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*Research Article*

# Nonuniform Code Multiple Access

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For sparse code multiple access advanced (SCMAA), the quality of initial information on each resource node and the convergence reliability of the detected user in each decision process were unsatisfactory at the message passing algorithm (MPA) receiver. Driven by these problems, this paper proposes a nonuniform code multiple access (NCMA) scheme. In the codebook design of NCMA, different transmitted layers are generated from different complex multidimension constellations, respectively, and a novel basic complex multidimension constellation design is proposed to increase the minimum intrapartition distance. Then a novel criterion of permutation set is proposed to maximize the sum of distances between interfering dimensions of transmitted codewords multiplexed on any resource node, where the number of nonzero elements of transmitted codewords is more than 1. On the other side, an advanced MPA receiver is proposed to improve the reliability of detection on each transmitted layer of NCMA. Simulation results show that the block error rate performance of NCMA outperforms SCMAA and sparse code multiple access (SCMA) under the same spectral efficiency.

## 1. 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, nonorthogonal multiple access, such as sparse code multiple access (SCMA), is proposed. SCMA [2–5] was a multidimension codebook-based nonorthogonal multiple access [5, 6]. In SCMA, there were $J$ transmitted layers multiplexed on $K$ resource nodes. Each layer (a transmitted layer represents a transmitted user) had its dedicated codebook. A codebook contained a plurality of $K$-dimension codewords [3, 4]. A $K$-dimension codeword was a sparse column vector, where there were $N < K$ nonzero elements, and was generated from a complex $N$-dimension constellation point by a binary mapping matrix. In order to improve spectral efficiency, more than one layer was multiplexed on limited resource nodes. The constellation length and size were the same in all the transmitted layers of SCMA.

In the SCMA scheme, 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 [4, 7]. Driven by these problems, a sparse code multiple access advanced (SCMAA) scheme was proposed [7]. Under the same minimum Euclidean distance, 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 SCMA [7–9]. However, in the SCMAA scheme, the increase of the sum of distances between interfering dimensions of transmitted codewords multiplexed on each resource node was limited by the suboptimal minimum intrapartition distance (the minimum intrapartition distance is the minimum Euclidean distance between basic complex multidimension constellation points in each partition). Moreover, the criterion of permutation set of SCMAA failed to maximize the sums of distances between interfering dimensions of transmitted codewords on some resource nodes (detailed explanation is offered in fifth line of Section 3.3.2). Hence the quality of initial information of MPA receiver was unsatisfactory. On the other side, the increase of differences between the reliabilities of detections on all undetected transmitted layers in each decision process was limited by the uniform characteristic of SCMAA, and 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 (detailed analysis is offered in Section 3.3.2 and the sixth paragraph of Section 4.2). Hence the convergence reliability of the detected layer in each decision process was unsatisfactory at the MPA receiver of SCMAA.

Driven by these problems, this paper proposes a nonuniform code multiple access (NCMA) scheme. Compared with SCMAA, some major improvements made in the proposed NCMA scheme are as follows. (i) Different transmitted layers of NCMA are generated from different complex multidimension constellations, respectively, while all the transmitted layers of SCMAA are generated from the same complex multidimension constellation. Therefore, in NCMA, the number of nonzero elements of transmitted codewords multiplexed on each resource node is totally different or not exactly the same (detailed explanation is offered in Section 3.2), and the number of nonzero elements occupied by each transmitted layer is totally different. However, in SCMAA, the number of nonzero elements of transmitted codewords multiplexed on each resource node is the same and so is the number of nonzero elements occupied by each transmitted layer. (ii) A novel basic complex multidimension constellation design is proposed. Compared with the basic complex multidimension constellation design of SCMAA, the proposed basic complex multidimension constellation design can further increase the minimum intrapartition distance. (iii) This paper proposes a novel criterion of permutation set, which can maximize the sum of distances (detailed definition is offered in the fourth paragraph of Section 3.3) between interfering dimensions of transmitted codewords multiplexed on any resource node, where the number of nonzero elements of transmitted codewords is more than 1. (iv) This paper proposes an advanced MPA receiver. At the proposed MPA receiver, the detection order of transmitted layers is fixed, and the function of initial information is equal to the function of initial information at traditional MPA receiver (traditional MPA receiver is short for the MPA receiver of SCMAA) multiplied by an amplification factor. On the other side, the complexity of the proposed MPA receiver is less than that of traditional MPA receiver (detailed explanation is offered in the fourth paragraph of Section 4.2).

Section 2 introduces the system model of NCMA. The codebook design of NCMA is presented in Section 3. The proposed MPA receiver and the performance analysis of NCMA scheme are offered in Section 4. Finally, in Section 5, the block error rate (BLER) performance of NCMA is compared with that of SCMAA and SCMA according to simulations.

## 2. System Model

In NCMA system, there are $J$ transmitted layers multiplexed on $K$ resource nodes. Each transmitted layer has its dedicated 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 $j$ includes $N_j$ nonzero elements and $K-N_j$ zero elements. In NCMA system, different transmitted layers are generated from different complex multidimension constellations, respectively; that is, $C_i \neq C_j, N_i \neq N_j, i \neq j, \forall i, j = 1, \ldots, J$. If $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$, the codebooks of transmitted layers of NCMA are shown in Figure 1.

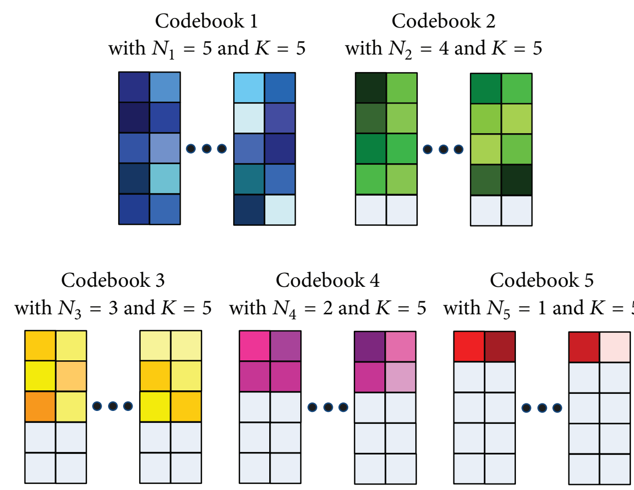


Figure 1: The codebooks of transmitted layers of NCMA with $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$.

In order to improve spectral efficiency, more than one layer is multiplexed on limited resource nodes. In NCMA system, the received symbol after $J$ layers multiplexing can be defined as

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

where $h_j = (h_{1j}, h_{2j}, \ldots, h_{Kj})^T$ is the channel vector of layer $j$, $x_j = (x_{1j}, x_{2j}, \ldots, x_{Kj})^T$ is the codeword of layer $j$, $\operatorname{diag}(h_j)$ is a diagonal matrix with elements from $h_j$, and $n_0$ is the white Gaussian noise vector.

In NCMA, the set of resource nodes occupied by layer $j$ is determined by the indices of nonzero elements in $f_j, \forall j = 1, \ldots, J$. $f_j$ is a binary indicator vector, where the nonzero elements are determined by the indices of nonzero rows in $V_j$. As there are $J$ transmitted layers in NCMA system, the structure of NCMA can be represented by a factor graph matrix $F = (f_1, \ldots, f_J)$. In $F$, if $(F)_{kj} = 1$, layer node $j$ and resource node $k$ are connected. Figure 2 shows the factor graph representation of $F$ with $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$.

