An Advanced Criterion of Permutation Set for SCMA

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Abstract—For Sparse Code Multiple Access (SCMA) with the dimension distance-based codebook design, the convergence reliability of some detected layers in their corresponding decision processes was unsatisfactory at the Message Passing Algorithm (MPA) receiver. Driven by this problem, in the dimension distance-based codebook design of SCMA, an advanced criterion of permutation set is proposed to increase the variance of the set of absolute differences between the sums of distances between interfering dimensions of transmitted codewords multiplexed on all resource nodes. Simulation results show that the Bit Error Rate (BER) performance of the proposed criterion outperforms that of traditional criterion under the same spectral efficiency.

Index Terms—Codebook, MPA, SCMA, permutation set

I. Introduction

Higher spectral efficiency is one of main requirements in future 5G system [1]. Compared with 4G system, future 5G system improves spectral efficiency by 5~15 times [1]. Driven by this requirement, non-orthogonal multiple access, such as sparse code multiple access (SCMA) [2], is proposed. SCMA is a multi-dimension codebook-based non-orthogonal spreading technique, and the structure of SCMA is similar to low-density signature (LDS) [3].

For SCMA with the codebook design in [2] [4]-[6], the initial information of message passing algorithm (MPA) receiver was susceptible to noise and multipath fading, and the criterion of permutation set failed to increase power differences between transmitted codewords [5], [7]. Driven by these problems, a dimension distance-based codebook design was proposed for SCMA [7]. In the following, sparse code multiple access advanced (SCMAA) is short for SCMA with the dimension distance-based codebook design in [7]. Under the same minimum intra-partition distance[1], SCMAA increased the sum of distances between interfering dimensions of transmitted codewords multiplexed on each resource node, which could improve the quality of initial information of MPA receiver on its corresponding resource node compared with traditional SCMA[2]. However, the criterion of permutation set of SCMAA did not increase the variance of the set of absolute differences between the sums of distances between interfering dimensions of transmitted codewords multiplexed on all resource nodes, which would attenuate the convergence reliability of some detected layers in their corresponding decision processes at the MPA receiver.

Driven by these problems, this paper proposes an advanced criterion of permutation set for SCMAA. Compared with the traditional criterion of permutation set [7], the proposed criterion increases the variance of the set of absolute differences between the sums of distances between interfering dimensions of transmitted codewords multiplexed on all resource nodes.

The system model of SCMAA is presented in Section II. The proposed criterion of permutation set is presented in Section III. The performance analysis of the proposed criterion of permutation set is offered in Section IV. Finally, in Section V, the BER performance of SCMAA with the proposed criterion is compared with that of SCMAA with the traditional criterion according to simulations.

II. System Model

In SCMAA, there are J transmitted layers multiplexed on K resource nodes. Each layer[3] has its corresponding codebook. A codebook contains a plurality of K-dimension codewords. For layer j, a K-dimension codeword is generated by multiplying the binary mapping matrix V_j by a point from the complex N_j-dimension constellation C_j, and the size of C_j is M_j. V_j includes $K-N_j$ all-zero rows, and the rest can be expressed as identity matrix I_{N_j} after removing the all-zero rows from V_j. Hence each codeword of layer j contains $K-N_j$ zero elements and N_j nonzero elements. For SCMAA, the constellation length and size are the same in J transmitted layers, i.e. $M_j=M$, $N_j=N$, $C_j=C, \forall j=1,...,J$. If $N=2, K=4$ and $J=6$, the codebooks of transmitted layers of SCMAA are shown in Fig. 1.

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[1]The minimum intra-partition distance is the minimum Euclidean distance between basic complex multi-dimension constellation points in each partition.
[2]Traditional SCMA is short for SCMA with the codebook design in [2], [4], [5].
[3]A transmitted layer represents a transmitted user
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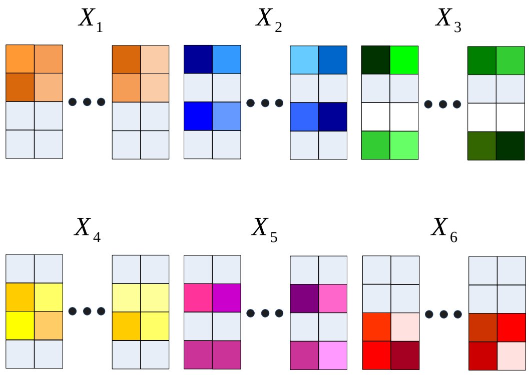

