

Quantum k -uniform states for heterogeneous systems from irredundant mixed orthogonal arrays

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Quantum multipartite entangled states play significant roles in quantum information processing. By using difference schemes and orthogonal partitions, we construct a series of infinite classes of irredundant mixed orthogonal arrays (IrMOAs) and thus provide positive answers to two open problems. The first is the extension of the method for constructing homogeneous systems from orthogonal arrays (OAs) to heterogeneous multipartite systems with different individual levels. The second is the existence of k -uniform states in heterogeneous quantum systems. We present explicit constructions of two and three-uniform states for arbitrary heterogeneous multipartite systems with coprime individual levels, and characterize the entangled states in heterogeneous systems consisting of subsystems with nonprime power dimensions as well. Moreover, we obtain infinite classes of k -uniform states for heterogeneous multipartite systems for any $k \geq 2$. The non-existence of a class of IrMOAs is also proved.

Keywords: Quantum entanglement, Quantum k -uniform states, Heterogeneous systems, Irredundant mixed orthogonal arrays, Orthogonal partitions, Expansive replacement method

1 Introduction

Quantum entanglement has been used as a resource to experimentally demonstrate various modern quantum technologies. Genuinely multipartite quantum states are particularly useful in quantum information theory [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. Recently considerable progress has been achieved in the construction and characterization of k -uniform states for homogeneous systems [1, 5, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. Among the constructions of k -uniform states for homogeneous systems, Goyeneche et al. [5] provided a link between an irredundant orthogonal array (IrOA) and quantum k -uniform state and constructed two-uniform states for an arbitrary number of $N \geq 6$ qubits by using known Hadamard matrices. Based on Hamming distances of orthogonal arrays (OAs) with difference schemes and orthogonal partitions, Pang et al. [22] explicitly constructed infinite classes of k -uniform states for $k = 2, 3$. Furthermore, by using the product construction [25], Bush's construction, binary double-error-correcting BCH codes and expansive replacement method [26], Pang et al. [27] constructed infinitely classes of k -uniform states for $k \geq 4$. In addition, k -uniform states can be constructed from mutually orthogonal Latin squares and Latin cubes [21], graph states [28] and quantum combinatorial designs [1]. Based on symmetric matrices and the concatenation of algebraic geometry

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codes, Feng et al. [23] gave an explicit construction of k -uniform quantum state when k tends to infinity. However, for heterogeneous systems despite some related nice results [20, 29, 30, 31, 32, 33, 34], little is known about the k -uniform states, especially for five-partite systems or $k \geq 3$.

A highly entangled quantum state of heterogeneous multipartite systems composed of $N > 2$ parties is said to be k -uniform if every reduction to k parties is maximally mixed [20]. If an $r \times N$ array having n_i columns with d_i levels, where $i = 1, 2, \dots, l$, l is an integer, $N = \sum_{i=1}^l n_i$, and $d_i \neq d_j$ for $i \neq j$, satisfies all possible k -tuples appeared as a row equally often in any $r \times k$ submatrix, then it is a mixed OA, written as $\text{MOA}(r, N, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, k)$ or $\text{MOA}(r, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, k)$. If $l = 1$, then it is called a symmetrical OA, written as $\text{OA}(r, N, d_1, k)$ [26]. An $\text{MOA}(r, N, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, k)$ is said to be an IrMOA if all of its rows in any $r \times (N - k)$ subarray are different [20]. Let \mathbb{C}^d be a d -dimensional Hilbert space. An IrMOA($r, N, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, k$) has been shown to lead to a k -uniform state which belongs to a Hilbert space $(\mathbb{C}^{d_1})^{\otimes n_1} \otimes (\mathbb{C}^{d_2})^{\otimes n_2} \otimes \cdots \otimes (\mathbb{C}^{d_l})^{\otimes n_l}$ [20]. If

$$L = \begin{pmatrix} a_1^1 & a_2^1 & \cdots & a_N^1 \\ a_1^2 & a_2^2 & \cdots & a_N^2 \\ \vdots & \vdots & \cdots & \vdots \\ a_1^r & a_2^r & \cdots & a_N^r \end{pmatrix}$$

is an IrMOA($r, N, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, k$), then the superposition of r product states,

$$|\phi_{d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}}\rangle = |a_1^1 a_2^1 \cdots a_N^1\rangle + |a_1^2 a_2^2 \cdots a_N^2\rangle + \cdots + |a_1^r a_2^r \cdots a_N^r\rangle,$$

is a k -uniform state of the heterogeneous system $d_1^{n_1} \times d_2^{n_2} \times \cdots \times d_l^{n_l}$.

Although the characterization of quantum k -uniform states in heterogeneous systems is notoriously hard, the quantum k -uniform states in heterogeneous play fundamental roles in quantum information processing such as quantum teleportation [8, 9, 10, 11], quantum key distribution [12], dense coding and error correcting codes [6, 7] and quantum computation [13]. An absolutely maximally entangled (AME) state of heterogeneous system consisting N subsystems requires that all the reductions to $\lfloor \frac{N}{2} \rfloor$ parties are maximally mixed [20]. The k -uniform states include AME states as the special ones, which play a critical role in obtaining certain classes of multipartite protocols and have close connection to holography. As stated in [22], the higher the uniformity of the multipartite entangled states, the more advantages they offer. Remarkably, the subsystems of more than two levels can improve the security of some quantum information protocols [35] and enhance the capacity of quantum channels [36] and the efficiency of quantum gates [37]. A genuinely tripartite entangled state consisting of one qubit and two qutrits had been produced experimentally [38]. The heterogeneous systems enable one to implement quantum steering more efficiently. One may expect that multipartite entangled states of heterogeneous systems will be implemented experimentally too in quantum information processing in the near future.

These researches have motivated further studies on protecting entanglement under decoherence [39, 40] and finding k -uniform states with higher uniformity in heterogeneous systems. However, the theory of quantum entanglement in heterogeneous systems is far from satisfactory. In this article, we aim to solve two open problems. One is the extension of the method for constructing homogeneous systems from OAs to heterogeneous systems [5]. The second open problem is the existence of k -uniform states for heterogeneous quantum systems [20].

The OAs have been used for designing experiments to systematically plan statistical data collection. As is often the case, OAs can be very useful for quantum information theory [22, 41, 42, 43]. Recently, many new construction methods of MOAs with high strength have been provided [44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54]. Such new developments in MOAs make it possible to obtain infinitely many new k -uniform states in heterogeneous systems from IrMOAs.

In this paper, we generalize difference scheme method and orthogonal partition method for constructing IrOAs [22] to IrMOAs. In addition, the expansive replacement method is introduced for constructing more IrMOAs. As a result, we obtain a series of infinite classes of IrMOAs and thus provide positive answers to the above two open problems. In particular, we find several infinite classes of examples of three-uniform states for heterogeneous systems. We not only present explicit constructions of two and three-uniform states for heterogeneous multipartite systems consisting of subsystems with coprime levels, but also characterize entanglement states in heterogeneous systems consisting of subsystems with nonprime power dimensions. Moreover, we obtain infinite classes of k -uniform states for heterogeneous multipartite systems for every $k \geq 2$. Finally, we prove that the non-existence of $\text{IrMOA}(r, 5, d_1 \times d_2 \times d_3 \times d_4 \times d_5, 2)$ under certain conditions.

This paper is organized as follows. In Sect. 2 we introduce some concepts and related Lemmas. In Subsect. 3.1, by using difference schemes and orthogonal partitions, we find several infinite classes of two and three-uniform states for heterogeneous systems with coprime levels. In Subsect. 3.2, by using expansive replacement method, we construct several new infinite classes of k -uniform states for arbitrary heterogeneous multipartite systems consisting of subsystems with coprime and nonprime power dimensions or with different powers of a prime for any $k \geq 2$. Section 3 provides positive answers to the two above-mentioned open problems and the proof of the non-existence of $\text{IrMOA}(r, 5, d_1 \times d_2 \times d_3 \times d_4 \times d_5, 2)$ under certain conditions. Section 4 draws the concluding remarks. Proofs of some lemmas, theorems and corollaries are presented in Appendix A. In Appendix B, we give further examples of k -uniform states for heterogeneous systems. All tables are relegated to Appendix C. The IrMOAs constructed in Example 6 are summarized in Supplementary information.

2 Preliminaries

We first introduce some notations, concepts and lemmas that will be used in this paper. Let A^T be the transpose of matrix A and $(\mathbf{d}) = (0, 1, \dots, d-1)^T$. Let $\mathbf{0}_r$ and $\mathbf{1}_r$ denote the $r \times 1$ vectors of 0s and 1s, respectively. The Kronecker product $A \otimes B$ is defined in [26] and the Kronecker sum $A \oplus B$ is the Kronecker product with multiplication replaced by a binary operation on a group G . Let H_n be a Hadamard matrix of order n with elements from a finite field $F_2 = \{0, 1\}$. $\text{HD}(A)$ represents all the values of the Hamming distances [26] between two distinct rows of a matrix A . The minimal distance of A , written as $\text{MD}(A)$, is defined as the minimal value of $\text{HD}(A)$. For simplicity, we introduce the following notation:

$$(A_{[1,2,\dots,u]}, r) = \begin{pmatrix} A_1 \otimes \mathbf{1}_r \\ A_2 \otimes \mathbf{1}_r \\ \vdots \\ A_u \otimes \mathbf{1}_r \end{pmatrix} \text{ and } (r, A_{[1,2,\dots,u]}) = \begin{pmatrix} \mathbf{1}_r \otimes A_1 \\ \mathbf{1}_r \otimes A_2 \\ \vdots \\ \mathbf{1}_r \otimes A_u \end{pmatrix} \text{ for matrix } A_j (j = 1, 2, \dots, u) \text{ and}$$

positive integers u and r .

Lemma 2.1. Suppose that A is an MOA($r, N, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, 2$) and that B is a difference scheme $D(r, r, d)$. Then, $C = [A \oplus \mathbf{0}_d, B \oplus (\mathbf{d})]$ is an MOA($dr, N + r, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l} d^r, 2$) and $\text{MD}(C) = \min\{r, \text{MD}(A) + r - \frac{r}{d}\}$.

Lemma 2.2. The existence of an MOA($r, N, d_1^{n_1} d_2^{n_2} \cdots d_l^{n_l}, k$) with minimal distance $w \geq k + 1$ implies the existence of an IrMOA($r, N', d_1^{x_1} d_2^{x_2} \cdots d_l^{x_l}, k$) for $N - w + k + 1 \leq N' \leq N$ with $0 \leq x_i \leq n_i$ and $1 \leq i \leq l$.

By using orthogonal partition, we present a method for constructing symmetrical OAs whose Hamming distances can be determined in Ref. [22]. The following lemma extends the result for constructing MOAs.

Lemma 2.3. Let $\{A_1, A_2, \dots, A_u\}$ be an orthogonal partition of strength 1 of $A = \text{OA}(r', N', d', k')$, and let $\{B_1, B_2, \dots, B_v\}$ be an orthogonal partition of strength 1 of $B = \text{OA}(r'', N'', d'', k'')$ for $r' = d'u, r'' = d''v, u \leq v$, and $k', k'' \geq 3$. Suppose that $\text{MD}(A) = w_1$ and $\text{MD}(B) = w_2$. Let $h = \text{l.c.m.}\{u, v\}$. Then, the matrix $M = (\mathbf{1}_{\frac{h}{u}} \otimes (A_{[1,2,\dots,u]}, d''), \mathbf{1}_{\frac{h}{v}} \otimes (d', B_{[1,2,\dots,v]}))$ is an MOA($d'd''h, N' + N'', d'^N d''^{N''}, 3$), and

$$\text{MD}(M) \geq \begin{cases} \min\{w_1 + w_2, N', N''\}, & \text{if } u = v, \\ \min\{N', w_2\}, & \text{if } u \neq v, u < v, \\ \min\{w_1, w_2\}, & \text{otherwise.} \end{cases}$$

Lemma 2.4. (Expansive replacement method). Suppose A is an MOA of strength k with column 1 having d_1 levels and that B also is an MOA of strength k with d_1 rows. After making a one-to-one mapping between the levels of column 1 in A and the rows of B , if each level of column 1 in A is replaced by the corresponding row from B , we can obtain an MOA of strength k .

3 Quantum k -uniform states of heterogeneous systems

3.1 Uniform states from orthogonal partition and difference schemes

By using known MOAs and MOAs constructed from orthogonal partition, difference schemes and Hamming distances, we construct abundant infinite classes of two and three-uniform states for heterogeneous multipartite systems of coprime levels and three-uniform states of the system $6^4 \times 2^n$ from an IrMOA($r, 4 + n, 6^4 2^n, 3$) for $n \geq 13$.

Theorem 3.1. If a $D(r, r, 2)$ and an MOA($r, a + b, 3^a 2^b, 2$) exist for $a \geq 1, b \geq 2$, then there exist an IrMOA($r', M + N, 3^M 2^N, 2$) and two-uniform states of the system $3^M \times 2^N$ for $1 \leq M \leq a$ and every $N \geq \frac{r}{2} + 3$. In particular, we have an IrMOA($r', M + N, 3^M 2^N, 2$) and two-uniform states of the system $3^M \times 2^N$ for $1 \leq M \leq 2^m 3$ and $N \geq 2^{m-1} 3^2 + 3$ with $m \geq 2$.

Let $A_0 = \text{MOA}(12, 5, 3^1 2^4, 2)$ in [55] and $B_0 = D(12, 12, 2)$ in [56]. Then we can obtain $A_1 = [A_0 \oplus \mathbf{0}_2, B_0 \oplus (\mathbf{2})] = \text{MOA}(24, 17, 3^1 2^{16}, 2)$ by Lemma 2.1. Consequently, an IrMOA($24, 1 + N_1, 3^1 2^{N_1}, 2$) exists for $9 \leq N_1 \leq 16$ by deleting $0 \leq j \leq 7$ columns from A_1 by Lemma 2.2. In fact, by deleting

any j ($0 \leq j \leq 3$) 2-level columns in A_1 , we obtain an IrMOA($24, 1 + l, 3^1 2^l, 2$) for $13 \leq l \leq 16$. However, for $3 < j \leq 7$, we need to first delete all the 2-level columns in $A_0 \oplus \mathbf{0}_2$, then delete any $j - 4$ columns in $B_0 \oplus \mathbf{(2)}$ and obtain an IrMOA($24, 1 + l, 3^1 2^l, 2$) for $9 \leq l < 13$. In addition, we have an IrMOA($48, 1 + N_2, 3^1 2^{N_2}, 2$) for $15 \leq N_2 \leq 40$ from $A_2 = [A_1 \oplus \mathbf{0}_2, B_1 \oplus \mathbf{(2)}] = \text{MOA}(48, 41, 3^1 2^{40}, 2)$, where $B_1 = D(24, 24, 2) = D(12, 12, 2) \oplus H_2$ and H_2 is a Hadamard matrix of order 2. Similarly, we can also obtain IrMOAs from A_3, A_4 and so on. Therefore, we can obtain an IrMOA($r', 1 + N, 3^1 2^N, 2$) and two-uniform states of the system $3^1 \times 2^N$ for every $N \geq 9$; especially, we can delete eight columns from A_1 to obtain a new IrMOA($24, 9, 3^1 2^8, 2$) and two-uniform state of the system $3^1 \times 2^8$.

Investigation of entanglement in heterogeneous systems was recently performed in several particular cases, e.g., for three-partite systems, $2 \times 2 \times n = 2^2 \times n$ [29, 30] and $2 \times n_1 \times n_2$ [31, 32, 33], and for four-partite systems, $2^3 \times n$ [34]. In addition, Goyeneche et al. [20] constructed one-uniform states and two-uniform states of the system $d^N \times p_1^1 \times \cdots \times p_m^1$ for m distinct primes p_1, \dots, p_m and a prime power d . However, in Theorem 3.1, by using $A_0 = \text{MOA}(r, a + b, 3^a 2^b, 2)$, $B_0 = D(r, r, 2)$ and $A_1 = [A_0 \oplus \mathbf{0}_2, B_0 \oplus \mathbf{(2)}]$, we can obtain an IrMOA($r', M + N, 3^M 2^N, 2$) for $M > 1$ and $N > 1$ which can produce two-uniform states of the system $3^M \times 2^N$. These states cannot be obtained from existing methods.

It is obvious that for any given $M \geq 1$, there is an n_M such that an IrMOA($r, M + N, 3^M 2^N, 2$) and two-uniform states of the system $3^M \times 2^N$ exist for every $N \geq n_M$.

The smaller the number of subsystems is, the more difficult to find the state in heterogeneous systems is. The method of Theorem 3.1 is recursive. By further analyzing and using the results in each step of Theorem 3.1, we can obtain more entanglement states with less subsystems.

Corollary 3.2. (1) *There exist an IrMOA($r, 1 + N, 3^1 2^N, 2$) and two-uniform states of the system $3^1 \times 2^N$ for every $N \geq 8$.*

(2) *There exist an IrMOA($r, 2 + N, 3^2 2^N, 2$) and two-uniform states of the system $3^2 \times 2^N$ for every $N \geq 12$. There exist an IrMOA($r, 3 + N, 3^3 2^N, 2$) and two-uniform states of the system $3^3 \times 2^N$ for every $N \geq 11$, and an IrMOA($r, 4 + N, 3^4 2^N, 2$) and two-uniform states of the system $3^4 \times 2^N$ for every $N \geq 10$.*

As an application of Corollary 3.2, some two-uniform states are given in Example 1 of Appendix B.

We will extend the construction of two-uniform states of the system $3^M \times 2^N$ in Theorem 3.1 to that of the system $d^M \times 2^N$ for any $d > 3$.

Theorem 3.3. *If a $D(r, r, 2)$ and an MOA($r, a + b, d^a 2^b, 2$) exist for $d > 3$, $a \geq 1$, and $b \geq 2$, then there exist an IrMOA($r', M + N, d^M 2^N, 2$) and two-uniform states of the system $d^M \times 2^N$ for $1 \leq M \leq a$ and every $N \geq \frac{r}{2} + 3$.*

Interestingly, the corresponding states obtained from the above results are not separable [57]. In fact, these states are genuinely entangled. In addition, by computing Hamming distance of known MOAs, we also construct more IrMOAs and the corresponding two-uniform states. For example, the MOA($28, 13, 7^1 2^{12}, 2$) [55] with MD= 5 yields an IrMOA($28, 1 + n, 7^1 2^n, 2$) for $n = 10, 11, 12$ by deleting

any $j(j = 0, 1, 2)$ 2-level columns of A_1 , respectively. By deleting the last $j(j = 0, 1, \dots, 9)$ 2-level columns of $\text{MOA}(60, 24, 5^1 2^{23}, 2)$ [55], respectively, we can obtain $\text{IrMOA}(60, 1 + n, 5^1 2^n, 2)$ for $n = 14, 15, \dots, 23$. Further, deleting the first 2-level column from the $\text{IrMOA}(60, 15, 5^1 2^{14}, 2)$ generates an $\text{IrMOA}(60, 14, 5^1 2^{13}, 2)$. Deleting the last $j(j = 0, 1, \dots, 6)$ 2-level columns of $\text{MOA}(60, 20, 5^1 3^1 2^{18}, 2)$ [55], we can construct an $\text{IrMOA}(60, 2 + n, 5^1 3^1 2^n, 2)$ for $n = 12, 13, \dots, 18$. Moreover, two-uniform states of the systems $7^1 \times 2^{10}$, $5^1 \times 2^{14}$, $5^1 \times 2^{13}$, $5^1 \times 3^1 \times 2^{15}$ and $5^1 \times 3^1 \times 2^{12}$ are given in Example 2 of Appendix B.

Now we consider construction of three-uniform states of heterogeneous systems by Lemma 2.3. From two OAs $A = D_3(18, 5, 3) \oplus (3)$ and $B = D_3(36 \cdot 2^{h_1}, 36 \cdot 2^{h_1}, 2) \oplus (2)$, we can obtain an $\text{IrMOA}(216 \cdot 2^{h_1}, m + n_{h_1}, 3^m 2^{n_{h_1}}, 3)$ for $4 \leq m \leq 5$ and $18 \cdot 2^{h_1} + 4 \leq n_{h_1} \leq 36 \cdot 2^{h_1}$ with every $h_1 \geq 0$. From two OAs A and $C = D_3(108 \cdot 2^{h_2}, 108 \cdot 2^{h_2}, 2) \oplus (2)$, we can construct an $\text{IrMOA}(648 \cdot 2^{h_2}, m + n'_{h_2}, 3^m 2^{n'_{h_2}}, 3)$ for $4 \leq m \leq 5$ and $54 \cdot 2^{h_2} + 4 \leq n'_{h_2} \leq 108 \cdot 2^{h_2}$ with every $h_2 \geq 0$. Therefore, we can obtain the following result.

Theorem 3.4. *There exist an $\text{IrMOA}(r, 5 + n, 3^5 2^n, 3)$, an $\text{IrMOA}(r, 4 + n, 3^4 2^n, 3)$ and three-uniform states of the systems $3^5 \times 2^n$ and $3^4 \times 2^n$ for $n \geq 16$.*

Using Theorem 3.4, we construct three-uniform states $|\phi_{3^4 2^{22}}\rangle$, $|\phi_{3^5 2^{16}}\rangle$, and $|\phi_{3^4 2^{16}}\rangle$ in Example 3 of Appendix B. The following result generalizes Theorem 3.4.