## 3. NCMA Codebook Design

Figure 3 shows the codebook design of NCMA with $N = 2$ and $K = 5$. According to Figure 3, we can conclude that the

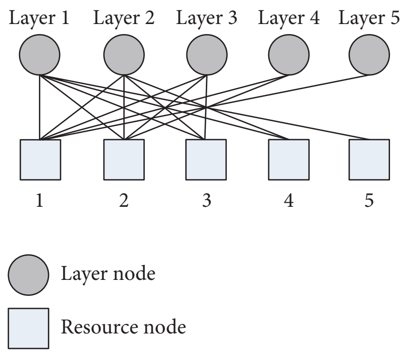


FIGURE 2: Factor graph of NCMA with $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$.

codebook design of NCMA includes complex $N$-dimension constellation design (here $N$ is short for $N_j$), permutation set, and mapping matrix. The complex $N$-dimension constellation design includes basic complex $N$-dimension constellation design, coordinate interleaving, and phase rotation. In the proposed codebook design of NCMA, coordinate interleaving and phase rotation are the same as the codebook deign of SCMAA [7, 10, 11]. In the following, we will focus on the basic complex $N$-dimension constellation design, mapping matrix, and permutation set.

*3.1. Basic Complex N-Dimension Constellation Design*

*3.1.1. The Basic Complex N-Dimension Constellation Design of SCMAA.* The basic complex $N$-dimension constellation design of SCMAA was divided into two steps. First, the set of basic complex $N$-dimension signals was constructed by $N$-fold Cartesian product of a QAM signal set [12]. Then, in order to increase the minimum intrapartition distance, the set of basic complex $N$-dimension signals was divided into $P$ partitions by Turbo Trellis Coded Modulation (Turbo TCM) technology [13, 14]. As Turbo TCM was applied in set partitioning, the minimum intrapartition distance was asymptotically suboptimal as the number of partitions increased.

*3.1.2. The Basic Complex N-Dimension Constellation Design of NCMA.* In order to further increase the minimum intrapartition distance, a novel basic complex $N$-dimension constellation design is proposed for NCMA. The proposed basic complex $N$-dimension constellation design is divided into three steps.

(i) We construct a real $2N$-dimension constellation by sphere packing with the known densest lattice [15].

(ii) The real $2N$-dimension constellation is divided into $P$ partitions. The $P$ partitions themselves will be translation-equivalent lattices; that is, each partition can be translated from any other partition. Hence they are all generated by the same set of basis vectors $V_{\text{per}}$, and the minimum intrapartition distance $d_{\min}$ is the same in each partition. If we draw spheres centered at points in each partition and the spheres just touch each other, we must choose the radius of the spheres to be $r = d_{\min}/2$. Maximizing $d_{\min}$ for a given $P$ is equivalent to maximizing $r$ for given $|\det V_{\text{per}}|$, where $P = |\det V_{\text{per}}|$, and $|\det V_{\text{per}}|$ is the absolute value of determinant of $V_{\text{per}}$. Hence the real $2N$-dimension constellation partitioning is a sphere packing problem; that is, $V_{\text{per}} = a * V_{\text{gen}}^T$, where $V_{\text{gen}}^T$ is the transpose of the generator matrix $V_{\text{gen}}$ of the densest $2N$-dimension lattice and $a$ is a constant that is determined by $P$. For example, for a real 2-dimension constellation, the hexagonal lattice is the densest sphere packing in two dimensions, and therefore each partition is also hexagonal. Hence $V_{\text{per}} = [v_1 \;\; v_2] = \begin{bmatrix} 2a & a \\ 0 & \sqrt{3}a \end{bmatrix}$, where $a = \sqrt{P/(2\sqrt{3})}$. The minimum intrapartition distance can be expressed as $d_{\min} = \min(\|v_1\|, \|v_2\|, \|v_1 - v_2\|, \|v_1 + v_2\|) = \sqrt{2P/\sqrt{3}}$, and $d_{\min} > d_{\min}^T = \sqrt{P}$, where $d_{\min}^T$ is the maximum $d_{\min}$ of the basic complex 1-dimension constellation of SCMAA. It will do the same for other real multidimension constellations.

(iii) As a real $2N$-dimension constellation point $s = [s_1, s_2, \ldots, s_{2N}]$ is given, we can obtain a basic complex $N$-dimension constellation point $s_c = [s_1 + js_2, s_3 + js_4, \ldots, s_{2N-1} + js_{2N}]$.

According to (i), (ii), and (iii), we can conclude that the proposed basic complex $N$-dimension constellation design can increase the minimum intrapartition distance compared with the basic complex $N$-dimension constellation design of SCMAA.

*3.2. Mapping Matrix of NCMA.* The nonuniform characteristic of NCMA is determined by a mapping matrix set $V = \{V_1, V_2, \ldots, V_J\}$. The mapping matrix design rules of NCMA are as follows. (i) $V_j \in B^{K \times N_j}$, where $B$ represents a binary matrix. (ii) $V_i \neq V_j$, $\forall i \neq j, i, j = 1, \ldots, J$. (iii) $V_j^{[\Theta]} = I_{N_j}$, where $V_j^{[\Theta]}$ is $V_j$ after removing its all-zero rows. The mapping properties of $V$ are as follows.

(i) The number of nonzero elements of transmitted codewords multiplexed on each resource node is totally different or not exactly the same. Moreover, $d_{1f}$ is the maximum in $\{d_{1f}, \ldots, d_{kf}, \ldots, d_{Kf}\}$, and $d_{Kf} = 1$. In other words, $1 \leq d_{kf} \leq d_{1f}$, where $d_{kf}$ is the number of nonzero elements of transmitted codewords multiplexed on resource node $k$.

(ii) The number of nonzero elements occupied by each transmitted layer is totally different, and $n_{1f} > \cdots > n_{jf} > \cdots > n_{Jf}$, where $n_{jf}$ is the number of nonzero elements occupied by layer $j$, $\forall j = 2, \ldots, J-1$.

(iii) $K = N_1$, and $N_1 > \cdots > N_j > \cdots > N_J$, $\forall j = 2, \ldots, J-1$.

(iv) $J = d_{1f}$.

For example, if $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$, there are five transmitted layers multiplexed on $K = N_1 = 5$ resource nodes, and therefore the factor graph matrix can be expressed as $F_1 = \begin{bmatrix} 1&1&1&1&1 \\ 1&1&1&1&0 \\ 1&1&1&0&0 \\ 1&1&0&0&0 \\ 1&0&0&0&0 \end{bmatrix}$. In $F_1$, $d_{1f} > d_{2f} > d_{3f} > d_{4f} > d_{5f}$. Hence the number of nonzero elements of transmitted codewords multiplexed on each resource node is totally different. For another example, if $N_1 = 4$, $N_2 = 3$, and $N_3 = 1$, there are three transmitted layers multiplexed on $K = N_1 = 4$ resource nodes, and therefore the factor graph matrix can

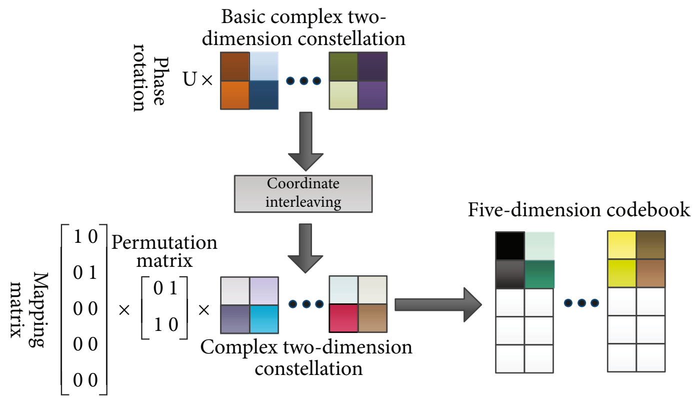


Figure 3: NCMA codebook design with $N = 2$ and $K = 5$.

be expressed as $F_2 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$. In $F_2$, $d_{1f} > d_{2f} = d_{3f} > d_{4f}$. Hence the number of nonzero elements of transmitted codewords multiplexed on each resource node is not exactly the same.

