y}|\mathbf{x}_i) = \prod_{k=1}^{K} p(y_k|\mathbf{x}_i). \tag{13}$$

Based on the factor graph and factor matrix, we know that kth channel does not transmit the signals of all the user layers.

Algorithm 1 PM-MPA Algorithm

```
Input: $I_T$, $m$, $p = J - t + 1$
  Initialization:
    $I_{v_j\to r_k}(\mathbf{x}_j) = 1/M, P(\mathbf{x}_j) = 1/M, i = 1, \bar{\mathbf{X}} = \breve{\mathbf{X}} = \emptyset$
  If $i \le m$ then
    $I^i_{r_k\to v_j}(\tilde{\mathbf{x}}_j) = \sum_{\mathbf{X}^{[\eta_k]}, \mathbf{x}_j = \tilde{\mathbf{x}}_j} \mathbf{M}_k(\mathbf{X}^{[\eta_k]}) \prod_{\delta\in\eta_k/j} (I^{i-1}_{v_\delta\to r_k}(\mathbf{x}_\delta))$
    $I^i_{v_j\to r_k}(\tilde{\mathbf{x}}_j) = P(\tilde{\mathbf{x}}_j) normalize (\prod_{\delta\in\varepsilon_j} (I^{i-1}_{r_\delta\to v_j}(\tilde{\mathbf{x}}_j)))$
  End if
  If $i = m$ then
    For $s = p : J$ do
      $\hat{\mathbf{x}}^m_s = \arg\max (\prod_{\delta\in\varepsilon_j} (I^m_{r_\delta\to v_s}(\tilde{\mathbf{x}}_s))) \in \breve{\mathbf{X}}$
    End for
    $\dot{\mathbf{X}} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{J-t}, \tilde{\mathbf{x}}^m_{J-t+1}, \ldots, \tilde{\mathbf{x}}^m_J\} = \{\bar{\mathbf{X}}, \breve{\mathbf{X}}\}$
  End if
  If $m < i \le I_T$ then
    For $\mathbf{x}_s \in \bar{\mathbf{X}}$ do
      $I^i_{r_k\to v_j}(\tilde{\mathbf{x}}_j) = \sum_{\mathbf{X}^{[\eta_k]} \subseteq \dot{\mathbf{X}}, \mathbf{x}_j = \tilde{\mathbf{x}}_j} \mathbf{M}_k(\mathbf{X}^{[\eta_k]}) \prod_{\delta\in\eta_k/j} (I^{i-1}_{v_\delta\to r_k}(\mathbf{x}_\delta))$
      $I^i_{v_j\to r_k}(\tilde{\mathbf{x}}_j) = P(\tilde{\mathbf{x}}_j) normalize (\prod_{\delta\in\varepsilon_j} (I^{i-1}_{r_\delta\to v_j}(\tilde{\mathbf{x}}_j)))$
    End for
  End if
  For $\mathbf{x}_u \in \bar{\mathbf{X}}$do
    $\hat{\mathbf{x}}^{I_T}_u = normalize (\prod_{\delta\in\varepsilon_j} (I^{I_T}_{r_\delta\to v_s}(\tilde{\mathbf{x}}_u))) \in \breve{\mathbf{X}}$
  End for
```

Taking advantages of the sparsity of SCMA system, (13) can be simply rewritten as

$$P(\mathbf{y}|\mathbf{x}_i) = \prod_{k\in\eta_k} p(y_k|\mathbf{x}_i). \tag{14}$$

Based on (9)–(14), the most posterior algorithm can be finally written as

$$\tilde{\mathbf{x}}_j = \arg\max_{\mathbf{x}'\in\chi} \sum_{\substack{\mathbf{x}_i \in \chi,\, i \neq j \\ \mathbf{x}_j = \mathbf{x}'}} \prod_{k\in\eta_k} p(y_k|\mathbf{x}_i)P(\mathbf{x}). \tag{15}$$

So, the most posterior algorithm in SCMA system is turned into a marginalize product problem [31]. Even though the sparsity of SCMA facilitates the computation of detection, the complexity is not improved essentially. To continually lower the complexity of SCMA system, the MPA is derived by MAP based on the factor graph and sun-product algorithm.