Theorem 3.5. *Let $d > 4$ be an odd prime power. If $D_3(4d^2, 4d^2, 2)$ and $D_3(12d^2, 12d^2, 2)$ exist, then there exist an $\text{IrMOA}(r, m + n, d^m 2^n, 3)$ and three-uniform states of the system $d^m \times 2^n$ for $4 \leq m \leq d$, $2d^2 + 4 \leq n \leq 4d^2$, and $n \geq 4d^2 + 4$.*

By using Theorem 3.5 and Lemma 2.3, three-uniform states of the system $5^m \times 2^n$ can be obtained for $m = 4$, $n \geq 14$ and $m = 5$, $n \geq 13$. Let $d = 5$ in Theorem 3.5. We can obtain an $\text{IrMOA}(r, m + n, 5^m 2^n, 3)$ for $4 \leq m \leq 5$, $54 \leq n \leq 100$ and $n \geq 104$. The following IrMOAs can be obtained from Lemma 2.3. From $D_3(25, 5, 5)$ and $D_3(200, 200, 2) = H_{100} \oplus H_2$ where H_{100} in [56], we can obtain an $\text{IrMOA}(2000, 205, 5^5 2^{200}, 3)$. By deleting the last 97, 98, and 99 columns, we have an $\text{IrMOA}(2000, m + n, 5^m 2^n, 3)$ for $4 \leq m \leq 5$ and $n = 101, 102, 103$. From $D_3(25, 5, 5)$ and $D_3(100, 100, 2) = H_{100}$ in [56], we can obtain an $\text{IrMOA}(1000, 105, 5^5 2^{100}, 3)$. By deleting the last few 2-level columns, an $\text{IrMOA}(1000, m + n, 5^m 2^n, 3)$ for $m = 4$, $n = 14, 15, \dots, 53$ and $m = 5$, $n = 13, 14, \dots, 53$ can be constructed.

By arguments similar to those used in the proof of Theorem 3.5, we can obtain an $\text{IrMOA}(r, 4 + n, 6^4 2^n, 3)$ and three-uniform states of the system $6^4 \times 2^n$ for $n \geq 13$. From $A = D_3(36, 4, 6) \oplus (6)$, $B_0 = D_3(36, 36, 2) \oplus (2)$ and $C_0 = D_3(108, 108, 2) \oplus (2)$, we can obtain an $\text{IrMOA}(r, 4 + n, 6^4 2^n, 3)$ for $22 \leq n \leq 36$ and $n \geq 40$, including $\text{IrMOA}(432, 40, 6^4 2^{36}, 3)$ and $\text{IrMOA}(864, 76, 6^4 2^{72}, 3)$. The $\text{IrMOA}(432, 40, 6^4 2^{36}, 3)$ can produce an $\text{IrMOA}(432, 4 + n, 6^4 2^n, 3)$ for $13 \leq n \leq 21$ and deleting the last $j(j = 33, 34, 35)$ 2-level columns of the $\text{IrMOA}(864, 76, 6^4 2^{72}, 3)$ can generate an $\text{IrMOA}(864, 4 + n, 6^4 2^n, 3)$ for $n = 37, 38, 39$.

It is difficult to construct k -uniform states for heterogeneous systems because of the lack of a suitable mathematical tool. By using orthogonal partition method, we can validly avoid depending on Galois

fields. The results obtained give a positive answer to two open problems. On the one hand, we generalize the construction method from OAs for homogeneous systems to heterogeneous systems consisting of subsystems with coprime levels. On the other hand, we have found several infinite classes of k -uniform states of heterogeneous quantum systems. Now, we will further solve the two problems by using the expansive replacement method.

3.2 Uniform states from difference schemes and the expansive replacement method

By using expansive replacement method and difference schemes method, we obtain several new infinite classes of k -uniform states of heterogeneous multipartite systems for an arbitrary number of subsystems with coprime and nonprime power dimensions or with different powers of a prime.

Theorem 3.6. *There is an IrMOA($r, N - s + \sum_{w=s+1}^N (m_w - 1)u_w + \sum_{w=1}^s v_{iw}, d_{s+1}^{1-u_{s+1}}d_{s+2}^{1-u_{s+2}} \dots d_N^{1-u_N}d_{11}^{v_{11}} \dots d_{m_11}^{v_{m_11}} \dots d_{1s}^{v_{1s}} \dots d_{ms}^{v_{ms}}d_{1(s+1)}^{u_{s+1}} \dots d_{m_{s+1}(s+1)}^{u_{s+1}} \dots d_{1N}^{u_N} \dots d_{m_NN}^{u_N}, k$) and k -uniform states of the system $d_{s+1}^{1-u_{s+1}} \times d_{s+2}^{1-u_{s+2}} \times \dots \times d_N^{1-u_N} \times d_{11}^{v_{11}} \times \dots \times d_{m_11}^{v_{m_11}} \times \dots \times d_{1s}^{v_{1s}} \times \dots \times d_{ms}^{v_{ms}} \times d_{1(s+1)}^{u_{s+1}} \times \dots \times d_{m_{s+1}(s+1)}^{u_{s+1}} \times \dots \times d_{1N}^{u_N} \times \dots \times d_{m_NN}^{u_N}$ for any integers $0 \leq v_{1w}, \dots, v_{mw} \leq 1$ ($w = 1, 2, \dots, s$) and $0 \leq u_w \leq 1$ ($w = s+1, s+2, \dots, N$), if there exists an MOA($r, N, d_1^1 d_2^1 \dots d_N^1, k$) such that the minimal Hamming distance of its $N - s$ columns subarray $\text{MD}(\text{MOA}(r, N - s, d_{s+1}^1 d_{s+2}^1 \dots d_N^1, k)) \geq k + 1$, and N MOAs $B_w = \text{MOA}(d_w, m_w, d_{1w}^1 \dots d_{mw}^1, k)$ for $w = 1, 2, \dots, N$ such that $\text{MD}(B_w) \geq 1$ for $w \geq s+1$ once $u_w = 1$.*

Theorem 3.7. *If there exists $A = \text{OA}(r, N, d, k)$ and $B_w = \text{MOA}(d, m_w, d_{1w}^1 \dots d_{mw}^1, k)$ for $w = 1, 2, \dots, t$, then we have the followings:*

- (1) *When $\text{MD}(A) = k + 1$ and $\text{MD}(B_w) \geq 1$ for each w , there is an IrMOA($r, N + \sum_{j=1}^t (m_j - 1)n_j, d^{N-(n_1+n_2+\dots+n_t)}d_{11}^{n_1} \dots d_{m_11}^{n_1} \dots d_{1t}^{n_t} \dots d_{mt}^{n_t}, k$) and k -uniform states of the system $d_{11}^{n_1} \times \dots \times d_{m_11}^{n_1} \times \dots \times d_{1t}^{n_t} \times \dots \times d_{mt}^{n_t}$ for any non-negative integers $1 \leq n_1 + n_2 + \dots + n_t \leq N$.*
- (2) *When $\text{MD}(\text{OA}(r, N - s, d, k)) \geq k + 1$, there is an IrMOA($r, N - s + \sum_{j=1}^t \sum_{i=1}^{m_j} v_{ij}, d^{N-s}d_{11}^{v_{11}} \dots d_{m_11}^{v_{m_11}} \dots d_{1t}^{v_{1t}} \dots d_{mt}^{v_{mt}}, k$) and k -uniform states of the system $d^{N-s} \times d_{11}^{v_{11}} \times \dots \times d_{m_11}^{v_{m_11}} \times \dots \times d_{1t}^{v_{1t}} \times \dots \times d_{mt}^{v_{mt}}$ for any non-negative integers $1 \leq n_1 + \dots + n_t \leq s$ and $0 \leq v_{1w}, \dots, v_{mw} \leq n_w$ and $\sum_{j=1}^t \sum_{i=1}^{m_j} v_{ij} \geq 1$.*
- (3) *When $\text{MD}(\text{OA}(r, N - s, d, k)) \geq k + 1$ and $\text{MD}(B_w) \geq 1$ for each w , there is an IrMOA($r, N - s + \sum_{j=1}^t [(m_j - 1)u_j + \sum_{i=1}^{m_j} v_{ij}], d^{N-s-(u_1+u_2+\dots+u_t)}d_{11}^{u_1+v_{11}} \dots d_{m_11}^{u_1+v_{m_11}} \dots d_{1t}^{u_t+v_{1t}} \dots d_{mt}^{u_t+v_{mt}}, k$) and k -uniform states of the system for any non-negative integers $1 \leq u_1 + u_2 + \dots + u_t \leq N - s$ and $1 \leq n_1 + n_2 + \dots + n_t \leq s$, and $0 \leq v_{1w}, \dots, v_{mw} \leq n_w$.*

From Theorem 3.7 and IrOAs with strength two and three in Ref. [22], we can construct two and three-uniform states of heterogeneous systems. For example, we have an IrOA($r_N, N, 6, 3$) for $N = 8$ and every $N \geq 12$. By replacing n_1 6-level columns by an MOA($6, 2, 3^1 2^1, 2$), we can obtain an IrMOA($r_N, N + n_1, 6^{N-n_1} 3^{n_1} 2^{n_1}, 3$) and three-uniform states of the system $6^{N-n_1} \times 3^{n_1} \times 2^{n_1}$ with $1 \leq n_1 < N$ for $N = 8$ and every $N \geq 12$ as follows. When $N = 8$ and $n_1 = 1, 2, \dots, 8$, we can obtain three-uniform states of the systems $6^7 \times 3^1 \times 2^1, 6^6 \times 3^2 \times 2^2, \dots, 6^1 \times 3^7 \times 2^7$ and $3^8 \times 2^8$ consisting of

$N' = 9, 10, \dots, 16$ subsystems, respectively. When $N = 12$ and $n_1 = 1, 2, \dots, 12$, we can obtain three-uniform states of the systems $6^{11} \times 3^1 \times 2^1$, $6^{10} \times 3^2 \times 2^2$, \dots and $3^{12} \times 2^{12}$ consisting of $N' = 13, 14, \dots, 24$ subsystems, respectively. For every $N \geq 13$ and $n_1 = 1, 2, \dots, N$, then $N' = N+1, N+2, \dots, 2N$. So we can obtain three-uniform states of heterogeneous systems consisting of N' subsystems for every $N' \geq 9$. Similarly, we can construct the two and three-uniform states of heterogeneous systems in Table 1 (see Appendix C).

It is much more challenging to construct AME states in heterogeneous systems than in homogeneous systems because the heterogeneous systems are unruly and lack of efficient mathematical tools. Interestingly, from an IrMOA, we can obtain an AME state sometimes. For example, in Table 1, the three-uniform states of seven subsystems and two-uniform states of five subsystems are AME states of heterogeneous systems. An IrMOA(6, 3, 6¹3¹2¹, 1) can produce an AME state in $\mathbb{C}^6 \otimes \mathbb{C}^3 \otimes \mathbb{C}^2$.

To further explain Table 1, we give Examples 4 and 5 in Appendix B. The resulting two and three-uniform states consisting of $N' \leq 22$ heterogeneous subsystems from Table 1 are presented in Table 2 in Appendix C.

The following result indicates that for every $k \geq 1$, we can construct an IrMOA with non-prime power levels and corresponding k -uniform states of heterogeneous systems.

Theorem 3.8. *For every $k \geq 1$ and any non-negative integers $1 \leq n_1 + n_2 + \dots + n_t \leq 2k$, there exist an IrMOA($d^k, d^{2k-(n_1+n_2+\dots+n_t)}d_{11}^{n_1} \cdots d_{m_1 1}^{n_1} \cdots d_{1t}^{n_t} \cdots d_{m_t t}^{n_t}, k$) and k -uniform states of the system $d^{2k-(n_1+n_2+\dots+n_t)} \times d_{11}^{n_1} \times \cdots \times d_{m_1 1}^{n_1} \times \cdots \times d_{1t}^{n_t} \cdots \times d_{m_t t}^{n_t}$, where $d = d_{1w} \cdots d_{m_w w}$ for $w = 1, 2, \dots, t$ and $d_{11}, \dots, d_{m_1 1}$ are m_1 distinct prime powers and each $d_{u1} \geq 2k - 1$.*

For a given k , there are infinitely many IrMOAs and k -uniform states of heterogeneous systems, since there are infinitely many primes. We construct a large number of four-uniform states in Example 6 in Appendix C to illustrate an application of Theorem 3.8. AME states can be applied in designing holographic quantum codes [58]. Very interestingly, the above four-uniform states of nine subsystems are AME states of heterogeneous systems.

Let $s = 0$ and $s = 1$ for $u_2 = \dots = u_N = 0$ in Theorem 3.6. Starting from a difference scheme $D(N, M, d)$, we can obtain the following theorem which allows us to obtain two-uniform states of a heterogeneous system having subsystems with a non-prime power number of levels and generalizes the result in [20].

Theorem 3.9. *Suppose that $D(N, M, d)$ is a difference scheme and that B is an MOA($N, m, p_1^1 p_2^1 \cdots p_m^1, 2$). Let $A = [A_1, A_2] = [(\mathbf{N}) \oplus \mathbf{0}_d, D(N, M, d) \oplus (\mathbf{d})]$. Then, we have that:*

- (1) *If $\text{MD}(A) = 3$ and $\text{MD}(B) \geq 1$, then there is an IrMOA($dN, M + m, d^M p_1^1 p_2^1 \cdots p_m^1, 2$) and two-uniform states of the system $d^M \times p_1^1 \times p_2^1 \times \cdots \times p_m^1$.*
- (2) *If $\text{MD}(A_2) \geq 3$, then there is an IrMOA($dN, M + m, d^M p_1^1 p_2^1 \cdots p_m^1, 2$) and two-uniform states of the system $d^M \times p_1^1 \times p_2^1 \times \cdots \times p_m^1$.*

Especially, if $M = N$, then $\text{HD}(D(N, M, d)) = N - \frac{N}{d}$. So the OA($Nd, N, d, 2$) = $D(N, N, d) \oplus (\mathbf{d})$ has two Hamming distances N and $N - \frac{N}{d}$ [59]. In Theorem 3.9. If $d = N$ and d is a prime, we can

only obtain IrOAs. Otherwise, consider the case $M = N$. Only if $d = 2$ and $N = 4$, we can obtain $\text{MD}(A) = 3$ and $\text{IrMOA}(8, 5, 4^1 2^4, 2)$; for the other cases, we have $\text{MD}(A_2) \geq 3$. Moreover, a difference scheme $D(d^n, d^n, d)$ exists for $n \geq 1$ [26]. Then we have the following corollary.

Corollary 3.10. *If d is a prime power and $B = \text{MOA}(d^n, m, p_1^1 p_2^1 \cdots p_m^1, 2)$ with $\text{MD}(B) \geq 1$, then an $\text{IrMOA}(d^{n+1}, d^n + m, d^{d^n} p_1^1 p_2^1 \cdots p_m^1, 2)$ exists.*

Tables 3, 4 and 5 (see Appendix C) provide some IrMOAs with 24, 36 and 72 rows, respectively, and corresponding two-uniform states constructed from Theorems 3.6 and 3.9 and Corollary 3.10. Especially, Table 5 only provides the IrMOAs obtained from the $\text{MOA}(72, 7, 12^1 6^6, 2) = [(\mathbf{12}) \oplus \mathbf{0}_6, D(12, 6, 6) \oplus (\mathbf{6})]$.

Remark 3.1. *Besides the IrMOAs in Tables 4 and 5, other numerous types of IrMOAs of runsize ≥ 36 can be also obtained from the known MOAs in [55] by using the expansive replacement method. For instance, we can construct more IrMOAs with coprime levels and corresponding two-uniform states.*

The non-existence of a class of IrMOAs is discussed.

Theorem 3.11. *Let d_1, d_2, d_3, d_4 and d_5 be not all identical integers. If $d_i \neq d_j$, their greatest common divisor is 1. Then there is no $\text{IrMOA}(r, 5, d_1 \times d_2 \times d_3 \times d_4 \times d_5, 2)$ except $\text{IrMOA}(ab^2, 5, a^1 b^4, 2)$ for $a < b$.*

However, an $\text{IrMOA}(18, 5, 2^1 3^4, 2)$ and an $\text{IrMOA}(r, 6, 3^1 2^5, 2)$ do not exist.

4 Conclusions and discussions

We have presented positive answers to two open problems raised in [5, 20]. First, we have generalized the method for constructing homogeneous systems from IrOAs to heterogeneous systems with different individual levels from IrMOAs. Then, we have addressed the existence of a series of infinite classes of k -uniform states for heterogeneous quantum systems. In particular, we found several infinite classes of examples of three-uniform states for such systems. Our results can be summarized as follows.

(1) By using known MOAs and MOAs constructed from difference schemes, Hamming distances, we obtained abundant infinite classes of two-uniform states of heterogeneous multipartite systems. For example, for any given $a \geq 1$, there is an n_a such that two-uniform states $|\phi_{3^a 2^b}\rangle$ exist for every $b \geq n_a$. For any given $M \geq 1$, there is an n_M such that an $\text{IrMOA}(r, M + N, d^M 2^N, 2)$ and two-uniform states of the system $d^M \times 2^N$ exist for any $d \geq 4$ and every $N \geq n_M$ if the Hadamard conjecture holds.

(2) By using orthogonal partition, difference schemes, and Hamming distances, we obtained additional infinite classes of three-uniform states of heterogeneous systems.

(3) By using Hamming distances and the expansive replacement method, we obtained infinite classes of two and three-uniform states of heterogeneous multipartite systems for an arbitrary number of subsystems with coprime and nonprime power levels or with different powers of a prime levels.

(4) By using the constructed IrMOAs, Hamming distances, and the expansive replacement method, we obtained infinite classes of k -uniform states of heterogeneous multipartite systems for every $k \geq 2$.

It is worth mentioning that finding OAs and MOAs with some factors having a non-prime power number of levels is more difficult than finding ones in which all of the factors have a prime power number of levels. In particular, it is more challenging to construct such irredundant OAs and MOAs. Characterizing entanglement in heterogeneous systems consisting of at least one subsystem with nonprime power dimension is more complex than doing so in homogeneous systems, as the Galois fields do not exist in nonprime power dimensions. However, our method can efficiently avoid dependence on the Galois fields to obtain a large number of infinite classes of such entanglement states.

Furthermore, our methods are effective and robust. They do not require the calculation of the rank of a tensor with three indices over any finite field that is NP-complete with respect to the dimension of the tensor [20, 60]. These states obtained in this paper may be useful for experimental implementations and facilitate the quantification of entanglement in some multipartite heterogeneous systems [61]. Moreover, remarkable progress is expected to be made in the field of QECCs over mixed alphabets [20, 62] by applying the results presented herein.

As stated in [5, 20], many open problems remain unresolved with regard to the construction and characterization of entanglement in multipartite quantum systems, such as the problem of whether N -qubit states exist in which all k -body reduced densities are maximally mixed for $k < \lfloor \frac{N}{2} \rfloor$ in [17]. These problems are central to quantum error correction. The results presented herein will facilitate further investigations on such related open problems. For example, we can construct IrOA($r, N, 2^m, k$) for $k \geq 4$ [26], and obtain such states by using expansive replacement method.

Although in Table 1 (see Appendix C), AME states of seven-partite and five-partite heterogeneous systems are obtained, the knowledge about the existence and non-existence of AME states of subsystems with coprime levels is still limited. The present results we obtained will lay a foundation for obtaining AME states for heterogeneous subsystems from IrMOAs. One can investigate the nonexistence of AME states by using the nonexistence of symmetric matrix in [23] and IrMOAs. Our results would highlight further investigations on the properties of quantum multipartite entanglement.

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Appendix A: Proofs of some lemmas, theorems and corollaries

Proof of Lemma 2.1.

It follows from [59] and [50] that $\text{MD}(B \oplus (\mathbf{d})) = r - \frac{r}{d}$ and that C is an MOA, respectively. Suppose that c_1 and c_2 are any two rows of C . Let a_j and b_j denote rows of A and B , respectively, for $j = 1, 2$.

Now, consider the following two cases.

- (1) If $c_1 = (a_1, b_1)$ and $c_2 = (a_1, i + b_1)$ for $i = 1, 2, \dots, d - 1$, then $\text{HD}(c_1, c_2) = r$.
- (2) If $c_1 = (a_1, b_1)$ and $c_2 = (a_2, i + b_2)$ for $i = 0, 1, \dots, d - 1$, then $\text{HD}(c_1, c_2) \geq \text{MD}(A) + r - \frac{r}{d}$.

When $\text{HD}(a_1, a_2) = \text{MD}(A)$, $\text{HD}(c_1, c_2) = \text{MD}(A) + r - \frac{r}{d}$.

Therefore, $\text{MD}(C) = \min\{r, \text{MD}(A) + r - \frac{r}{d}\}$. ■

Proof of Lemma 2.3.

It follows from [52] that the matrix M is the MOA desired. For the Hamming distance between any two rows of M , we proceed with three cases.

- (1) If $u = v$, then the matrix $M = ((A_{[1,2,\dots,u]}, d''), (d', B_{[1,2,\dots,u]}))$.

If any two rows x and y are in $(A_i \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_i)$ for some $i \in \{1, 2, \dots, u\}$, then there are three values N' , N'' , and $N' + N''$ for $\text{HD}(x, y)$. If x is from $(A_i \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_i)$ and y is from $(A_j \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_j)$ for $i, j \in \{1, 2, \dots, u\}$ and $i \neq j$, then $\text{HD}(x, y) \geq w_1 + w_2$. Therefore, $\text{MD}(M) \geq \min\{w_1 + w_2, N', N''\}$.