*3.3. Permutation Set.* For layer $j$, if the operator on constellation $C_j$ is limited to permutation matrix $\pi_j$, the codeword can be defined as

$$x_j = q_j = V_j \pi_j z_j, \quad \forall j = 1, \ldots, J, \tag{2}$$

where $z_j = (z_j^1, z_j^2, \ldots, z_j^{N_j})^T$ represents an arbitrary alphabet of constellation $C_j$, $z_j^n \in {}^n C_j = \{c_{nm_j} = (c_{m_j})_n \mid \forall c_{m_j} \in C_j, m_j = 1, \ldots, M_j\}$, and ${}^n C_j$ represents the $n$th dimension of constellation $C_j$. Under these conditions, the aggregate received symbol can be expressed as

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

where $p(z) = (p_1(z), \ldots, p_k(z), \ldots, p_K(z))^T$ is a $K \times 1$ vector, $p_k(z) = d_{k1} z^{1,k} + d_{k2} z^{2,k} + \cdots + d_{kN_s} z^{N_s,k}$ represents the interfering polynomial on resource node $k$, $z^{n,k}$ represents the $n$th dimension of any constellation on resource node $k$, $1 \le N_s \le N_{\max}$, $N_{\max}$ is the maximum in $\{N_1, N_2, \ldots, N_J\}$, and $\forall k = 1, \ldots, K$. As the number of nonzero elements of transmitted codewords multiplexed on resource node $k$ is $d_{kf}$, we can conclude that $\sum_{n=1}^{N_s} d_{kn} = d_{kf}, \forall k = 1, \ldots, K$. For example, according to $F_1$ in Section 3.2, the interfering polynomial on resource node 2 can be expressed as $p_2(z) = 2z^{1,2} + 2z^{2,2}$. According to $p_2(z)$, we can conclude that there are four nonzero elements of transmitted codewords multiplexed on resource node 2. In the four nonzero elements, two of them come from ${}^1C$, and the others come from ${}^2C$, where ${}^1C = \{{}^1C_1, {}^1C_2, {}^1C_3, {}^1C_4\}$ and ${}^2C = \{{}^2C_1, {}^2C_2, {}^2C_3, {}^2C_4\}$. In summary, for a given mapping matrix set $V$, the set $d_{\text{set}}^k = \{d_{k1}, \ldots, d_{kn}, \ldots, d_{kN_s}\}$ depends on permutation set $\Pi = [\pi_j]_{j=1}^J$, $\forall k = 1, \ldots, K$. Hence there is a one-to-one mapping between permutation set $\Pi$ and $p(z)$. Permutation set $\Pi$ determines the sum of distances between interfering dimensions of transmitted codewords multiplexed on any resource node, where the number of nonzero elements of transmitted codewords is more than 1. If $d_{kf} > 1$, the sum of distances between interfering dimensions of transmitted codewords multiplexed on resource node $k$ can be expressed as

$$\begin{aligned}
E_r^k &= \left| x_{j1,n1}^{k,r} - x_{j2,n2}^{k,r} \right|^2 + \cdots \\
&\quad + \left| x_{j1,n1}^{k,r} - x_{jd_{kf},nd_{kf}}^{k,r} \right|^2 + \cdots \\
&\quad + \left| x_{j(d_{kf}-2),n(d_{kf}-2)}^{k,r} - x_{jd_{kf},nd_{kf}}^{k,r} \right|^2 \\
&\quad + \left| x_{j(d_{kf}-1),n(d_{kf}-1)}^{k,r} - x_{jd_{kf},nd_{kf}}^{k,r} \right|^2, \\
E_{\text{im}}^k &= \left| x_{j1,n1}^{k,\text{im}} - x_{j2,n2}^{k,\text{im}} \right|^2 + \cdots \\
&\quad + \left| x_{j1,n1}^{k,\text{im}} - x_{jd_{kf},nd_{kf}}^{k,\text{im}} \right|^2 + \cdots \\
&\quad + \left| x_{j(d_{kf}-2),n(d_{kf}-2)}^{k,\text{im}} - x_{jd_{kf},nd_{kf}}^{k,\text{im}} \right|^2 \\
&\quad + \left| x_{j(d_{kf}-1),n(d_{kf}-1)}^{k,\text{im}} - x_{jd_{kf},nd_{kf}}^{k,\text{im}} \right|^2, \\
n(p_k(z)) &= \sqrt{E_r^k + E_{\text{im}}^k},
\end{aligned} \tag{4}$$

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 $k$, $x_{j,n}^{k,\text{im}}$ is the imaginary part of the signal on the $n$th dimension of the codeword of layer $j$ on resource node $k$, and $n(p_k(z))$ is the sum of distances between interfering dimensions of transmitted codewords multiplexed on resource node $k$. As illustrated in the third paragraph of Section 3.3, there is a one-to-one mapping between permutation set $\Pi$ and $p(z)$. Hence there is a one-to-one mapping between permutation set $\Pi$ and $n(p(z))$, where $n(p(z)) = \{n(p_1(z)), n(p_2(z)), \ldots, n(p_{K_s}(z))\}$, and $K_s$ is the number of resource nodes where the number of nonzero elements of transmitted codewords is more than 1.

*3.3.1. The Novel Criterion of Permutation Set of NCMA.* In the NCMA scheme, a novel criterion of permutation set is proposed to maximize $n(p_k(z))$, and the proposed criterion is divided into two steps (the first step corresponds to formula (5), and the second step corresponds to formula (6)). First, formula (5) selects the permutation sets where $n(p_1(z))+\cdots+n(p_{K_s}(z))$ is maximum.

$$\{\Pi^{1*}, \Pi^{2*}, \ldots\} = \arg\max_{\Pi} \left(n\left(p_1(z)\right) + \cdots + n\left(p_{K_s}(z)\right)\right). \quad (5)$$

There is more than one permutation set selected by formula (5); that is, $\Pi^* = \{\Pi^{1*}, \Pi^{2*}, \ldots\}$. Then, among $\Pi^*$, formula (6) selects the most appropriate permutation set $\Pi^{l**}$, which can minimize the variance of all the elements in $n(p(z)) = \{n(p_1(z)), n(p_2(z)), \ldots, n(p_{K_s}(z))\}$.

$$\Pi^{l**} = \arg\min_{\Pi^{l*}} \operatorname{var}\left(n\left(p(z)\right)\right), \quad \Pi^{l*} \in \Pi^*, \quad (6)$$

where var is the variance function.

*3.3.2. The Criterion of Permutation Set of SCMAA.* The criterion of permutation set of SCMAA was divided into two steps [7]. First, the criterion of SCMAA selected the permutation sets where the minimum in corresponding $n(p(z))$ was maximum. Secondly, among the selected permutation sets, the criterion of SCMAA selected the most appropriate permutation set, which could maximize the variance of all the elements in $n(p(z))$. But the criterion of SCMAA did not maximize some elements in the set (the set $n^*(p(z))$ is the set $n(p(z))$ selected in the second step) $n^*(p(z))$. On the other side, the criterion of SCMAA did not increase the variance of all the elements in $n_{\text{set}}$, where $n_{\text{set}} = \{n_{1,2}, n_{1,3}, \ldots, n_{K_s-1,K_s}\}$, $n_{k_1,k_2} = |n(p_{k_1}(z)) - n(p_{k_2}(z))|$, and $k_1 < k_2$, $\forall k_1 = 1, \ldots, K_s - 1$, $\forall k_2 = 2, \ldots, K_s$.

