A Differential QAM Scheme for Uplink Massive MIMO Systems

Peng Zhang[1(✉)], Shuaishuai Guo[2], and Haixia Zhang[2]

[1] School of Computer Engineering, Weifang University, Weifang, People's Republic of China
sduzhangp@163.com

[2] School of Information Science and Engineering, Shandong University, Jinan, People's Republic of China
guoshuai@mail.sdu.edu.cn, haixia.zhang@sdu.edu.cn

Abstract. An uplink massive MIMO system with a single antenna transmitter and a single receiver with a large number of antennas is considered. For this system we propose one new differential QAM scheme based on the division operation. Specially, by designing one looking-up table, we provide the transmitted differential QAM symbol generating process and the non-coherent detection method, which is only based on two adjacent received signals, while not using any instantaneous channel state information. At last the bit error rate (BER) performance is simulated and the simulation results have shown that the new proposed differential QAM scheme achieves much better performance than the other differential QAM or differential amplitude phase shift keying (DAPSK) schemes in uplink massive MIMO systems, especially for higher dimensional modulation constellations.

Keywords: Differential modulation · QAM · Massive MIMO

1 Introduction

Recently, in order to improve the transmission performance and spectrum efficiency, an increasing number of antennas are being used in the transmitter and receiver of wireless communications. In fact, massive multiple input multiple output (MIMO) has become the preferred technology for the development of 5G communications. By using hundreds of antennas, a significant antenna array gain can be achieved [1–4]. However, in massive MIMO systems, channel estimation is really one challenging problem. Because, the huge number of antennas greatly increases the complexity of the channel estimation algorithms. Furthermore, if using pilots to perform channel estimation, there may be no enough orthogonal pilot sequences available for use, and the pilot overhead will also become an important issue. Aiming at the channel estimation problem, there are two main research branches. One is trying to find the channel estimation algorithms with reduced pilot overhead, such as the recent literatures [5–7]. The other is to adopt non-coherence detection approaches, such as [8–12].

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In this paper, we only focus on the non-coherence schemes for the uplink massive MIMO systems. Hereafter, let's give a brief overview of the research results in this area. In [8, 9], one non-coherent detection method for massive MIMO systems is proposed based on the concept of autocorrelation-based detection by using differential M-ary PSK constellation. In [10, 11], the non-coherent detection for uplink multi-users massive MIMO systems is proposed based on the received average signal energy, which need that the signal constellation for each user is different and should be further designed. Obviously, these studies of [8–11] did not involve the cases of QAM modulation. As we have known, in order to pursue higher spectrum efficiency, M-ary QAM constellation is often used. Especially, for the uplink massive MIMO Systems, the combined signal to noise ratio will be good enough to use QAM constellation. Therefore, it is of great significance to study the differential schemes based on QAM constellation for uplink massive MIMO systems. The latest research in [12] has addressed differential non-coherence detections in uplink massive MIMO systems by utilizing the channel statistics information, wherein the differential quadrature amplitude modulation (QAM) based on the finite group theory of [13] is adopted. But it is really regrettable that there exists the detection performance floor, especially when the number of receive antennas is not large enough, or higher dimensional QAM constellation is adopted.

In order to overcome the shortcomings of the current schemes for uplink massive MIMO systems, we proposed one new differential QAM scheme based on the division operation. At the transmitter, the transmit symbol is derived from the QAM constellation, and the next transmit symbol are generated by looking up one table based on the last transmit symbol and current input source information. At the receiver, the differential non-coherence detection is only based on two adjacent received signals while without considering any channel state information. The simulation results have shown that the new proposed differential QAM scheme achieves much better performance than the previous differential QAM scheme in [12] and other differential amplitude phase shift keying (DAPSK) [13].

In this paper, the following notations are adopted. Upper and lower bold face letters denote matrices and vectors, respectively. The superscripts T and H stand for the transpose and Hermitian operators, respectively. x with the top mark $-$, i.e., $\bar{x}$, denotes the conjugate of x. $j = \sqrt{-1}$. The capital letter of the Greek alphabet accounts for the symbol set.

2 System Model and Differential Design for Uplink Massive MIMO Systems

2.1 System Model

Here, the uplink massive MIMO system is considered which contains only one transmit antenna at the mobile station and a large number of receive antennas at the base station. In the following, N denotes the number of receive antennas. The transmitted symbols are generated from one M-ary QAM constellation, which denoted as $\mathbb{C}_M$. h_{it} denotes the channel gain between the transmit antenna and the i-th receive antenna at the t-th time instant, which is supposed to be independent and identically distributed, and satisfy the complex normal distribution with zero mean and one variance, i.e., $h_{it} \sim CN(0,1)$. And the channel vector at the t-th time instant is defined as $\mathbf{h}_t = [h_{1t}, h_{2t}, \ldots, h_{Nt}]$.