- (2) If $u|v$ and $u < v$, then the matrix $M = (\mathbf{1}_{\frac{u}{v}} \otimes (A_{[1,2,\dots,u]}, d''), (d', B_{[1,2,\dots,v]}))$.

If any two rows x and y are in $(A_i \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_j)$ for some $(i, j) \in \{1, 2, \dots, u\} \times \{1, 2, \dots, v\}$, then $\text{HD}(x, y) = N'$, N'' , and $N' + N''$. If x is from $(A_{i_1} \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_{j_1})$ and y is from $(A_{i_2} \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_{j_2})$ for $j_1 \neq j_2$, then $\text{HD}(x, y) \geq w_2$ if $i_1 = i_2$; otherwise, $\text{HD}(x, y) \geq w_1 + w_2$. Therefore, $\text{MD}(M) \geq \min\{N', w_2\}$.

- (3) If $u < v$ and $u \nmid v$, then the matrix $M = (\mathbf{1}_{\frac{u}{v}} \otimes (A_{[1,2,\dots,u]}, d''), \mathbf{1}_{\frac{v}{u}} \otimes (d', B_{[1,2,\dots,v]}))$.

If any two rows x and y are in $(A_i \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_j)$ for some $(i, j) \in \{1, 2, \dots, u\} \times \{1, 2, \dots, v\}$, then $\text{HD}(x, y) = N'$, N'' , and $N' + N''$. If x is from $(A_{i_1} \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_{j_1})$ and y is from $(A_{i_2} \otimes \mathbf{1}_{d''}, \mathbf{1}_{d'} \otimes B_{j_2})$ for $(i_1, j_1) \neq (i_2, j_2)$ and $i_1, i_2 \in \{1, 2, \dots, u\}$, $j_1, j_2 \in \{1, 2, \dots, v\}$, then

$$\text{HD}(x, y) \geq \begin{cases} w_2, & \text{if } i_1 = i_2, j_1 \neq j_2, \\ w_1, & \text{if } i_1 \neq i_2, j_1 = j_2, \\ w_1 + w_2, & \text{if } i_1 \neq i_2, j_1 \neq j_2. \end{cases}$$

Therefore, $\text{MD}(M) \geq \min\{w_1, w_2\}$. ■

Proof of Lemma 2.4.

Suppose that $A = \text{MOA}(r, N, d_1^1 d_2^1 \cdots d_N^1, k)$ and $B = \text{MOA}(d_1, N_B, f_1^1 f_2^1 \cdots f_{N_B}^1, k)$. Then, we will prove that the resulting array C is an $\text{MOA}(r, N - 1 + N_B, f_1^1 f_2^1 \cdots f_{N_B}^1 d_1^1 \cdots d_N^1, k)$. Consider the following two cases.

(1) If any k columns are chosen from either the first N_B columns or the last $N - 1$ columns in C , then it is obvious that they constitute an MOA of strength k .

(2) For any k columns of C , if their k_1 columns (i.e., i_1 -th, \dots , i_{k_1} -th) are chosen from the first N_B columns and k_2 columns (i.e., j_1 -th, \dots , j_{k_2} -th) are chosen from the last $N - 1$ columns, where $k_1 + k_2 = k$, then each k -tuple as a row occurs $\frac{r}{d_1 d_{j_1} \cdots d_{j_{k_2}}} \cdot \frac{d_1}{f_{i_1} \cdots f_{i_{k_1}}} = \frac{r}{d_{j_1} \cdots d_{j_{k_2}} f_{i_1} \cdots f_{i_{k_1}}}$ times. The k columns constitute an MOA of strength k .

Therefore, we complete the proof. ■

Proof of Theorem 3.1.

Let $A_0 = \text{MOA}(r, a + b, 3^a 2^b, 2)$ and $B_0 = D(r, r, 2)$. Then by Lemma 2.1, we can obtain $A_1 = [A_0 \oplus \mathbf{0}_2, B_0 \oplus \mathbf{(2)}] = \text{MOA}(2r, a + b + r, 3^a 2^{b+r}, 2)$ with $\text{MD}(A_1) = \min\{r, \text{MD}(A_0) + \frac{r}{2}\} \geq \frac{r}{2}$. Consequently, we can construct an IrMOA($2r, a + N_1, 3^a 2^{N_1}, 2$) for $\frac{r}{2} + 3 \leq N_1 \leq b + r$ by deleting $0 \leq j \leq b + \frac{r}{2} - 3$

columns from A_1 . In fact, by deleting any j ($0 \leq j \leq \frac{r}{2} - 3$) 2-level columns in A_1 , we obtain an $\text{IrMOA}(2r, a + l, 3^a 2^l, 2)$ for $b + \frac{r}{2} + 3 \leq l \leq b + r$. However, for $\frac{r}{2} - 3 < j \leq b + \frac{r}{2} - 3$, we need to first delete all 2-level columns in $A_0 \oplus \mathbf{0}_2$, then delete any $j - b$ columns in $B_0 \oplus \mathbf{(2)}$ and obtain $\text{IrMOA}(2r, a + l, 3^a 2^l, 2)$ for $\frac{r}{2} + 3 \leq l < b + \frac{r}{2} + 3$.

Similarly, we have an $\text{IrMOA}(4r, a + N_2, 3^a 2^{N_2}, 2)$ for $r + 3 \leq N_2 \leq b + 3r$ from $A_2 = [A_1 \oplus \mathbf{0}_2, B_1 \oplus \mathbf{(2)}] = \text{MOA}(4r, a + b + 3r, 3^a 2^{b+3r}, 2)$, where $B_1 = D(r, r, 2) \oplus H_2$ and H_2 is a Hadamard matrix of order 2.

Let H_{2^n} be a Hadamard matrix of order 2^n for $n \geq 0$. Take $B_n = D(r, r, 2) \oplus H_{2^n} = D(r \cdot 2^n, r \cdot 2^n, 2)$. By mathematical induction, we have $A_{n+1} = [A_n \oplus \mathbf{0}_2, B_n \oplus \mathbf{(2)}] = \text{MOA}(r \cdot 2^{n+1}, a + b + r \cdot 2^{n+1} - r, 3^a 2^{b+r \cdot 2^{n+1}-r}, 2)$ and $\text{MD}(A_{n+1}) \geq r \cdot 2^{n-1}$. Then, by the above-mentioned similar methods, we can obtain an $\text{IrMOA}(r \cdot 2^n, a + N_{n+1}, 3^a 2^{N_{n+1}}, 2)$ for $r \cdot 2^{n-1} + 3 \leq N_{n+1} \leq b + r \cdot 2^{n+1} - r$.

It can easily be shown that $r \cdot 2^n + 3 \leq N_{n+2} \leq b + r \cdot 2^{n+2} - r$ and $b + r \cdot 2^{n+1} - r - (r \cdot 2^n + 3) \geq -1$ for $n \geq 0$ and $b \geq 2$.

Therefore, we can obtain an $\text{IrMOA}(r', M + N, 3^M 2^N, 2)$ and two-uniform states of the system $3^M \times 2^N$ for $1 \leq M \leq a$ and every $N \geq \frac{r}{2} + 3$.

In particular, let $m \geq 2$. The $D(3, 3, 3) = \begin{pmatrix} 000 \\ 012 \\ 021 \end{pmatrix}$ implies the existence of a $D(2^m 3, 2^m 3, 3)$ [63]. From Lemma 2.1, $D(2^m 3, 2^m 3, 2)$ and $\text{OA}(12, 11, 2, 2)$, we have $M_m = \text{OA}(2^m 3, 2^m 3 - 1, 2, 2)$ with $\text{MD} = 2^{m-1} 3$. Then, by Lemma 2.1, we have $A_0 = \text{MOA}(2^m 3^2, 2^{m+1} 3 - 1, 3^{2^m} 3 2^{2^m 3 - 1}, 2) = [M_m \oplus \mathbf{0}_3, D(2^m 3, 2^m 3, 3) \oplus \mathbf{(3)}]$ and $B_0 = D(2^m 3^2, 2^m 3^2, 2) = D(36, 36, 2) \oplus H_{2^{m-2}}$.

Therefore, there exist an $\text{IrMOA}(r, M + N, 3^M 2^N, 2)$ and two-uniform states of the system $3^M \times 2^N$ for $1 \leq M \leq 2^m 3$ and $N \geq 2^{m-1} 3^2 + 3$ with any $m \geq 2$. ■

Proof of Corollary 3.2.

(1) Starting from the $\text{MOA}(12, 5, 3^1 2^4, 2)$ in [55] and the $D(12, 12, 2)$ in [56], we have an $\text{IrMOA}(r, 1 + N, 3^1 2^N, 2)$ and two-uniform states of the system $3^1 \times 2^N$ for every $N \geq 9$ by Theorem 3.1. Moreover, in Table 3 (see Appendix C), there exist an $\text{IrMOA}(24, 9, 3^1 2^8, 2)$ and two-uniform state of the system $3^1 \times 2^8$.

(2) Beginning with $A_0 = \text{MOA}(36, 20, 3^4 2^{16}, 2)$ in [55] and $B_0 = D(36, 36, 2)$ in [56], Theorem 3.1 can produce an $\text{IrMOA}(r, M + N_0, 3^M 2^{N_0}, 2)$ and two-uniform states of the system $3^M \times 2^{N_0}$ for $2 \leq M \leq 4$ and every $N_0 \geq 21$.

From $\text{MD}(A_0) = 8$ and Lemma 2.2, we have an $\text{IrMOA}(36, 2 + N_1, 3^2 2^{N_1}, 2)$ for $13 \leq N_1 \leq 16$. In particular, we can obtain an $\text{IrMOA}(36, 14, 3^2 2^{12}, 2)$. From the $\text{MOA}(36, 22, 3^2 2^{20}, 2)$ in [55] with $\text{MD} = 8$, we can obtain an $\text{IrMOA}(36, 2 + N_2, 3^2 2^{N_2}, 2)$ for $15 \leq N_2 \leq 20$. Therefore, there exist an $\text{IrMOA}(r, 2 + N, 3^2 2^N, 2)$ and two-uniform states of the system $3^2 \times 2^N$ for every $N \geq 12$.

Similarly, we have an $\text{IrMOA}(36, 3 + m_1, 3^3 2^{m_1}, 2)$ for $12 \leq m_1 \leq 16$ and an $\text{IrMOA}(36, 4 + n_1, 3^4 2^{n_1}, 2)$ for $11 \leq n_1 \leq 16$ from A_0 .

From Lemma 2.1 and A_0 and B_0 , we have $A_1 = [A_0 \oplus \mathbf{0}_2, B_0 \oplus \mathbf{(2)}] = \text{MOA}(72, 56, 3^4 2^{52}, 2)$. By deleting the last 3-level column and the first 32, 33, 34, and 35 2-level columns from A_1 , respectively, we can obtain an $\text{IrMOA}(72, 3 + m_2, 3^3 2^{m_2}, 2)$ for $17 \leq m_2 \leq 20$. If deleting only the first 32, 33, 34, and 35

2-level columns from A_1 , respectively, we can obtain an IrMOA($72, 4 + n_2, 3^4 2^{n_2}, 2$) for $17 \leq n_2 \leq 20$.

By Lemma 2.1, we can obtain an MOA($36, 23, 3^{12} 2^{11}, 2$) = [OA(12, 11, 2, 2) \oplus $\mathbf{0}_3$, $D(12, 12, 3)$ \oplus $(\mathbf{3})$] with MD= 12. Then, we have an IrMOA($36, 14, 3^l 2^{14-l}, 2$) for $l = 3, 4, \dots, 12$. In particular, we can obtain an IrMOA($36, 14, 3^3 2^{m_0}, 2$) for $m_0 = 11$ and an IrMOA($36, 14, 3^4 2^{n_0}, 2$) for $n_0 = 10$. \blacksquare

Then, we finish the proof.

Proof of Theorem 3.4.

Let $D_3(18, 5, 3) = (a_1^T, a_2^T, \dots, a_{18}^T)^T = \begin{pmatrix} 011100002222011210 \\ 011021102200220122 \\ 012121021012002121 \\ 012000121001111002 \\ 102212201202011122 \end{pmatrix}^T$. Take $D_3(36 \cdot 2^{h_1}, 36 \cdot 2^{h_1}, 2) = H_{36} \otimes H_{2^{h_1}}$ for $h_1 \geq 0$.

When $h_1 = 0$, $D_3(36, 36, 2) = (b_1^T, b_2^T, \dots, b_{36}^T)^T = [\mathbf{0}_{36}, \text{OA}(36, 35, 2, 2)]$, where the OA($36, 35, 2, 2$) can be found in [55]. Let $A = \text{OA}(54, 5, 3, 3) = D_3(18, 5, 3) \oplus (\mathbf{3})$ and $B = \text{OA}(72, 36, 2, 3) = D_3(36, 36, 2) \oplus (\mathbf{2})$. Then, $\{A_i = a_i \oplus (\mathbf{3}) | i = 1, 2, \dots, 18\}$ and $\{B_j = b_j \oplus (\mathbf{2}) | j = 1, 2, \dots, 36\}$ are orthogonal partitions of strength 1 of A and B , respectively. So we can obtain $M = (\mathbf{1}_2 \otimes (A_{[1, 2, \dots, 18]}, 2), (\mathbf{3}, B_{[1, 2, \dots, 36]})) = \text{IrMOA}(216, 41, 3^5 2^{36}, 3)$ from Lemma 2.3. As $\text{MD}(B) = 18$ from [22], deleting 1-14 2-level columns from B , we can obtain B'_1, \dots, B'_{14} , each of which has $\text{MD} \geq 4$ and an orthogonal partition of strength 1. Then, from A and each B'_i and Lemma 2.3, we can obtain an IrMOA($216, 5 + n_0, 3^5 2^{n_0}, 3$) for $n_0 = 22, 23, \dots, 35$.

On the other hand, deleting a 3-level column from A , we can obtain A' and its orthogonal partition of strength 1. Then, from A' and each of B'_{14}, \dots, B'_1, B and Lemma 2.3, we have an IrMOA($216, 4 + n_0, 3^4 2^{n_0}, 3$) for $n_0 = 22, 23, \dots, 36$, respectively.

In particular, from the IrMOA($216, 27, 3^5 2^{22}, 3$) and the IrMOA($216, 26, 3^4 2^{22}, 3$), we can further delete some columns to obtain an IrMOA($216, 5 + n_0^0, 3^5 2^{n_0^0}, 3$) and an IrMOA($216, 4 + n_0^0, 3^4 2^{n_0^0}, 3$), respectively, for $n_0^0 = 16, 17, \dots, 21$.

When $h_1 \geq 1$, we can obtain $M = \text{MOA}(216 \cdot 2^{h_1}, 5 + 36 \cdot 2^{h_1}, 3^5 2^{36 \cdot 2^{h_1}}, 3)$ from A and $B_{h_1} = D_3(36 \cdot 2^{h_1}, 36 \cdot 2^{h_1}, 2) \oplus (\mathbf{2})$ with $\text{MD}(B_{h_1}) = 18 \cdot 2^{h_1}$ by Ref. [22] and Lemma 2.3. By arguments similar to the case of $h_1 = 0$, we can obtain an MOA($216 \cdot 2^{h_1}, m + n_{h_1}, 3^m 2^{n_{h_1}}, 3$) with $\text{MD} \geq \min\{m, 18 \cdot 2^{h_1} - (36 \cdot 2^{h_1} - n_{h_1})\} = \{m, n_{h_1} - 18 \cdot 2^{h_1}\} \geq 4$ for $4 \leq m \leq 5$ and $18 \cdot 2^{h_1} + 4 \leq n_{h_1} \leq 36 \cdot 2^{h_1}$. So it is an IrMOA. When $h_1 = 1$, then $40 \leq n_1 \leq 72$. In particular, by Lemma 2.3, we can obtain MOA($432, 77, 3^5 2^{72}, 3$) from A and $D_3(72, 72, 2) \oplus (\mathbf{2})$, where the $D_3(72, 72, 2)$ is in [56]. Deleting the last 33, 34, and 35 2-level columns, respectively, we can obtain an IrMOA($432, m + n_1^0, 3^m 2^{n_1^0}, 3$) for $4 \leq m \leq 5$ and $n_1^0 = 37, 38, 39$.

Take $D_3(108 \cdot 2^{h_2}, 108 \cdot 2^{h_2}, 2) = H_{108} \oplus H_{2^{h_2}}$ for $h_2 \geq 0$. Then, we can obtain $M = \text{MOA}(648 \cdot 2^{h_2}, 5 + 108 \cdot 2^{h_2}, 3^5 2^{108 \cdot 2^{h_2}}, 3)$ from A and $C_{h_2} = D_3(108 \cdot 2^{h_2}, 108 \cdot 2^{h_2}, 2) \oplus (\mathbf{2})$ with $\text{MD}(C_{h_2}) = 54 \cdot 2^{h_2}$ by Ref. [22] and Lemma 2.3. By arguments similar to the case of $h_1 = 0$, we can obtain an IrMOA($648 \cdot 2^{h_2}, m + n'_{h_2}, 3^m 2^{n'_{h_2}}, 3$) for $4 \leq m \leq 5$ and $54 \cdot 2^{h_2} + 4 \leq n'_{h_2} \leq 108 \cdot 2^{h_2}$.

From n_{h_1} and n'_{h_2} , we can obtain an IrMOA($r, m + n, 3^m 2^n, 3$) for $4 \leq m \leq 5$ and $n \geq 16$. \blacksquare

Proof of Theorem 3.5.

If $D_3(4d^2, 4d^2, 2)$ and $D_3(12d^2, 12d^2, 2)$ exist, then we have $D_3(4d^2, 4d^2, 2) \oplus H_{2^h}$ and $D_3(12d^2, 12d^2, 2) \oplus$

H_{2^h} for $h \geq 0$, i. e. $D_3(v, v, 2)$ for $v = 4 \cdot 2^h d^2$ and $v = 12 \cdot 2^h d^2$. By Ref. [64], $D_3(d^2, d, d)$ exists for an odd prime power $d > 4$. By Lemma 2.3, $A = D_3(d^2, d, d) \oplus (\mathbf{d})$ and $B = D_3(v, v, 2) \oplus (\mathbf{2})$ with $\text{MD}(B) = \frac{v}{2}$, we can obtain an MOA($2dv, d+v, d^d 2^v, 3$) for $v = 4 \cdot 2^h d^2$ and $v = 12 \cdot 2^h d^2$. By selectively deleting some columns from the MOA($2dv, d+v, d^d 2^v, 3$) such that an IrMOA($2dv, m+n, d^m 2^n, 3$) exists for $4 \leq m \leq d$ and $\frac{v}{2} + 4 \leq n \leq v$.

For $4 \leq m \leq d$, we have an IrMOA($8 \cdot 2^h d^3, m+n_h, d^m 2^{n_h}, 3$) for $2^{h+1} d^2 + 4 \leq n_h \leq 4 \cdot 2^h d^2$ and an IrMOA($24 \cdot 2^h d^3, m+n_h, d^m 2^{n_h}, 3$) for $6 \cdot 2^h d^2 + 4 \leq n_h \leq 12 \cdot 2^h d^2$, respectively. \blacksquare

Then, the desired result follows. \blacksquare

Proof of Theorem 3.6.

The expansive replacement method enables us to replace any d_w^1 in the MOA($r, N, d_1^1 d_2^1 \cdots d_N^1, k$) by a subarray of B_w for $w = 1, 2, \dots, s$ or B_w for $w = s+1, s+2, \dots, N$, since $\text{MD}(\text{MOA}(r, N - s, d_{s+1}^1 d_{s+2}^1 \cdots d_N^1, k) \geq k+1$, and $\text{MD}(B_w) \geq 1$ for $w = s+1, s+2, \dots, N$ once $u_w = 1$. Then, the resulting MOAs are irredundant and the corresponding states exist. \blacksquare

Proof of Theorem 3.7.

This proof is analogous to the proof of Theorem 3.6. \blacksquare

First, we use examples to illustrate a trivial MOA since it will be used in the proof of Theorem 3.8. The matrix $[(\mathbf{7}) \otimes \mathbf{1}_8, \mathbf{1}_7 \otimes (\mathbf{4}) \otimes \mathbf{1}_2, \mathbf{1}_{28} \otimes (\mathbf{2})]$ is a trivial MOA($56, 3, 7^1 4^1 2^1, 3$). Moreover, the array $[(\mathbf{28}) \otimes \mathbf{1}_2, \mathbf{1}_{28} \otimes (\mathbf{2})]$ is a trivial MOA($56, 2, 28^1 2^1, 3$). The array $[(\mathbf{7}) \otimes \mathbf{1}_8, \mathbf{1}_7 \otimes (\mathbf{2}) \otimes \mathbf{1}_4, \mathbf{1}_{14} \otimes (\mathbf{2}) \otimes \mathbf{1}_2, \mathbf{1}_{28} \otimes (\mathbf{2})]$ is also a trivial MOA($56, 4, 7^1 2^3, 3$).

Proof of Theorem 3.8.

As $d_{11}, \dots, d_{m_1 1}$ are m_1 distinct prime powers and $d_{u1} \geq 2k - 1$ for $u = 1, 2, \dots, m_1$, we obtain an IrOA($d^k, 2k, d, k$) from Refs. [22, 26, 65]. For $w = 1, 2, \dots, t$, $d = d_{1w} \cdots d_{m_w w}$, take an MOA($d, m_w, d_{1w}^1 \cdots d_{m_w w}^1, k$) to be a trivial MOA($d, m_w, d_{1w}^1 \cdots d_{m_w w}^1, m_w$). Then, the desired result holds by Theorem 3.7. \blacksquare

Proof of Theorem 3.11.