## 4. The Proposed MPA Receiver and the Performance Analysis of NCMA Scheme

*4.1. The Proposed MPA Receiver of NCMA.* In this paper, the proposed MPA receiver of NCMA uses an advanced min-sum algorithm. The structure of NCMA can be represented by a factor graph F with $J$ layer nodes and $K$ resource nodes. At the proposed MPA receiver, layer nodes can be seen as check nodes, resource nodes can be seen as variable nodes, and the process where messages are exchanged between variable nodes and check nodes is as follows.

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

$$v_{k\to j}\left(x_j\right) = \gamma_k\left(x_j\right) + \sum_{i\in\Psi(k)\setminus j} \mu_{i\to k}\left(x_i\right), \quad (7)$$

$$\gamma_k\left(x_j\right) = -\varepsilon_k \ln\left(\frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\left\|y_k - \sum_{i\in\psi(k)} x_{i,k} h_k\right\|^2}{2\sigma^2}\right)\right), \quad (8)$$

where $y_k$ is the received symbol on resource 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 $x_j$, $\gamma_k(x_j)$ is the function of initial information on variable node $k$ when the value of check node $j$ is $x_j$, $\varepsilon_k$ is the amplification factor in $\gamma_k(x_j)$, $\varepsilon_k > 0$, $\sigma^2$ is noise power, $\mu_{i\to k}(x_i)$ is the cost function where message is exchanged from check node $i$ to variable node $k$ when the value of check node $i$ is $x_i$, $\Psi(k) \setminus j$ represents the set of all check nodes connecting to variable node $k$ except check node $j$, and exp( ) is the exponential function.

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

$$\mu_{j\to k}\left(x_j\right) = \min\left(\sum_{l\in\Phi(j)\setminus k} v_{l\to j}\left(x_j\right)\right), \quad (9)$$

where $\Phi(j) \setminus k$ 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

$$\mu\left(x_j\right) = \sum_{l\in\Phi(j)} v_{l\to j}\left(x_j\right). \quad (10)$$

At the proposed MPA receiver, the process where messages are exchanged between variable nodes and check nodes is similar to that at traditional MPA receiver [16, 17]. However, on each resource node, the function of initial information at the proposed MPA receiver is equal to the function of initial information at traditional MPA receiver multiplied by the corresponding amplification factor. As the number of nonzero elements of transmitted codewords of NCMA multiplexed on each resource node is totally different or not exactly the same, the amplification factor on each resource node is totally different or not exactly the same. Moreover, if $d_{k_1 f}$ is less than $d_{k_2 f}$, $\varepsilon_{k_1}$ is more than $\varepsilon_{k_2}$, where $k_1 \neq k_2$, $\forall k_1, k_2 = 1, 2, \ldots, K$.

*4.2. Performance Analysis of NCMA Scheme.* In this paper, the NCMA scheme is proposed to improve the quality of initial information on each resource node and the convergence reliability of the detected layer in each decision process at the proposed MPA receiver. The performance analysis of the proposed NCMA scheme is presented in two aspects as follows.

(i) The quality of initial information on resource node $k$ can be improved by enlarging the decision region of $\widehat{y_k}$ [7], where $\widehat{y_k}$ is the expected symbol on resource node $k$, $\forall k = 1, \ldots, K$. On resource node $k$, if there are interfering nonzero elements of transmitted codewords, increasing $n(p_k(z))$ will enlarge the decision region of $\widehat{y_k}$. In the codebook design of NCMA, a novel criterion of permutation set is proposed. The proposed criterion of permutation set maximizes $n(p_1(z)) + \cdots + n(p_{K_s}(z))$ and minimizes the variance of all the elements in $n(p(z)) = \{n(p_1(z)), n(p_2(z)), \ldots, n(p_{K_s}(z))\}$ and therefore can maximize $n(p_k(z))$, $\forall k = 1, \ldots, K_s$. On the other side, on resource node $k$, if there are no interfering nonzero elements of transmitted codewords, the decision region of $\widehat{y_k}$ can be enlarged by increasing the minimum intrapartition distance. If $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$, the factor graph matrix of NCMA can be expressed as $F_1 = \begin{bmatrix} 1&1&1&1&1 \\ 1&1&1&1&0 \\ 1&1&1&0&0 \\ 1&1&0&0&0 \\ 1&0&0&0&0 \end{bmatrix}$. According to $F_1$, we can conclude that there are no interfering nonzero elements of transmitted codewords multiplexed on resource node 5 in the first decision process. If the transmitted codeword of layer 1 has been detected in the first decision process, there will be no interfering nonzero elements of transmitted codewords multiplexed on resource node 4 in the second decision process. It will do the same for resource node 1, resource node 2, and resource node 3 in the other decision processes. In the codebook design of NCMA, a novel basic complex multidimension constellation design is proposed. As illustrated in Section 3.1.2, the proposed basic complex multidimension constellation design increases the minimum intrapartition distance compared with the basic complex multidimension constellation design of SCMAA.

(ii) In each decision process, the convergence reliability of the detected layer is related to the differences between the reliabilities of detections on all undetected layers and the differences between the reliabilities of detections on the codewords of each undetected layer [7]. Therefore, a novel mapping matrix and an advanced MPA receiver are proposed in the NCMA scheme.

According to the proposed mapping matrix of NCMA, we can conclude that the number of nonzero elements occupied by each transmitted layer is totally different, and the number of nonzero elements of transmitted codewords multiplexed on each resource node is totally different or not exactly the same. Benefiting from the nonuniform characteristic of NCMA, the differences between the reliabilities of detections on all undetected layers will be increased in each decision process, and the detection order of transmitted layers is fixed at the proposed MPA receiver; that is, layer 1 is detected in the first decision process, layer 2 is detected in the second decision process, ..., and layer $J$ is detected in the $J$th decision process. Detailed analysis is shown as follows. According to $F_1$ in second paragraph of Section 4.2, we can conclude that $n_{1f} > n_{2f} > n_{3f} > n_{4f} > n_{5f}$ and $d_{1f} > d_{2f} > d_{3f} > d_{4f} > d_{5f}$. In formula (10), $\mu(x_j)$ is equal to $\sum_{l\in\Phi(j)} v_{l\to j}(x_j)$, and $\Phi(j)$ is determined by $n_{jf}$. The more $n_{jf}$ is, the more detection information layer $j$ obtains, $\forall j = 1,\ldots,J$. On the other side, in formula (8), the value of $\|y_k - \sum_{i\in\psi(k)} x_{i,k}h_k\|^2$ is determined by $\psi(k)$, and $\psi(k)$ is determined by $d_{kf}$. The less $d_{kf}$ is, the less the value of $\|y_k - \sum_{i\in\psi(k)} x_{i,k}h_k\|^2$ is, $\forall k = 1,\ldots,K$. Hence the quality of initial information on resource node $k$ can be improved by decreasing $d_{kf}$, $\forall k = 1,\ldots,K$. As $d_{5f} < d_{kf}$ and there are no interfering nonzero elements of transmitted codewords multiplexed on resource node 5, the quality of initial information on resource node 5 obviously outperforms that on resource node $k$, $\forall k = 1,2,3,4$. In the first decision process at the proposed MPA receiver, as $n_{1f} > n_{jf}$ and resource node 5 is only occupied by layer 1, layer 1 can obtain more reliable detection information than layer $j$ ($\forall j = 2,3,4,5$), and therefore layer 1 is detected. After layer 1 has been detected, there will be no interfering nonzero elements of transmitted codewords multiplexed on resource node 4 and $d_{4f} < d_{kf}$, and therefore the quality of initial information on resource node 4 will obviously outperform that on resource node $k$, $\forall k = 1,2,3$. In the second decision process, as $n_{2f} > n_{jf}$ and resource node 4 is occupied by layer 2, layer 2 can obtain more reliable detection information than layer $j$ ($\forall j = 3,4,5$), and therefore layer 2 is detected. It will do the same for layer 3, layer 4, and layer 5 in their corresponding decision processes. Therefore, for $F_1$, layer 1 is detected in the first decision process, layer 2 is detected in the second decision process, layer 3 is detected in the third decision process, layer 4 is detected in the fourth decision process, and layer 5 is detected in the fifth decision process. In any other NCMA scheme with different parameters, the detection order of transmitted layers is similar to that of transmitted layers in the NCMA scheme with $N_1 = 5$, $N_2 = 4$, $N_3 = 3$, $N_4 = 2$, and $N_5 = 1$. In addition, in each decision process, the proposed MPA receiver of NCMA selects the codeword of which the value of final cost function is the least, after detecting the codewords of a given transmitted layer. However, in each decision process, traditional MPA receiver selects the codeword of which the value of final cost function is the least, after detecting the codewords of all the undetected transmitted layers. Therefore, the complexity of the proposed MPA receiver is less than that of traditional MPA receiver.