The philosophy of MPA detection is to iteratively update the belief associated with the edges in the factor graph by passing the extrinsic information of constellation points between the user layers and recourse layers [17]. Fig. 2 gives a general description of MPA in one iteration. The message passing from the user layer to the recourse layer and the message passing form recourse layer to user layer are denoted by $I_{v_j \to r_k}$ and $I_{r_k \to v_j}$, respectively. In each iteration, the message passed from one edge is calculated by the messages associated with the rest edges of the layer (user layer or resource layer). For example, the message passing in one iteration can be formulated as follows:

$$I^i_{r_k \to v_j}(\tilde{\mathbf{x}}_j) = \sum_{\mathbf{X}^{[\eta_k]}, \mathbf{x}_j = \tilde{\mathbf{x}}_j} M_k\left(\mathbf{X}^{[\eta_k]}\right) \prod_{\delta \in \eta_k / j} \left(I^{i-1}_{v_\delta \to r_k}(\mathbf{x}_\delta)\right) \tag{16}$$

$$I^i_{v_j \to r_k}(\tilde{\mathbf{x}}_j) = \text{normalize}\left(\prod_{\delta \in \varepsilon_j} \left(I^{i-1}_{r_\delta \to v_j} \tilde{\mathbf{x}}_j\right)\right) \tag{17}$$

where $\mathbf{M}_k(\mathbf{X}^{[\eta_k]}) = \exp(-(1/\sigma^2)(y_k - \sum_{j \in \eta_k} x_{j,k}))$.

The message stops updating if the message converges into a specific codeword or the number of iteration meets the predetermined one. After iteration, the codeword can be determined as follows:

$$\hat{\mathbf{x}}^m_s = \arg\max\left(\prod_{\delta \in \varepsilon_j} \left(I^m_{r_\delta \to v_s}(\tilde{\mathbf{x}}_s)\right)\right). \tag{18}$$

It is apparent that most computation concentrates on calculating $I^i_{r_k \to v_j}$ whose complexity is $o(M^{d_c})$. To reduce the computation, the PM-MPA determines the codewords of last t users in the mth iteration. So in the residual iterations, only the message of first $J - t$ users will be updated with the determined codewords. After the maximum number of iterations I_T, the codewords of first $J - t$ users will be finally determined. The whole PM-MPA procedure is described in detail in Algorithm 1.

B. Improved PM-MPA

PM-MPA gives a method to reduce the computation of original MPA detection, but the BER increases largely when the computation gets down. The main reason is the t users determined in mth iteration are chosen randomly. As a result, some unreliable (the messages of these users may not be iterated effectively) codewords deteriorate the performance of SCMA system. In this paper, an IPM-MPA is proposed to choose t users intentionally based on the codewords reliability and to further improve the BER performance while keeping the same complexity. The algorithm can be summarized into three parts.

1) In the first m iterations, the message pass through the user layers and resource layers with the roles of original MPA.
2) In the mth iteration, after exchanging message, we define a parameter w to measure the reliability of codewords of all the user layers and choose t user layers to determine their codewords.
3) In the last $I_T - m$ iterations, the undetermined users will go on exchanging the message but with the determined codewords of t users.