We consider the following two cases.

(1) Assume that an IrMOA($r, 5, a^1 b^4, 2$) exists for $a > b$. Then we have $ab^2 | r$. Since any two rows in its any $r \times 3$ subarray are different, $r \leq b^3$. So $r < ab^2$. A contradiction.

(2) If an MOA($r, 5, a^2 b^3, 2$) exists, then $a^2 b^2 | r$. Therefore, it is not irredundant.

Similarly, there are no IrMOA($r, 5, a^2 b^2 c^1, 2$), IrMOA($r, 5, a^3 b^1 c^1, 2$), IrMOA($r, 5, a^2 b^1 c^1 d^1, 2$) and IrMOA($r, 5, a^1 b^1 c^1 d^1 e^1, 2$). \blacksquare

Appendix B: Some examples

Example 1. Two-uniform states of the systems $3^1 \times 2^{10}$, $3^1 \times 2^9$, $3^2 \times 2^{13}$, $3^2 \times 2^{12}$, $3^3 \times 2^{11}$ and $3^4 \times 2^{10}$.

$$\begin{aligned} |\phi_{3^1 2^{10}}\rangle = & |0011111111\rangle + |0100000000\rangle + |1001011100\rangle + |1110100011\rangle + |2000101110\rangle + \\ & |2111010001\rangle + |2010010110\rangle + |2101101001\rangle + |0001001011\rangle + |0110110100\rangle + |10001001011\rangle + \\ & |11110110100\rangle + |10000100101\rangle + |11111011010\rangle + |20100010010\rangle + |21011101101\rangle + |00110001001\rangle + \end{aligned}$$

$$|01001110110\rangle + |10111000100\rangle + |11000111011\rangle + |20011100010\rangle + |21100011101\rangle + |00101110001\rangle + |01010001110\rangle.$$

$$|\phi_{3^1 2^9}\rangle = |001111111\rangle + |010000000\rangle + |1001011100\rangle + |1110100011\rangle + |2000101110\rangle + |2111010001\rangle + |2010010111\rangle + |2101101000\rangle + |0001001011\rangle + |0110110100\rangle + |1000100101\rangle + |1111011010\rangle + |1000010010\rangle + |1111101101\rangle + |2010001001\rangle + |2101110110\rangle + |0011000100\rangle + |0100111011\rangle + |1011100010\rangle + |1100011101\rangle + |2001110001\rangle + |2110001110\rangle + |0010111000\rangle + |0101000111\rangle.$$

$$|\phi_{3^2 2^{13}}\rangle = |010000001001001\rangle + |000000010000010\rangle + |000001000111100\rangle + |010001111011111\rangle + |110010011110111\rangle + |210010101010100\rangle + |100010110011100\rangle + |110011100101010\rangle + |020011111100011\rangle + |100100100100001\rangle + |220100101010010\rangle + |210101010101111\rangle + |220101011100100\rangle + |120101100000111\rangle + |020110001101100\rangle + |120110110111001\rangle + |200111000011010\rangle + |200111011010001\rangle + |201000101101101\rangle + |201000110100110\rangle + |101001001110011\rangle + |121001011111000\rangle + |021001110010000\rangle + |221010000111011\rangle + |121010001000110\rangle + |21101100000001\rangle + |22101110001101\rangle + |02110000001111\rangle + |111100010010101\rangle + |21110011111101\rangle + |111101101001000\rangle + |011110010100000\rangle + |001110111001011\rangle + |101111011001110\rangle + |01111100110110\rangle + |001111101110101\rangle.$$

$$|\phi_{3^2 2^{12}}\rangle = |01000000100100\rangle + |00000001000001\rangle + |0000010001110\rangle + |0100011110111\rangle + |11001001111011\rangle + |21001010101010\rangle + |10001011001110\rangle + |11001110010101\rangle + |02001111110001\rangle + |10010010010000\rangle + |22010010101001\rangle + |21010101010111\rangle + |22010101110010\rangle + |12010110000011\rangle + |02011000110110\rangle + |12011011011100\rangle + |20011100001101\rangle + |20011101101000\rangle + |20100010110110\rangle + |20100011010011\rangle + |10100100111001\rangle + |12100101111100\rangle + |02100111001000\rangle + |22101000011101\rangle + |12101000100011\rangle + |21101100000000\rangle + |2210111000110\rangle + |0211000000111\rangle + |11110001001010\rangle + |21110011111101\rangle + |11110110100100\rangle + |01111001010000\rangle + |00111011100101\rangle + |10111101100111\rangle + |0111110011011\rangle + |00111110111010\rangle.$$

$$|\phi_{3^3 2^{11}}\rangle = |01200000010010\rangle + |00000000100000\rangle + |0000001000111\rangle + |01200011110111\rangle + |11100100111101\rangle + |21000101010101\rangle + |10200101100111\rangle + |11100111001010\rangle + |0210011111000\rangle + |10201001001000\rangle + |22201001010100\rangle + |21001010101011\rangle + |22201010111001\rangle + |12001011000001\rangle + |02101100011011\rangle + |12001101101110\rangle + |20101110000110\rangle + |20101110110100\rangle + |20110001011011\rangle + |20110001101001\rangle + |10210010011100\rangle + |12010010111110\rangle + |02110011100100\rangle + |22210100001110\rangle + |12010100010001\rangle + |21010110000000\rangle + |22210111100011\rangle + |02111000000111\rangle + |11111000100101\rangle + |21011001111110\rangle + |11111011010010\rangle + |01211100101000\rangle + |00011101110010\rangle + |10211110110011\rangle + |0121111001101\rangle + |00011111011101\rangle.$$

$$|\phi_{3^4 2^{10}}\rangle = |01210000001001\rangle + |00000000010000\rangle + |00000001000111\rangle + |01210001111011\rangle + |11100010011110\rangle + |21020010101010\rangle + |10220010110011\rangle + |11100011100101\rangle + |0212001111100\rangle + |10220100100100\rangle + |22200100101010\rangle + |21020101010101\rangle + |22200101011100\rangle + |12010101100000\rangle + |02120110001101\rangle + |12010110110111\rangle + |20110111000011\rangle + |20110111011010\rangle + |20111000101101\rangle + |20111000110100\rangle + |10221001001110\rangle + |12011001011111\rangle + |02121001110010\rangle + |22201010000111\rangle + |12011010001000\rangle + |21021011000000\rangle + |22201011110001\rangle + |02121100000011\rangle + |11101100010010\rangle + |21021100111111\rangle + |11101101101001\rangle + |01211110010100\rangle + |00001110111001\rangle + |10221111011001\rangle + |01211111001101\rangle + |00001111101110\rangle.$$

Example 2. Two-uniform states of the systems $7^1 \times 2^{10}$, $5^1 \times 2^{14}$, $5^1 \times 2^{13}$, $5^1 \times 3^1 \times 2^{15}$, $5^1 \times 3^1 \times 2^{12}$.

$$|\phi_{7^1 2^{10}}\rangle = |0000000000\rangle + |0000001111\rangle + |30001101001\rangle + |40001110110\rangle + |50010011010\rangle + |60010110111\rangle + |20011111001\rangle + |10100110011\rangle + |50101010100\rangle + |60101011101\rangle + |20110100100\rangle + |40110101010\rangle + |30111000011\rangle + |10111001100\rangle + |31000110100\rangle + |21001011010\rangle + |11001101110\rangle + |11010010001\rangle + |51010101101\rangle + |61011000010\rangle + |41011000101\rangle + |21100000111\rangle + |41100011001\rangle + |61100101000\rangle + |51101100011\rangle + |3110011110\rangle + |01111110000\rangle + |01111111111\rangle.$$

$$|\phi_{5^1 2^{14}}\rangle = |2000000000000000\rangle + |4000000000001110\rangle + |300000000011101\rangle + |100010010111000\rangle + |000010010111111\rangle + |400011101101000\rangle + |200011101101101\rangle + |300011101110110\rangle + |000100101110000\rangle + |100100101110111\rangle + |100101110001000\rangle + |000101110001111\rangle + |300111011000011\rangle + |400111011010100\rangle + |200111011011011\rangle + |401000111000111\rangle + |201000111010001\rangle + |301000111011010\rangle + |001001011100001\rangle + |101001011100110\rangle + |001011100010001\rangle + |101011100010110\rangle + |201101000100111\rangle + |30110100011001\rangle + |401101000111010\rangle + |101110001001001\rangle + |001110001001110\rangle + |401110110100000\rangle + |301110110101110\rangle + |201110110111101\rangle + |110001001011010\rangle + |010001001011101\rangle + |410001110100011\rangle + |210001110110100\rangle + |310001110111011\rangle + |010010111000010\rangle + |110010111000101\rangle + |210100011101000\rangle + |310100011101101\rangle + |410100011110110\rangle + |310110100000111\rangle + |410110100010001\rangle + |210110100011010\rangle + |011100010010011\rangle + |110111000100101\rangle + |111000100101011\rangle + |011000100101100\rangle + |211010001100011\rangle + |311010001110100\rangle + |411010001111011\rangle + |311011010001000\rangle + |411011010001101\rangle + |211011010010110\rangle + |011100010010011\rangle + |111111111111011\rangle + |011111111111100\rangle.$$

$$|\phi_{5^1 2^{13}}\rangle = |200000000000000\rangle + |40000000001110\rangle + |30000000011101\rangle + |10010010111000\rangle + |000100101111111\rangle + |40011101101000\rangle + |20011101101101\rangle + |30011101110110\rangle + |001001011100000\rangle + |101001011101111\rangle + |10101110001000\rangle + |00101110001111\rangle + |301110110000011\rangle + |40111011010100\rangle + |20111011011011\rangle + |41000111000111\rangle + |21000111010001\rangle + |31000111011010\rangle + |010010111000001\rangle + |11001011100110\rangle + |01011100010001\rangle + |11011100010110\rangle + |21101000100111\rangle + |31101000110001\rangle + |41101000111010\rangle + |11110001001001\rangle + |01110001001110\rangle + |41110110100000\rangle + |31110110101110\rangle + |21110110111101\rangle + |10001001011010\rangle + |00001001011101\rangle + |40001110100011\rangle + |20001110110100\rangle + |30001110111011\rangle + |00010111000010\rangle + |10010111000101\rangle + |20100011101000\rangle + |30100011101101\rangle + |40100011110110\rangle + |30110100000111\rangle + |40110100010001\rangle + |20110100011010\rangle + |001110001000101\rangle + |10111000100101\rangle + |11000100101011\rangle + |01000100101100\rangle + |21010001100011\rangle + |31010001110100\rangle + |41010001111011\rangle + |310110100001000\rangle + |41011010001101\rangle + |21011010010110\rangle + |011100010010011\rangle + |111111111111011\rangle + |011111111111100\rangle.$$

$$|\phi_{5^1 3^1 2^{15}}\rangle = |40000001010100000\rangle + |31000001111001011\rangle + |42000011011101101\rangle + |21000100010001011\rangle + |41000100111000101\rangle + |31000110001110000\rangle + |32000110100101001\rangle + |1200011101110110\rangle + |00001000101110011\rangle + |10001001000100000\rangle + |20001011010011111\rangle + |30001101001000100\rangle + |3000111001111101\rangle + |40001110111010010\rangle + |1100111111011110\rangle + |01010000010110111\rangle + |2201000111110110\rangle + |02010010001000101\rangle + |41010011000010010\rangle + |3201001110110110\rangle + |4201010000011010\rangle + |22010110110011001\rangle + |02011000001111010\rangle + |00011001110001100\rangle + |12011010110001000\rangle + |21011011100110101\rangle + |11011100000100011\rangle + |10011100101001111\rangle + |20011101101011001\rangle + |01011111010000100\rangle + |12100000000011101\rangle +$$

$$\begin{aligned}
& |1100000011011100\rangle + |1010001101011101\rangle + |20100100100100110\rangle + |01100101101011010\rangle + \\
& |02100101110000111\rangle + |00100111000010001\rangle + |41101000100111100\rangle + |22101001001001000\rangle + \\
& |32101001011010111\rangle + |42101010100000110\rangle + |01101010101101001\rangle + |21101010111000010\rangle + \\
& |22101110000100111\rangle + |0210111110111000\rangle + |30110000110101010\rangle + |20110010011100000\rangle + \\
& |30110011100010011\rangle + |1110011101000001\rangle + |2110101001111100\rangle + |40110101100101101\rangle + \\
& |00110110011101110\rangle + |10110110111010100\rangle + |3111000110110101\rangle + |40111010001011111\rangle + \\
& |32111100010010000\rangle + |12111101011100011\rangle + |42111101111110001\rangle + |31111111000001110\rangle + \\
& |41111111011101011\rangle.
\end{aligned}$$

$$\begin{aligned}
|\phi_{513^12^{12}}\rangle = & |40000001010100\rangle + |31000001111001\rangle + |42000011011101\rangle + |21000100010001\rangle + \\
& |41000100111000\rangle + |31000110001110\rangle + |32000110100101\rangle + |12000111101110\rangle + |00001000101110\rangle + \\
& |10001001000100\rangle + |20001011010011\rangle + |30001101001000\rangle + |30001110011111\rangle + |40001110111010\rangle + \\
& |1100111110111\rangle + |0101000010110\rangle + |22010001111110\rangle + |02010010001000\rangle + |41010011000010\rangle + \\
& |32010011101101\rangle + |42010100000011\rangle + |22010110110011\rangle + |02011000001111\rangle + |00011001110001\rangle + \\
& |12011010110001\rangle + |21011011100110\rangle + |11011100000100\rangle + |10011100101001\rangle + |20011101101011\rangle + \\
& |0101111010000\rangle + |121000000000011\rangle + |11100000011011\rangle + |10100011010111\rangle + |20100100100100\rangle + \\
& |01100101101011\rangle + |02100101110000\rangle + |00100111000010\rangle + |41101000100111\rangle + |22101001001001\rangle + \\
& |32101001011010\rangle + |42101010100000\rangle + |01101010101101\rangle + |21101010111000\rangle + |22101110000100\rangle + \\
& |0210111110111\rangle + |30110000110101\rangle + |20110010011100\rangle + |30110011100010\rangle + |11110011101000\rangle + \\
& |21110101001111\rangle + |40110101100101\rangle + |00110110011101\rangle + |10110110111010\rangle + |31111000110110\rangle + \\
& |40111010001011\rangle + |32111100010010\rangle + |12111101011100\rangle + |42111101111110\rangle + |31111111000001\rangle + \\
& |41111111011101011\rangle.
\end{aligned}$$

Example 3. Three three-uniform states obtained from Theorem 3.4.

$$\begin{aligned}
|\phi_{3^42^{22}}\rangle = & |00010000000000000000000000000000\rangle + |11120000000000000000000000000000\rangle + \\
& |22200000000000000000000000000000\rangle + |00011111111111111111111111111111\rangle + |11121111111111111111111111111111\rangle + \\
& |22201111111111111111111111111111\rangle + |11100000010011000010110111\rangle + |22210000010011000010110111\rangle + \\
& |00020000010011000010110111\rangle + |1110111101100111101001000\rangle + |2221111101100111101001000\rangle + \\
& |0002111101100111101001000\rangle + |1222000001110000010101111\rangle + |2000000001110000010101111\rangle + \\
& |0111000001110000010101111\rangle + |122211110001111010100000\rangle + |200011110001111010100000\rangle + \\
& |011111110001111010100000\rangle + |0102000011100000101110001\rangle + |12100000111000001011110001\rangle + \\
& |20210000111000001011110001\rangle + |0102111100011110100001110\rangle + |1210111100011110100001110\rangle + \\
& |2021111100011110100001110\rangle + |2201000101010101110101110\rangle + |0012000101010101110101110\rangle + \\
& |1120000101010101110101110\rangle + |220111101010100001010001\rangle + |001211101010100001010001\rangle + \\
& |112011101010100001010001\rangle + |110200011011101100101001\rangle + |221000011011101100101001\rangle + \\
& |002100011011101100101001\rangle + |11021110010001001101010110\rangle + |22101110010001001101010110\rangle + \\
& |0021111001000101101010110\rangle + |10120001101111000001001110\rangle + |21200001101111000001001110\rangle + \\
& |02010001101111000001001110\rangle + |1012111001000011110110001\rangle + |2120111001000011110110001\rangle + \\
& |0201111001000011110110001\rangle + |02200001101111011100110001\rangle + |10010001101111011100110001\rangle + \\
& |21120001101111011100110001\rangle + |02201110010000100011001110\rangle + |10011110010000100011001110\rangle + \\
& |21121110010000100011001110\rangle + |2110001110000111101000011\rangle + |02220001110000111101000011\rangle +
\end{aligned}$$

$$\begin{aligned}
& |1000000111000011101000011\rangle + |211111000111000010111100\rangle + |022211000111000010111100\rangle + \\
& |1000111000111000010111100\rangle + |2002001000001111000111101\rangle + |0110001000001111000111101\rangle + \\
& |1221001000001111000111101\rangle + |2002110111100000111000010\rangle + |0110110111100000111000010\rangle + \\
& |122110111100000111000010\rangle + |01000010001100111010010010\rangle + |12110010001100111010010010\rangle + \\
& |20220010001100111010010010\rangle + |01001101110011000101101101\rangle + |1211101110011000101101101\rangle + \\
& |20221101110011000101101101\rangle + |0212001001110111101001101\rangle + |1020001001111011101001101\rangle + \\
& |2101001001111011101001101\rangle + |02121101100001000010110010\rangle + |10201101100001000010110010\rangle + \\
& |21011101100001000010110010\rangle + |20100010101001010111101010\rangle + |01210010101001010111101010\rangle + \\
& |12020010101001010111101010\rangle + |20101101010110101000010101\rangle + |01211101010110101000010101\rangle + \\
& |12021101010110101000010101\rangle + |20110010111011100110011100\rangle + |01220010111011100110011100\rangle + \\
& |12000010111011100110011100\rangle + |20111101000100011001100011\rangle + |01221101000100011001100011\rangle + \\
& |12001101000100011001100011\rangle + |02110011000100100101110100\rangle + |10220011000100100101110100\rangle + \\
& |21000011000100100101110100\rangle + |02111100111011011010001011\rangle + |10221100111011011010001011\rangle + \\
& |210011001110110110001011\rangle + |11010011010111010011000000\rangle + |22120011010111010011000000\rangle + \\
& |00200011010111010011000000\rangle + |11011100101000101100111111\rangle + |22121100101000101100111111\rangle + \\
& |00201100101000101100111111\rangle + |22020011100000101010001111\rangle + |00100011100000101010001111\rangle + \\
& |11210011100000101010001111\rangle + |22021100011111010101110000\rangle + |00101100011111010101110000\rangle + \\
& |11211100011111010101110000\rangle + |21220011110011101101110010\rangle + |02000011110011101101110010\rangle + \\
& |10110011110011101101110010\rangle + |21221100001100010010001101\rangle + |02001100001100010010001101\rangle + \\
& |10111100001100010010001101\rangle + |00010100000101110001111011\rangle + |11120100000101110001111011\rangle + \\
& |22200100000101110001111011\rangle + |0001101111010001110000100\rangle + |11121011111010001110000100\rangle + \\
& |22201011111010001110000100\rangle + |11100100010110101110101010\rangle + |22210100010110101110101010\rangle + \\
& |00020100010110101110101010\rangle + |111010111010010001010101\rangle + |22211011101001010001010101\rangle + \\
& |000210111010010001010101\rangle + |12220100100001110100000100\rangle + |20000100100001110100000100\rangle + \\
& |01110100100001110100000100\rangle + |1222101101111000101111011\rangle + |2000101101111000101111011\rangle + \\
& |01111011011110001011111011\rangle + |01020100110010011001100\rangle + |12100100110010011001100\rangle + \\
& |20210100110010011001100\rangle + |0102101100110100110010011\rangle + |12101011001101100110010011\rangle + \\
& |20211011001101100110010011\rangle + |220101001111011110110100\rangle + |001201001111011110110100\rangle + \\
& |112001001111011110110100\rangle + |22011011000010000100101011\rangle + |00121011000010000100101011\rangle + \\
& |11201011000010000100101011\rangle + |1102010100101110010110\rangle + |221001010010101110010110\rangle + \\
& |00210101001010011110010110\rangle + |11021010110101100001101001\rangle + |22101010110101100001101001\rangle + \\
& |00211010110101100001101001\rangle + |101201010010100111100101\rangle + |212001010010100111100101\rangle + \\
& |020101010010100111100101\rangle + |101210101101011000011010\rangle + |21201010110101011000011010\rangle + \\
& |02011010110101011000011010\rangle + |02200101001011101001011010\rangle + |10010101001011101001011010\rangle + \\
& |21120101001011101001011010\rangle + |022010110100010110100101\rangle + |100110101110100010110100101\rangle + \\
& |21121010110100010110100101\rangle + |21110101110101100110011001\rangle + |02220101110101100110011001\rangle + \\
& |10000101110101100110011001\rangle + |21111010001010011001100110\rangle + |02221010001010011001100110\rangle + \\
& |10001010001010011001100110\rangle + |20020110000111001111000001\rangle + |01100110000111001111000001\rangle + \\
& |12210110000111001111000001\rangle + |2002100111100011000011110\rangle + |0110100111100011000011110\rangle +
\end{aligned}$$