In each decision process at the proposed MPA receiver, the amplification factor in the function of initial information can increase the differences between the reliabilities of detections on the codewords of each undetected layer and therefore can improve the reliability of detection on each transmitted layer. Detailed analysis is shown as follows. As illustrated in the fourth paragraph of Section 4.2, the less $d_{kf}$ is, the higher the quality of initial information on resource node $k$ is, $\forall k = 1,\ldots,K$. Therefore, in the process of detection on a transmitted codeword, we can prefer the information of such resource node occupied by the codeword, the interferences on which are less than those on another resource node. According to $F_1$ in second paragraph of Section 4.2, we can conclude that $d_{1f} > d_{2f} > d_{3f} > d_{4f} > d_{5f}$. As illustrated in Section 4.1, if $d_{k_1 f}$ is less than $d_{k_2 f}$, $\varepsilon_{k_1}$ is more than $\varepsilon_{k_2}$, where $k_1 \neq k_2$, $\forall k_1, k_2 = 1,2,\ldots,K$. Hence $\varepsilon_5 > \varepsilon_4 > \varepsilon_3 > \varepsilon_2 > \varepsilon_1$, and therefore the ratio of detection information on the resource nodes with less interferences to that on all the resource nodes in $\mu(x_1)$ will be increased. On the other side, $\varepsilon_k$ can increase the difference between $\gamma_k(x_1^i)$ and $\gamma_k(x_1^j)$, and therefore the difference between $\mu(x_1^i)$ and $\mu(x_1^j)$ will be increased, where $x_1^i$ and $x_1^j$ are the codewords of layer 1, $\forall i \neq j, i, j = 1,\ldots,M_1$, $\forall k = 1,\ldots,5$. All in all, the amplification factor can further increase the differences between the reliabilities of detections on the codewords of layer 1 and therefore improve the reliability of detection on layer 1. It will do the same for the other layers. For the factor graph of NCMA with other parameters, the amplification factor can also improve the reliability of detection on each transmitted layer.

For SCMAA, the convergence reliability of the detected layer in each decision process is unsatisfactory at traditional

MPA receiver. Detailed analysis is shown as follows. If $J = 6$ and $K = 4$, the factor graph matrix of SCMAA can be expressed as $F_S = \begin{bmatrix} 1&1&1&0&0&0 \\ 1&0&0&1&1&0 \\ 0&1&0&1&0&1 \\ 0&0&1&0&1&1 \end{bmatrix}$. According to $F_S$, we can conclude that $n_{1f} = n_{2f} = n_{3f} = n_{4f} = n_{5f} = n_{6f}$ and $d_{1f} = d_{2f} = d_{3f} = d_{4f}$. Limited by the uniform characteristic of SCMAA, the differences between the reliabilities of detections on all undetected transmitted layers in each decision process cannot be obtained by increasing the differences between any two elements in $n_f = \{n_{1f}, n_{2f}, n_{3f}, n_{4f}, n_{5f}, n_{6f}\}$ and the differences between any two elements in $d_f = \{d_{1f}, d_{2f}, d_{3f}, d_{4f}\}$. On the other side, under some initial conditions (these initial conditions are as follows. (i) The value of $x_j^S$ is expectation, where $x_j^S$ is the value of layer node $j$ of SCMAA, $\forall j = 1, 2, \ldots, 6$. (ii) The initial values of $v_{k\to j}(x_j^S)$ and $\mu_{j\to k}(x_j^S)$ are 0, $\forall k = 1, 2, 3, 4, \forall j = 1, 2, \ldots, 6$), the difference between $\mu(x_1^S)$ and $\mu(x_6^S)$ can be expressed as $\mu(x_1^S) - \mu(x_6^S) = |\gamma_2^S - \gamma_4^S| - |\gamma_1^S - \gamma_3^S|$, and the difference between $\mu(x_3^S)$ and $\mu(x_4^S)$ can be expressed as $\mu(x_3^S) - \mu(x_4^S) = |\gamma_3^S - \gamma_4^S| - |\gamma_1^S - \gamma_2^S|$, where $\mu(x_j^S)$ is the final cost function of layer node $j$ when the value of layer node $j$ of SCMAA is $x_j^S$ and $\gamma_k^S$ is the function of initial information on resource node $k$ at traditional MPA receiver. Detailed derivation process of the difference between $\mu(x_1^S)$ and $\mu(x_6^S)$ refers to [7] and so is the difference between $\mu(x_3^S)$ and $\mu(x_4^S)$. At traditional MPA receiver, the larger the difference between any two elements in $\mu^S = \{\mu(x_1^S), \mu(x_2^S), \ldots, \mu(x_J^S)\}$ is, the larger the differences between the reliabilities of detections on all undetected layers in each decision process. Moreover, in each decision process, the larger the differences between the reliabilities of detections on all undetected layers are, the higher the convergence reliability of the detected layer is [7]. As illustrated in Section 3.3.2, the criterion of permutation set of SCMAA increases neither the difference between $|n(p_2(z)) - n(p_4(z))|$ and $|n(p_1(z)) - n(p_3(z))|$ nor the difference between $|n(p_3(z)) - n(p_4(z))|$ and $|n(p_1(z)) - n(p_2(z))|$. That is, the criterion of permutation set of SCMAA increases neither the difference between $|\gamma_2^S - \gamma_4^S|$ and $|\gamma_1^S - \gamma_3^S|$ nor the difference between $|\gamma_3^S - \gamma_4^S|$ and $|\gamma_1^S - \gamma_2^S|$ ($\gamma_k^S$ is determined by $n(p_k(z))$ [7], $\forall k = 1, \ldots, 4$). Therefore, the criterion of permutation set of SCMAA will attenuate the convergence reliability of layer 1, layer 3, layer 4, and layer 6 in their corresponding decision processes at traditional MPA receiver. It will do the same in the process of detections on the transmitted layers of SCMAA scheme with other parameters. In summary, in each decision process, the increase of the differences between the reliabilities of detections on all undetected transmitted layers is limited by the uniform characteristic of SCMAA, and the criterion of SCMAA fails to increase the differences between the reliabilities of detections on some undetected layers. Hence the convergence reliability of the detected layer of SCMAA in each decision process is unsatisfactory.

According to (ii), we can conclude that, benefiting from the proposed mapping matrix and the proposed MPA receiver, NCMA can further improve the convergence reliability of the detected layer in each decision process compared with SCMAA.