Algorithm 2 IPM-MPA Algorithm

```
Input: $I_T, m, t$
  Initialization:
      $I_{v_j \to r_k}(\mathbf{x}_j) = 1/M, P(\mathbf{x}_j) = 1/M, i = 1, \bar{\mathbf{X}} = \check{\mathbf{X}} = \emptyset$
  If $i \le m$ then
      $I^i_{r_k \to v_j}(\tilde{\mathbf{x}}_j) = \sum_{\mathbf{X}^{[\eta_k]}, \mathbf{x}_j = \tilde{\mathbf{x}}_j} M_k\left(\mathbf{X}^{[\eta_k]}\right) \prod_{\delta \in \eta_k / j} \left(I^{i-1}_{v_\delta \to r_k}(\mathbf{x}_\delta)\right)$
      $I^i_{v_j \to r_k}(\tilde{\mathbf{x}}_j) = P(\tilde{\mathbf{x}}_j) normalize\left(\prod_{\delta \in \varepsilon_j} \left(I^{i-1}_{r_\delta \to v_j}(\tilde{\mathbf{x}}_j)\right)\right)$
  End if
  If $i = m$ then
    For $k = 1 : J$ do
      For $t = 1 : M$ do
          $l_{kt} = \prod_{\delta \in \varepsilon_k} \left(I^m_{r_\delta \to v_s}(\mathbf{x}_{kt})\right)$
Where $\mathbf{x}_{kt}$ represents the $t^{th}$ $N$-dimensional constellation of $k^{th}$ user
      End for
          $\mathbf{L}_k = sort(\{l_{k1}, l_{k2}, \ldots, l_{kM}\}, 'descend')$
          $W_k = \frac{\mathbf{L}_k[1]}{\mathbf{L}_k[2]}$
    End for
          $\mathbf{W} = \{W_1, W_2, \ldots, W_k\} = \mathbf{W}_\theta \cup \mathbf{W}_\phi$
Where $\mathbf{W}_\theta$ contains the largest $t$ elements and
          $\mathbf{W}_\theta \cap \mathbf{W}_\phi = \emptyset$
    For $s = 1 : J$ do
      If $W_s \in \mathbf{W}_\theta$ then
          $\hat{\mathbf{x}}^m_s = \arg\max\left(\prod_{\delta \in \varepsilon_j} \left(I^m_{r_\delta \to v_s}(\tilde{\mathbf{x}}_s)\right)\right) \in \check{\mathbf{X}}$
      Else
          $\mathbf{x}_s \in \bar{\mathbf{X}}$
      End if
    End for
          $\dot{\mathbf{X}} = \left\{\check{\mathbf{X}}, \bar{\mathbf{X}}\right\}$
    End if
    If $m < i \le I_T$ then
      For $\mathbf{x}_s \in \bar{\mathbf{X}}$ do
      $I^i_{r_k \to v_j}(\tilde{\mathbf{x}}_j) = \sum_{\mathbf{X}^{[\eta_k]} \subseteq \dot{\mathbf{X}}, \mathbf{x}_j = \tilde{\mathbf{x}}_j} \mathbf{M}_k\left(\mathbf{X}^{[\eta_k]}\right) \prod_{\delta \in \eta_k / j} \left(I^{i-1}_{v_\delta \to r_k}(\mathbf{x}_\delta)\right)$
      $I^i_{v_j \to r_k}(\tilde{\mathbf{x}}_j) = P(\tilde{\mathbf{x}}_j) normalize\left(\prod_{\delta \in \varepsilon_j} \left(I^{i-1}_{r_\delta \to v_j}(\tilde{\mathbf{x}}_j)\right)\right)$
      End for
    End if
    For $\mathbf{x}_u \in \bar{\mathbf{X}}$ do
          $\hat{\mathbf{x}}^{I_T}_u = normalize\left(\prod_{\delta \in \varepsilon_j} \left(I^{I_T}_{r_\delta \to v_s}(\tilde{\mathbf{x}}_u)\right)\right) \in \check{\mathbf{X}}$
    End for
```

Detailed procedure of IPM-MPA is described in Algorithm 2. Algorithm 2 depicts the difference between IPM-MPA and PM-MPA. In IPM-MPA, the iterated message