At the receiver, the received signals at two adjacent t-th and (t + 1)-th time instants could be written as

$$\mathbf{y}_t = s_t \mathbf{h}_t + \mathbf{n}_t \tag{1}$$

$$\mathbf{y}_{t+1} = s_{t+1} \mathbf{h}_{t+1} + \mathbf{n}_{t+1} \tag{2}$$

where $s_t \in \mathbb{C}_M$ and $s_{t+1} \in \mathbb{C}_M$ denote the transmit modulation symbols at the t-th and (t + 1)-th time instant, respectively; $\mathbf{y}_t = [y_{1t}, y_{2t}, \ldots, y_{Nt}]$, $\mathbf{y}_{t+1} = [y_{1t+1}, y_{2t+1}, \ldots, y_{Nt+1}]$ with y_{it}, y_{it+1}, $i = 1, 2, \ldots, N$ denoting the received signal from the i-th receive antenna at the t-th and (t + 1)-th time instant, respectively; $\mathbf{n}_t = [n_{1t}, n_{2t}, \ldots, n_{Nt}]$, $\mathbf{n}_{t+1} = [n_{1t+1}, n_{2t+1}, \ldots, n_{Nt+1}]$ with n_{it}, n_{it+1}, $i = 1, 2, \ldots, N$ denoting the additive white Gaussian noise (AWGN) with mean zero and variance σ^2 received from the i-th receive antenna at the t-th and (t + 1)-th time instant, respectively. In order to achieve the non-coherent signal detection without the need of channel estimation, here we assume that the channel remains unchanged at the two adjacent time instants, i.e., $\mathbf{h}_t = \mathbf{h}_{t+1}$.

2.2 Differential Design for Uplink Massive MIMO Systems

From (1) and (2), we have

$$\begin{aligned} \frac{\mathbf{y}_{t+1}\mathbf{y}_{t+1}^H}{\mathbf{y}_t\mathbf{y}_{t+1}^H} &= \frac{(s_{t+1}\mathbf{h}_{t+1} + \mathbf{n}_{t+1})(s_{t+1}\mathbf{h}_{t+1} + \mathbf{n}_{t+1})^H}{(s_t\mathbf{h}_t + \mathbf{n}_t)(s_{t+1}\mathbf{h}_{t+1} + \mathbf{n}_{t+1})^H} \\ &= \frac{s_{t+1}\bar{s}_{t+1}\mathbf{h}_{t+1}\mathbf{h}_{t+1}^H + s_{t+1}\mathbf{h}_{t+1}\mathbf{n}_{t+1}^H + \bar{s}_{t+1}\mathbf{n}_{t+1}\mathbf{h}_{t+1}^H + \mathbf{n}_{t+1}\mathbf{n}_{t+1}^H}{s_t\bar{s}_{t+1}\mathbf{h}_t\mathbf{h}_{t+1}^H + s_t\mathbf{h}_t\mathbf{n}_{t+1}^H + \bar{s}_{t+1}\mathbf{n}_t\mathbf{h}_{t+1}^H + \mathbf{n}_t\mathbf{n}_{t+1}^H} \end{aligned} \tag{3}$$

Note that, when the number of receive antennas is very large, it could be obtained that

$$\lim_{N\to\infty} \frac{s_t\mathbf{h}_t\mathbf{n}_{t+1}^H + \bar{s}_{t+1}\mathbf{n}_t\mathbf{h}_{t+1}^H + \mathbf{n}_t\mathbf{n}_{t+1}^H}{N} = 0 \tag{4}$$

$$\lim_{N\to\infty} \frac{s_{t+1}\mathbf{h}_{t+1}\mathbf{n}_{t+1}^H + \bar{s}_{t+1}\mathbf{n}_{t+1}\mathbf{h}_{t+1}^H}{N} = 0 \tag{5}$$

$$\lim_{N\to\infty} \frac{\mathbf{n}_{t+1}\mathbf{n}_{t+1}^H}{N} = \sigma^2 \tag{6}$$

Then, with the massive receive antennas as well as $\mathbf{h}_t = \mathbf{h}_{t+1}$ (3) can be approximately rewritten as

$$\frac{\mathbf{y}_{t+1}\mathbf{y}_{t+1}^{H} - N\sigma^2}{\mathbf{y}_t\mathbf{y}_{t+1}^{H}} \approx \frac{s_{t+1}\bar{s}_{t+1}\mathbf{h}_{t+1}\mathbf{h}_{t+1}^{H}}{s_t\bar{s}_{t+1}\mathbf{h}_t\mathbf{h}_{t+1}^{H}} = \frac{s_{t+1}}{s_t} \tag{7}$$

According to the received signals (1) and (2), (7) has given one non-coherent signal detection method. In fact, there is another non-coherent signal detection method as follows.

$$\frac{\mathbf{y}_{t+1}\mathbf{y}_t^{H}}{\mathbf{y}_t\mathbf{y}_t^{H} - N\sigma^2} \approx \frac{s_{t+1}\bar{s}_t\mathbf{h}_{t+1}\mathbf{h}_t^{H}}{s_t\bar{s}_t\mathbf{h}_t\mathbf{h}_t^{H}} = \frac{s_{t+1}}{s_t} \tag{8}$$