Fig. 1. The codebooks of transmitted layers of SCMAA with J=6, N=2 and K=4

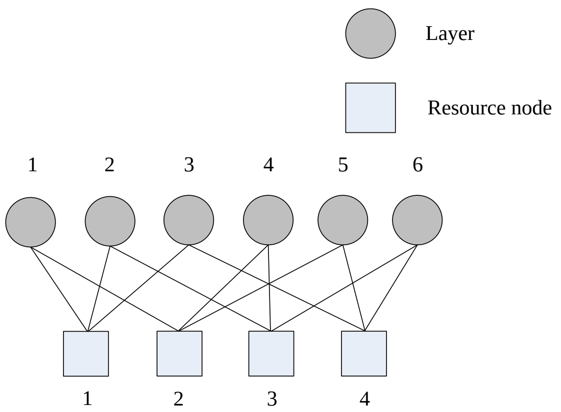

Fig. 2. Factor graph of SCMAA with J=6, N=2 and K=4

In order to improve spectral efficiency, we can increase the number of transmitted layers multiplexed on limited resource nodes. The received symbol after J layers multiplexing can be defined as

$$y = \sum_{j=1}^{J} diag(h_j) x_j + n_0 \tag{1}$$

where $h_j = (h_{1j}, h_{2j}, h_{3j}, ..., h_{Kj})^T \in \mathbb{C}^{K\times 1}$ is the channel vector of layer j, $x_j = (x_{1j}, x_{2j}, x_{3j}, ..., x_{Kj})^T \in \mathbb{C}^{K\times 1}$ is the transmitted codeword of layer j, $diag(h_j)$ is a diagonal matrix with elements from h_j, n_0 is the white Gaussion noise vector, and $\mathbb{C}$ denotes the complex field.

In SCMAA, the set of resource nodes occupied by layer j is determined by the indices of nonzero elements in $f_j \in \mathrm{B}^{K\times 1}$, where B is the set of binary numbers, $\forall j = 1,..., J$. f_j is a binary indicator vector where the nonzero elements is determined by the indices of nonzero rows in V_j, $\forall j = 1,..., J$. As there are J layers, the structure of SCMAA can be represented by a factor graph matrix $F = \{f_1,..., f_J\} \in \mathrm{B}^{K\times J}$. In F, if $F_{kj} = 1$, layer node j and resource node k are connected. Fig. 2 shows the factor graph representation of F with N=2,$K = 4$ and $J = 6$. The sparse characteristic of SCMAA allows the use of the MPA receiver with maximum likelihood-like (ML-like) performance [8]. The complexity of MPA receiver is proportional to M^{d_f} where d_f is the number of nonzero elements of transmitted codewords multiplexing on each resource node. Due to the sparse characteristic of SCMAA, d_f is less than J, and therefore the complexity of MPA receiver is lower than that of ML receiver.

III. Permutation Set

For SCMAA, if the operator on constellation C of layer j is limited to permutation matrix π_j, the codeword of layer j can be defined as

$$x_j = q_j = V_j \pi_j z, \forall j = 1,..., J \tag{2}$$

where $z = (z^1, z^2 ..., z^N)^T$ represents an arbitrary alphabet of constellation C, $z^n \in {}^nC = \{c_{nm} = (c_m)_n \mid \forall c_m \in C, m = 1,..., M\}$, and ${}^nC$ represents the n-th dimension of constellation C. Under these conditions, the aggregate received symbol can be expressed as

$$p(\mathrm{z}) = \sum_{j=1}^{J} q_j(\mathrm{z}) = \sum_{j=1}^{J} V_j \pi_j z \tag{3}$$

where $p(z) = (p_1(z),..., p_k(z),..., p_K(z))^T$ is a $K\times 1$ vector, $p_k(z) = d_{k1}z^1 + d_{k2}z^2 + ... + d_{kN_s}z^{N_s}$ denotes the interfering polynomial on resource node k, $1 \le N_s \le N$, and $\forall k = 1,..., K$. As the number of nonzero elements of transmitted codewords multiplexed on resource node k is d_f, $\sum_{n=1}^{N_s} d_{kn} = d_f$, $\forall k = 1,..., K$. For example, if $N = 2$ and $d_f = 3$, $p_2(z) = 2z^1 + z^2$. According to $p_2(z)$, we can conclude that there are three nonzero elements of transmitted codewords multiplexed on resource node 2. In the three nonzero elements, two of them are from ${}^1C$ and the other is from ${}^2C$. According to (3), we can conclude that there is a one-to-one mapping between permutation set $\Pi = [\pi_j]_{j=1}^{J}$ and $p(z)$, and Π determines the sum of distances between interfering dimensions of transmitted codewords of SCMAA multiplexed on each resource node. The sum of distances between interfering dimensions of transmitted codewords of SCMAA multiplexed on resource node k can be expressed as