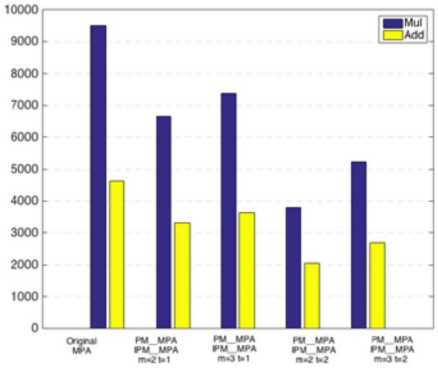

Fig. 3. Comparison of computation of various algorithms.

in *m*th iteration is taken as a credential of reliability and *m* reliable codewords will be determined based on it. However, in PM-MPA, we can see in [35] that the determined codewords are selected randomly, which obviously means that PM-MPA does not utilize the message efficiently.

IV. COMPUTATIONAL ANALYSIS

This section presents an analysis of computation of the above three detection method. The three type algorithms only differ in the process of iteration. So the multiplications and additions of iteration procedures are formulated.

A. Original MPA

$$\mathrm{Mul}_{\mathrm{MPA}} = \Big((d_k-1)M^{d_k}d_vJ + (d_v-1)Md_kK\Big)I_T \tag{19}$$

$$\mathrm{Add}_{\mathrm{MPA}} = M^{d_f}d_vJI_T. \tag{20}$$

B. PM-MPA and IPM-MPA

The universal equations that describe the computations of PM-MPA are too complicated to formulate. Here, we give the computation under the condition $t = 1$ and a particular circumstance when $t = 2$

$$\begin{aligned}\mathrm{Mul}_{t=1} = {}&\Big((d_k-1)M^{d_k}d_vJ + (d_v-1)Md_kK\Big)(I_T-m)\\ &+\Big((d_k-1)M^{d_k}(K-d_v)d_k + (d_k-2)M^{d_k-1}\\ &\quad d_v(d_k-1) + (d_v-1)Md_v(J-t)\Big)m\end{aligned} \tag{21}$$

$$\begin{aligned}\mathrm{Add}_{t=1} = {}&M^{d_k}d_vJ(I_T-m)\\ &+\Big(M^{d_k}(K-d_v)d_k + M^{d_k-1}\Big)d_v(d_k-1)\,)m.\end{aligned} \tag{22}$$

To simplify the computation, we suppose that the chosen two users do not connect the same recourse layers.

So the formula can be described as follows:

$$\begin{aligned}\mathrm{Mul}_{t=2} = {}&\Big((d_k-1)M^{d_k}d_vJ + (d_v-1)Md_kK\Big)(I_T-m)\\ &+ (d_k-1)M^{d_k}(K-2d_v)d_k + (d_k-2)M^{d_k-1}\\ &2d_v(d_k-1) + (d_v-1)Md_v(J-t))m\end{aligned} \tag{23}$$

$$\begin{aligned}\mathrm{Add}_{t=2} = {}&M^{d_k}d_vJ(I_T-m)\\ &+\Big(M^{d_k}(K-2d_v)d_k + \ 2M^{d_k-1}\Big)d_v(d_k-1)\,)m.\end{aligned} \tag{24}$$

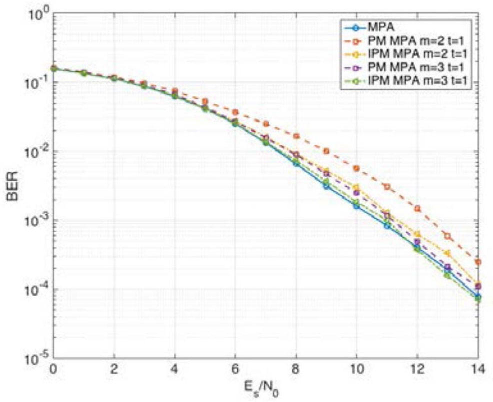

Fig. 4. BER comparison with $t = 1$.