Here, the transmitted differential constellation is denoted as $\mathbb{C}_M$ with $s_t \in \mathbb{C}_M$ and $s_{t+1} \in \mathbb{C}_M$. For simplicity, we use a special mapping operator $F[\bullet]$ to denote differential operation. Specially, $s_{t+1} = F[d_t, s_t]$ with $d_t \in \mathbb{C}_M$ denoting the transmit source symbol, which carries the source information bits. On the basis of (7), our hope is to find one differential operator $F[\bullet]$ to achieve the source information detection directly only based on two adjacent receive signals y_t and y_{t+1} while without considering any channel state information. That is to say, for the differential operator $s_{t+1} = F[d_t, s_t]$, it should have one corresponding reverse differential operator denoted as $d_t = F^{-1}[s_{t+1}, s_t]$. According to (7), the reverse differential operator $d_t = F^{-1}[s_{t+1}, s_t]$ should be based on the division operation $\frac{s_{t+1}}{s_t}$, i.e., the transmit source symbol d_t should be only determined by the division $\frac{s_{t+1}}{s_t}$. For the sake of clarity, we define the reverse differential operation as $d_t = F^{-1}[s_{t+1}, s_t] = F^{-1}\left[\frac{s_{t+1}}{s_t}\right]$.

It must be noted that for the traditional differential M-ary PSK constellation [8, 9], $s_{t+1} = F[d_t, s_t] = d_t \cdot s_t$. However, for the new differential QAM constellation $s_{t+1} = F[d_t, s_t]$ will represent a more general mapping operation instead of the multiplication operation.

In order to ensure the correct detection, the operation $d_t = F^{-1}[s_{t+1}, s_t] = F^{-1}\left[\frac{s_{t+1}}{s_t}\right]$ should satisfy the following properties for any complex modulation symbols $s_t \in \mathbb{C}_M$, $s'_t \in \mathbb{C}_M$, $s_{t+1} \in \mathbb{C}_M$ and $s'_{t+1} \in \mathbb{C}_M$.

$$\text{If } \frac{s_{t+1}}{s_t} = \frac{s'_{t+1}}{s'_t}, F^{-1}\left[\frac{s_{t+1}}{s_t}\right] = F^{-1}\left[\frac{s'_{t+1}}{s'_t}\right]. \tag{9}$$

$$\text{If } s_{t+1} \neq s'_{t+1},\ F^{-1}\left[\frac{s_{t+1}}{s_t}\right] \neq F^{-1}\left[\frac{s'_{t+1}}{s_t}\right]. \tag{10}$$

(9) means that the same division results will generate the same differential detection results. While (10) expresses that with the same t-th transmit symbol s_t, different input source symbols will produce different (t + 1)-th transmit symbols. At this point, as long as we can find a mapping operator $s_{t+1} = F[d_t, s_t]$ to meet (9) and (10), then we can achieve the non-coherent detection on the base of (7).

In the following section, we will present the detailed differential QAM design process based on (7), (9) and (10).

3 Differential QAM Design for Uplink Massive MIMO Systems

3.1 Differential QAM Design

For the sake of clarity, M-ary QAM constellation $\mathbb{C}_M$ are listed as $\mathbb{C}_M = \{g_1, g_2, \ldots, g_M\}$. Furthermore, one looking-up table T_M with M rows and M columns is constructed to express the differential operation with the properties of (9) and (10), and $T_M(u, v)$ stands for the element of the u-th, $u = 1, 2, \ldots, M$ row and the v-th, $v = 1, 2, \ldots, M$ column of T_M. And then, the reverse differential operator $d_t = F^{-1}\left[\frac{s_{t+1}}{s_t}\right]$ could be represented by $T_M(u, v) = g_x$ with $s_{t+1} = g_u$, $s_t = g_v$ and $d_t = g_x$, i.e., $g_x = F^{-1}\left[\frac{g_u}{g_v}\right]$. With the help of such definitions, the differential properties (7), (9) and (10) could be further rewritten as

$$T_M(u, v) = i, \text{ if } F^{-1}\left[\frac{g_u}{g_v}\right] = g_i \tag{11}$$

$$T_M(u, v) = T_M(u', v'), \text{if } \frac{g_u}{g_v} = \frac{g_{u'}}{g_{v'}} \tag{12}$$

$$T_M(u, v) \neq T_M(u', v), \text{ if } g_u \neq g_{u'} \tag{13}$$

According to (13), we could know that each symbol of $\mathbb{C}_M = \{g_1, g_2, \ldots, g_M\}$ will appear in each column of T_M and will appear only once. Therefore, for given g_i, there are a total of M different combinations of $\{g_u, g_v\}$ satisfying $F^{-1}\left[\frac{g_u}{g_v}\right] = g_i$. Obviously, these M different divisions should be as close as possible in order to combat the incorporated noise interference in the transmission process. In other words, if the two different while very close divisions mapped to different source symbols, the result is very small noise pollution may cause the demodulation error. We define this design idea as the nearest group theory.