$$E_r^k = |x_{j1,n1}^{k,r} - x_{j2,n2}^{k,r}|^2 + ... + |x_{j1,n1}^{k,r} - x_{jd_f,nd_f}^{k,r}|^2 + ... + |x_{j2,n2}^{k,r} - x_{jd_f,nd_f}^{k,r}|^2 + ... + |x_{j(d_f-2),n(d_f-2)}^{k,r} - x_{jd_f,nd_f}^{k,r}|^2 + |x_{j(d_f-1),n(d_f-1)}^{k,r} - x_{jd_f,nd_f}^{k,r}|^2 \quad (4)$$

$$E_{im}^k = |x_{j1,n1}^{k,im} - x_{j2,n2}^{k,im}|^2 + ... + |x_{j1,n1}^{k,im} - x_{jd_f,nd_f}^{k,im}|^2 + ... + |x_{j2,n2}^{k,im} - x_{jd_f,nd_f}^{k,im}|^2 + ... + |x_{j(d_f-2),n(d_f-2)}^{k,im} - x_{jd_f,nd_f}^{k,im}|^2 + |x_{j(d_f-1),n(d_f-1)}^{k,im} - x_{jd_f,nd_f}^{k,im}|^2 \quad (5)$$

$$n(\mathrm{p}_k(\mathrm{z})) = \sqrt{E_r^k + E_{im}^k} \quad (6)$$

where $x_{j,n}^{k,r}$ is the real part of the signal on the n-th dimension of the codeword of layer j on resource node k, $x_{j,n}^{k,im}$ is the imaginary part of the signal on the n-th dimension of the codeword of layer j on resource node k, and $n(\mathrm{p}_k(\mathrm{z}))$ is the sum of distances between interfering dimensions of transmitted codewords multiplexed on resource node k. As illustrated in the third paragraph of subsection III, there is a one-to-one mapping between permutation set Π and $p(z)$, and therefore there is a one-to-one mapping between Π and $n(p(z))$ ($n(p(z)) = \{n(p_1(z)),...,n(p_k(z)),...,n(p_K(z))\}$).

A. *The Proposed Criterion of Permutation set of SCMAA*

The proposed criterion is divided into three steps. The first step corresponds to (7), the second step corresponds to (8), and the third step corresponds to (9). First, equation (7) selects the permutation sets that the minimum in corresponding $n(p(z))$ is the maximum:

$$\{\Pi^{1*}, \Pi^{2*}, ...\} = \arg\max_{\Pi} \min_k n(p_k(\mathrm{z})), \quad \forall k = 1,...,K \cdot \quad (7)$$

There is more than one permutation set selected by (7), i.e. $\Pi^* = \{\Pi^{1*}, \Pi^{2*}, ...\}$. At the MPA receiver, if the detected layer in its decision process is an error, the interference in the detection process of undetected layers will increase. Therefore it will degrade the performance of MPA receiver. In order to improve the convergence reliability of the detected layer in each decision process, equation (8) selects the permutation sets $\Pi^{**} = \{\Pi^{1**}, \Pi^{2**}, ...\}$ from Π^*, which can maximize the minimum in corresponding $n_{set} = (n_{1,2}, n_{1,3}, ..., n_{K-1,K})^T$. Then among Π^{**}, equation (9) selects the most appropriate permutation set Π^{l***}, which can maximize the variance of all the elements in n_{set}:

$$\{\Pi^{1**}, \Pi^{2**}, ...\} = \arg\max_{\Pi^{l*}} \min_{(k_1,k_2)} n_{k_1,k_2}, \Pi^{l*} \in \Pi^* \quad (8)$$

$$\Pi^{l***} = \arg\max_{\Pi^{l**}} \mathrm{var}(n_{set}), \Pi^{l**} \in \Pi^{**} \quad (9)$$

where $n_{k_1,k_2} = |n(p_{k_1}(z)) - n(p_{k_2}(z))|, k_1 < k_2$, $\forall k_1 = 1,...,K-1, \forall k_2 = 2,...,K$.