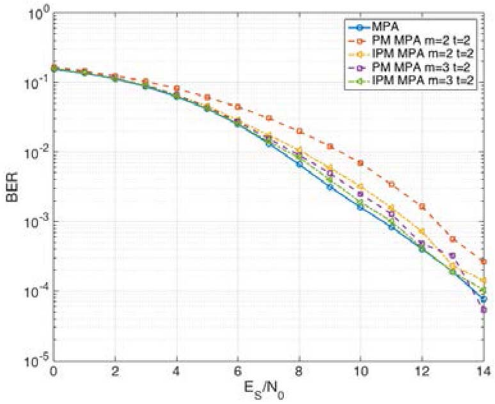

Fig. 5. BER comparison with $t = 2$.

Compared with PM-MPA, the computation of IPM-PMA only differs in the *m*ths iteration, which could not count for essential computation increase, so it is reasonable to approximate the computation of IPM-MPA to that of PM-MPA.

Fig. 3 depicts the computational complexity of MPA, PM-MPA, and IPM-MPA with different parameters. Parameters are setting with $J = 6$, $K = 4$, $d_v = 2$, $d_k = 3$, $M = 4$, and $I_T = 6$. It is clear to conclude that with the increase of m, and decrease of t, PM-MPA and IPM-MPA can obtain lower computations. The computation can be reduced by more than 50% when $m = 2$ and $t = 2$.

V. SIMULATION RESULT

This part will compare MPA, PM-MPA, and IPM-MPA in terms of BER and convergence. The parameters are assigned as $J = 6$, $d_v = 2$, $d_k = 3$, $M = 4$, and $I_T = 6$.

In the transition end, the uncoded bits are mapped to a 4-D codeword with cardinality $M = 4$, the indicator matrix is depicted as follows:

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

The codebook in this paper refers to [36], which is given in the equations at the bottom of the next page.

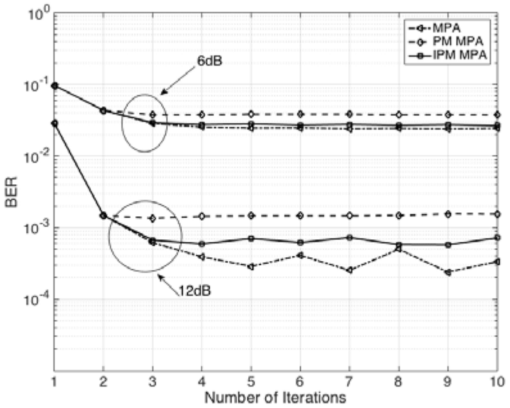

Fig. 6. Convergence performance when $m = 2$ and $t = 1$.

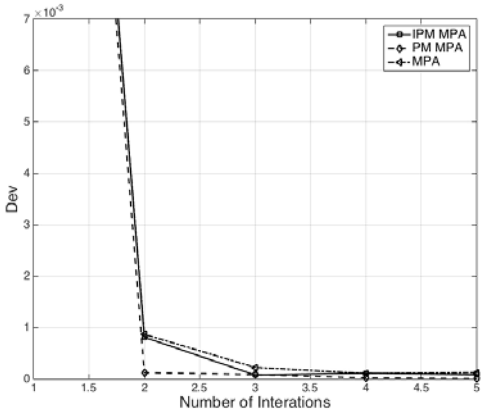

Fig. 7. Dev of three algorithms with $m = 2$, $t = 1$, and $E_S/N_0 = 12$ dB.

A. BER

The BERs under the conditions that $t = 1$ and $t = 2$, are described in Figs. 4 and 5, respectively. Some conclusions can be drawn: 1) the BER of IPM-MPA, compared with PM-MPA improved obviously when $m = 2$ and 2) the BER of IPM-MPA is closer to the BER of MPA when $m = 2$. Besides, Fig. 4 shows that the BER performance of IPM-MPA with $m = 2$ and $t = 1$ is similar to the BER performance of PM-MPA with $m = 3$ and $t = 1$, which shows that IPM-MPA only needs less computation to reach the same performance with PM-MPA.

