A Flexible Iterative Log-MPA Detector for Uplink SCMA Systems

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Abstract. The development of the communications industry is changing with each passing day. At present, 5G research work is in full swing. In the SCMA (Sparse Code Multiple Access) system, this paper proposes a flexible iterative logarithmic domain message passing algorithm(FI-Log-MPA) aiming at the traditional logarithmic domain message passing algorithm to magnify the number of iterations in the codeword decision process, which results in a waste of running resources. The algorithm determines whether to perform subsequent iterations by adding a link to determine the convergence rate of the codeword during the update process of the variable node. If the codeword convergence rate is lower than a preset threshold, the iteration is stopped, otherwise the iteration is continued. Based on the principle of the optimization algorithm, we built a SCMA and NOMA (Non-Orthogonal Multiple Access) simulation platform to verify that the algorithm can effectively reduce the number of iterations. Although there is a loss in bit error rate and throughput performance, it remains at the same order of magnitude. In general, the complexity is reduced, and the decoding performance is optimized.

Keywords: 5G · Message passing algorithm · Sparse code division multiple access · Power domain non-orthogonal multiple access

1 Introduction

The innovation of each generation of mobile communication systems is accompanied by the evolution of communication access technologies. However, whether it is time or frequency division multiple access, or code division multiple access,

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it belongs to orthogonal multiple access technology, which is accessed through orthogonal resources [1]. However, orthogonal multiple access technology has some drawbacks. Not only the peak rate is far from being able to meet the requirements, but also the number of access users is still severely limited, and overload cannot be achieved. In order to achieve the high speed, high coverage and low latency requirements of 5G, it is urgent to introduce a new multiple access technology.

It is worth noting that the potential wireless access technology for 5G has flourished. This article mainly introduces two new wireless access technologies, SCMA and NOMA. In the SCMA system, the MPA (Message Passing Algorithm) is a key issue. In response to this problem, the industry recognizes two major challenges:

1. Number of iterations. In the current MPA algorithm, the number of iterations is generally a fixed value. That is, regardless of whether the decoded sequence is sufficiently convergent, a certain number of iterations must be completed, which will result in a waste of a large amount of running resources. Therefore, it is urgent to propose a new scheme to achieve an iterative number of effective times.
2. Iterative process. Since each iteration needs to complete the update of the variable node and the function node, the calculation process is too cumbersome and even contains some repeated calculations, so it needs to be simplified.

1.1 Related Works

In 2014, NTT DoCoMo, Japan's largest communications operator, proposed Non-Orthogonal Multiple Access (NOMA) technology, which significantly improves spectrum utilization. It implements power domain or code domain multiplexing at the transmitting end, and the receiving end uses Serial Interference Cancellation (SIC) demodulation. A number of documents have made in-depth analysis of the applicability of the most relevant LTE (Long Term Evolution) features, indicating that NOMA can be easily combined with SU-MIMO (Single User MIMO) and MU-MIMO (Multi-user MIMO). Effective benefits of high throughput. Further results can be found in the literature [2] and [3]. In summary, NOMA has good applicability and superiority for the Internet of Things. In 2015, at the Mobile World Congress (MWC), Huawei released the Sparse Code Division Multiple Access (SCMA) technology, which is one of the new air interface technologies for 5G. By adding the code domain dimension at the transmitting end, the receiver demodulates with a specific algorithm [4]. In the same year, Huawei and NTT DoCoMo cooperated to test the new 5G air interface technology. The results show that SCMA technology has excellent throughput performance. For the decoding algorithm MPA used by its receiving end, many articles have been studied in depth. Literature [5] proposes a SCMA low complexity decoding algorithm based on variable node serial strategy that can be accepted and transmitted simultaneously. Literature [6] also proposes a grouping threshold MPA algorithm based on serial update. Literature [7] proposed a SCMA multi-user detection system based on weighted message transfer.