In order to facilitate the practical design process, a heuristic algorithm is designed based on the nearest group theory. Firstly, define one set containing all the division elements $\frac{g_u}{g_v}$, i.e., $\mathbb{Q} = \left\{\frac{g_u}{g_v} | g_u \in \mathbb{C}_M, g_v \in \mathbb{C}_M\right\}$. It should be noted that for two different pairs $\{g_u, g_v\}$ and $\{g_{u'}, g_{v'}\}$ with the same division result, i.e., $\frac{g_u}{g_v} = \frac{g_{u'}}{g_{v'}}$, they will be consider one element in $\mathbb{Q}$. Correspondingly, one counting number set is define as $\mathbb{N} = \{n(g_u/g_v) | g_u \in \mathbb{C}_M, g_v \in \mathbb{C}_M\}$ with its element $n(g_u/g_v)$ denoting the total number of $\{g_u, g_v\}$ with the same division result. We further define one counting vector $\mathbf{c} = [c_1, c_2, \ldots, c_n]$ with $c_i, i = 1, 2, \ldots, M$ denoting the number of $T_M(u, v) = i$ in the looking-up table T_M, which will be equal to M after finishing the construction of T_M. Define the group set $\Omega_{g_i} = \left\{ \frac{g_u}{g_v} \middle| F^{-1}\left[\frac{g_u}{g_v}\right] = g_i, g_u \in \mathbb{C}_M, g_v \in \mathbb{C}_M \right\}$.

Without loss of generality and for simplicity, we define $g_1 = \varepsilon = 1$, and then the heuristic algorithm to design the reverse differential table T_M corresponding to (11) is presented as follows.

Step 1: Set $c_i = 0$ and $\Omega_{g_i} = \emptyset$, $i = 1, 2, \ldots, M$ with $\emptyset$ denoting empty set. Let $T_M(u, v) = 0$ with 0 denoting an invalid symbol; $F^{-1}\left[\frac{g_u}{g_v}\right] = 0$ denotes that the division $\frac{g_u}{g_v}$ has not been assign one valid differential symbol.
Step 2: Examine symbol pair $\{g_u, g_v\}$ one by one. If $\frac{g_u}{g_v} = g_i$, let $T_M(u, v) = i$, $c_i = c_i + 1$ and $\Omega_{g_i} = \Omega_{g_i} \cup \{g_i\}$, i.e., $F^{-1}\left[\frac{g_u}{g_v}\right] = g_i$.
Step 3: Find one valid $\frac{g_{u'}}{g_{v'}}$ and its nearest group set Ω_{g_i}, do differential symbol assignment for $\frac{g_{u'}}{g_{v'}} \neq g_i$.

(A) Divide the division set $\mathbb{Q} = \left\{ \frac{g_u}{g_v} | g_u \in \mathbb{C}_M, g_v \in \mathbb{C}_M \right\}$ into two subset, one is $\mathbb{Q}_{\mathrm{Y}}$ with its elements having been assigned one differential symbol successfully, the other is $\mathbb{Q}_{\mathrm{N}}$ with its elements having not completed assignment. Correspondingly, the number set $\mathbb{N} = \{n(g_u/g_v) | g_u \in \mathbb{C}_M, g_v \in \mathbb{C}_M\}$ is also divided into two subsets with $\mathbb{N}_{\mathrm{Y}}$ and $\mathbb{N}_{\mathrm{N}}$ corresponding to $\mathbb{Q}_{\mathrm{Y}}$ and $\mathbb{Q}_{\mathrm{N}}$, respectively.

(B) For each $\frac{g_u}{g_v} \in \mathbb{Q}_{\mathrm{N}}$, determine the nearest group set Ω_{g_i} close to $\frac{g_u}{g_v}$, and calculate the minimum distance between $\frac{g_u}{g_v}$ and the nearest group set Ω_{g_i} as follows:

$$\Omega_{g_i} = \arg \min_{g_x \in \mathbb{C}_M M - c_x \geq n(g_u/g_v)} \left(\min_{a_y \in \Omega_{g_x}} \left| \frac{g_u}{g_v} - a_y \right| \right) \tag{14}$$

$$d\left(\frac{g_u}{g_v}\right) = \min_{g_x \in \mathbb{C}_M M - c_x \geq n(g_u/g_v)} \left(\min_{a_y \in \Omega_{g_x}} \left| \frac{g_u}{g_v} - a_y \right| \right) \tag{15}$$

In (14), the condition $M - c_x \geq n(g_u/g_v)$ means that the total number of $\{g_u, g_v\}$ with the same division result $(n(g_u/g_v))$ should be no more than the number of symbol pair $\{g_u, g_v\}$ that can be accepted by $\Omega_{g_x}(M - c_x)$.