B. Convergence Analysis

Fig. 6 gives the simulation results of the convergence of three detection algorithms with $m = 2$ and $t = 1$ under the E_s/N_0 6 and 12 dB. In this paper, we introduce a new criterion, Dev, to describe the convergence performance. Dev of ith iteration can be formulated as

$$\mathrm{Dev}(i) = abs(\mathrm{BER}_i - \mathrm{BER}_{i+1}) \tag{25}$$

where BER_i is the BER when i iterations are conduct. Fig. 7 gives the Dev when $m = 2$, $t = 1$, $E_S/N_0 = 12$ dB. Though converging faster compared with two other algorithms based on Fig. 7, the BER of PM-MPA keeps a relative high level after three iterations, which indicates that PM-MPA cannot utilize the received signal efficiently before convergence. IPM-MPA convergences faster with respect to original MPA while updating the message more efficiently than PM-MPA to obtain reliable codewords.

$$\mathrm{User\_1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.1815 - 0.1318i & -0.6351 - 0.4615i & 0.6351 + 0.4615i & 0.1815 + 0.1318i \\ 0 & 0 & 0 & 0 \\ 0.7851 & -0.2243 & 0.2243 & -07851 \end{bmatrix}$$

$$\mathrm{User\_2} = \begin{bmatrix} 0.7851 & -0.2243 & 0.2243 & -0.7851 \\ 0 & 0 & 0 & 0 \\ -0.1815 - 0.1318i & -0.6351 - 0.4615i & 0.6351 + 0.4615i & 0.1815 + 0.1318i \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathrm{User\_3} = \begin{bmatrix} -0.6351 + 0.4615 & 0.1815 - 0.1318i & -0.1815 + 0.1318i & 0.6351 - 0.4615i \\ 0.1392 - 0.1759i & 0.4873 - 0.6156i & -0.4873 - 0.6156i & -0.1392 + 0.1759i \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathrm{User\_4} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.7851 & -0.2243 & 0.2243 & -0.7851 \\ -0.0055 - 0.2242i & -0.0193 - 0.7848i & 0.0193 + 0.7848i & 0.0055 + 0.2242i \end{bmatrix}$$

$$\mathrm{User\_5} = \begin{bmatrix} -0.0055 - 0.2242i & -0.0193 - 0.7848i & 0.0193 + 0.7848i & 0.0055 + 0.2242i \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -0.6351 + 0.4615i & 0.1815 - 0.1318i & -0.1815 + 01318i & 0.6351 - 0.4615i \end{bmatrix}$$

$$\mathrm{User\_6} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0.7851 & -0.2243 & 0.2243 & -0.7851 \\ 0.1392 - 0.1759i & 0.4873 - 0.6156i & -0.4873 + 0.6156i & -0.1392 + 0.1759i \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

VI. CONCLUSION

In this paper, an IPM-MPA detection scheme for the fixed up-link SCMA system is proposed. The detector aims to reduce the computation of the MPA algorithm while keeping the BER at a sustainable level. In the first m iterations, the message pass through the user layers and resource layers with the roles of original MPA. In the mth iteration, after exchanging message, we define a parameter $w$to measure the reliability of codewords of all the user layers and choose t user layers to determine their codewords. In the last $I_T - m$ iterations, the undetermined users will go on exchanging the message but with the determined codewords of t users. Some features are concluded as follows.

1) The computation of IPM-MPA is similar as PM-MPA, which is less than that of MPA.
2) The BER of IPM-MPA, compared with PM-MPA, can be improved obviously.
3) IPM-MPA updates the message more efficiently than PM-MPA to obtain reliable codewords.

REFERENCES

[1] S. D. T. Kelly, N. K. Suryadevara, and S. C. Mukhopadhyay, "Towards the implementation of IoT for environmental condition monitoring in homes," *IEEE Sensors J.*, vol. 13, no. 10, pp. 3846–3853, Oct. 2013.

[2] J. A. Stankovic, "Research directions for the Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 3–9, Feb. 2014.