Literature [8] proposed a SCMA multi-user detection algorithm based on the serial-to-parallel combination strategy. Literature [9] combines the literature [8] and the log-domain message passing algorithm, which not only has fast convergence speed, low algorithm complexity, but also can approach the optimal detector. The above is some improvement of the MPA algorithm. In general, both NOMA and SCMA are non-orthogonal technologies. Although the interference between users becomes larger, it can achieve overload and significantly improve the throughput of the system [10].

Motivation and Contribution. Since the solution of the above documents only considers the simplification of the iterative process, the optimization problem of the iteration number is not solved. However, in the process of codeword decision, the traditional logarithmic domain message passing algorithm uses a fixed number of fixed iterations, which will result in waste of running resources. Therefore, for the number of iterations, we propose a flexible iterative logarithmic domain messaging algorithm (Flexible Iterative-Log-MPA, FI-Log-MPA). Specifically, our contribution is to control the number of effective iterations while using the log-domain messaging algorithm to simplify the computational process. The optimization scheme is verified on the established SCMA platform, which shows that the scheme can achieve performance optimization.

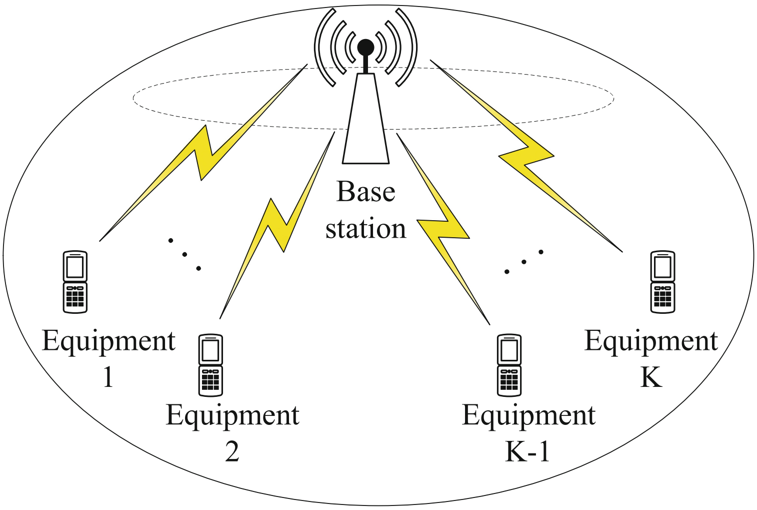

Fig. 1. Uplink SCMA system.

2 System Model

The Fig. 1 below shows the uplink SCMA system model. It is divided into three aspects: sender, receiver and uplink and downlink [11]. First we introduce

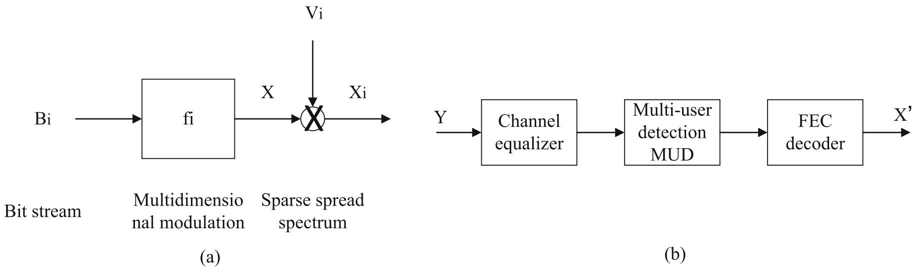

Fig. 2. (a) Basic model of the sender; (b) Receiver basic model.

the model of the sender. Its working principle generally includes the following three steps: error correction coding, multi-dimensional modulation and sparse spread spectrum [12]. The process of generating the SCMA codeword is shown in Fig. 2(a). The expression of the i-th bit multiplexed user SCMA codeword of the i-th layer is:

$$X_i = V_i f_i(B_i) \tag{1}$$

wherein, V_i represents a mapping matrix for spreading, and f_i represents a modulation function for designing a multi-dimensional constellation, and B_i represents information processed by error correction encoding. Next, we introduce the model of the receiver. At the receiving end, three steps of information processing are required: first, the received signal is passed through a channel equalizer, then multi-user detection (MUD) is performed, and finally, forward error correction (FEC) decoding is performed. The basic model of the receiving end is shown in Fig. 2(b). Finally, the system model of the uplink and downlink is introduced. As shown in Fig. 3(a) and (b). The channel matrix H_i and the codeword X_i are independent of each other. J is the number of users, k is the antenna, and N is the noise. When there are multiple antennas at the receiving end, the signal at the receiving end is:

$$Y^k = diag(H_i) \sum_{i=1}^{J} X_i^k + N^k \tag{2}$$

3 Proposed Detector

The number of iterations for the decoding algorithm in the SCMA system is fixed. We propose a flexible iterative log domain message passing algorithm (FI-Log-MPA). The scheme determines whether the decoding result after the iteration can achieve a sufficiently low error rate by adding a link determining the probability convergence rate of the codeword in each iteration process.

3.1 FI-Log-MPA

Considering that the current research on MPA algorithms mainly focuses on the optimization in each iteration process, the decision of each codeword needs to be

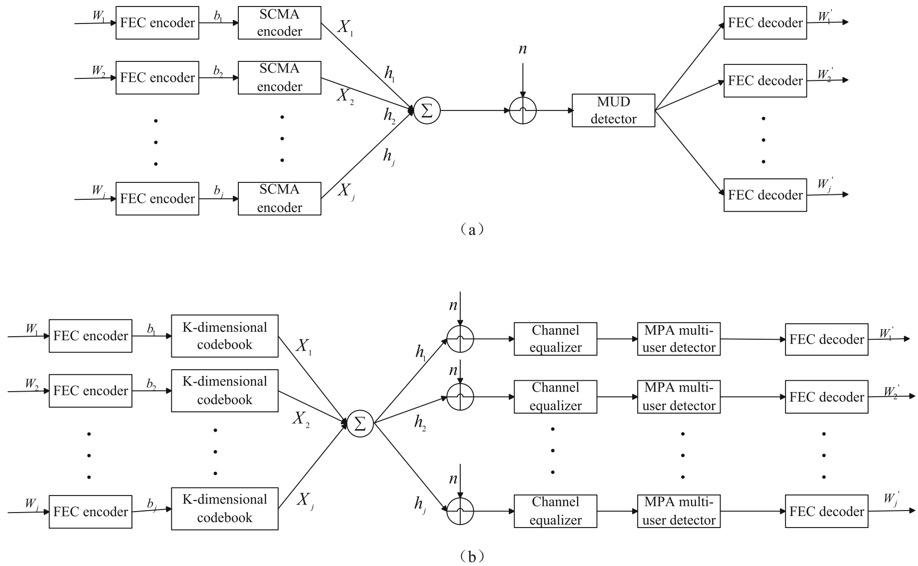

Fig. 3. (a) Basic model of the SCMA system uplink; (b) Basic model of the downlink of the SCMA system.

repeated a fixed number of iterations. In order to simplify the iterative process, a log-domain messaging algorithm Log-MPA capable of converting multiplication into addition is selected. For the number of iterations, since the codeword convergence of different time slots is different, the number of iterations required is different. Iterative redundancy is caused by a fixed number of iterations. In the paper [13], a message passing algorithm (Delete Redundant Iterations-MPA, DRI-MPA) that can remove redundant iterations is proposed for this problem. On this basis, we achieve similar results by optimizing the message passing algorithm in the log domain. The principle of the algorithm is to determine whether to perform subsequent iterative processes by supervising the convergence rate of each codeword probability, so as to ensure that the complexity can be reduced under the premise of achieving specific performance. The convergence rate of the codeword probability is defined as the ratio of the difference between the current iteration probability and the previous iteration probability to the previous iteration probability. The specific formula is as follows:

$$w^t(k) = \left|\frac{Q_{m,k}^t - Q_{m,k}^{t-1}}{Q_{m,k}^{t-1}}\right| \tag{3}$$

wherein w_k^t represents the codeword probability convergence rate of the k-th user in the t-th iteration process. m represents the number of codewords in each codebook. Q represents the probability of iteration, the specific formula is as follows:

$$Q_{m,k}^0 = 1/M \tag{4}$$

$$Q_{m,k}^{t} = \log(1/M) + Igv_{m,k}^{n_1} + Igv_{m,k}^{n_2} \tag{5}$$

where M represents the number of codewords in each codebook, and $Igv_{m,k}^{n_1}$ and $Igv_{m,k}^{n_2}$ represent the function node update values corresponding to the user's two non-zero value sequence numbers, respectively. The function node update formula will be described in detail below. The algorithm compares the convergence rate of the codeword with the threshold set in advance when each iteration process is completed. If

$$w^{t}(k) \geq h_d \tag{6}$$

we continue the next iteration. h_d represents the threshold.

3.2 FI-Log-MPA

The model of the flexible iterative log domain message passing algorithm is shown in Fig. 4.

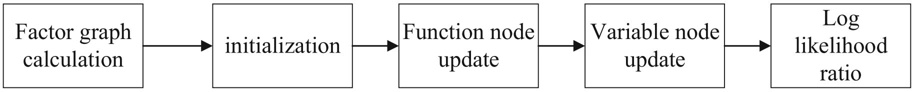

Fig. 4. FI-Log-MPA decoding flow chart.

In the first step, the factor graph calculation is completed according to the given codebook. The resulting factor matrix is as follows:

$$F = \begin{bmatrix} 0\,1\,1\,0\,1\,0 \\ 1\,0\,1\,0\,0\,1 \\ 0\,1\,0\,1\,0\,1 \\ 1\,0\,0\,1\,1\,0 \end{bmatrix} \tag{7}$$

According to the factor matrix, the mapping matrix corresponding to each layer user j is further solved. The solution process is: taking the j-th column of the factor matrix, and placing the corresponding values on the four subcarriers into the diagonal position of one diagonal matrix in turn, and the remaining elements are 0. After that, the all-zero column in the diagonal matrix is deleted, and the mapping matrix corresponding to user j is obtained:

$$V_1 = \begin{bmatrix} 0\,0 \\ 1\,0 \\ 0\,0 \\ 0\,1 \end{bmatrix}, V_2 = \begin{bmatrix} 1\,0 \\ 0\,0 \\ 0\,1 \\ 0\,0 \end{bmatrix}, V_3 = \begin{bmatrix} 1\,0 \\ 0\,1 \\ 0\,0 \\ 0\,0 \end{bmatrix}, V_4 = \begin{bmatrix} 0\,0 \\ 0\,0 \\ 1\,0 \\ 0\,1 \end{bmatrix}, V_5 = \begin{bmatrix} 1\,0 \\ 0\,0 \\ 0\,0 \\ 0\,1 \end{bmatrix}, V_6 = \begin{bmatrix} 0\,0 \\ 1\,0 \\ 0\,1 \\ 0\,0 \end{bmatrix} \tag{8}$$

The second step is to initialize the variable node, the function node, the iteration probability Q and the number of iterations. The third step is to complete the function node update during an iteration. The fourth step is to complete the variable node update in an iterative process, that is, to update the non-zero location information of all users. In this process, the calculated codeword convergence rate is compared with the threshold set in the main program. Finally, the maximum log likelihood ratio is calculated according to the Q value, that is, the iteration probability, and the bit error rate is obtained. The error rate calculation formula is as follows:

$$BER = \frac{N_{\mathrm{err}}}{N_{bits}} \tag{9}$$

Among them, N_{err} represents the total number of errors, and N_{bits} represents the total number of bits. The simulation of the designed new decoding algorithm is based on the SCMA platform. The specific steps are as follows: **Step 1:** Select the appropriate codebook. The codebook selected here is a matrix. The first dimension of the codebook represents the number of orthogonal resources, the second dimension represents the number of codewords in each codebook, and the third dimension represents the number of users. **Step 2:** Complete the parameter initialization settings, such as the maximum number of bits, the maximum number of errors, and so on. **Step 3:** The rationality of the parameters, here is divided into two parts. One is to determine whether the number of bits is smaller than the maximum number of bits under a certain SNR; the second is to determine whether the number of errors is less than the maximum number of errors under the SNR. If they are all satisfied, follow the process. **Step 4:** The transmission sequence is randomly generated. **Step 5:** The sequence obtained in the previous step is propagated through the SCMA joint coding and fading channel to obtain the fading SCMA signal. **Step 6:** The signal is added with a Gaussian white noise corresponding to a specific signal to noise ratio. **Step 7:** The receiver uses a flexible iterative log-domain messaging algorithm FI-Log-MPA to decode the SCMA signal and output a Maximum Log Likelihood Ratio (LLR). Its calculation formula is as follows:

$$LLR_{j,k} = \log(\sum\nolimits_{b_{k,i}=0} Q^{t}_{m,k} / \sum\nolimits_{b_{k,i}=0} Q^{t}_{m,k}) \tag{10}$$

where $LLR_{j,k}$ represents the maximum log likelihood ratio of the j-th bit of the kth user, and $b_{k,i} = 0$ represents the codeword of the k-th user bit being zero. **Step 8:** The decoded sequence is XORed with the original sequence, and the error rate is calculated and obtained. Its throughput calculation formula is:

$$Throughput_{SCMA} = (1 - BER_{SCMA}) \cdot N_{bits} \cdot K_{SCMA} \tag{11}$$

where BER_{SCMA} represents the average error rate of users of the sparse code division multiple access system, and N_{bits} represents the number of binary bits carried by each user codeword. In the system, it is set to 4, and K_{SCMA} represents the number of accessible users of the system, which is set to 6.

3.3 Comparison Between FI-Log-MPA and Log-MPA

The log-domain messaging algorithm Log-MPA is an optimization scheme proposed by the traditional messaging algorithm MPA. The specific principle is that when the function node is updated, a method of evaluating the logarithm is adopted in the update process of different codewords in each codebook. The formula can be expressed as follows:

$$Igv = \sum_{i=1}^{M \times M} \log(e^{xx_i - \max(xx_i)}) + \max(xx_i) \quad (12)$$

xx_i represents the results obtained in the pre-link of the function update. Compared with the Log-MPA algorithm, FI-Log-MPA differs mainly in variable node update. Because the variable node is updated, the convergence rate of the codeword in each iteration is also calculated. Each iteration requires increasing the number of multiplications and comparison algorithms.

4 Simulation Results

The simulation parameter settings are shown in Table 1. Based on the SCMA system, this paper completes the performance comparison between two decoding algorithms Log-MPA and FI-Log-MPA. Figure 5(a) and (b) show the six user error rates for the two decoding algorithms, respectively (Table 2).

Table 1. Parameter initial value setting table.

Parameter	Set value
Number of orthogonal resources	4
User number	6
Number of codewords in each codebook	4
Number of frames	10,000
Eb/N0	020
Maximum number of bits	10,000,000
Maximum number of errors	100
Maximum number of iterations	10
Threshold	0

Table 2. Average bit error rate (20 dB).

Log-MPA	FI-Log-MPA
0.5×10^{-4}	0.8×10^{-4}

In Fig. 5(a), the error rates of the six users approach each other. This is because the graphs drawn are semi-logarithmic graphs. In fact, their true values

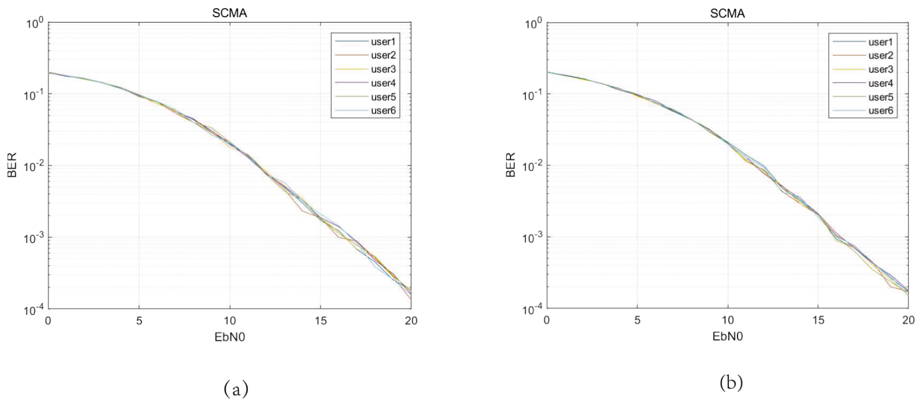

Fig. 5. (a) Bit error rate of Log-MPA; (b) Bit error rate of FI-Log-MPA.