$$\begin{aligned}
& |12211001111000110000111110\rangle + |01000110100010010111011011\rangle + |12110110100010010111011011\rangle + \\
& |20220110100010010111011011\rangle + |01001001011101101000100100\rangle + |12111001011101101000100100\rangle + \\
& |20221001011101101000100100\rangle + |02120110101101001100100111\rangle + |10200110101101001100100111\rangle + \\
& |21010110101101001100100111\rangle + |02121001010010110011011000\rangle + |10201001010010110011011000\rangle + \\
& |21011001010010110011011000\rangle + |2010011011110100000100010\rangle + |0121011011110100000100010\rangle + \\
& |1202011011110100000100010\rangle + |2010100100000101111011101\rangle + |0121100100000101111011101\rangle + \\
& |1202100100000101111011101\rangle + |20110111011000010100111000\rangle + |01220111011000010100111000\rangle + \\
& |12000111011000010100111000\rangle + |20111000100111101011000111\rangle + |01221000100111101011000111\rangle + \\
& |12001000100111101011000111\rangle + |02110111011001001000001001\rangle + |10220111011001001000001001\rangle + \\
& |21000111011001001000001001\rangle + |0211100010011011011110110\rangle + |1022100010011011011110110\rangle + \\
& |2100100010011011011110110\rangle + |11010111011001110011100111\rangle + |22120111011001110011100111\rangle + \\
& |00200111011001110011100111\rangle + |11011000100110001100011000\rangle + |22121000100110001100001100\rangle + \\
& |00201000100110001100011000\rangle + |220201110010000101111100\rangle + |0010011110010000101111100\rangle + \\
& |1121011110010000101111100\rangle + |22021000011011110100000011\rangle + |00101000011011110100000011\rangle + \\
& |11211000011011110100000011\rangle + |21220111110110010000010111\rangle + |02000111110110010000010111\rangle + \\
& |10110111110110010000010111\rangle + |2122100000100110111101000\rangle + |0200100000100110111101000\rangle + \\
& |1011100000100110111101000\rangle.
\end{aligned}$$

$$\begin{aligned}
|\phi_{3^5 2^{16}}\rangle = & |00001000000000000000\rangle + |11112000000000000000\rangle + |22220000000000000000\rangle + \\
& |00001111111111111111\rangle + |11112111111111111111\rangle + |22220111111111111111\rangle + \\
& |111100000010011000010\rangle + |222210000010011000010\rangle + |000020000010011000010\rangle + \\
& |111101111101100111101\rangle + |22221111101100111101\rangle + |00002111101100111101\rangle + \\
& |112220000011100000101\rangle + |220000000011100000101\rangle + |001110000011100000101\rangle + \\
& |11222111110001111010\rangle + |220011110001111010\rangle + |0011111110001111010\rangle + \\
& |101020000111000001011\rangle + |212100000111000001011\rangle + |020210000111000001011\rangle + \\
& |1010211100011110100\rangle + |2121011100011110100\rangle + |0202111100011110100\rangle + \\
& |022010001010101110\rangle + |100120001010101110\rangle + |21120000101010101110\rangle + \\
& |022011110101010001\rangle + |100121110101010001\rangle + |211201110101010001\rangle + \\
& |0110200011011101100\rangle + |1221000011011101100\rangle + |2002100011011101100\rangle + \\
& |01102111001001101\rangle + |12210111001001101\rangle + |20021111001001101\rangle + \\
& |0101200011011100001\rangle + |1212000011011100001\rangle + |20201000110111100001\rangle + \\
& |0101211100100011110\rangle + |1212011100100011110\rangle + |2020111100100011110\rangle + \\
& |002200001101111011100\rangle + |110010001101111011100\rangle + |221120001101111011100\rangle + \\
& |00220111001000100011\rangle + |11001111001000100011\rangle + |22112111001000100011\rangle + \\
& |221110001110000111101\rangle + |002220001110000111101\rangle + |110000001110000111101\rangle + \\
& |221111110001111000010\rangle + |002221110001111000010\rangle + |110001110001111000010\rangle + \\
& |22002001000001111000\rangle + |00110001000001111000\rangle + |11221001000001111000\rangle + \\
& |220021101111100000111\rangle + |001101101111100000111\rangle + |112211101111100000111\rangle + \\
& |201000010001100111010\rangle + |012110010001100111010\rangle + |120220010001100111010\rangle + \\
& |2010011011110011000101\rangle + |0121111011110011000101\rangle + |1202211011110011000101\rangle +
\end{aligned}$$

$$\begin{aligned}
& |20212001001110111101\rangle + |01020001001110111101\rangle + |12101001001110111101\rangle + \\
& |202121101100001000010\rangle + |010201101100001000010\rangle + |121011101100001000010\rangle + \\
& |02010001010100101011\rangle + |10121001010100101011\rangle + |21202001010100101011\rangle + \\
& |0201011010110101000\rangle + |1012111010101101000\rangle + |2120211010110101000\rangle + \\
& |120110010111011100110\rangle + |201220010111011100110\rangle + |012000010111011100110\rangle + \\
& |120111101000100011001\rangle + |201221101000100011001\rangle + |012001101000100011001\rangle + \\
& |102110011000100100101\rangle + |210220011000100100101\rangle + |021000011000100100101\rangle + \\
& |102111100111011011010\rangle + |210221100111011011010\rangle + |021001100111011011010\rangle + \\
& |211010011010111010011\rangle + |022120011010111010011\rangle + |100200011010111010011\rangle + \\
& |211011100101000101100\rangle + |022121100101000101100\rangle + |100201100101000101100\rangle + \\
& |122020011100000101010\rangle + |200100011100000101010\rangle + |011210011100000101010\rangle + \\
& |12202110001111010101\rangle + |20010110001111010101\rangle + |01121110001111010101\rangle + \\
& |021220011110011101101\rangle + |102000011110011101101\rangle + |210110011110011101101\rangle + \\
& |021221100001100010010\rangle + |102001100001100010010\rangle + |210111100001100010010\rangle + \\
& |000010100000101110001\rangle + |111120100000101110001\rangle + |222200100000101110001\rangle + \\
& |00001101111010001110\rangle + |11112101111010001110\rangle + |222201011111010001110\rangle + \\
& |111100100010110101110\rangle + |222210100010110101110\rangle + |000020100010110101110\rangle + \\
& |111101011101001010001\rangle + |222211011101001010001\rangle + |000021011101001010001\rangle + \\
& |112220100100001110100\rangle + |220000100100001110100\rangle + |001110100100001110100\rangle + \\
& |112221011011110001011\rangle + |220001011011110001011\rangle + |001111011011110001011\rangle + \\
& |1012020100110010011001\rangle + |212100100110010011001\rangle + |020210100110010011001\rangle + \\
& |101021011001101100110\rangle + |212101011001101100110\rangle + |020211011001101100110\rangle + \\
& |02201010011110111011\rangle + |10012010011110111011\rangle + |21120010011110111011\rangle + \\
& |022011011000010000100\rangle + |100121011000010000100\rangle + |211201011000010000100\rangle + \\
& |01102010100101110\rangle + |12210010100101001110\rangle + |20021010100101001110\rangle + \\
& |01102101011010100001\rangle + |12210101011010100001\rangle + |20021101011010100001\rangle + \\
& |0101201010010100111\rangle + |1212001010010100111\rangle + |2020101010010100111\rangle + \\
& |0101210101101011000\rangle + |1212010101101011000\rangle + |2020110101101011000\rangle + \\
& |002200101001011101001\rangle + |110010101001011101001\rangle + |221120101001011101001\rangle + \\
& |002201010110100010110\rangle + |110011010110100010110\rangle + |221121010110100010110\rangle + \\
& |221110101110101100110\rangle + |002220101110101100110\rangle + |110000101110101100110\rangle + \\
& |221111010001010011001\rangle + |002221010001010011001\rangle + |110001010001010011001\rangle + \\
& |220020110000111001111\rangle + |001100110000111001111\rangle + |112210110000111001111\rangle + \\
& |220021001111000110000\rangle + |001101001111000110000\rangle + |112211001111000110000\rangle + \\
& |201000110100010010111\rangle + |012110110100010010111\rangle + |120220110100010010111\rangle + \\
& |201001001011101101000\rangle + |012111001011101101000\rangle + |120221001011101101000\rangle + \\
& |202120110101101001100\rangle + |010200110101101001100\rangle + |121010110101101001100\rangle + \\
& |202121001010010110011\rangle + |010201001010010110011\rangle + |121011001010010110011\rangle + \\
& |02010011011110100000\rangle + |10121011011110100000\rangle + |21202011011110100000\rangle +
\end{aligned}$$

$$\begin{aligned}
& |020101001000001011111\rangle + |101211001000001011111\rangle + |212021001000001011111\rangle + \\
& |120110111011000010100\rangle + |201220111011000010100\rangle + |012000111011000010100\rangle + \\
& |120111000100111101011\rangle + |201221000100111101011\rangle + |012001000100111101011\rangle + \\
& |102110111011001001000\rangle + |210220111011001001000\rangle + |021000111011001001000\rangle + \\
& |102111000100110110111\rangle + |210221000100110110111\rangle + |021001000100110110111\rangle + \\
& |211010111011001110011\rangle + |022120111011001110011\rangle + |100200111011001110011\rangle + \\
& |211011000100110001100\rangle + |022121000100110001100\rangle + |100201000100110001100\rangle + \\
& |122020111100100001011\rangle + |200100111100100001011\rangle + |011210111100100001011\rangle + \\
& |122021000011011110100\rangle + |200101000011011110100\rangle + |011211000011011110100\rangle + \\
& |021220111110110010000\rangle + |102000111110110010000\rangle + |210110111110110010000\rangle + \\
& |021221000001001101111\rangle + |102001000001001101111\rangle + |210111000001001101111\rangle.
\end{aligned}$$

$$\begin{aligned}
|\phi_{3^4 2^{16}}\rangle = & |00010000000000000000\rangle + |11120000000000000000\rangle + |22200000000000000000\rangle + \\
& |00011111111111111111\rangle + |11121111111111111111\rangle + |22201111111111111111\rangle + \\
& |11100000010011000010\rangle + |22210000010011000010\rangle + |00020000010011000010\rangle + \\
& |1110111101100111101\rangle + |2221111101100111101\rangle + |0002111101100111101\rangle + \\
& |12220000011100000101\rangle + |20000000011100000101\rangle + |01110000011100000101\rangle + \\
& |1222111100011111010\rangle + |2000111100011111010\rangle + |0111111100011111010\rangle + \\
& |01020000111000001011\rangle + |12100000111000001011\rangle + |20210000111000001011\rangle + \\
& |01021111000111110100\rangle + |12101111000111110100\rangle + |20211111000111110100\rangle + \\
& |2201000101010101110\rangle + |0012000101010101110\rangle + |1120000101010101110\rangle + \\
& |220111101010100001\rangle + |001211101010100001\rangle + |112011101010100001\rangle + \\
& |11020001101110110010\rangle + |22100001101110110010\rangle + |00210001101110110010\rangle + \\
& |11021110010001001101\rangle + |22101110010001001101\rangle + |00211110010001001101\rangle + \\
& |10120001101111000001\rangle + |21200001101111000001\rangle + |02010001101111000001\rangle + \\
& |1012111001000011110\rangle + |2120111001000011110\rangle + |0201111001000011110\rangle + \\
& |02200001101111011100\rangle + |10010001101111011100\rangle + |21120001101111011100\rangle + \\
& |02201110010000100011\rangle + |10011110010000100011\rangle + |21121110010000100011\rangle + \\
& |21110001110000111101\rangle + |02220001110000111101\rangle + |10000001110000111101\rangle + \\
& |21111110001111000010\rangle + |02221110001111000010\rangle + |10001110001111000010\rangle + \\
& |2002001000001111100\rangle + |0110001000001111100\rangle + |1221001000001111100\rangle + \\
& |20021101111100000111\rangle + |01101101111100000111\rangle + |12211101111100000111\rangle + \\
& |01000010001100111010\rangle + |12110010001100111010\rangle + |20220010001100111010\rangle + \\
& |01001101110011000101\rangle + |12111101110011000101\rangle + |20221101110011000101\rangle + \\
& |0212001001111011101\rangle + |1020001001111011101\rangle + |2101001001111011101\rangle + \\
& |02121101100001000010\rangle + |10201101100001000010\rangle + |21011101100001000010\rangle + \\
& |20100010101010111\rangle + |01210010101010111\rangle + |1202001010101010111\rangle + \\
& |201011010110101000\rangle + |012111010110101000\rangle + |120211010110101000\rangle + \\
& |2011001011011100110\rangle + |01220010111011100110\rangle + |12000010111011100110\rangle + \\
& |20111101000100011001\rangle + |01221101000100011001\rangle + |12001101000100011001\rangle +
\end{aligned}$$

$$\begin{aligned}
& |02110011000100100101\rangle + |10220011000100100101\rangle + |21000011000100100101\rangle + \\
& |02111100111011011010\rangle + |10221100111011011010\rangle + |21001100111011011010\rangle + \\
& |11010011010111010011\rangle + |22120011010111010011\rangle + |00200011010111010011\rangle + \\
& |11011100101000101100\rangle + |22121100101000101100\rangle + |00201100101000101100\rangle + \\
& |22020011100000101010\rangle + |00100011100000101010\rangle + |11210011100000101010\rangle + \\
& |2202110001111010101\rangle + |0010110001111010101\rangle + |1121110001111010101\rangle + \\
& |21220011110011101101\rangle + |02000011110011101101\rangle + |10110011110011101101\rangle + \\
& |21221100001100010010\rangle + |02001100001100010010\rangle + |10111100001100010010\rangle + \\
& |00010100000101110001\rangle + |11120100000101110001\rangle + |22200100000101110001\rangle + \\
& |0001101111010001110\rangle + |1112101111010001110\rangle + |2220101111010001110\rangle + \\
& |1100100010110101110\rangle + |22210100010110101110\rangle + |00020100010110101110\rangle + \\
& |111010111010010001\rangle + |222110111010010001\rangle + |000210111010010001\rangle + \\
& |12220100100001110100\rangle + |20000100100001110100\rangle + |01110100100001110100\rangle + \\
& |1222101101110001011\rangle + |2000101101110001011\rangle + |0111101101110001011\rangle + \\
& |01020100110010011001\rangle + |12100100110010011001\rangle + |20210100110010011001\rangle + \\
& |01021011001101100110\rangle + |12101011001101100110\rangle + |20211011001101100110\rangle + \\
& |2201010011101111011\rangle + |0012010011101111011\rangle + |11200100111101111011\rangle + \\
& |22011011000010000100\rangle + |00121011000010000100\rangle + |11201011000010000100\rangle + \\
& |110201010010011110\rangle + |221001010010011110\rangle + |002101010010011110\rangle + \\
& |11021010110101100001\rangle + |22101010110101100001\rangle + |00211010110101100001\rangle + \\
& |101201010010100111\rangle + |212001010010100111\rangle + |020101010010100111\rangle + \\
& |10121010110101011000\rangle + |21201010110101011000\rangle + |02011010110101011000\rangle + \\
& |0220010100101101001\rangle + |10010101001011101001\rangle + |21120101001011101001\rangle + \\
& |02201010110100010110\rangle + |10011010110100010110\rangle + |21121010110100010110\rangle + \\
& |2111010110101100110\rangle + |02220101110101100110\rangle + |10000101110101100110\rangle + \\
& |21111010001010011001\rangle + |02221010001010011001\rangle + |10001010001010011001\rangle + \\
& |20020110000111001111\rangle + |01100110000111001111\rangle + |12210110000111001111\rangle + \\
& |20021001111000110000\rangle + |01101001111000110000\rangle + |12211001111000110000\rangle + \\
& |01000110100010010111\rangle + |12110110100010010111\rangle + |20220110100010010111\rangle + \\
& |01001001011101101000\rangle + |12111001011101101000\rangle + |20221001011101101000\rangle + \\
& |02120110101101001100\rangle + |10200110101101001100\rangle + |21010110101101001100\rangle + \\
& |02121001010010110011\rangle + |10201001010010110011\rangle + |21011001010010110011\rangle + \\
& |2010011011110100000\rangle + |0121011011110100000\rangle + |1202011011110100000\rangle + \\
& |20101001000001011111\rangle + |01211001000001011111\rangle + |12021001000001011111\rangle + \\
& |20110111011000010100\rangle + |01220111011000010100\rangle + |12000111011000010100\rangle + \\
& |20111000100111101011\rangle + |01221000100111101011\rangle + |12001000100111101011\rangle + \\
& |02110111011001001000\rangle + |10220111011001001000\rangle + |21000111011001001000\rangle + \\
& |02111000100110110111\rangle + |10221000100110110111\rangle + |21001000100110110111\rangle + \\
& |11010111011001110011\rangle + |22120111011001110011\rangle + |00200111011001110011\rangle +
\end{aligned}$$

$$\begin{aligned}
& |11011000100110001100\rangle + |22121000100110001100\rangle + |00201000100110001100\rangle + \\
& |220201110010001011\rangle + |001001110010001011\rangle + |112101110010001011\rangle + \\
& |2202100001101110100\rangle + |0010100001101110100\rangle + |1121100001101110100\rangle + \\
& |2122011110110010000\rangle + |0200011110110010000\rangle + |1011011110110010000\rangle + \\
& |212210000100110111\rangle + |020010000100110111\rangle + |1011100000100110111\rangle.
\end{aligned}$$

Example 4. Three-uniform states of the systems $4^5 \times 2^2$, $4^4 \times 2^4$, $4^3 \times 2^6$, $4^2 \times 2^8$ and $4^1 \times 2^{10}$.

$$\begin{aligned}
|\phi_{4^5 2^2}\rangle = & |0000000\rangle + |0122001\rangle + |0233010\rangle + |0311011\rangle + |0212100\rangle + |0330101\rangle + |0021110\rangle + \\
& |0103111\rangle + |0323200\rangle + |0201201\rangle + |0110210\rangle + |0032211\rangle + |0131300\rangle + |0013301\rangle + |0302310\rangle + |0220311\rangle + \\
& |1111101\rangle + |1033100\rangle + |1322111\rangle + |1200110\rangle + |1303001\rangle + |1221000\rangle + |1130011\rangle + |1012010\rangle + |1232301\rangle + \\
& |1310300\rangle + |1001311\rangle + |1123310\rangle + |1020201\rangle + |1102200\rangle + |1213211\rangle + |1331210\rangle + |2222210\rangle + |2300211\rangle + \\
& |2011200\rangle + |2133201\rangle + |2030310\rangle + |2112311\rangle + |2203300\rangle + |2321301\rangle + |2101010\rangle + |2023011\rangle + |2332000\rangle + \\
& |2210001\rangle + |2313110\rangle + |2231111\rangle + |2120100\rangle + |2002101\rangle + |3333311\rangle + |3211310\rangle + |3100301\rangle + |3022300\rangle + \\
& |3121211\rangle + |3003210\rangle + |3312201\rangle + |3230200\rangle + |3010111\rangle + |3132110\rangle + |3223101\rangle + |3301100\rangle + |3202011\rangle + \\
& |3320010\rangle + |3031001\rangle + |3113000\rangle.
\end{aligned}$$

$$\begin{aligned}
|\phi_{4^4 2^4}\rangle = & |00000000\rangle + |01220001\rangle + |02330010\rangle + |03110011\rangle + |02120100\rangle + |03300101\rangle + |00210110\rangle + \\
& |01030111\rangle + |03231000\rangle + |02011001\rangle + |01101010\rangle + |00321011\rangle + |01311100\rangle + |00131101\rangle + |03021110\rangle + \\
& |02201111\rangle + |11110101\rangle + |10330100\rangle + |13220111\rangle + |12000110\rangle + |13030001\rangle + |12210000\rangle + |11300011\rangle + \\
& |10120010\rangle + |12321101\rangle + |13101100\rangle + |10011111\rangle + |11231110\rangle + |10201001\rangle + |11021000\rangle + |12131011\rangle + \\
& |13311010\rangle + |22221010\rangle + |23001011\rangle + |20111000\rangle + |21331001\rangle + |20301110\rangle + |21121111\rangle + |22031100\rangle + \\
& |23211101\rangle + |21010010\rangle + |20230011\rangle + |23320000\rangle + |22100001\rangle + |23130110\rangle + |22310111\rangle + |21200100\rangle + \\
& |20020101\rangle + |33331111\rangle + |32111110\rangle + |31001101\rangle + |30221100\rangle + |31211011\rangle + |30031010\rangle + |33121001\rangle + \\
& |32301000\rangle + |30100111\rangle + |31320110\rangle + |32230101\rangle + |33010100\rangle + |32020011\rangle + |33200010\rangle + |30310001\rangle + \\
& |31130000\rangle.
\end{aligned}$$