(C) Find one valid $\frac{g_{u'}}{g_{v'}} \in \mathbb{Q}_{\mathrm{N}}$ and its nearest group set Ω_{g_i} by examining (14) and (15), specially,

$$\left[\frac{g_{u'}}{g_{v'}}, \Omega_{g_i}\right] = \arg \min_{\frac{g_u}{g_v} \in \mathbb{Q}_{\mathrm{N}}} \left(\min_{g_x \in \mathbb{C}_M M - c_x \geq n(g_u/g_v)} \left(\min_{d_y \in \Omega_{g_x}} \left| \frac{g_u}{g_v} - d_y \right| \right) \right) \tag{16}$$

Which further satisfy the following condition (17).

Define $\mathbf{c}' = [c'_1, c'_2, \ldots, c'_n] = \mathbf{c} = [c_1, c_2, \ldots, c_n]$, and update $c'_i = c_i + n(g_{u'}/g_{v'})$. Define $\mathbb{N}'_{\mathrm{N}} = \mathbb{N}_{\mathrm{N}} | \{n(g_{u'}/g_{v'})\}$, i.e., $\mathbb{N}'_{\mathrm{N}}$ is formed by deleting element $n(g_{u'}/g_{v'})$ from $\mathbb{N}_{\mathrm{N}}$. And then, for all elements $n_p \in \mathbb{N}'_{\mathrm{N}}, p = 1, 2, \ldots, P_{\mathrm{N}}$ with P_{N} denoting the total element number of $\mathbb{N}'_{\mathrm{N}}$, we should be able to find P_{N} elements $\breve{c}_p, p = 1, 2, \ldots, P_{\mathrm{N}}$ in $\mathbf{c}' = \left[c'_1, c'_2, \ldots, c'_n\right]$ to satisfy

$$M - \breve{c}_p \geq n_p \tag{17}$$

Condition (17) can ensure the convergence of the algorithm.

(D) For the valid selection $\left[\frac{g_{u'}}{g_{v'}}, \Omega_{g_i}\right]$, by examining symbol pair $\{g_u, g_v\}$ one by one, if $\frac{g_u}{g_v} = \frac{g_{u'}}{g_{v'}}$, let $T_M(u, v) = i$, i.e., $F^{-1}\left[\frac{g_u}{g_v}\right] = g_i$. After finishing assignment, update $c_i = c_i + n(g_{u'}/g_{v'})$ and $\Omega_{g_i} = \Omega_{g_i} \cup \left\{\frac{g_{u'}}{g_{v'}}\right\}$.

Return to step 3 to re-execute until all elements of table T_M are assigned successfully.

3.2 Simplified Differential Design for Square QAM

In this sub-section, we mainly consider a square M-ary QAM constellation with $M = 2^m$, just because square M-ary QAM constellation has a wide range of practical applications, and has very good symmetrical properties. From the above analysis of the nearest group theory we will conclude that these symmetrical properties are of great significance to simplify the differential operation design.

As we have known, for a square M-ary QAM constellation with $M = 2^m$, if $g_x \in \mathbb{C}_M$, we have $jg_x \in \mathbb{C}_M$, $-g_x \in \mathbb{C}_M$ and $-jg_x \in \mathbb{C}_M$. It is not difficult to know that the division $\frac{g_u}{g_v}$ also have these symmetrical properties. Therefore, it is reasonable to assume that the differential operation also have these symmetrical properties, specifically, we have

$$\begin{aligned} F^{-1}\left[\frac{g_u}{g_v}\right] &= g_x, F^{-1}\left[j\frac{g_u}{g_v}\right] = jg_x, \\ F^{-1}\left[-\frac{g_u}{g_v}\right] &= -g_x, F^{-1}\left[-j\frac{g_u}{g_v}\right] = -jg_x \end{aligned} \tag{18}$$

Therefore, in the heuristic algorithm to design the differential table T_M, we could only focus on a quarter of division elements to complete all division elements assignment. More details could be found in the following design examples.

3.3 Differential 16QAM Design Example

Here, the 16QAM constellation set $\mathbb{C}_{16}$ is defined as

$$\begin{aligned} \mathbb{C}_{16} = \{ & g_1 = \varepsilon = 1, \quad g_2 = 3, \quad g_3 = 2 + 1j, \quad g_4 = 2 - 1j, \\ & g_5 = jg_1, \quad g_6 = jg_2, \quad g_7 = jg_3, \quad g_8 = jg_4, \\ & g_9 = -g_1, \quad g_{\mathrm{A}} = -g_2, \quad g_{\mathrm{B}} = -g_3, \quad g_{\mathrm{C}} = -g_4, \\ & g_{\mathrm{D}} = -jg_1, \quad g_{\mathrm{E}} = -jg_2, \quad g_{\mathrm{F}} = -jg_3, \quad g_{\mathrm{G}} = -jg_4 \} \end{aligned} \tag{19}$$