B. *Traditional Criterion of Permutation Set of SCMAA*

The traditional criterion of permutation set of SCMAA was divided into two steps [7]. The first step was the same as the proposed criterion. Then among the selected permutation sets, the second step selected the most appropriate permutation set, which could maximize the variance of all the elements in $n(p(z)) = \{n(p_1(z)),...,n(p_k(z)),...,n(p_K(z))\}$. However, the traditional criterion of permutation set of SCMAA did not increase the variance of all the elements in n_{set}.

IV. The MPA Receiver and Performance Analysis of the Proposed Criterion

A. *The MPA Receiver*

In this paper, the MPA receiver uses the min-sum algorithm. The whole structure of SCMAA can be represented by a factor graph F with J layers and K resource nodes. Resource nodes can be seen as variable nodes, and layers can be seen as check nodes [9]. For the MPA receiver, the process that messages are exchanged between variable nodes and check nodes is as follows[10] [11].

The message exchanged from variable node k to check node j is given by

$$v_{k\to j}(x_j) = \gamma_k(x_j) + \sum_{i\in\psi(k)\setminus j} \mu_{i\to k}(x_i) \quad (10)$$

$$\gamma_k(x_j) = -\ln\left(\frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\| y_k - \sum_{i\in\psi(k)} x_{i,k} h_k \|^2}{2\sigma^2}\right)\right) \quad (11)$$

where y_k is the received symbol on variable node k, $v_{k\to j}(x_j)$ is the cost function where message is exchanged from variable node k to check node j when the value of check node j is x_j, $\mu_{i\to k}(x_i)$ is the cost function where message is exchanged from check node i to variable node k when the value of check node i is x_i, $\gamma_k(x_j)$ is the function of initial information on variable node k when the value of check node j is x_j, $\psi(k)\setminus j$ represents the set of all check nodes connecting to variable node k except check node j, and $\exp()$ is exponential function.

The message exchanged from check node j to variable node k is given by

$$\mu_{j\to k}(x_j) = \min\left(\sum_{l\in\phi(j)\setminus k} v_{l\to j}(x_j)\right) \quad (12)$$

where $\phi(j)\backslash k$ represents the set of all variable nodes connecting to check node j except variable node k. After several iterations, the final cost function of check node j, when the value of check node j is x_j, is

$$\mu(x_j)=\sum_{l\in\phi(j)} v_{l\to j}(x_j) \tag{13}$$

B. The Performance Analysis of the Proposed Criterion

The purpose of the proposed criterion of permutation set is to improve the convergence reliability of some detected layers in their corresponding decision processes at the MPA receiver. The performance analysis of the proposed criterion of permutation set is shown as below.

If N=2,$K=4$ and $J=6$, the factor graph matrix of SCMAA can be expressed as

$$F=\begin{bmatrix}1\,1\,1\,0\,0\,0\\1\,0\,0\,1\,1\,0\\0\,1\,0\,1\,0\,1\\0\,0\,1\,0\,1\,1\end{bmatrix} \tag{14}$$

Based on F, the process that messages are exchanged between layer nodes and resource nodes at the MPA receiver can be expressed as

$$\begin{gathered}\mu_{1\to1}(x_1)=\min(v_{2\to1}(x_1))\\ \mu_{1\to2}(x_1)=\min(v_{1\to1}(x_1))\\ .\\ .\\ .\\ \mu_{6\to3}(x_6)=\min(v_{4\to6}(x_6))\\ \mu_{6\to4}(x_6)=\min(v_{3\to6}(x_6))\end{gathered} \tag{15}$$

$$\begin{gathered}v_{1\to1}(x_1)=\gamma_1(x_1)+\mu_{2\to1}(x_2)+\mu_{3\to1}(x_3)\\ v_{2\to1}(x_1)=\gamma_2(x_1)+\mu_{4\to2}(x_4)+\mu_{5\to2}(x_5)\\ .\\ .\\ .\\ v_{3\to6}(x_6)=\gamma_3(x_6)+\mu_{2\to3}(x_2)+\mu_{4\to3}(x_4)\\ v_{4\to6}(x_6)=\gamma_4(x_6)+\mu_{3\to4}(x_3)+\mu_{5\to4}(x_5)\end{gathered} \tag{16}$$