## 5. Simulation Results

In this section, simulations are based on long-term evolution (LTE) system [18], and the channel code uses Turbo code with the rate 1/2. In NCMA, SCMAA, and SCMA, the number of iterations is 4 at the proposed MPA receiver and traditional MPA receiver (traditional MPA receiver is applied in SCMAA and SCMA). For NCMA, the real 2-dimension constellation is constructed by sphere packing with $A_2$, the real 4-dimension constellation is constructed by sphere packing with $D_4$, the real 6-dimension constellation is constructed by sphere packing with $E_6$, the real 8-dimension constellation is constructed by sphere packing with $E_8$, and the real 10-dimension constellation is constructed by sphere packing with $\Lambda_{10}$ [15]. For SCMAA and SCMA, the set of basic complex two-dimension signals is constructed by 2-fold Cartesian product of a QPSK set. As the spectral efficiency is 2 bits/tone, NCMA uses the factor graph with $N_1 = 4, N_2 = 3$, and $N_3 = 1$, while SCMAA and SCMA use the factor graph (for SCMAA and SCMA, the factor graph is shown in [7]) with $J = 4$ and $K = 4$. As the spectral efficiency is 3 bits/tone, NCMA uses the factor graph with $N_1 = 5, N_2 = 4, N_3 = 3, N_4 = 2$, and $N_5 = 1$, while SCMAA and SCMA use the factor graph with $J = 6$ and $K = 4$. In the following, NCMA with traditional MPA receiver is short for the NCMA scheme, where the proposed codebook design and traditional MPA receiver are applied, and NCMA with proposed MPA receiver is short for the NCMA scheme, where the proposed codebook design and the proposed MPA receiver are applied.

Figure 4 is the BLER performance of NCMA with traditional MPA receiver, SCMAA with traditional MPA receiver, and SCMA with traditional MPA receiver over AWGN channel with spectral efficiency 2 bits/tone. As can be observed in Figure 4, the BLER performance of NCMA with traditional MPA receiver outperforms that of SCMAA with traditional MPA receiver, while the BLER performance of SCMAA with traditional MPA receiver outperforms that of SCMA with traditional MPA receiver. NCMA with traditional MPA receiver has 1.1 dB gain over SCMAA with traditional MPA receiver. Figure 5 is the BLER performance of NCMA with traditional MPA receiver, SCMAA with traditional MPA receiver, and SCMA with traditional MPA receiver over AWGN channel with spectral efficiency of 3 bits/tone. As can be observed in Figure 5, the BLER performance of NCMA with traditional MPA receiver outperforms that of SCMAA with traditional MPA receiver, while the BLER performance of SCMAA with traditional MPA receiver outperforms that of SCMA with traditional MPA receiver. NCMA with traditional MPA receiver has 1.4 dB gain over SCMAA with traditional MPA receiver. Simulation results show that the proposed codebook design of NCMA can improve the performance of traditional MPA receiver compared with the codebook design of SCMAA over AWGN channel.

Figure 6 is the BLER performance of NCMA with proposed MPA receiver, SCMAA with traditional MPA receiver,

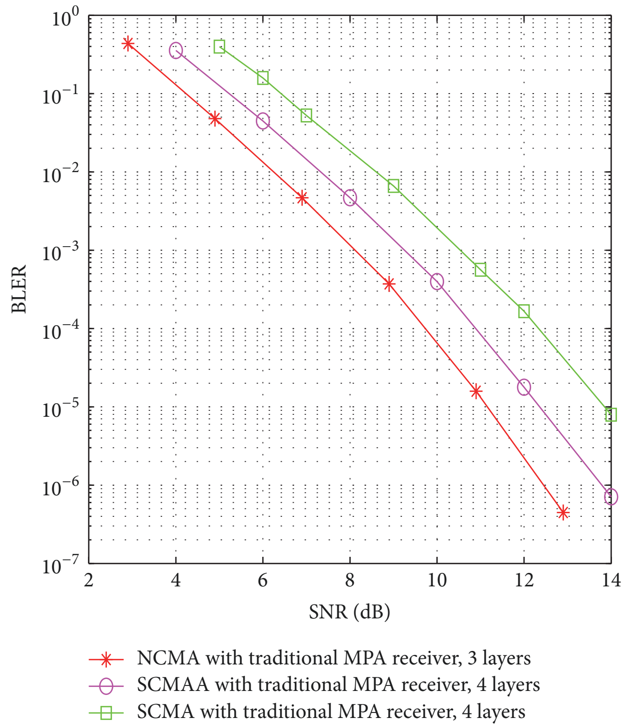


Figure 4: NCMA with traditional MPA receiver versus SCMAA with traditional MPA receiver and SCMA with traditional MPA receiver over AWGN channel with 2 bits/tone.

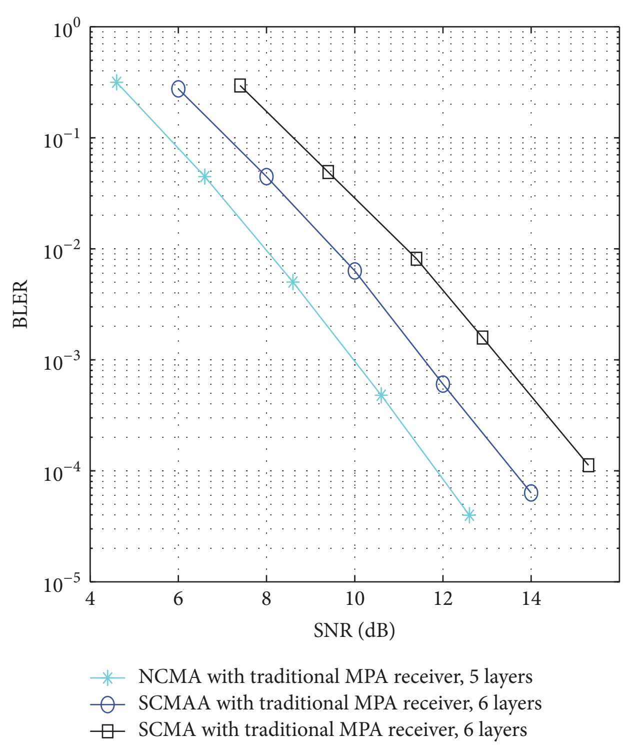


Figure 5: NCMA with traditional MPA receiver versus SCMAA with traditional MPA receiver and SCMA with traditional MPA receiver over AWGN channel with 3 bits/tone.

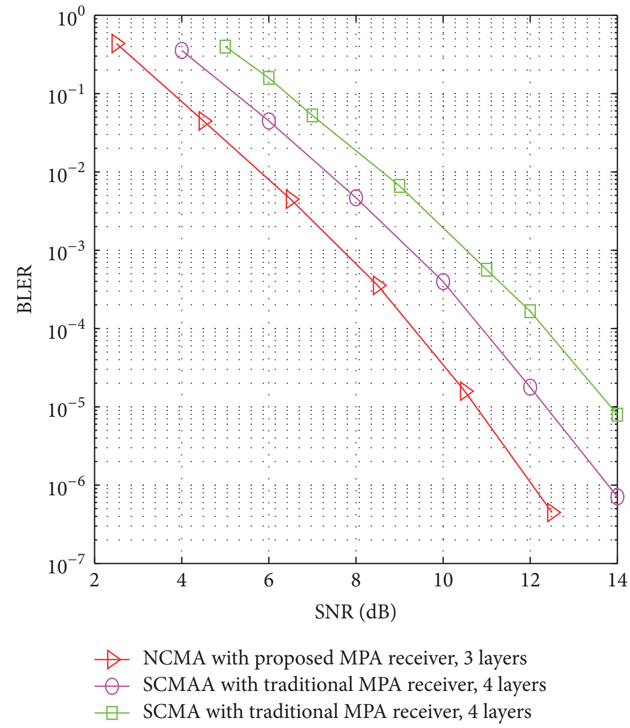


Figure 6: NCMA with proposed MPA receiver versus SCMAA with traditional MPA receiver and SCMA with traditional MPA receiver over AWGN channel with 2 bits/tone.

