Smart User Pairing for Massive MIMO Enabled Industrial IoT Communications

Jingjie Zong*, Shuangzhi Li*, Di Zhang*, Gangtao Han*, Xiaomin Mu*,
Ali Kashif Bashir** and Joel J. P. C. Rodrigues †‡ (Fellow, IEEE)
*Zhengzhou University, China
**Manchester Metropolitan University, Manchester, U.K.
†Federal University of Piauí (UFPI), Teresina-PI, Brazil
‡Instituto de Telecomunicações, Portugal
e-mail: zongjingjiecn@163.com; {ielsz, iegthan, iexmmu}@zzu.edu.cn;
{dr.di.zhang, dr.alikashif.b, joeljr}@ieee.org

***Abstract*—In this paper, we concern the uplink of an industrial Internet of Things (IIoT) communication system, in which multiple single-antenna users timely upload data to a receiver having a large number of antennas over Rayleigh fading channels. To satisfy the stringent requirement of latency in the channel estimation phase of this system, we first use a phase-shift keying (PSK) modulation division scheme for each pair of users. Specifically, the absolutely additively uniquely decomposable constellation pair (AAUDCP) is allocated for two random users. With the same pilot sequence, it proves the modulated PSK symbols can be uniquely identified when the number of receiver antennas goes to infinity in a noise-free case. In a noise case, to improve the reliability of this system, we propose a smart user pairing algorithm with low complexity by maximizing the minimum signal to interference plus noise ratio at the receiver for all pairs of users. Finally, the computer simulations show that the proposed scheme can improve the system's error performance effectively.**

***Index Terms*—massive MIMO, IIoT, PSK modulation division, smart user pairing.**

I. Introduction

5G wireless communication network is expected to achieve significant improvements in several key performance indicators [1], of which ultra-reliable low-latency communication (URLLC) is being used by many emerging IIoT services (telemedicine operations, automatic drive, etc). How to satisfy the two seemingly contradictory technical requirements in wireless communication systems, i.e., ultra-reliability and low latency [2], has attracted lots of researchers' attention [3]. Among the potential schemes, exploiting diversity resources is considered to be a feasible solution [4], [5].

The work of S. Li was supported in part by the National Natural Science Foundation of China under Grant No. 61901416; in part by the China Postdoctoral Science Foundation under Grant No. 2019M662529; in part by the Science and Technology Development Project of Henan Province under Grant No. 192102210090 and in part by the Postdoctoral Research Grant in Henan Province. The work of G. Han was supported by the Science and Technology Development Project of Henan Province under Grant No. 202102210123. The work of J. Rodrigue was supported by FCT/MCTES through national funds and when applicable co-funded EU funds under the Project UIDB/EEA/50008/2020 and by Brazilian National Council for Research and Development (CNPq) via Grant No. 309335/2017-5.

In wireless communication systems, diversity resources mainly include space diversity [6], frequency diversity [7] and time diversity [8]. Considering the stringent requirements for latency and bandwidth in IoT applications, the time diversity and frequency diversity gain may be limited, making spatial diversity a solution [9]. Massive MIMO techniques can reduce transmission delays by improving spectral efficiency and improve the reliability by exploiting the large spatial diversity gain. So massive MIMO is considered as a potential enabling technique for URLLC [10]. However, the main feature of URLLC is the transmission of short data packets [5], [11], [12], the use of pilot sequences will reduce spectral efficiency. So the number of available orthogonal pilot sequences is limited, resulting in pilot contamination, which is one of the bottlenecks of the performance of massive MIMO systems.

Some works have been done for mitigating the pilot contamination of massive MIMO systems. The time-shifted pilot transmission scheme in [13] mitigates the inter-cell pilot contamination by asynchronous transmission among users with the correlated pilot but causes the mutual interferences between data and pilot. Pilot contamination precoding [14] mitigates the pilot interference by the joint processing of multi-cell but this method results in the decrease of spectral efficiency due to signaling overhead required by information exchange. The greedy pilot assignment algorithm [15] can mitigate the pilot contamination by using the statistical channel covariance information but the computation complexity is too high.