Assuming that the values of $x_1,x_2,\ldots$ and x_6 are expectations, and the initial values of $v_{k\to j}(x_j)$ and $\mu_{j\to k}(x_j)$ are 0. As the values of $x_1,x_2,\ldots$ and x_6 are expectations, $\gamma_k(x_j)=\gamma_k(x_i)=\gamma_k$, $\forall k=1,\ldots,4$, $\forall i,j=1,\ldots,6, i\neq j$. After several iterations, the difference between $\mu(x_1)$ and $\mu(x_6)$ and the difference between $\mu(x_3)$ and $\mu(x_4)$ can be expressed as

$$\begin{gathered}\mu(x_1)-\mu(x_6)=|\gamma_2-\gamma_4|-|\gamma_1-\gamma_3|\\ \mu(x_3)-\mu(x_4)=|\gamma_3-\gamma_4|-|\gamma_1-\gamma_2|\end{gathered} \tag{17}$$

At the MPA receiver, the larger the difference between any two elements in $\mu=\{\mu(x_1),\mu(x_2),\ldots,\mu(x_J)\}$ is, the larger the differences between the reliability of detections on all undetected layers in each decision process. Moreover, in each decision process, the larger the differences between the reliability of detections on all undetected layers are, the higher the convergence reliability of the detected layer [7]. In this example, the proposed criterion of permutation set increases both the difference between $n_{1,3}$ and $n_{2,4}$ and the difference between $n_{1,2}$ and $n_{3,4}$, while the traditional criterion of permutation set of SCMAA does not. That is, the proposed criterion increases both the difference between $\gamma_{1,3}$ and $\gamma_{2,4}$ and the difference between $\gamma_{1,2}$ and $\gamma_{3,4}$ (γ_k is related to $n(\mathrm{p}_k(\mathrm{z}))$ [7], and $\gamma_{k_1,k_2}=|\gamma_{k_1}-\gamma_{k_2}|, k_1<k_2$, $\forall k_1=1,\ldots,3$, $\forall k_2=2,\ldots,4$), while the traditional criterion of permutation set does not. Therefore, compared with the traditional criterion of permutation set, the proposed criterion of permutation set can further improve the convergence reliability of layer 1, layer 3, layer 4 and layer 6 in their corresponding decision processes. It will do the same in the process of detections on the transmitted layers of SCMAA with other parameters.

V. Simulation Results

In this section, simulations are based on long term evolution (LTE) system [12]. Turbo code is applied as the channel code, and the rate of Turbo code is 1/2. In the following, SCMAA is short for SCMAA with the traditional criterion of permutation set, and SCMAAA is short for SCMAA with the proposed criterion of permutation set. In SCMAA and SCMAAA, the basic complex two-dimension constellation is designed by Turbo TCM [13], [14], and the set of basic complex two-dimension signals is constructed by two-fold Cartesian product of a QPSK set [15], [16]. SCMAAA and SCMAA use the MPA receiver. As the spectral efficiency is 2 bits/tone, SCMAAA and SCMAA use factor graph with N=2,$K=4$ and $J=4$. As the spectral efficiency is 3 bits/tone, SCMAAA, and SCMAA use factor graph with N=2,$K=4$ and $J=6$.

Fig. 3 is the BER performance of SCMAAA and SCMAA over AWGN channel with the spectral efficiency 2 bits/tone. As can be observed in Fig. 3, the BER performance of SCMAAA outperforms that of SCMAA, and SCMAAA has 0.6 dB gain over SCMAA. Fig.4 is the BER performance of SCMAAA and SCMAA over AWGN channel with the spectral efficiency 3 bits/tone. As can be observed in Fig. 4, the BER performance of SCMAAA outperforms that of SCMAA, and SCMAAA has 1 dB gain over SCMAA. Simulation results show that the proposed criterion of permutation set improves the convergence reliability of some detected layers in their corresponding decision processes at the MPA receiver compared with the traditional criterion of permutation set over AWGN channel.

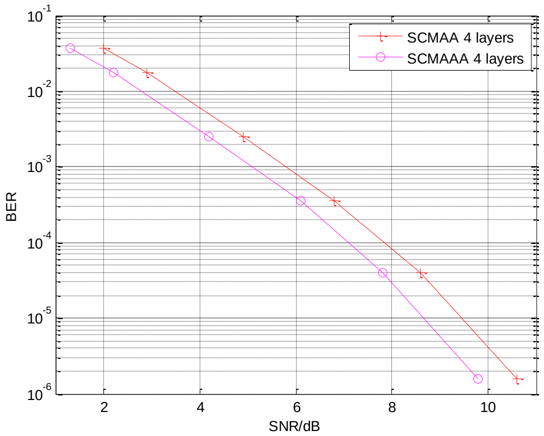

Fig. 3. The BER performance of SCMAAA and SCMAA over AWGN channel with 2 bits/tone