and SCMA with traditional MPA receiver over AWGN channel with spectral efficiency of 2 bits/tone. As can be observed in Figure 6, the BLER performance of NCMA with proposed MPA receiver outperforms that of SCMAA with traditional MPA receiver, while the BLER performance of SCMAA with traditional MPA receiver outperforms that of SCMA with traditional MPA receiver. NCMA with proposed MPA receiver has 1.5 dB gain over SCMAA with traditional MPA receiver. As can be observed in Figures 4 and 6, the BLER performance of NCMA with proposed MPA receiver outperforms that of NCMA with traditional MPA receiver. Figure 7 is the BLER performance of NCMA with proposed MPA receiver, SCMAA with traditional MPA receiver, and SCMA with traditional MPA receiver over AWGN channel with spectral efficiency of 3 bits/tone. As can be observed in Figure 7, the BLER performance of NCMA with proposed MPA receiver outperforms that of SCMAA with traditional MPA receiver, while the BLER performance of SCMAA with traditional MPA receiver outperforms that of SCMA with traditional MPA receiver. NCMA with proposed MPA receiver has 1.9 dB gain over SCMAA with traditional MPA receiver. As can be observed in Figures 5 and 7, the BLER performance of NCMA with proposed MPA receiver outperforms that of NCMA with traditional MPA receiver. Simulation results show that the proposed MPA receiver can further improve the convergence reliability of the detected layer in each decision process compared with traditional MPA receiver over AWGN channel.

Figure 8 is the capacity of NCMA with proposed MPA receiver, SCMAA with traditional MPA receiver, and SCMA

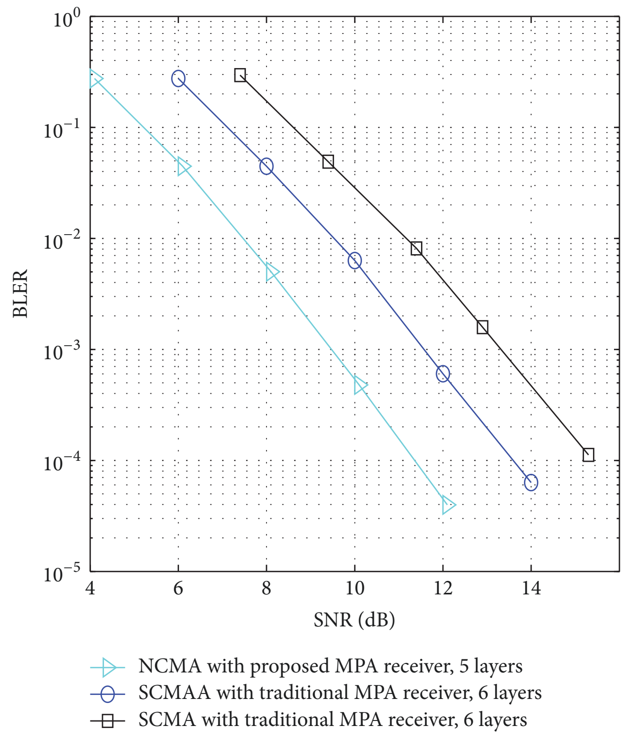


Figure 7: NCMA with proposed MPA receiver versus SCMAA with traditional MPA receiver and SCMA with traditional MPA receiver over AWGN channel with 3 bits/tone.

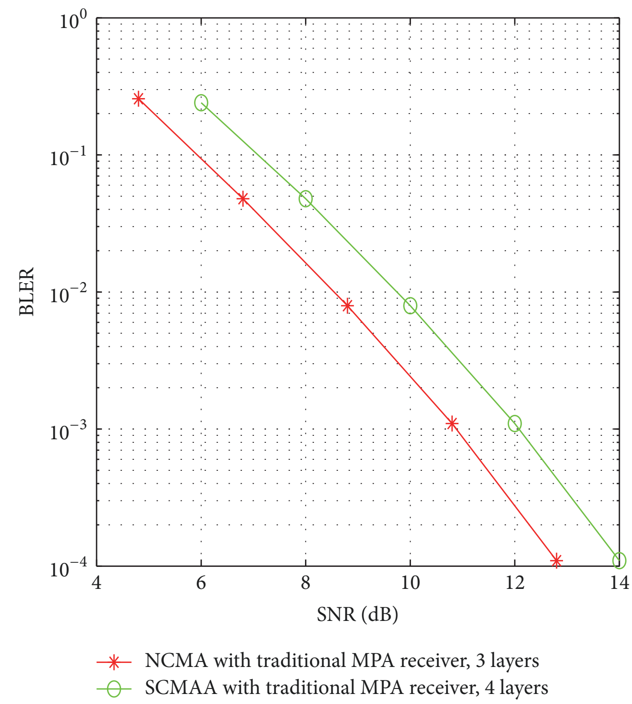


Figure 9: NCMA with traditional MPA receiver versus SCMAA with traditional MPA receiver over fading channel with 2 bits/tone.

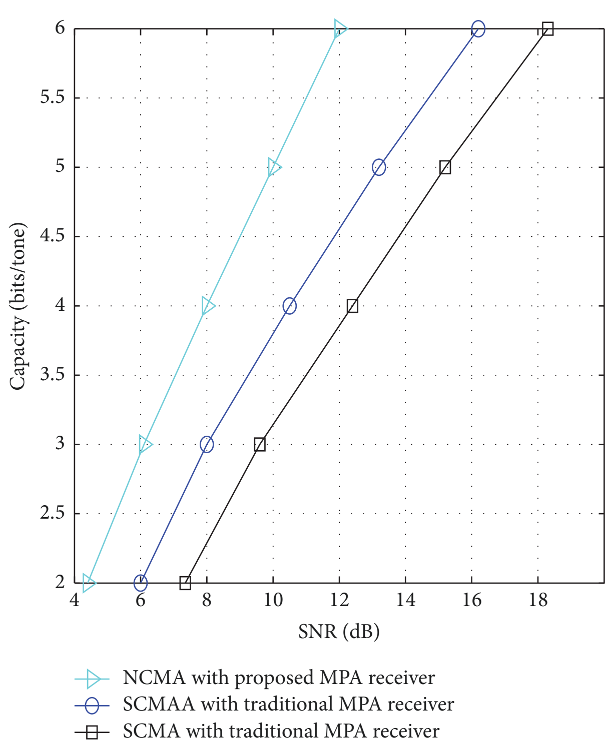


Figure 8: Capacity of NCMA with proposed MPA receiver, SCMAA with traditional MPA receiver, and SCMA with traditional MPA receiver over AWGN channel.

with traditional MPA receiver over AWGN channel. For each target spectral efficiency, the minimum SNR is selected to guarantee the appropriate performance for each waveform. As can be observed in Figure 8, we can conclude that, compared with SCMAA with traditional MPA receiver and SCMA with traditional MPA receiver, the gain of NCMA with proposed MPA receiver is obvious, and it grows as the SNR increases.