$$\begin{aligned}
|\phi_{4^3 2^6}\rangle = & |000000000\rangle + |012100001\rangle + |023110010\rangle + |031010011\rangle + |021100100\rangle + |033000101\rangle + \\
& |002010110\rangle + |010110111\rangle + |032111000\rangle + |020011001\rangle + |011001010\rangle + |003101011\rangle + |013011100\rangle + \\
& |001111101\rangle + |030101110\rangle + |022001111\rangle + |111010101\rangle + |103110100\rangle + |132100111\rangle + |120000110\rangle + \\
& |130110001\rangle + |122010000\rangle + |113000011\rangle + |101100010\rangle + |123101101\rangle + |131001100\rangle + |100011111\rangle + \\
& |112111110\rangle + |102001001\rangle + |110101000\rangle + |121111011\rangle + |133011010\rangle + |222101010\rangle + |230001011\rangle + \\
& |201011000\rangle + |213111001\rangle + |203001110\rangle + |211101111\rangle + |220111100\rangle + |232011101\rangle + |210010010\rangle + \\
& |202110011\rangle + |233100000\rangle + |221000001\rangle + |231110110\rangle + |223010111\rangle + |212000100\rangle + |200100101\rangle + \\
& |333111111\rangle + |321011110\rangle + |310001101\rangle + |302101100\rangle + |312011011\rangle + |300111010\rangle + |331101001\rangle + \\
& |323001000\rangle + |301000111\rangle + |313100110\rangle + |322310101\rangle + |330101000\rangle + |320200011\rangle + |332000010\rangle + \\
& |303010001\rangle + |311110000\rangle.
\end{aligned}$$

$$\begin{aligned}
|\phi_{4^2 2^8}\rangle = & |0000000000\rangle + |0110100001\rangle + |0211110010\rangle + |0301010011\rangle + |0201100100\rangle + |0311000101\rangle + \\
& |0010010110\rangle + |0100110111\rangle + |0310111000\rangle + |0200011001\rangle + |0101001010\rangle + |0011101011\rangle + |0111011100\rangle + \\
& |0001111101\rangle + |0300101110\rangle + |0210001111\rangle + |1101010101\rangle + |1011110100\rangle + |1310100111\rangle + |1200000110\rangle + \\
& |1300110001\rangle + |1210010000\rangle + |1111000011\rangle + |1001100010\rangle + |1211101101\rangle + |1301001100\rangle + |1000111111\rangle + \\
& |1110111110\rangle + |1010001001\rangle + |1100101000\rangle + |1201111011\rangle + |1311011010\rangle + |2210101010\rangle + |2300001011\rangle + \\
& |2001011000\rangle + |2111110001\rangle + |2011001110\rangle + |2101101111\rangle + |2200111100\rangle + |2310011101\rangle + |2100100101\rangle +
\end{aligned}$$

$$|2010110011\rangle + |2311100000\rangle + |2201000001\rangle + |2301110110\rangle + |2211010111\rangle + |2110000100\rangle + |2000100101\rangle + |3311111111\rangle + |3201011110\rangle + |3100001101\rangle + |3010101100\rangle + |3110011011\rangle + |3000111010\rangle + |3301101001\rangle + |3211001000\rangle + |3001000111\rangle + |311100110\rangle + |3210110101\rangle + |3300010100\rangle + |3200100011\rangle + |3310000010\rangle + |3011010001\rangle + |3101110000\rangle.$$

$$\begin{aligned} |\phi_{4^1 2^{10}}\rangle = & |00000000000\rangle + |00110100001\rangle + |0101110010\rangle + |01101010011\rangle + |01001100100\rangle + \\ & |01111000101\rangle + |00010010110\rangle + |00100110111\rangle + |01110111000\rangle + |01000011001\rangle + |00101001010\rangle + \\ & |00011101011\rangle + |00111011100\rangle + |00001111101\rangle + |01100101110\rangle + |01010001111\rangle + |10101010101\rangle + \\ & |10011110100\rangle + |11110100111\rangle + |11000000110\rangle + |11100110001\rangle + |11010010000\rangle + |10111000011\rangle + \\ & |10001100010\rangle + |11011101101\rangle + |11101001100\rangle + |10000011111\rangle + |10110111110\rangle + |10010001001\rangle + \\ & |10100101000\rangle + |11001111011\rangle + |11111011010\rangle + |21010101010\rangle + |21100001011\rangle + |20001011000\rangle + \\ & |20111111001\rangle + |20011001110\rangle + |20101101111\rangle + |21000111100\rangle + |21110011101\rangle + |20100010010\rangle + \\ & |20010110011\rangle + |21111100000\rangle + |21001000001\rangle + |21101110110\rangle + |21011010111\rangle + |20110000100\rangle + \\ & |20000100101\rangle + |31111111111\rangle + |31001011110\rangle + |30100001101\rangle + |30010101100\rangle + |30110011011\rangle + \\ & |30000111010\rangle + |31101101001\rangle + |31011001000\rangle + |30001000111\rangle + |30111100110\rangle + |31010110101\rangle + \\ & |31100010100\rangle + |31000100011\rangle + |31110000010\rangle + |30011010001\rangle + |30101110000\rangle. \end{aligned}$$

Example 5. By Table 1 in Ref. [22], we have an IrOA($r_N, N, 12, 3$) for $N = 8$ and every $N \geq 12$. Using $\text{MOA}(12, 2, 6^{12}, 3) = ((\mathbf{6}) \otimes \mathbf{1}_2, \mathbf{1}_6 \otimes (\mathbf{2}))$, $\text{MOA}(12, 2, 4^{13}, 3) = ((\mathbf{4}) \otimes \mathbf{1}_3, \mathbf{1}_4 \otimes (\mathbf{3}))$, $\text{MOA}(12, 3, 3^{12}, 3)$, and Theorem 3.7, there exist an IrMOA($r_N, N + n_1 + n_2 + 2n_3, 12^{N-(n_1+n_2+n_3)} 6^{n_1} 2^{n_1} 4^{n_2} 3^{n_2} 3^{n_3} 2^{2n_3}, 3$), and three-uniform states of the system $12^{N-(n_1+n_2+n_3)} \times 6^{n_1} \times 4^{n_2} \times 3^{n_2+n_3} \times 2^{n_1+2n_3}$ with $1 \leq n_1 + n_2 + n_3 \leq N$ for $N = 8$ and every $N \geq 12$.

For the case of $N = 8$ and $r_N = 12^4$, we can obtain 164 IrMOAs from 164 non-negative integer solutions to the inequation $1 \leq n_1 + n_2 + n_3 \leq 8$.

For example, when $n_1 + n_2 + n_3 = 1$, we can obtain 3 IrMOAs as follows.

$$\begin{aligned} n_1 = 0, n_2 = 0, n_3 = 1, & \text{IrMOA}(r_8, 10, 12^7 3^{12}, 3), \\ n_1 = 0, n_2 = 1, n_3 = 0, & \text{IrMOA}(r_8, 9, 12^7 4^{13}, 3), \\ n_1 = 1, n_2 = 0, n_3 = 0, & \text{IrMOA}(r_8, 9, 12^7 6^{12}, 3). \end{aligned}$$

When $n_1 + n_2 + n_3 = 2$, we can obtain 6 IrMOAs as follows.

$$\begin{aligned} n_1 = 0, n_2 = 0, n_3 = 2, & \text{IrMOA}(r_8, 12, 12^6 3^2 2^4, 3), \\ n_1 = 0, n_2 = 2, n_3 = 0, & \text{IrMOA}(r_8, 10, 12^6 4^2 3^2, 3), \\ n_1 = 2, n_2 = 0, n_3 = 0, & \text{IrMOA}(r_8, 10, 12^6 6^2 2^2, 3), \\ n_1 = 0, n_2 = 1, n_3 = 1, & \text{IrMOA}(r_8, 11, 12^6 4^1 3^2 2^2, 3), \\ n_1 = 1, n_2 = 0, n_3 = 1, & \text{IrMOA}(r_8, 11, 12^6 6^1 3^1 2^3, 3), \\ n_1 = 1, n_2 = 1, n_3 = 0, & \text{IrMOA}(r_8, 10, 12^6 6^1 4^1 3^1 2^1, 3). \end{aligned}$$

When $n_1 + n_2 + n_3 = 3$, we can obtain 10 IrMOAs as follows.

$$\begin{aligned} n_1 = 0, n_2 = 0, n_3 = 3, & \text{IrMOA}(r_8, 14, 12^5 3^3 2^6, 3), \\ n_1 = 0, n_2 = 3, n_3 = 0, & \text{IrMOA}(r_8, 11, 12^5 4^3 3^3, 3), \\ n_1 = 3, n_2 = 0, n_3 = 0, & \text{IrMOA}(r_8, 11, 12^5 6^3 2^3, 3), \\ n_1 = 0, n_2 = 1, n_3 = 2, & \text{IrMOA}(r_8, 13, 12^5 4^1 3^3 2^4, 3), \end{aligned}$$

$$\begin{aligned}
n_1 &= 1, n_2 = 0, n_3 = 2, \text{IrMOA}(r_8, 13, 12^5 6^1 3^2 2^5, 3), \\
n_1 &= 1, n_2 = 2, n_3 = 0, \text{IrMOA}(r_8, 11, 12^5 6^1 4^2 3^2 2^1, 3), \\
n_1 &= 0, n_2 = 2, n_3 = 1, \text{IrMOA}(r_8, 12, 12^5 4^2 3^3 2^2, 3), \\
n_1 &= 2, n_2 = 0, n_3 = 1, \text{IrMOA}(r_8, 12, 12^5 6^2 3^1 2^4, 3), \\
n_1 &= 2, n_2 = 1, n_3 = 0, \text{IrMOA}(r_8, 11, 12^5 6^2 4^1 3^1 2^2, 3), \\
n_1 &= 1, n_2 = 1, n_3 = 1, \text{IrMOA}(r_8, 12, 12^5 6^1 4^1 3^2 2^3, 3).
\end{aligned}$$

When $n_1 + n_2 + n_3 = 4$, we can obtain 15 IrMOAs as follows.

$$\begin{aligned}
n_1 &= 0, n_2 = 0, n_3 = 4, \text{IrMOA}(r_8, 16, 12^4 3^4 2^8, 3), \\
n_1 &= 0, n_2 = 4, n_3 = 0, \text{IrMOA}(r_8, 12, 12^4 4^4 3^4, 3), \\
n_1 &= 4, n_2 = 0, n_3 = 0, \text{IrMOA}(r_8, 12, 12^4 6^4 2^4, 3), \\
n_1 &= 0, n_2 = 1, n_3 = 3, \text{IrMOA}(r_8, 15, 12^4 4^1 3^4 2^6, 3), \\
n_1 &= 1, n_2 = 0, n_3 = 3, \text{IrMOA}(r_8, 15, 12^4 6^1 3^3 2^7, 3), \\
n_1 &= 1, n_2 = 3, n_3 = 0, \text{IrMOA}(r_8, 12, 12^4 6^1 4^3 3^3 2^1, 3), \\
n_1 &= 0, n_2 = 3, n_3 = 1, \text{IrMOA}(r_8, 13, 12^4 4^3 3^4 2^2, 3), \\
n_1 &= 3, n_2 = 0, n_3 = 1, \text{IrMOA}(r_8, 13, 12^4 6^3 3^1 2^5, 3), \\
n_1 &= 3, n_2 = 1, n_3 = 0, \text{IrMOA}(r_8, 12, 12^4 6^3 4^1 3^1 2^3, 3), \\
n_1 &= 0, n_2 = 2, n_3 = 2, \text{IrMOA}(r_8, 14, 12^4 4^2 3^4 2^4, 3), \\
n_1 &= 2, n_2 = 0, n_3 = 2, \text{IrMOA}(r_8, 14, 12^4 6^2 3^2 2^6, 3), \\
n_1 &= 2, n_2 = 2, n_3 = 0, \text{IrMOA}(r_8, 12, 12^4 6^2 4^2 3^2 2^2, 3), \\
n_1 &= 1, n_2 = 1, n_3 = 2, \text{IrMOA}(r_8, 14, 12^4 6^1 4^1 3^3 2^5, 3), \\
n_1 &= 1, n_2 = 2, n_3 = 1, \text{IrMOA}(r_8, 13, 12^4 6^1 4^2 3^3 2^3, 3), \\
n_1 &= 2, n_2 = 1, n_3 = 1, \text{IrMOA}(r_8, 13, 12^4 6^2 4^1 3^2 2^4, 3).
\end{aligned}$$

Similarly, when $n_1 + n_2 + n_3 = 5, 6, 7, 8$, we can obtain 21, 28, 36, and 45 IrMOAs, respectively.

Example 6. Let $k = 4$, $d_{11} = 7$, $d_{21} = 8$ in Theorem 3.8. We can obtain an IrOA(56⁴, 8, 56, 4) and a four-uniform state of eight qudits ($d = 56$) from an OA(7⁴, 8, 7, 4) and an OA(8⁴, 9, 8, 4). Take $d_{12} = 7$, $d_{22} = 4$, $d_{32} = 2$ and $d_{13} = 7$, $d_{23} = d_{33} = d_{43} = 2$ and $d_{14} = 14$, $d_{24} = 4$ and $d_{15} = 14$, $d_{25} = d_{35} = 2$ and $d_{16} = 28$, $d_{26} = 2$, and $t = 6$. Then, we can obtain the following results.

When $n_1 = 1$ and $n_2 = \dots = n_6 = 0$, we obtain an IrMOA(56⁴, 9, 56⁷8¹7¹, 4) and a four-uniform state of the system 56⁷ × 7¹ × 8¹.

When $n_2 = 1$ and $n_1 = n_3 = \dots = n_6 = 0$, we obtain an IrMOA(56⁴, 10, 56⁷7¹4¹2¹, 4) and a four-uniform state of the system 56⁷ × 7¹ × 4¹ × 2¹.

When $n_1 = 1$, $n_2 = 1$, and $n_3 = \dots = n_6 = 0$, we obtain an IrMOA(56⁴, 11, 56⁶8¹7²4¹2¹, 4) and a four-uniform state of the system 56⁶ × 8¹ × 7² × 4¹ × 2¹.

The inequation $1 \leq n_1 + n_2 + \dots + n_6 \leq 8$ has many solutions of n_i for $i = 1, \dots, 6$. From these solutions, we can obtain all IrMOAs, which are provided in the Supplementary information. Then, we have the corresponding four-uniform states.

Appendix C: Tables

Table 1. Two and three-uniform states of heterogeneous systems obtained from IrOA(r, N, d, k) in Table 1 of Ref. [22]

k	d	t	d_{uv} ($v = 1, 2, \dots, t$ $u = 1, 2, \dots, m_t$)	N	k -uniform states of the system $d^{N-(n_1+\dots+n_t)} \times d_{11}^{n_1} \times \dots \times d_{m_1 1}^{n_1} \times \dots \times d_{1t}^{n_t} \dots \times d_{mt}^{n_t}$	$N' = N + \sum_{j=1}^t (m_j - 1)n_j$
3	4	1	$d_{11} = d_{21} = 2.$	$N = 6,$ $N \geq 8$	$4^{N-n_1} \times 2^{2n_1}$	$N' \geq 7$
	6	1	$d_{11} = 3, d_{21} = 2.$	$N = 8,$ $N \geq 12$	$6^{N-n_1} \times 3^{n_1} \times 2^{n_1}$	$N' \geq 9$
	8	3	$d_{11} = 4, d_{21} = 2;$ $d_{12} = d_{22} = d_{32} = 2;$ $d_{13} = \dots = d_{43} = 2.$	$N \geq 6$	$8^{N-(n_1+n_2+n_3)} \times$ $4^{n_1} \times 2^{n_1+3n_2+4n_3}$	$N' \geq 7$
	9	1	$d_{11} = d_{21} = 3.$	$N \geq 6$	$9^{N-n_1} \times 3^{2n_1}$	$N' \geq 7$
	10	1	$d_{11} = 5, d_{21} = 2.$	$N = 8,$ $N \geq 12$	$10^{N-n_1} \times 5^{n_1} \times 2^{n_1}$	$N' \geq 9$
	12	3	$d_{11} = 6, d_{21} = 2;$ $d_{12} = 4, d_{22} = 3;$ $d_{13} = 3, d_{23} = d_{33} = 2.$	$N = 8,$ $N \geq 12$	$12^{N-(n_1+n_2+n_3)} \times$ $6^{n_1} \times 4^{n_2} \times 3^{n_2+n_3} \times 2^{n_1+2n_3}$	$N' \geq 9$
	p^n	1	$d_{11} = p^{n'_1}, d_{21} = p^{n'_2},$ $n'_1 + n'_2 = n$	$N \geq 6,$	$d^{N-1} d_{11}^1 d_{21}^1$	$N' \geq 7$
	$d_1 d_2$	1	$d_{11} = d_1, d_{21} = d_2,$	$N = 8,$ $N \geq 12$	$d^{N-1} d_1^1 d_2^1;$ $d_1^6 d_2^2 d_2^2; d_1^3 d_2^3 d_2^3;$ $d_1^4 d_1^4 d_2^4; d_1^3 d_2^5 d_2^5;$	$N' \geq 9$
2	4	2	$d_{11} = d_{21} = 2;$ $d_{12} = d_{22} = d_{32} = 2.$	$N \geq 4$	$4^{N-(n_1+n_2)} \times$ $2^{2n_1+3n_2}$	$N' \geq 5$
	6	1	$d_{11} = 3, d_{21} = 2.$	$N \geq 5$	$6^{N-n_1} \times 3^{n_1} \times 2^{n_1}$	$N' \geq 6$
	8	9	$d_{11} = 4, d_{21} = 2;$ $d_{12} = 4, d_{22} = d_{32} = 2;$ $d_{13} = 4, d_{23} = d_{33} = d_{43} = 2;$ $d_{14} = 4, d_{24} = \dots = d_{54} = 2;$ $d_{15} = d_{25} = d_{35} = 2;$ $d_{16} = \dots = d_{46} = 2;$ $d_{17} = \dots = d_{57} = 2;$ $d_{18} = \dots = d_{68} = 2;$ $d_{19} = \dots = d_{79} = 2.$	$N \geq 4$	$8^{N-(n_1+n_2+\dots+n_9)} \times$ $4^{n_1+\dots+n_4} \times 2^x,$ $x = n_1 + 2n_2 +$ $3n_3 + 4n_4 + 3n_5 +$ $4n_6 + 5n_7 + 6n_8 +$ $7n_9$	$N' \geq 5$
	9	3	$d_{11} = d_{21} = 3;$ $d_{12} = d_{22} = d_{32} = 3;$ $d_{13} = \dots = d_{43} = 3.$	$N \geq 4$	$9^{N-(n_1+n_2+n_3)} \times$ $3^{2n_1+3n_2+4n_3}$	$N' \geq 5$
	10	1	$d_{11} = 5, d_{21} = 2.$	$N = 4,$ $N \geq 6$	$10^{N-n_1} \times 5^{n_1} \times 2^{n_1}$	$N' \geq 5$
	12	12	$d_{11} = 6, d_{21} = 2;$ $d_{12} = 6, d_{22} = d_{32} = 2;$ $d_{13} = 4, d_{23} = 3;$ $d_{14} = 3, d_{24} = d_{34} = 2;$ $d_{15} = 3, d_{25} = \dots = d_{45} = 2;$ $d_{16} = 3, d_{26} = \dots = d_{56} = 2;$ $d_{17} = \dots = d_{67} = 2;$ $d_{18} = \dots = d_{78} = 2;$ $d_{19} = \dots = d_{89} = 2;$ $d_{1,10} = \dots = d_{9,10} = 2;$ $d_{1,11} = \dots = d_{10,11} = 2;$ $d_{1,12} = \dots = d_{11,12} = 2;$	$N \geq 4$	$12^{N-(n_1+n_2+\dots+n_{12})} \times$ $6^{n_1+n_2} \times 4^{n_3} \times$ $3^{n_3+n_4+n_5+n_6} \times 2^x$ $x = n_1 + 2n_2 +$ $2n_4 + 3n_5 + 4n_6 +$ $6n_7 + 7n_8 + 8n_9 +$ $9n_{10} + 10n_{11} + 11n_{12}$	$N' \geq 5$
	$f_1 f_2$	1	$d_{11} = f_1, d_{21} = f_2,$	$N \geq 4,$	$d^{N-1} f_1^1 f_2^1;$	$N' \geq 5$

Note: In the column headed “d”, $p \geq 4$ is a prime, $n \neq 1$, $d_1 d_2$ is not a prime power and $f_1 f_2 \neq 6$.