[3] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[4] M. A. Razzaque, M. Milojevic-Jevric, A. Palade, and S. Clarke, "Middleware for Internet of Things: A survey," *IEEE Internet Things J.*, vol. 3, no. 1, pp. 70–95, Feb. 2016.

[5] S. Chen, H. Xu, D. Liu, B. Hu, and H. Wang, "A vision of IoT: Applications, challenges, and opportunities with China perspective," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 349–359, Aug. 2014.

[6] L. Catarinucci *et al.*, "An IoT-aware architecture for smart healthcare systems," *IEEE Internet Things J.*, vol. 2, no. 6, pp. 515–526, Dec. 2015.

[7] M. Jia, X. Gu, Q. Guo, W. Xiang, and N. Zhang, "Broadband hybrid satellite-terrestrial communication systems based on cognitive radio toward 5G," *IEEE Wireless Commun.*, vol. 23, no. 6, pp. 96–106, Dec. 2016.

[8] I. Bisio, A. Delfino, F. Lavagetto, and A. Sciarrone, "Enabling IoT for in-home rehabilitation: Accelerometer signals classification methods for activity and movement recognition," *IEEE Internet Things J.*, vol. 4, no. 1, pp. 135–146, Feb. 2017.

[9] M. Jia, L. Wang, Z. Yin, Q. Guo, and X. Gu, "A novel spread slotted ALOHA based on cognitive radio for satellite communications system," *EURASIP J. Wireless Commun. Netw.*, vol. 1, no. 50, pp. 1–9, 2016.

[10] S. Elbouanani, M. A. E. Kiram, and O. Achbarou, "Introduction to the Internet of Things security: Standardization and research challenges," in *Proc. Int. Conf. Inf. Assurance Security*, Marrakesh, Morocco, 2015, pp. 32–37.

[11] Y. Li, T. Nakasone, K. Ohta, and K. Sakiyama, "Privacy-mode switching: Toward flexible privacy protection for RFID tags in Internet of Things," in *Proc. IEEE Consum. Commun. Netw. Conf.*, Las Vegas, NV, USA, 2014, pp. 519–520.

[12] L. Xiong, "Harnessing personal data from Internet of Things: Privacy enhancing dynamic information monitoring," in *Proc. IEEE Int. Conf. Collaboration Technol. Syst.*, Atlanta, GA, USA, 2015, p. 37.

[13] Y. Saito *et al.*, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Proc. IEEE Veh. Technol. Conf.*, Dresden, Germany, 2013, pp. 1–5.

[14] Z. Yuan, G. Yu, and W. Li, "Multi-user shared access for 5G wireless networks," *Telecommun. Netw. Tech.*, vol. 5, no. 5, pp. 28–30, 2015.

[15] L. Dai *et al.*, "Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015.

[16] X. Dai *et al.*, "Successive interference cancelation amenable multiple access (SAMA) for future wireless communications," in *Proc. IEEE ICCS*, 2014, pp. 1–5.

[17] H. Nikopour and H. Baligh, "Sparse code multiple access," in *Proc. IEEE 24th Annu. Int. Symp. Pers. Indoor Mobile Radio Commun.*, London, U.K., 2013, pp. 332–336.

[18] D. Guo and C.-C. Wang, "Multiuser detection of sparsely spread CDMA," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 3, pp. 421–431, Apr. 2008.

[19] M. Taherzadeh, H. Nikopour, A. Bayesteh, and H. Baligh, "SCMA codebook design," in *Proc. IEEE Veh. Technol. Conf.*, Vancouver, BC, Canada, 2014, pp. 1–5.

[20] Y. Du, B. Dong, Z. Chen, P. Gao, and J. Fang, "Joint sparse graph-detector design for downlink MIMO-SCMA systems," *IEEE Wireless Commun. Lett.*, vol. 6, no. 1, pp. 14–17, Feb. 2017.

[21] Z. Zhang, K. Han, J. Hu, and J. Chen, "Joint detection and decoding schemes for turbo coded SCMA systems," in *Proc. IEEE Globecom Workshops*, Washington, DC, USA, 2016, pp. 1–6.