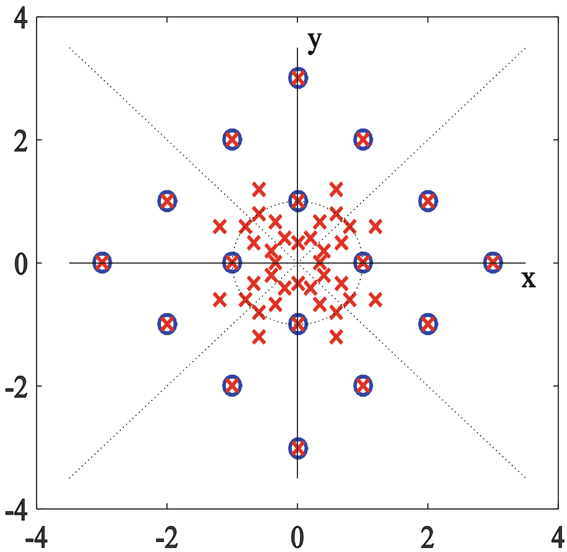

Fig. 1. 16QAM constellation (“◯”) and $\frac{g_u}{g_v}$ results (“×”)

herein, A = 10, B = 11, C = 12, D = 13, E = 14, F = 15, G = 16 .

As shown in Fig. 1, the mark “◯” denotes the symbols of 16QAM set $\mathbb{C}_{16}$, and the mark “×” accounts for the division results of $\frac{g_u}{g_v}$ with $g_u \in \mathbb{C}_{16}, g_v \in \mathbb{C}_{16}$.

Based on symmetrical properties of Fig. 1, we only focus on a quarter of plane located between the two straight lines $y = \pm x$ with $x > 0$. In which there are only 4 baseband 16QAM symbols $\{g_1 = \varepsilon = 1, g_2 = 3, g_3 = 2 + 1j, g_4 = 2 - 1j\}$ and 13 division symbols. And hereby the design complexity is really very small. Once one division symbol in the focus area has completed assignment, we could use (18) to realize the other symmetric division symbols’ assignment.

By carry out the heuristic algorithm presented in sub-Sect. 3.1, the reverse differential looking-up table T_{16} is constructed, as demonstrated in Table 1.

It should be noted that Table 1 is the reverse differential looking-up table corresponding to $F^{-1}\left[\frac{g_u}{g_v}\right] = g_x$. In the practical applications one differential looking-up table corresponding to $s_{t+1} = F[d_t, s_t]$ could be also constructed according to $F^{-1}\left[\frac{g_u}{g_v}\right] = g_x$, which will be used to accelerate the transmitted differential symbols generation.

3.4 Differential 64QAM Design Example

Here, the 64QAM constellation set $\mathbb{C}_{64}$ is defined as

$$\mathbb{C}_{64} = \{\mathbb{C}_{16}^1, j * \mathbb{C}_{16}^1, -1 * \mathbb{C}_{16}^1, -j * \mathbb{C}_{16}^1\} \tag{20}$$

Table 1. Reverse differential looking-up Table (16QAM).

	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G
1	1	4	2	2	D	G	E	E	9	C	A	A	5	8	6	6
2	2	1	3	3	E	D	F	F	A	9	B	B	6	5	7	7
3	3	2	1	8	F	E	D	4	B	A	9	G	7	6	5	C
4	4	3	G	1	G	F	C	D	C	B	8	9	8	7	4	5
5	5	8	6	6	1	4	2	2	D	G	E	E	9	C	A	A
6	6	5	7	7	2	1	3	3	E	D	F	F	A	9	B	B
7	7	6	5	C	3	2	1	8	F	E	D	4	B	A	9	G
8	8	7	4	5	4	3	G	1	G	F	C	D	C	B	8	9
9	9	C	A	A	5	8	6	6	1	4	2	2	D	G	E	E
A	A	9	B	B	6	5	7	7	2	1	3	3	E	D	F	F
B	B	A	9	G	7	6	5	C	3	2	1	8	F	E	D	4
C	C	B	8	9	8	7	4	5	4	3	G	1	G	F	C	D
D	D	G	E	E	9	C	A	A	5	8	6	6	1	4	2	2
E	E	D	F	F	A	9	B	B	6	5	7	7	2	1	3	3
F	F	E	D	4	B	A	9	G	7	6	5	C	3	2	1	8
G	G	F	C	D	C	B	8	9	8	7	4	5	4	3	G	1

with

$$\begin{aligned}\mathbb{C}_{16}^{1} = \{ & g_1 = \varepsilon = 1,\ g_2 = 3,\ g_3 = 5,\ g_4 = 7, \\ & g_5 = 2 + 1\mathrm{j},\ g_6 = 2 - 1\mathrm{j},\ g_7 = 4 + 1\mathrm{j}, g_8 = 4 - 1\mathrm{j}, \\ & g_9 = 6 + 1\mathrm{j},\ g_A = 6 - 1\mathrm{j},\ g_B = 3 + 2\mathrm{j}, g_C = 3 - 2\mathrm{j}, \\ & g_D = 5 + 2\mathrm{j},\ g_E = 5 - 2\mathrm{j},\ g_F = 4 + 3\mathrm{j}, g_G = 4 - 3\mathrm{j}\}\end{aligned} \tag{21}$$