Table 2. Resulting two and three-uniform states consisting of $N' \leq 22$ heterogeneous subsystems from Table 1

k	N'	k -uniform states
3	7	$ \phi_{4^5 \times 2^2}\rangle, \phi_{8^5 \times 4^1 \times 2^1}\rangle, \phi_{9^5 \times 3^2}\rangle$
	8	$ \phi_{4^4 \times 2^4}\rangle, \phi_{8^4 \times 4^2 \times 2^2}\rangle, \phi_{9^4 \times 3^4}\rangle$
	9	$ \phi_{6^7 \times 3^1 \times 2^1}\rangle, \phi_{4^3 \times 2^6}\rangle, \phi_{4^7 \times 2^2}\rangle, \phi_{8^3 \times 4^3 \times 2^3}\rangle, \phi_{9^3 \times 3^6}\rangle, \phi_{10^7 \times 5^1 \times 2^1}\rangle, \phi_{12^7 \times 4^1 \times 3^1}\rangle$
	10	$ \phi_{6^6 \times 3^2 \times 2^2}\rangle, \phi_{4^2 \times 2^8}\rangle, \phi_{4^6 \times 2^4}\rangle, \phi_{8^2 \times 4^4 \times 2^4}\rangle, \phi_{9^2 \times 3^8}\rangle, \phi_{10^6 \times 5^2 \times 2^2}\rangle, \phi_{12^6 \times 4^2 \times 3^2}\rangle$
	11	$ \phi_{6^5 \times 3^3 \times 2^3}\rangle, \phi_{4^1 \times 2^{10}}\rangle, \phi_{4^5 \times 2^6}\rangle, \phi_{8^1 \times 4^5 \times 2^5}\rangle, \phi_{9^1 \times 3^{10}}\rangle, \phi_{10^5 \times 5^3 \times 2^3}\rangle, \phi_{12^5 \times 4^3 \times 3^3}\rangle$
	12	$ \phi_{6^4 \times 3^4 \times 2^4}\rangle, \phi_{4^4 \times 2^8}\rangle, \phi_{10^4 \times 5^4 \times 2^4}\rangle, \phi_{12^4 \times 6^4 \times 2^4}\rangle, \phi_{12^4 \times 4^4 \times 3^4}\rangle, \phi_{12^6 \times 3^3 \times 2^4}\rangle$
	13	$ \phi_{6^{11} \times 3^1 \times 2^1}\rangle, \phi_{4^3 \times 2^{10}}\rangle, \phi_{6^3 \times 3^5 \times 2^5}\rangle, \phi_{10^3 \times 5^5 \times 2^5}\rangle, \phi_{12^3 \times 6^5 \times 2^5}\rangle, \phi_{12^3 \times 4^5 \times 3^5}\rangle$
	14	$ \phi_{6^{12} \times 3^1 \times 2^1}\rangle, \phi_{4^2 \times 2^{12}}\rangle, \phi_{6^2 \times 3^6 \times 2^6}\rangle, \phi_{10^2 \times 5^6 \times 2^6}\rangle, \phi_{12^2 \times 6^6 \times 2^6}\rangle, \phi_{12^2 \times 4^6 \times 3^6}\rangle, \phi_{12^5 \times 3^3 \times 2^6}\rangle$
	15	$ \phi_{6^{13} \times 3^1 \times 2^1}\rangle, \phi_{4^1 \times 2^{14}}\rangle, \phi_{6^1 \times 3^7 \times 2^7}\rangle, \phi_{8^3 \times 2^{12}}\rangle, \phi_{10^1 \times 5^7 \times 2^7}\rangle, \phi_{12^1 \times 6^7 \times 2^7}\rangle, \phi_{12^1 \times 4^7 \times 3^7}\rangle$
	16	$ \phi_{6^{14} \times 3^1 \times 2^1}\rangle, \phi_{3^8 \times 2^8}\rangle, \phi_{5^8 \times 2^8}\rangle, \phi_{6^8 \times 2^8}\rangle, \phi_{4^8 \times 3^8}\rangle, \phi_{12^4 \times 3^4 \times 2^8}\rangle$
	17	$ \phi_{6^{15} \times 3^1 \times 2^1}\rangle, \phi_{10^7 \times 5^5 \times 2^5}\rangle, \phi_{12^7 \times 6^5 \times 2^5}\rangle$
	18	$ \phi_{6^{16} \times 3^1 \times 2^1}\rangle, \phi_{10^6 \times 5^6 \times 2^6}\rangle, \phi_{12^6 \times 6^6 \times 2^6}\rangle, \phi_{12^3 \times 3^5 \times 2^{10}}\rangle$
	19	$ \phi_{6^{17} \times 3^1 \times 2^1}\rangle, \phi_{10^5 \times 5^7 \times 2^7}\rangle, \phi_{12^5 \times 6^7 \times 2^7}\rangle$
	20	$ \phi_{6^{18} \times 3^1 \times 2^1}\rangle, \phi_{10^4 \times 5^8 \times 2^8}\rangle, \phi_{12^4 \times 6^8 \times 2^8}\rangle, \phi_{12^2 \times 3^6 \times 2^{12}}\rangle$
	21	$ \phi_{6^{19} \times 3^1 \times 2^1}\rangle, \phi_{10^3 \times 5^9 \times 2^9}\rangle, \phi_{12^3 \times 6^9 \times 2^9}\rangle$
	22	$ \phi_{6^{20} \times 3^1 \times 2^1}\rangle, \phi_{10^2 \times 5^{10} \times 2^{10}}\rangle, \phi_{12^2 \times 6^{10} \times 2^{10}}\rangle, \phi_{12^1 \times 3^7 \times 2^{14}}\rangle$
2	5	$ \phi_{12^3 \times 4^1 \times 3^1}\rangle, \phi_{10^3 \times 5^1 \times 2^1}\rangle$
	6	$ \phi_{12^4 \times 4^1 \times 3^1}\rangle, \phi_{4^3 \times 2^3}\rangle, \phi_{6^4 \times 3^1 \times 2^1}\rangle, \phi_{10^2 \times 5^2 \times 2^2}\rangle, \phi_{12^3 \times 6^1 \times 2^2}\rangle, \phi_{12^2 \times 4^2 \times 3^2}\rangle$
	7	$ \phi_{12^5 \times 4^1 \times 3^1}\rangle, \phi_{4^4 \times 2^3}\rangle, \phi_{6^3 \times 3^2 \times 2^2}\rangle, \phi_{9^3 \times 3^4}\rangle, \phi_{10^1 \times 5^3 \times 2^3}\rangle, \phi_{12^1 \times 4^3 \times 3^3}\rangle$
	8	$ \phi_{12^6 \times 4^1 \times 3^1}\rangle, \phi_{4^2 \times 2^6}\rangle, \phi_{6^2 \times 3^3 \times 2^3}\rangle, \phi_{8^3 \times 4^1 \times 2^4}\rangle, \phi_{12^2 \times 6^2 \times 2^4}\rangle, \phi_{12^3 \times 3^1 \times 2^4}\rangle$
	9	$ \phi_{12^7 \times 4^1 \times 3^1}\rangle, \phi_{4^3 \times 2^6}\rangle, \phi_{6^1 \times 3^4 \times 2^4}\rangle$
	10	$ \phi_{12^8 \times 4^1 \times 3^1}\rangle, \phi_{4^1 \times 2^9}\rangle, \phi_{8^3 \times 2^7}\rangle, \phi_{9^2 \times 3^8}\rangle, \phi_{12^1 \times 6^3 \times 2^6}\rangle$
	11	$ \phi_{12^9 \times 4^1 \times 3^1}\rangle, \phi_{4^2 \times 2^9}\rangle$
	12	$ \phi_{12^{10} \times 4^1 \times 3^1}\rangle, \phi_{8^2 \times 4^2 \times 2^8}\rangle, \phi_{12^2 \times 3^2 \times 2^8}\rangle$
	13	$ \phi_{12^{11} \times 4^1 \times 3^1}\rangle, \phi_{4^1 \times 2^{12}}\rangle, \phi_{9^1 \times 3^{12}}\rangle$
	14	$ \phi_{12^{12} \times 4^1 \times 3^1}\rangle, \phi_{12^3 \times 2^{11}}\rangle$
	15	$ \phi_{12^{13} \times 4^1 \times 3^1}\rangle, \phi_{6^1 \times 3^7 \times 2^7}\rangle, \phi_{10^1 \times 5^7 \times 2^7}\rangle$
	16	$ \phi_{12^{14} \times 4^1 \times 3^1}\rangle, \phi_{8^2 \times 2^{14}}\rangle, \phi_{8^1 \times 4^3 \times 2^{12}}\rangle, \phi_{12^1 \times 3^3 \times 2^{12}}\rangle$
	17	$ \phi_{12^{15} \times 4^1 \times 3^1}\rangle, \phi_{6^1 \times 3^8 \times 2^8}\rangle, \phi_{10^1 \times 5^8 \times 2^8}\rangle$
	18	$ \phi_{12^{16} \times 4^1 \times 3^1}\rangle, \phi_{3^9 \times 2^9}\rangle, \phi_{5^9 \times 2^9}\rangle$
	19	$ \phi_{12^{17} \times 4^1 \times 3^1}\rangle, \phi_{6^1 \times 3^9 \times 2^9}\rangle, \phi_{10^1 \times 5^9 \times 2^9}\rangle$
	20	$ \phi_{12^{18} \times 4^1 \times 3^1}\rangle, \phi_{3^{10} \times 2^{10}}\rangle, \phi_{5^{10} \times 2^{10}}\rangle$
	21	$ \phi_{12^{19} \times 4^1 \times 3^1}\rangle, \phi_{6^1 \times 3^{10} \times 2^{10}}\rangle, \phi_{10^1 \times 5^{10} \times 2^{10}}\rangle$
	22	$ \phi_{12^{20} \times 4^1 \times 3^1}\rangle, \phi_{8^1 \times 2^{21}}\rangle, \phi_{3^{11} \times 2^{11}}\rangle, \phi_{5^{11} \times 2^{11}}\rangle$

Table 3. An IrMOA($24, a + b + c + d + e, 12^a 6^b 4^c 3^d 2^e, 2$) and the corresponding two-uniform states. Take the MOA($24, 21, 4^1 2^{20}, 2$), MOA($24, 13, 6^{14} 2^{11}, 2$), and MOA($24, 15, 4^{13} 2^{13}, 2$) in [55] whose MDs are 11, 6, and 6, respectively. From Lemma 2.2, we can obtain an IrMOA($24, 1 + e, 4^1 2^e, 2$) for $e = 12, \dots, 20$, an IrMOA($24, 2 + e, 6^{14} 2^e, 2$) for $e = 8, 9, 10, 11$, and an IrMOA($24, 15, 4^{13} 2^{13}, 2$). Moreover, in Theorem 3.9, let $A = \text{MOA}(24, 13, 12^{12}, 2) = [A_1, A_2] = [(12) \oplus \mathbf{0}_2, D(12, 12, 2) \oplus \mathbf{(2)}]$, where $\text{MD}(A_2) = 6$ and $D(12, 12, 2)$ is from [55]. Then, we can obtain the other IrMOAs including a special IrMOA($24, 9, 3^1 2^8, 2$) by replacing the 12-level column by an MOA($12, 5, 3^{12}, 2$), an MOA($12, 2, 4^{13}, 2$), and an MOA($12, 3, 6^{12}, 2$), respectively.

IrMOA($24, 12^a 6^b 4^c 3^d 2^e, 2$)					Two-uniform states
a	b	c	d	e	
1				8, 9, 10, 11, 12	$ \phi_{12^a 6^b 4^c 3^d 2^e}\rangle$
1				9, 10, 11, 12, 13, 14	$ \phi_{12^1 2^8}\rangle, \phi_{12^1 2^9}\rangle, \phi_{12^1 2^{10}}\rangle, \phi_{12^1 2^{11}}\rangle, \phi_{12^1 2^{12}}\rangle$
	1			9, 10, 11, ..., 20	$ \phi_{6^1 2^9}\rangle, \phi_{6^1 2^{10}}\rangle, \phi_{6^1 2^{11}}\rangle, \phi_{6^1 2^{12}}\rangle, \phi_{6^1 2^{13}}\rangle, \phi_{6^1 2^{14}}\rangle$
		1		8, 9, 10, ..., 16	$ \phi_{4^1 2^9}\rangle, \phi_{4^1 2^{10}}\rangle, \dots, \phi_{4^1 2^{20}}\rangle$
1	1			8, 9, 10, 11	$ \phi_{3^1 2^8}\rangle, \phi_{3^1 2^9}\rangle, \phi_{3^1 2^{10}}\rangle, \dots, \phi_{3^1 2^{16}}\rangle$
	1	1		9, 10, 11, 12, 13	$ \phi_{4^1 3^1 2^9}\rangle, \phi_{4^1 3^1 2^{10}}\rangle, \phi_{4^1 3^1 2^{11}}\rangle, \phi_{4^1 3^1 2^{12}}\rangle, \phi_{4^1 3^1 2^{13}}\rangle$

Table 4. Selective IrMOA($36, 12^a 9^b 6^c 4^d 3^e 2^f, 2$) and corresponding two-uniform states. By using $D(12, 12, 3)$ in [55], we have an MOA($36, 12^1 3^{12}, 2$) = $[(\mathbf{12}) \oplus \mathbf{0}_3, D(12, 12, 3) \oplus (\mathbf{3})]$, where $\text{MD}(D(12, 12, 3) \oplus (\mathbf{3})) = 8$. Then, by Theorem 3.9, we can obtain many IrMOAs by using any subarray of OA($12, 2^{11}, 2$), MOA($12, 3^{12} 2^4, 2$), MOA($12, 4^1 3^1, 2$), and MOA($12, 6^1 2^2, 2$) to replace the 12-level column. By Theorem 3.6, we can construct an IrMOA($36, 3^5 2^m, 2$) for $m = 8, 9, 10, 11$ and an IrMOA($36, 3^6 2^m, 2$) for $m = 8, 9, 10, 11$ from the MOA($36, 2^9 3^4 6^2, 2$) in [55]. By Lemma 2.2 and the known MOAs of size 36 in [55], we can obtain an IrMOA($36, 9^1 2^m, 2$) for $m = 13, 14, 15, 16$ from the MOA($36, 9^1 2^{16}, 2$); an IrMOA($36, 3^1 2^m, 2$) for $m = 17, \dots, 27$ from the MOA($36, 3^1 2^{27}, 2$); an IrMOA($36, 3^2 2^m, 2$) for $m = 15, \dots, 20$ from the MOA($36, 3^2 2^{20}, 2$); an IrMOA($36, 6^1 3^1 2^m, 2$) for $m = 13, \dots, 18$ and an IrMOA($36, 6^1 2^m, 2$) for $m = 14, 15, \dots, 18$ from the MOA($36, 6^1 3^1 2^{18}, 2$); an IrMOA($36, 3^4 2^m, 2$) for $m = 11, 12, \dots, 16$, an IrMOA($36, 3^3 2^m, 2$) for $m = 12, 13, \dots, 16$, an IrMOA($36, 3^2 2^m, 2$) for $m = 13, 14, \dots, 16$, and an IrMOA($36, 3^1 2^m, 2$) for $m = 14, 15, 16$ from the MOA($36, 3^4 2^{16}, 2$).

IrMOA($36, 12^a 9^b 6^c 4^d 3^e 2^f, 2$)						Two-uniform states
a	b	c	d	e	f	
1				7,8, ..., 12		$ \phi_{12^a 9^b 6^c 4^d 3^e 2^f}\rangle$
	1				13,14,15,16	$ \phi_{12^1 3^7}\rangle, \phi_{12^1 3^8}\rangle, \dots, \phi_{12^1 3^{12}}\rangle$
		1			14,15, ..., 18	$ \phi_{9^1 2^{13}}\rangle, \phi_{9^1 2^{14}}\rangle, \phi_{9^1 2^{15}}\rangle, \phi_{9^1 2^{16}}\rangle$
			1		13,14, ..., 18	$ \phi_{6^1 2^{14}}\rangle, \phi_{6^1 2^{15}}\rangle, \dots, \phi_{6^1 2^{18}}\rangle$
				7,8, ..., 12		$ \phi_{6^1 3^1 2^{13}}\rangle, \phi_{6^1 3^1 2^{14}}\rangle, \dots, \phi_{6^1 3^1 2^{18}}\rangle$
				7,8, ..., 12	1	$ \phi_{6^1 3^7 2^1}\rangle, \phi_{6^1 3^8 2^1}\rangle, \dots, \phi_{6^1 3^{12} 2^1}\rangle$
				7,8, ..., 12	2	$ \phi_{6^1 3^7 2^2}\rangle, \phi_{6^1 3^8 2^2}\rangle, \dots, \phi_{6^1 3^{12} 2^2}\rangle$
				7,8, ..., 13		$ \phi_{4^1 2^7}\rangle, \phi_{4^1 2^8}\rangle, \dots, \phi_{4^1 2^{13}}\rangle$
					1	$ \phi_{3^1 2^{14}}\rangle, \phi_{3^1 2^{15}}\rangle, \dots, \phi_{3^1 2^{27}}\rangle$
					2	$ \phi_{3^2 2^{13}}\rangle, \phi_{3^2 2^{14}}\rangle, \dots, \phi_{3^2 2^{20}}\rangle$
					3	$ \phi_{3^3 2^{12}}\rangle, \phi_{3^3 2^{13}}\rangle, \dots, \phi_{3^3 2^{16}}\rangle$
					4	$ \phi_{3^4 2^{11}}\rangle, \phi_{3^4 2^{12}}\rangle, \dots, \phi_{3^4 2^{16}}\rangle$
					5	$ \phi_{3^5 2^8}\rangle, \phi_{3^5 2^9}\rangle, \phi_{3^5 2^{10}}\rangle, \phi_{3^5 2^{11}}\rangle$
					6	$ \phi_{3^6 2^8}\rangle, \phi_{3^6 2^9}\rangle, \phi_{3^6 2^{10}}\rangle, \phi_{3^6 2^{11}}\rangle$
					7	$ \phi_{3^7 2^1}\rangle, \phi_{3^7 2^2}\rangle, \dots, \phi_{3^7 2^{11}}\rangle$
					8	$ \phi_{3^8 2^1}\rangle, \phi_{3^8 2^2}\rangle, \dots, \phi_{3^8 2^{11}}\rangle$
					9	$ \phi_{3^9 2^1}\rangle, \phi_{3^9 2^2}\rangle, \dots, \phi_{3^9 2^{11}}\rangle$
					10	$ \phi_{3^{10} 2^1}\rangle, \phi_{3^{10} 2^2}\rangle, \dots, \phi_{3^{10} 2^{11}}\rangle$
					11	$ \phi_{3^{11} 2^1}\rangle, \phi_{3^{11} 2^2}\rangle, \dots, \phi_{3^{11} 2^{11}}\rangle$
					12	$ \phi_{3^{12} 2^1}\rangle, \phi_{3^{12} 2^2}\rangle, \dots, \phi_{3^{12} 2^{11}}\rangle$
					13	$ \phi_{3^{13} 2^1}\rangle, \phi_{3^{13} 2^2}\rangle, \phi_{3^{13} 2^3}\rangle, \phi_{3^{13} 2^4}\rangle$

Note: We can further obtain a large number of IrMOAs from the other known MOAs in [55].

Table 5. IrMOA($72, 12^a 6^b 4^c 3^d 2^e, 2$) and corresponding two-uniform states