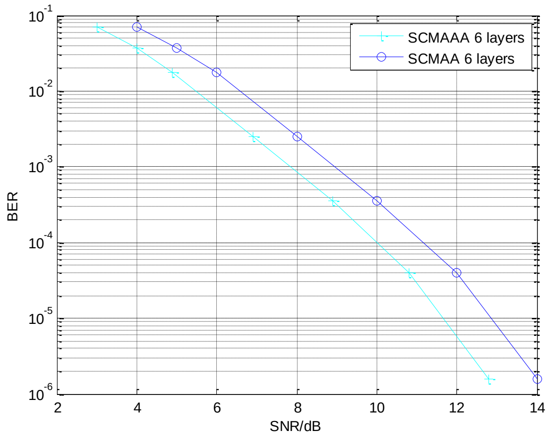

Fig. 4. The BER performance of SCMAAA and SCMAA over AWGN channel with 3 bits/tone

In Fig. 5 and Fig. 6, all transmitted layers are multiplexed on orthogonal frequency division multiple access (OFDMA) tones in a pedestrian B (PB) fading channel with speed of 3 km/h [14]. The carrier frequency is 2 GHz and the frequency spacing is 15 KHz. A data payload occupies 6 LTE resource blocks (RBs). Fig. 5 is the BER performance of SCMAAA and SCMAA over fading channel with the spectral efficiency 2 bits/tone. As can be observed in Fig. 5, the BER performance of SCMAAA outperforms that of SCMAA, and SCMAAA has 0.8 dB gain over SCMAA. Fig. 6 is the BER performance of SCMAAA and SCMAA over fading channel with the spectral efficiency 3 bits/tone. As can be observed in Fig. 6, the BER performance of SCMAAA outperforms that of SCMAA, and SCMAAA has 1.1 dB gain over SCMAA. Simulation results show that the proposed criterion of permutation set improves the convergence reliability of some detected layers in their corresponding decision processes at the MPA receiver compared with the traditional criterion of permutation set over fading channel.

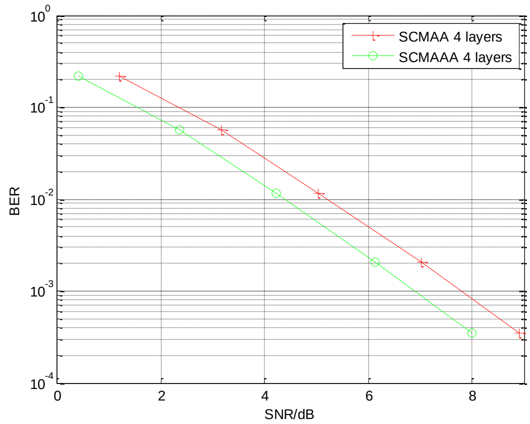

Fig. 5. The BER performance of SCMAAA and SCMAA over fading channel with 2 bits/tone

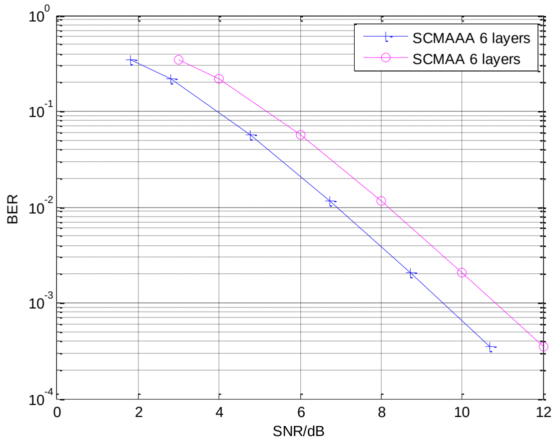

Fig. 6. The BER performance of SCMAAA and SCMAA over fading channel with 3 bits/tone

VI. Conclusions

This paper proposes an advanced criterion of permutation set for SCMAA. Compared with the traditional criterion of permutation set under the same spectral efficiency, the proposed criterion of permutation set further increases the variance of the set of absolute differences between the sums of distances between interfering dimensions of transmitted codewords multiplexed on all resource nodes, and therefore improves the convergence reliability of some detected layers in their corresponding decision processes at the MPA receiver.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Cheng Yan conducted the research; Cheng Yan and Lin Wang analyzed the data; Cheng Yan wrote the paper, all authors had approved the final version.

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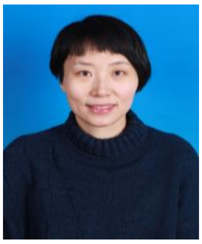

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