The reverse differential looking-up table for 64QAM is constructed as shown in Table 2. It should be noted that Table 2 only provides a part of elements, just because other elements could be derived from these elements according to (18). For example,

$$F^{-1}\left[\frac{g_{40}}{g_{18}}\right] = F^{-1}\left[\frac{-1 * g_8}{j * g_2}\right] = F^{-1}\left[j\frac{g_8}{g_2}\right] = jF^{-1}\left[\frac{g_8}{g_2}\right].$$

4 Simulation Results

In this section, the BER (Bit Error Rate) performances of the new differential 16QAM and 64QAM are simulated over Rayleigh fading channels. Gray mapping is adopted for the transmitted 16QAM and 64QAM constellations. The simulation results are shown in Figs. 2 and 3, in which N denotes the number of receive antennas. "Old DQAM", "New DQAM" and "DAPSK" represent the differential QAM schemes provided in [12], the new proposed differential QAM schemes and the differential amplitude phase shift keying (DAPSK) schemes [12, 14], respectively.

Table 2. Part of reverse differential looking-up Table (64QAM).

	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G
1	1	11	16	16	12	13	14	14	16	16	13	13	16	16	12	13
2	2	1	7	9	2	2	2	2	11	11	7	7	7	7	10	10
3	3	12	1	4	6	5	3	3	3	3	14	14	5	5	14	15
4	4	8	6	1	11	11	10	10	2	2	2	2	9	9	15	14
5	5	4	13	14	1	30	6	11	12	15	3	25	12	30	7	28
6	6	5	12	15	63	1	11	6	15	12	57	3	62	12	61	7
7	7	2	2	7	3	3	1	7	5	7	4	32	2	10	6	27
8	8	3	3	8	4	4	7	1	7	5	64	4	10	2	59	6
9	9	13	4	2	7	16	9	12	1	6	8	15	4	13	8	32
A	10	15	5	3	16	7	12	9	6	1	15	8	13	4	64	8
B	11	9	10	12	13	24	4	29	10	13	1	21	6	27	2	21
C	12	10	11	13	56	12	61	4	13	10	53	1	59	6	53	2
D	13	6	8	5	14	25	5	15	4	9	11	28	1	15	3	25
E	14	7	9	6	57	15	15	5	9	4	60	11	15	1	57	3
F	15	14	15	10	10	22	8	32	8	30	6	26	3	24	1	20
G	16	16	14	11	53	10	64	8	62	8	58	6	56	3	52	1

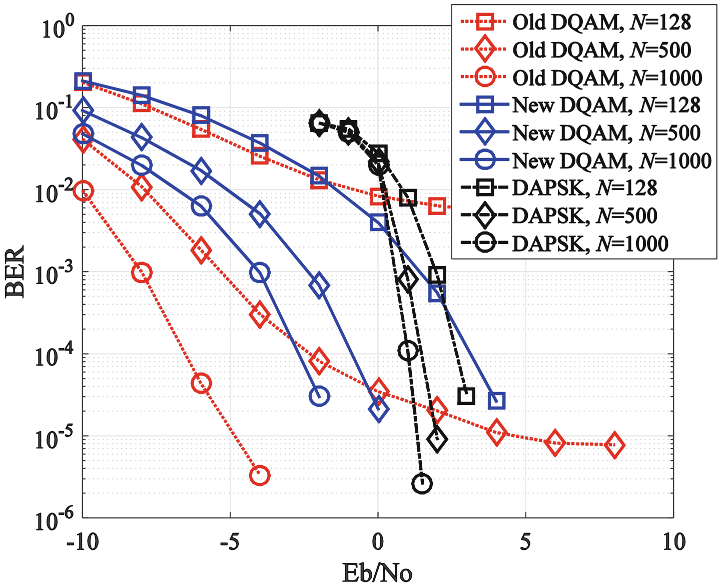

Fig. 2. BER performance of differential 16QAM and 16DAPSK

From Fig. 2 we could know that new designed differential 16QAM is superior to DAPSK schemes [12, 14]. Furthermore, our design method could be easily extend to higher dimensional modulation constellations, such as 64QAM, which is really difficult for the traditional DAPSK schemes.

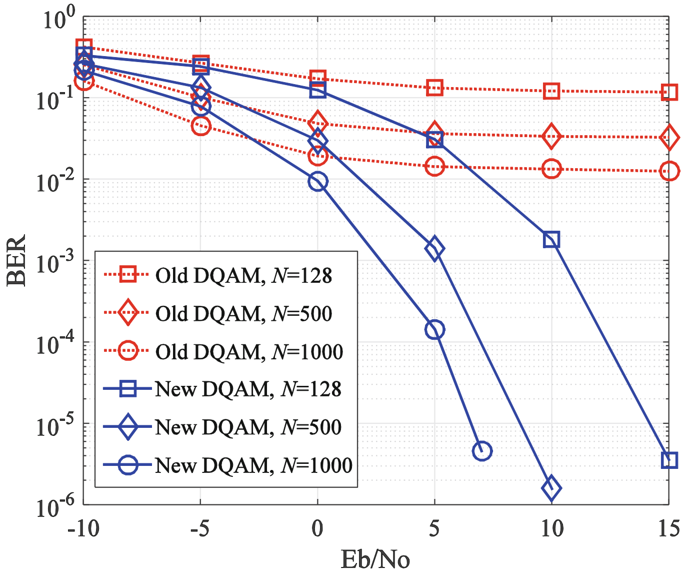

Fig. 3. BER performance of differential 64QAM.