IrMOA($72, 12^a 6^b 4^c 3^d 2^e, 2$)					Two-uniform states
a	b	c	d	e	$\phi_{12^a 6^b 4^c 3^d 2^e}$
1	6				$\phi_{12^1 6^6}$
1	5		1	0,1	$\phi_{12^1 6^5 3^1}, \phi_{12^1 6^5 3^1 2^1}\rangle$
1	5			0,1	$\phi_{12^1 6^5}, \phi_{12^1 6^5 2^1}\rangle$
1	4		2	0,1,2	$\phi_{12^1 6^4 3^2}, \phi_{12^1 6^4 3^2 2^1}\rangle, \phi_{12^1 6^4 3^2 2^2}\rangle$
1	4		1	0,1,2	$\phi_{12^1 6^4 3^1}, \phi_{12^1 6^4 3^1 2^1}\rangle, \phi_{12^1 6^4 3^1 2^2}\rangle$
1	4			0,1,2	$\phi_{12^1 6^4}, \phi_{12^1 6^4 2^1}\rangle, \phi_{12^1 6^4 2^2}\rangle$
1	3		3	1,2,3	$\phi_{12^1 6^3 3^3 2^1}, \phi_{12^1 6^3 3^3 2^2}\rangle, \phi_{12^1 6^3 3^3 2^3}\rangle$
1	3		2	1,2,3	$\phi_{12^1 6^3 3^2 2^1}, \phi_{12^1 6^3 3^2 2^2}\rangle, \phi_{12^1 6^3 3^2 2^3}\rangle$
1	3		1	1,2,3	$\phi_{12^1 6^3 3^1 2^1}, \phi_{12^1 6^3 3^1 2^2}\rangle, \phi_{12^1 6^3 3^1 2^3}\rangle$
1	2		4	2,3,4	$\phi_{12^1 6^2 3^4 2^2}, \phi_{12^1 6^2 3^4 2^3}\rangle, \phi_{12^1 6^2 3^4 2^4}\rangle$
1	2		3	2,3,4	$\phi_{12^1 6^2 3^3 2^2}, \phi_{12^1 6^2 3^3 2^3}\rangle, \phi_{12^1 6^2 3^3 2^4}\rangle$
1	2		2	2,3,4	$\phi_{12^1 6^2 3^2 2^2}, \phi_{12^1 6^2 3^2 2^3}\rangle, \phi_{12^1 6^2 3^2 2^4}\rangle$
1	1		5	3,4,5	$\phi_{12^1 6^1 3^5 2^3}, \phi_{12^1 6^1 3^5 2^4}\rangle, \phi_{12^1 6^1 3^5 2^5}\rangle$
1	1		4	3,4,5	$\phi_{12^1 6^1 3^4 2^3}, \phi_{12^1 6^1 3^4 2^4}\rangle, \phi_{12^1 6^1 3^4 2^5}\rangle$
1	1		3	3,4,5	$\phi_{12^1 6^1 3^3 2^3}, \phi_{12^1 6^1 3^3 2^4}\rangle, \phi_{12^1 6^1 3^3 2^5}\rangle$
1			6	4,5,6	$\phi_{12^1 6^0 3^6 2^4}, \phi_{12^1 6^0 3^6 2^5}\rangle, \phi_{12^1 6^0 3^6 2^6}\rangle$
1			5	4,5,6	$\phi_{12^1 6^0 3^5 2^4}, \phi_{12^1 6^0 3^5 2^5}\rangle, \phi_{12^1 6^0 3^5 2^6}\rangle$
1			4	4,5,6	$\phi_{12^1 6^0 3^4 2^4}, \phi_{12^1 6^0 3^4 2^5}\rangle, \phi_{12^1 6^0 3^4 2^6}\rangle$
			7		$ \phi_{6^7 2^1}\rangle, \phi_{6^7 2^2}\rangle$
			6	1	$ \phi_{6^6 4^1}\rangle$
			6	1	$ \phi_{6^6 4^1 3^1}\rangle$
			6	1	$ \phi_{6^6 3^1}, \phi_{6^6 3^1 2^1}\rangle, \dots, \phi_{6^6 3^1 2^4}\rangle$
			6		$ \phi_{6^6 2^1}, \phi_{6^6 2^2}\rangle, \dots, \phi_{6^6 2^{11}}\rangle$
			5	1	$ \phi_{6^5 4^1 3^2}\rangle, \phi_{6^5 4^1 3^2 2^1}\rangle$
			5	1	$ \phi_{6^5 4^1 3^1}, \phi_{6^5 4^1 3^1 2^1}\rangle$
			5	1	$ \phi_{6^5 4^1}, \phi_{6^5 4^1 2^1}\rangle$
			5	2	$ \phi_{6^5 3^2}, \phi_{6^5 3^2 2^1}\rangle, \dots, \phi_{6^5 3^2 2^5}\rangle$
			5	1	$ \phi_{6^5 3^1}, \phi_{6^5 3^1 2^1}\rangle, \dots, \phi_{6^5 3^1 2^{12}}\rangle$
			5		$ \phi_{6^5 2^1}, \phi_{6^5 2^2}\rangle, \dots, \phi_{6^5 2^{12}}\rangle$
			4	1	$ \phi_{6^4 4^1 3^3}, \phi_{6^4 4^1 3^3 2^1}\rangle, \phi_{6^4 4^1 3^3 2^2}\rangle$
			4	1	$ \phi_{6^4 4^1 3^2}, \phi_{6^4 4^1 3^2 2^1}\rangle, \phi_{6^4 4^1 3^2 2^2}\rangle$
			4	1	$ \phi_{6^4 4^1 3^1}, \phi_{6^4 4^1 3^1 2^1}\rangle, \phi_{6^4 4^1 3^1 2^2}\rangle$
			4	3	$ \phi_{6^4 3^3 2^1}, \phi_{6^4 3^3 2^2}\rangle, \dots, \phi_{6^4 3^3 2^6}\rangle$
			4	2	$ \phi_{6^4 3^2 2^1}, \phi_{6^4 3^2 2^2}\rangle, \dots, \phi_{6^4 3^2 2^{13}}\rangle$
			4	1	$ \phi_{6^4 3^1 2^1}, \phi_{6^4 3^1 2^2}\rangle, \dots, \phi_{6^4 3^1 2^{13}}\rangle$
			4		$ \phi_{6^4 2^6}, \phi_{6^4 2^7}\rangle, \dots, \phi_{6^4 2^{13}}\rangle$
			3	1	$ \phi_{6^3 4^1 3^4 2^1}, \phi_{6^3 4^1 3^4 2^2}\rangle, \phi_{6^3 4^1 3^4 2^3}\rangle$
			3	1	$ \phi_{6^3 4^1 3^3 2^1}, \phi_{6^3 4^1 3^3 2^2}\rangle, \phi_{6^3 4^1 3^3 2^3}\rangle$
			3	1	$ \phi_{6^3 4^1 3^2 2^1}, \phi_{6^3 4^1 3^2 2^2}\rangle, \phi_{6^3 4^1 3^2 2^3}\rangle$
			3	4	$ \phi_{6^3 4^1 3^4 2^2}, \phi_{6^3 3^4 2^3}\rangle, \dots, \phi_{6^3 3^4 2^7}\rangle$
			3	3	$ \phi_{6^3 3^3 2^2}, \phi_{6^3 3^3 2^3}\rangle, \dots, \phi_{6^3 3^3 2^{14}}\rangle$
			3	2	$ \phi_{6^3 3^2 2^2}, \phi_{6^3 3^2 2^3}\rangle, \dots, \phi_{6^3 3^2 2^{14}}\rangle$
			3	1	$ \phi_{6^3 3^1 2^7}, \phi_{6^3 3^1 2^8}\rangle, \dots, \phi_{6^3 3^1 2^{14}}\rangle$
			2	1	$ \phi_{6^2 4^1 3^5 2^2}, \phi_{6^2 4^1 3^5 2^3}\rangle, \phi_{6^2 4^1 3^5 2^4}\rangle$
			2	1	$ \phi_{6^2 4^1 3^4 2^2}, \phi_{6^2 4^1 3^4 2^3}\rangle, \phi_{6^2 4^1 3^4 2^4}\rangle$
			2	1	$ \phi_{6^2 4^1 3^3 2^2}, \phi_{6^2 4^1 3^3 2^3}\rangle, \phi_{6^2 4^1 3^3 2^4}\rangle$
			2	5	$ \phi_{6^2 3^5 2^3}, \phi_{6^2 3^5 2^4}\rangle, \dots, \phi_{6^2 3^5 2^8}\rangle$
			2	4	$ \phi_{6^2 3^4 2^3}, \phi_{6^2 3^4 2^4}\rangle, \dots, \phi_{6^2 3^4 2^{15}}\rangle$
			2	3	$ \phi_{6^2 3^3 2^3}, \phi_{6^2 3^3 2^4}\rangle, \dots, \phi_{6^2 3^3 2^{15}}\rangle$
			2	2	$ \phi_{6^2 3^2 2^3}, \phi_{6^2 3^2 2^4}\rangle, \dots, \phi_{6^2 3^2 2^{15}}\rangle$
			1	1	$ \phi_{6^1 4^1 3^6 2^3}, \phi_{6^1 4^1 3^6 2^4}\rangle, \phi_{6^1 4^1 3^6 2^5}\rangle$
			1	1	$ \phi_{6^1 4^1 3^5 2^3}, \phi_{6^1 4^1 3^5 2^4}\rangle, \phi_{6^1 4^1 3^5 2^5}\rangle$
			1	1	$ \phi_{6^1 4^1 3^4 2^3}, \phi_{6^1 4^1 3^4 2^4}\rangle, \phi_{6^1 4^1 3^4 2^5}\rangle$
			1	6	$ \phi_{6^1 4^1 3^6 2^3}, \phi_{6^1 4^1 3^6 2^4}\rangle, \phi_{6^1 4^1 3^6 2^5}\rangle$
			1	5	$ \phi_{6^1 4^1 3^5 2^3}, \phi_{6^1 4^1 3^5 2^4}\rangle, \phi_{6^1 4^1 3^5 2^5}\rangle$
			1	4	$ \phi_{6^1 4^1 3^4 2^3}, \phi_{6^1 4^1 3^4 2^4}\rangle, \phi_{6^1 4^1 3^4 2^5}\rangle$
			1	6	$ \phi_{6^1 3^6 2^4}, \phi_{6^1 3^6 2^5}\rangle, \dots, \phi_{6^1 3^6 2^9}\rangle$
			1	5	$ \phi_{6^1 3^5 2^4}, \phi_{6^1 3^5 2^5}\rangle, \dots, \phi_{6^1 3^5 2^{16}}\rangle$
			1	4	$ \phi_{6^1 3^4 2^4}, \phi_{6^1 3^4 2^5}\rangle, \dots, \phi_{6^1 3^4 2^{16}}\rangle$
			1	3	$ \phi_{6^1 3^3 2^9}, \phi_{6^1 3^3 2^{10}}\rangle, \dots, \phi_{6^1 3^3 2^{16}}\rangle$
			1	7	$ \phi_{4^1 3^7 2^4}\rangle, \phi_{4^1 3^7 2^5}\rangle, \phi_{4^1 3^7 2^6}\rangle$
			1	6	$ \phi_{4^1 3^6 2^4}\rangle, \phi_{4^1 3^6 2^5}\rangle, \phi_{4^1 3^6 2^6}\rangle$
			1	5	$ \phi_{4^1 3^5 2^4}\rangle, \phi_{4^1 3^5 2^5}\rangle, \phi_{4^1 3^5 2^6}\rangle$
			7	5,6,7,8,9,10	$ \phi_{3^7 2^5}\rangle, \phi_{3^7 2^6}\rangle, \dots, \phi_{3^7 2^{10}}\rangle$
			6	5,6,...,17	$ \phi_{3^6 2^5}\rangle, \phi_{3^6 2^6}\rangle, \dots, \phi_{3^6 2^{17}}\rangle$
			5	5,6,...,17	$ \phi_{3^5 2^5}\rangle, \phi_{3^5 2^6}\rangle, \dots, \phi_{3^5 2^{17}}\rangle$
			4	10,11,...,17	$ \phi_{3^4 2^{10}}\rangle, \phi_{3^4 2^{11}}\rangle, \dots, \phi_{3^4 2^{17}}\rangle$

The IrMOAs in Table 5 are constructed as follows.

We can obtain $A_2 = \text{OA}(72, 6, 6, 2) = D(12, 6, 6) \oplus \mathbf{(6)}$ with $\text{MD}(A_2) = 4 \geq 3$, where $D(12, 6, 6)$ is given in [55] and \oplus is the Kronecker product with multiplication replaced by the summation on the group \mathbb{Z}_6 . Let $A = \text{MOA}(72, 7, 12^1 6^6, 2) = [\mathbf{(12)} \oplus \mathbf{0}_6, D(12, 6, 6) \oplus \mathbf{(6)}]$. We have $\text{MD}(A) = 5$. So it is an IrMOA(72, 7, 12¹6⁶, 2).

Let $s = 2$ and $B_2 = B_3 = B_4 = B_5 = B_6 = B_7 = \text{MOA}(6, 2, 3¹2¹, 2)$. By Theorem 3.6, we have the following four cases.

(1) Take $B_1 = \text{OA}(12, 11, 2, 2)$. Then, we have an IrMOA($72, 5 + \sum_{w=3}^7 u_w + v_1 + v_{12} + v_{22}, 6^{5-\sum_{w=3}^7 u_w} 2^{v_1} 3^{v_{12}} 2^{v_{22}} 3^{\sum_{w=3}^7 u_w} 2^{\sum_{w=3}^7 u_w}, 2$) for $0 \leq v_1 \leq 11$, $0 \leq v_{12}, v_{22}, u_3, u_4, \dots, u_7 \leq 1$. More precisely, we have an IrMOA($72, 6 + e, 6^{5}3^{1}2^{e}, 2$) for $e = 0, 1, \dots, 12$ and an IrMOA($72, 5 + e, 6^{5}2^{e}, 2$) for $e = 1, 2, \dots, 12$; an IrMOA($72, 6 + e, 6^{4}3^{2}2^{e}, 2$) and an IrMOA($72, 5 + e, 6^{4}3^{1}2^{e}, 2$) for $e = 1, 2, \dots, 13$; an IrMOA($72, 6 + e, 6^{3}3^{3}2^{e}, 2$) and an IrMOA($72, 5 + e, 6^{3}3^{2}2^{e}, 2$) for $e = 2, 3, \dots, 14$; an IrMOA($72, 6 + e, 6^{2}3^{4}2^{e}, 2$) and an IrMOA($72, 5 + e, 6^{2}3^{3}2^{e}, 2$) for $e = 3, 4, \dots, 15$; an IrMOA($72, 6 + e, 6^{1}3^{5}2^{e}, 2$) and an IrMOA($72, 5 + e, 6^{1}3^{4}2^{e}, 2$) for $e = 4, 5, \dots, 16$; an IrMOA($72, 6 + e, 3^{6}2^{e}, 2$) and an IrMOA($72, 5 + e, 3^{5}2^{e}, 2$) for $e = 5, 6, \dots, 17$.

(2) Take $B_1 = \text{MOA}(12, 5, 3¹2⁴, 2)$. Then, we have an IrMOA($72, 5 + \sum_{w=3}^7 u_w + v_{11} + v_{21} + v_{12} + v_{22}, 6^{5-\sum_{w=3}^7 u_w} 3^{v_{11}+v_{12}+v_{21}+v_{22}} 3^{\sum_{w=3}^7 u_w} 2^{\sum_{w=3}^7 u_w}, 2$) for $0 \leq v_{11} \leq 1$, $0 \leq v_{21} \leq 4$ and $0 \leq v_{12}, v_{22}, u_3, u_4, \dots, u_7 \leq 1$. For details, we have an IrMOA($72, 7 + e, 6^{5}3^{2}2^{e}, 2$) for $e = 0, 1, \dots, 5$, an IrMOA($72, 7 + e, 6^{4}3^{3}2^{e}, 2$) for $e = 1, 2, \dots, 6$, an IrMOA($72, 7 + e, 6^{3}3^{4}2^{e}, 2$) for $e = 2, 3, \dots, 7$, an IrMOA($72, 7 + e, 6^{2}3^{5}2^{e}, 2$) for $e = 3, 4, \dots, 8$, an IrMOA($72, 7 + e, 6^{1}3^{6}2^{e}, 2$) for $e = 4, 5, \dots, 9$, and an IrMOA($72, 7 + e, 3^{7}2^{e}, 2$) for $e = 5, 6, \dots, 10$.

(3) Let $B_1 = \text{MOA}(12, 2, 4¹3¹, 2)$. Consequently, we have an IrMOA($72, 5 + \sum_{w=3}^7 u_w + v_{11} + v_{21} + v_{12} + v_{22}, 6^{5-\sum_{w=3}^7 u_w} 4^{v_{11}} 3^{v_{21}+v_{12}} 2^{v_{22}} 3^{\sum_{w=3}^7 u_w} 2^{\sum_{w=3}^7 u_w}, 2$) for $0 \leq v_{11}, v_{21}, v_{12}, v_{22}, u_3, u_4, \dots, u_7 \leq 1$. Then, the arrays IrMOA($72, 8 + e, 6^{5}4^{1}3^{2}2^{e}, 2$), IrMOA($72, 7 + e, 6^{5}4^{1}3^{1}2^{e}, 2$), and IrMOA($72, 6 + e, 6^{5}4^{1}2^{e}, 2$) can be obtained for $e = 0, 1$.

(4) Let $B_1 = B_2 = \text{MOA}(6, 2, 3¹2¹, 2)$. Then, we have an IrMOA($72, 5 + \sum_{w=4}^7 u_w + v_{11} + v_{21} + v_{12} + v_{22}, 12^{1}6^{4-\sum_{w=4}^7 u_w} 3^{v_{11}+v_{12}} 2^{v_{21}+v_{22}} 3^{\sum_{w=4}^7 u_w} 2^{\sum_{w=4}^7 u_w}, 2$) for $0 \leq v_{11}, v_{21}, v_{12}, v_{22}, u_3, u_4, \dots, u_7 \leq 1$. Thus, we have an IrMOA($72, 7 + e, 12^{1}6^{4}3^{2}2^{e}, 2$), an IrMOA($72, 6 + e, 12^{1}6^{4}3^{1}2^{e}, 2$), an IrMOA($72, 5 + e, 12^{1}6^{4}2^{e}, 2$) for $e = 0, 1, 2$; an IrMOA($72, 7 + e, 12^{1}6^{3}3^{3}2^{e}, 2$), an IrMOA($72, 6 + e, 12^{1}6^{3}3^{2}2^{e}, 2$), an IrMOA($72, 5 + e, 12^{1}6^{3}3^{1}2^{e}, 2$) for $e = 1, 2, 3$; an IrMOA($72, 7 + e, 12^{1}6^{2}3^{4}2^{e}, 2$), an IrMOA($72, 6 + e, 12^{1}6^{2}3^{3}2^{e}, 2$), an IrMOA($72, 5 + e, 12^{1}6^{2}3^{2}2^{e}, 2$) for $e = 2, 3, 4$; an IrMOA($72, 7 + e, 12^{1}6^{1}3^{5}2^{e}, 2$), an IrMOA($72, 6 + e, 12^{1}6^{1}3^{4}2^{e}, 2$), an IrMOA($72, 5 + e, 12^{1}6^{1}3^{3}2^{e}, 2$) for $e = 3, 4, 5$; an IrMOA($72, 7 + e, 12^{1}3^{6}2^{e}, 2$), an IrMOA($72, 6 + e, 12^{1}3^{5}2^{e}, 2$), an IrMOA($72, 5 + e, 12^{1}3^{4}2^{e}, 2$) for $e = 4, 5, 6$.

Replacing the 12^1 by $4^{1}3^1$, we can obtain an IrMOA($72, 6 + \sum_{w=4}^7 u_w + v_{11} + v_{21} + v_{12} + v_{22}, 4^{1}3^{1}6^{4-\sum_{w=4}^7 u_w} 3^{v_{11}+v_{12}} 2^{v_{21}+v_{22}} 3^{\sum_{w=4}^7 u_w} 2^{\sum_{w=4}^7 u_w}, 2$) for $0 \leq v_{11}, v_{21}, v_{12}, v_{22}, u_3, u_4, \dots, u_7 \leq 1$. Then, we have an IrMOA($72, 8 + e, 6^{4}4^{1}3^{3}2^{e}, 2$), an IrMOA($72, 7 + e, 6^{4}4^{1}3^{2}2^{e}, 2$) and an IrMOA($72, 6 + e, 6^{4}4^{1}3^{1}2^{e}, 2$) for $e = 0, 1, 2$; an IrMOA($72, 8 + e, 6^{3}4^{1}3^{4}2^{e}, 2$), an IrMOA($72, 7 + e, 6^{3}4^{1}3^{3}2^{e}, 2$) and an IrMOA($72, 6 + e, 6^{3}4^{1}3^{2}2^{e}, 2$) for $e = 1, 2, 3$; an IrMOA($72, 8 + e, 6^{2}4^{1}3^{5}2^{e}, 2$), an IrMOA($72, 7 + e, 6^{2}4^{1}3^{4}2^{e}, 2$) and an IrMOA($72, 6 + e, 6^{2}4^{1}3^{3}2^{e}, 2$) for $e = 2, 3, 4$; an IrMOA($72, 8 + e, 6^{1}4^{1}3^{6}2^{e}, 2$), an

$\text{IrMOA}(72, 7 + e, 6^{14}13^52^e, 2)$ and an $\text{IrMOA}(72, 6 + e, 6^{14}13^42^e, 2)$ for $e = 3, 4, 5$; an $\text{IrMOA}(72, 8 + e, 4^{13}72^e, 2)$, an $\text{IrMOA}(72, 7 + e, 4^{13}62^e, 2)$ and an $\text{IrMOA}(72, 6 + e, 4^{13}52^e, 2)$ for $e = 4, 5, 6$.

Similarly, replacing the 12^1 by 2^u for $6 \leq u \leq 11$, we can obtain an $\text{IrMOA}(72, 4 + u + \sum_{w=4}^7 u_w + v_{11} + v_{21} + v_{12} + v_{22}, 2^u 6^{4-\sum_{w=4}^7 u_w} 3^{v_{11}+v_{12}+v_{21}+v_{22}} 2^{\sum_{w=4}^7 u_w}, 2)$ for $6 \leq u \leq 11$, $0 \leq v_{11}, v_{21}, v_{12}, v_{22}, u_3, u_4, \dots, u_7 \leq 1$. Then, we have an $\text{IrMOA}(72, 4 + e, 6^{42^e}, 2)$ for $e = 6, 7, \dots, 13$; an $\text{IrMOA}(72, 4 + e, 6^{33^1}2^e, 2)$ for $e = 7, 8, \dots, 14$; an $\text{IrMOA}(72, 4 + e, 6^{23^2}2^e, 2)$ for $e = 8, 9, \dots, 15$; an $\text{IrMOA}(72, 4 + e, 6^{13^3}2^e, 2)$ for $e = 9, 10, \dots, 16$; an $\text{IrMOA}(72, 4 + e, 3^42^e, 2)$ for $e = 10, 11, \dots, 17$.

Let $s = 1$. We have the following two cases.

- (1) Take $B_1 = \text{OA}(12, 11, 2, 2)$, $\text{MOA}(12, 5, 3^{12^4}, 2)$, $\text{MOA}(12, 2, 4^{13^1}, 2)$ and $\text{MOA}(12, 3, 6^{12^2}, 2)$, respectively. We have an $\text{IrMOA}(72, 6 + e, 6^{62^e}, 2)$ for $e = 1, 2, \dots, 11$; an $\text{IrMOA}(72, 7 + e, 6^{63^1}2^e, 2)$ for $e = 0, 1, 2, 3, 4$; an $\text{IrMOA}(72, 7 + e, 6^{641}3^e, 2)$ for $e = 0, 1$; and an $\text{IrMOA}(72, 7 + e, 6^{72^e}, 2)$ for $e = 1, 2$.
- (2) By taking B_1 to be an $\text{MOA}(6, 2, 3^{12^1}, 2)$ we find an $\text{IrMOA}(72, 7 + e, 12^{16^5}3^12^e, 2)$ and an $\text{IrMOA}(72, 6 + e, 12^{16^5}2^e, 2)$ for $e = 0, 1$. ■

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Supplementary information for “Quantum k -uniform states for heterogeneous systems from irredundant mixed orthogonal arrays”

IrMOAs obtained in Example 6.

IrMOA(56⁴, 9, 56⁷28¹2¹, 4),
 IrMOA(56⁴, 10, 56⁷14¹2², 4),
 IrMOA(56⁴, 9, 56⁷14¹4¹, 4),
 IrMOA(56⁴, 11, 56⁷712³, 4),
 IrMOA(56⁴, 10, 56⁷714¹2¹, 4),
 IrMOA(56⁴, 9, 56⁷817¹, 4),
 IrMOA(56⁴, 10, 56⁶28²2², 4),
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