All the above pilot allocation schemes assign the pilot sequences to users randomly without considering the difference of channel quality. On the contrary, according to the difference of pilot sequences' interference and users' channel quality, [16] proposed a samrt pilot assignment scheme that assigns pilots in a sequential way. However, this scheme is aimed at the achievable capacity of the channel for traditional long data packets.

Motivated by this fact, by using fewer pilot sequences and PSK modulation division, a smart user pairing transmission scheme is proposed for massive MIMO uplink systems, to cope with the pilot allocation problem in IIoT services. The main contributions of this paper are summarized as follows.

1) In the proposed scheme, each pair of users can use the same pilot sequence. Compared with the traditional random pilot allocation scheme system, the proposed scheme can reduce the pilot overhead.
2) The concept of AAUDCP is formally introduced. The PSK modulation division scheme based on AAUDCP is proposed. When the number of receiver antennas goes to infinity, the modulated PSK symbols can be uniquely identified in a noise-free case.
3) In a noisy and finite number of antennas case, the relationship between the average symbol error rate (SER) with the large-scale fading coefficients is investigated. Based on this, we proposed a smart user pairing scheme with low complexity. Theoretical analysis proves that the scheme the optimal solution.

Notations: Matrices and column vectors are denoted by boldface characters with uppercase (e.g., $\mathbf{A}$) and lowercase (e.g.,$\mathbf{a}$), respectively. The transpose of $\mathbf{A}$ is denoted by $\mathbf{A}^T$ while the Hermitian transpose of $\mathbf{A}$ (i.e., the conjugate and transpose of $\mathbf{A}$) is denoted by $\mathbf{A}^H$, the diagonalized form of $\mathbf{A}$ is denoted by $\mathrm{diag}\{\mathbf{A}\}$.

II. PSK Modulation Division Scheme for Massive MIMO Enabled IIOT Uplink System

In this paper, we concern the uplink of an IIoT communication system, in which N single-antenna users timely upload data to a receiver having $M(M \gg N)$ antennas over Rayleigh fading channels. In this system, N users are assumed to be exactly synchronous and are divided into $K = N/2$ pairs with 2 users in each pair, where N is assumed to be an even number. There are K orthogonal pilot sequences $\boldsymbol{\phi}_k, k = 1, 2, \cdots, K$, and $\boldsymbol{\phi}_k$ is a $K \times 1$ vector. Hence $\boldsymbol{\phi}_i^H \boldsymbol{\phi}_j = 1$ while $i = j$, and $\boldsymbol{\phi}_i^H \boldsymbol{\phi}_j = 0$ while $i \neq j$. Both of the two users in the k-th pair adopt the same pilot $\boldsymbol{\phi}_k$ to partially estimate the channels. The equivalent baseband channel model for $T \geq K+1$ time slots is

$$\mathbf{Z} = \mathbf{H}\mathbf{S} + \mathbf{N}, \tag{1}$$

where $\mathbf{Z}$ is the $M \times T$ received signal matrix. The $M \times N$ channel matrix from N users to the BS is $\mathbf{H} = \tilde{\mathbf{H}}\mathbf{D}^{\frac{1}{2}}$ with $\mathbf{D} = \mathrm{diag}\{\beta_{11}, \beta_{12}, \cdots, \beta_{K1}, \beta_{K2}\}$ and $\tilde{\mathbf{H}} = [\tilde{\mathbf{h}}_{11}, \tilde{\mathbf{h}}_{12}, \tilde{\mathbf{h}}_{21}, \tilde{\mathbf{h}}_{22}, \cdots, \tilde{\mathbf{h}}_{K1}, \tilde{\mathbf{h}}_{K2}]$. In this paper, we consider a Rayleigh block fading channel model. Specifically, $\tilde{\mathbf{h}}_{ki} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$, $k = 1, 2, \cdots, K$, $i = 1, 2$; β_{ki} is the corresponding large-scale fading coefficient, it is assumed known to all users and the BS. $\mathbf{N}$ is the $M \times T$ noise matrix arising at BS with each entry following the circularly symmetric complex Gaussian distribution with zero mean and variance σ^2, and is assumed known to the BS.