In Figures 9, 10, 11, and 12, the simulations are based on downlink LTE system, and 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 [18]. The carrier frequency is 2 GHz and the frequency spacing is 15 KHz. A data payload occupies 6 LTE resource blocks (RBs). Figure 9 is the BLER performance of NCMA with traditional MPA receiver and SCMAA with traditional MPA receiver over fading channel with spectral efficiency of 2 bits/tone. As can be observed in Figure 9, the BLER performance of NCMA with traditional MPA receiver outperforms that of SCMAA with traditional MPA receiver, and NCMA with traditional MPA receiver has 1.2 dB gain over SCMAA with traditional MPA receiver. Figure 10 is the BLER performance of NCMA with traditional MPA receiver and SCMAA with traditional MPA receiver over fading channel with spectral efficiency of 3 bits/tone. As can be observed in Figure 10, the BLER performance of NCMA with traditional MPA receiver outperforms that of SCMAA with traditional MPA receiver, and NCMA with traditional MPA receiver has 1.8 dB gain over SCMAA with traditional MPA receiver. Simulation results show that the proposed

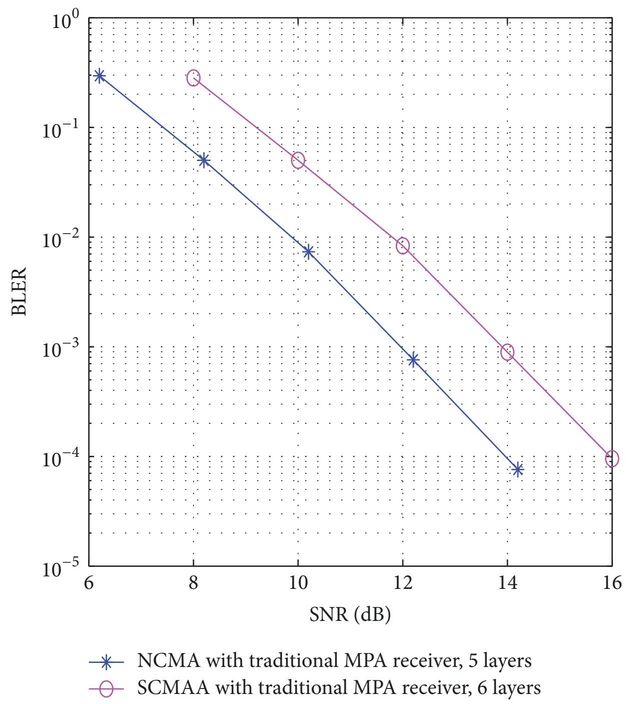


FIGURE 10: NCMA with traditional MPA receiver versus SCMAA with traditional MPA receiver over fading channel with 3 bits/tone.

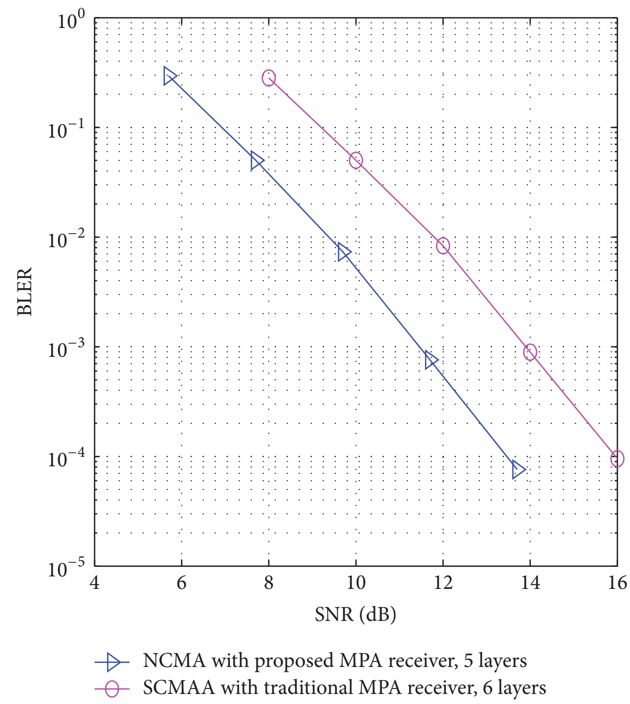


FIGURE 12: NCMA with proposed MPA receiver versus SCMAA with traditional MPA receiver over fading channel with 3 bits/tone.

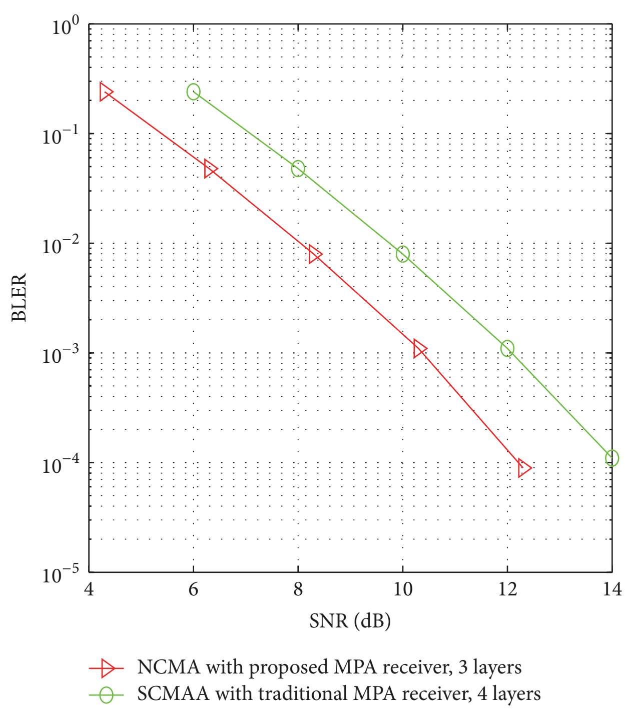


FIGURE 11: NCMA with proposed MPA receiver versus SCMAA with traditional MPA receiver over fading channel with 2 bits/tone.

codebook design of NCMA can improve the performance of traditional MPA receiver compared with the codebook design of SCMAA over fading channel.

Figure 11 is the BLER performance of NCMA with proposed MPA receiver and SCMAA with traditional MPA receiver over fading channel with spectral efficiency of 2 bits/tone. As can be observed in Figure 11, the BLER performance of NCMA with proposed MPA receiver outperforms that of SCMAA with traditional MPA receiver, and NCMA with proposed MPA receiver has 1.7 dB gain over SCMAA with traditional MPA receiver. As can be observed in Figures 9 and 11, the BLER performance of NCMA with proposed MPA receiver outperforms that of NCMA with traditional MPA receiver. Figure 12 is the BLER performance of NCMA with proposed MPA receiver and SCMAA with traditional MPA receiver over fading channel with spectral efficiency of 3 bits/tone. As can be observed in Figure 12, the BLER performance of NCMA with proposed MPA receiver outperforms that of SCMAA with traditional MPA receiver, and NCMA with proposed MPA receiver has 2.3 dB gain over SCMAA with traditional MPA receiver. As can be observed in Figures 10 and 12, the BLER performance of NCMA with proposed MPA receiver outperforms that of NCMA with traditional MPA receiver. Simulation results show that the proposed MPA receiver can further improve the convergence reliability of the detected layer in each decision process compared with traditional MPA receiver over fading channel.

## 6. Conclusions

This paper proposes a NCMA scheme. In the NCMA codebook design, different transmitted layers are generated from different complex multidimension constellations, respectively, and the proposed basic complex multidimension constellation design increases the minimum intrapartition distance compared with the basic complex multidimension constellation design of SCMAA. Then the proposed criterion of permutation set maximizes the sum of distances between interfering dimensions of transmitted codewords multiplexed on any resource node, where the number of nonzero elements of transmitted codewords is more than 1. On the other side, in each decision process, the proposed mapping matrix of NCMA and the proposed MPA receiver increase the differences between the reliabilities of detections on all undetected layers and the differences between the reliabilities of detections on the codewords of each undetected layer. In summary, benefiting from the proposed codebook design and the proposed MPA receiver, NCMA is superior to SCMAA in the interlayer interference cancellation.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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