[22] Y. Dong, L. Qiu, and X. Liang, "Energy efficiency maximization for uplink SCMA system using CCPSO," in *Proc. IEEE Globecom Workshops*, Washington, DC, USA, 2016, pp. 1–5.

[23] B. Xiao *et al.*, "Iterative detection and decoding for SCMA systems with LDPC codes," in *Proc. IEEE Int. Conf. Wireless Commun. Signal Process.*, Nanjing, China, 2015, pp. 1–5.

[24] C. Sun *et al.*, "System-level performance estimation of SCMA," in *Proc. IEEE Int. Conf. Commun. Syst. (ICCS)*, Shenzhen, China, 2016, pp. 14–16.

[25] L. Yu, X. Lei, P. Fan, and D. Chen, "An optimized design of SCMA codebook based on star-QAM signaling constellations," in *Proc. IEEE Int. Conf. Wireless Commun. Signal Process.*, Nanjing, China, 2015, pp. 1–5.

[26] D. Cai, P. Fan, X. Lei, Y. Liu, and D. Chen, "Multi-dimensional SCMA codebook design based on constellation rotation and interleaving," in *Proc. IEEE Veh. Technol. Conf.*, Nanjing, China, 2016, pp. 1–5.

[27] J. Bao, Z. Ma, M. A. Mahamadu, Z. Zhu, and D. Chem, "Spherical codes for SCMA codebook," in *Proc. IEEE Veh. Technol. Conf.*, Nanjing, China, 2016, pp. 1–5.

[28] R. Hoshyar, F. P. Wathan, and R. Tafazolli, "Novel low-density signature for synchronous CDMA systems over AWGN channel," *IEEE Trans. Signal Process.*, vol. 56, no. 4, pp. 1616–1626, Apr. 2008.

[29] J. V. D. Beek and B. M. Popovic, "Multiple access with low-density signatures," in *Proc. Global Telecommun. Conf. (GLOBECOM)*, Honolulu, HI, USA, 2009, pp. 1–6.

[30] R. Hoshyar, R. Razavi, and M. Al-Imari, "LDS-OFDM an efficient multiple access technique," in *Proc. Veh. Technol. Conf. (VTC-Spring)*, Taipei, Taiwan, 2010, pp. 1–5.

[31] F. R. Kschischang, B. J. Frey, and H.-A. Loeliger, "Factor graphs and the sum-product algorithm," *IEEE Trans. Inf. Theory*, vol. 47, no. 2, pp. 498–519, Feb. 2001.

[32] J. Liu, G. Wu, S. Li, and O. Tirkkonen, "On fixed-point implementation of Log-MPA for SCMA signals," *IEEE Wireless Commun. Lett.*, vol. 5, no. 3, pp. 324–327, Jun. 2016.

[33] K. Xiao, B. Xiao, S. Zhang, Z. Chen, and B. Xia, "Simplified multiuser detection for SCMA with sum-product algorithm," in *Proc. Int. Conf. Wireless Commun. Signal Process.*, Nanjing, China, 2015, pp. 1–5.

[34] A. Bayesteh, H. Nikopour, M. Taherzadeh, H. Baligh, and J. Ma, "Low complexity techniques for SCMA detection," in *Proc. IEEE Globecom Workshops*, San Diego, CA, USA, 2015, pp. 1–6.

[35] H. Mu, Z. Ma, M. Alhaji, P. Fan, and D. Chen, "A fixed low complexity message pass algorithm detector for up-link SCMA system," *IEEE Wireless Commun. Lett.*, vol. 4, no. 6, pp. 585–588, Dec. 2015.

[36] V. P. Klimentyev and A. B. Sergienko, "Detection of SCMA signal with channel estimation error," in *Proc. Conf. Open Innov. Assoc. Seminar Inf. Security Protect. Inf. Technol.*, Yaroslavl, Russia, 2016, pp. 106–112.

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