From Figs. 2 and 3, we also see that the new designed differential QAM schemes completely eliminates the performance floor compared with the differential QAM schemes provided in [12, 13]. Especially, for higher dimensional modulation constellations, such as 64QAM, the new designed differential QAM schemes are greatly superior to that of the differential 64QAM schemes presented in [12, 13] and the latter has very serious performance floor. This result proves that the new differential QAM schemes are very suitable for the applications in the next generation wireless communications.

5 Conclusions

In this paper, a new differential QAM scheme is proposed for the uplink massive MIMO systems. Specially, one looking-up table is constructed based on the division operation between two transmitted QAM symbols, which is used to generate the transmitted differential QAM symbols at the transmitter and to carry out the non-coherent detection at the receiver. The new differential detector only uses two adjacent received signals without requiring any channel state information. And hereby, there is no so-called phenomena of performance floor, while the performance floor really exists and may by very harmful for the newly presented differential QAM schemes in [12]. Furthermore, the new differential QAM schemes provides a better flexibility compared with the traditional DAPSK schemes, especially for higher dimensional constellations. Taken together, the new differential QAM schemes are especially suitable for massive MIMO systems to achieve great performance while without the requirement of large amounts of pilots and complicated channel estimations.

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References

1. Xiang, G., Edfors, O., Rusek, F., Tufvesson, F.: Massive MIMO performance evaluation based on measured propagation data. IEEE Trans. Wirel. Commun. **14**(7), 3899–3911 (2015). IEEE Press, New York
2. Jin, S., Liang, X., Wong, K.-K., Gao, X., Zhu, Q.: Ergodic rate analysis for multipair massive MIMO two-way relay networks. IEEE Trans. Wirel. Commun. **14**(3), 1480–1491 (2015). IEEE Press, New York
3. Lu, L., Li, G., Swindlehurst, A.L., Ashikhmin, A., Zhang, R.: An overview of massive MIMO: benefits and challenges. IEEE J. Sel. Top. Sig. Process. **8**(5), 742–758 (2014). IEEE Press, New York
4. Bogale, T.E., Le, L.B.: Massive MIMO and Millimeter Wave for 5G Wireless HetNet: Potentials and Challenges. IEEE Vehicular Technology Magazine (to appear)
5. Wen, C.K., Jin, S., Wong, K.K., Chen, J.C.: Channel estimation for massive MIMO using gaussian-mixture Bayesian learning. IEEE Trans. Wirel. Commun. **14**(3), 1356–1368 (2015). IEEE Press, New York
6. Ngo, B.Q., Larsson, E.G.: EVD-based channel estimation in multicell multiuser MIMO systems with very large antenna arrays. In: IEEE International Conference on Acoustics, Speech and Signal Processing, pp. 3249–3252. IEEE Press, New York (2012)
7. Wang, R., Chen, Y., Tan, H.: Data-assisted channel estimation for uplink massive MIMO systems. In: IEEE Global Communications Conference, pp. 3766–3771. IEEE Press, New York (2014)
8. Schenk, A., Fischer, R.F.H.: Noncoherent detection in massive MIMO systems. In: International ITG Workshop on Smart Antennas, pp. 1–8. IEEE Press, New York (2013)
9. Yammine, G., Fischer, R.F.H.: Soft-decision decoding in noncoherent massive MIMO systems. In: International ITG Workshop on Smart Antennas, pp. 53–59. IEEE Press, New York (2016)
10. Manolakos, A., Chowdhury, M., Goldsmith, A.J.: Constellation design in noncoherent massive SIMO systems. In: IEEE Global Communications Conference, pp. 3690–3695. IEEE Press, New York (2014)
11. Chowdhury, M., Manolakos, A., Goldsmith, A.J.: Design and Performance of Noncoherent Massive SIMO Systems. In: Annual Conference on Information Sciences and Systems, pp. 1–6. IEEE Press, New York (2014)
12. Kong, D., Xia, X.-G., Jiang, T.: A differential QAM detection in uplink massive MIMO systems. IEEE Trans. Wirel. Commun. **15**(9), 6371–6383 (2016)
13. Egri, R.G., Homgan, F.A.: A finite group of complex integers and its application to differentially coherent detection of QAM signals. IEEE Trans. Inf. Theory **40**(1), 216–219 (1994). IEEE Press, New York
14. Adachi, F., Sawahashi, M.: Decision feedback differential detection of differentially encoded 16APSK signals. IEEE Trans. Commun. **44**(4), 416–418 (1996). IEEE Press, New York