differ greatly, but they are in the same order of magnitude, so the curves drawn are closer. Moreover, under the algorithm, as the signal-to-noise ratio increases, the bit error rate reaches an order of magnitude. This has great advantages in the application of actual systems. In Fig. 5(b), the bit error rate trend of the six users is roughly the same as that of Fig. 5(a), and it has also reached the order of magnitude, but slightly increased. However, the performance is somewhat lower than the original. In addition, in the process of improving the signal-to-noise ratio, the difference of bit error rate between the six users is larger than that of the unoptimized algorithm, but the effect is not significant.

Figure 6(a) and (b) show the average user error rate and throughput for the two algorithms, respectively. The average bit error rate and user throughput performance degradation percentage of the two algorithms are shown in Table 3.

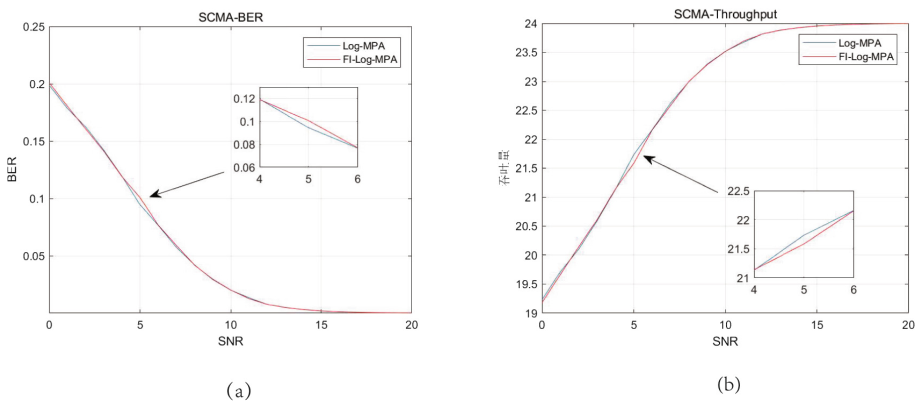

Fig. 6. (a) User average error rate of Log-MPA and FI-Log-MPA; (b) User throughput of Log-MPA and FI-Log-MPA.

Table 3. Percentage of average bit error rate and user throughput performance degradation (5 dB).

Average bit error rate	User throughput
8.69%	1.61%

Observing Fig. 6, we can find that the average error rate of the two algorithms is similar, but the error rate of the optimization algorithm is higher than the original algorithm in a certain interval, that is, the performance of the error rate after optimization is deteriorated. In addition, from Eq. (11), the throughput is inversely proportional to the bit error rate, so the throughput is slightly lower than the throughput of the original algorithm in some intervals. That is to say, the throughput performance is slightly worse after optimization, but the difference is small. In summary, after using the optimization algorithm, although the bit error rate and throughput performance have a certain loss, the difference is small and still can reach the same order of magnitude. Most importantly, after comparison, the complexity was found to be about 1/3 lower than Log-MPA. Therefore, the algorithm can be considered to achieve a balance between Bit Error Ratio (BER) and complexity.

5 Conclusion

In this paper, we propose a flexible iterative logarithmic domain message passing algorithm for the decoding algorithm MPA of SCMA system, and complete the construction and performance analysis of SCMA and NOMA platform, and verify the optimization algorithm. The results show that the complexity is reduced by about 1/3 compared to Log-MPA, and the performance is optimized. In the future, we can consider designing a more reasonable codeword probability convergence rate to achieve lower complexity.

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