$\mathbf{S}$ is the $N \times T$ transmitted signal matrix designed as:

$$\mathbf{S} = \begin{bmatrix} \boldsymbol{\phi}_1^T & x_{11} & x_{12} & \cdots & x_{1(T-K)} \\ \boldsymbol{\phi}_1^T & y_{11} & y_{12} & \cdots & y_{1(T-K)} \\ \boldsymbol{\phi}_2^T & x_{21} & x_{22} & \cdots & x_{2(T-K)} \\ \boldsymbol{\phi}_2^T & y_{21} & y_{22} & \cdots & y_{2(T-K)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{\phi}_K^T & x_{K1} & x_{K2} & \cdots & x_{K(T-K)} \\ \boldsymbol{\phi}_K^T & y_{K1} & y_{K2} & \cdots & y_{K(T-K)} \end{bmatrix}, \tag{2}$$

where $x_{kt} \in \mathcal{X}_k$, $y_{kt} \in \mathcal{Y}_k$, $k = 1, 2, \cdots, K$, $t = 1, \cdots, T-K$. x_{kt} and y_{kt} are taken from two PSK constellations $\mathcal{X}_k$ and $\mathcal{Y}_k$ respectively, they will be design in the next section.

Remark: The proposed scheme can reduce the pilot overhead by using the same pilot for each pair of users.

III. Smart User Pairing Scheme

In this section, we investigate the signal detection problem and the user pairing problem. The pilot assignment for a target cell is firstly formulated as an optimization problem. Then, the smart user pairing algorithm is proposed to solve the optimization problem by maximizing the minimum signal to interference plus noise ratio at the receiver for all pairs of users.

A. Signal Detection

Signal detection for the proposed scheme can be divided into two steps.

Step 1: Estimate the sum channel of each pair. Collect all the orthogonal pilot sequences in a matrix, we can obtain

$$\mathbf{P} = \begin{bmatrix} \boldsymbol{\phi}_1 & \boldsymbol{\phi}_2 & \cdots & \boldsymbol{\phi}_K \end{bmatrix}. \tag{3}$$

Let $\tilde{\mathbf{Z}}$ and $\tilde{\mathbf{N}}$ express the first K columns of $\mathbf{Z}$ and $\mathbf{N}$, respectively. It is obtained that

$$\tilde{\mathbf{Z}}\mathbf{P}^H = [\underbrace{\mathbf{h}_{11} + \mathbf{h}_{12}}_{\mathbf{h}_1}, \cdots, \underbrace{\mathbf{h}_{K1} + \mathbf{h}_{K2}}_{\mathbf{h}_K}] + \tilde{\mathbf{N}}\mathbf{P}^H, \tag{4}$$

where $\mathbf{h}_k = \mathbf{h}_{k1} + \mathbf{h}_{k2}, k = 1, 2, \cdots, K$ is the sum channel of the users in the k-th pair. Then, the k-th column of $\tilde{\mathbf{Z}}\mathbf{P}^H$ can treated as the estimate $\hat{\mathbf{h}}_k$ of the sum channel of the k-th pair.

Step 2: Let $\mathbf{z}_t$ and $\mathbf{n}_t$ $(t > K)$ denote the t-th column of $\mathbf{Z}$ and $\mathbf{N}$, we obtain

$$\mathbf{z}_t = \mathbf{h}_{11}x_{1t} + \mathbf{h}_{12}y_{1t} + \cdots + \mathbf{h}_{K1}x_{Kt} + \mathbf{h}_{K2}y_{Kt} + \mathbf{n}_t.$$

According to the central limit theorem, we can attain

$$\begin{aligned} \lim_{M\to\infty} \frac{1}{M}\mathbf{z}_t^T\hat{\mathbf{h}}_k^* &= \frac{1}{M}|\mathbf{h}_{k1}|^2 x_{kt} + \frac{1}{M}|\mathbf{h}_{k2}|^2 y_{kt} \\ &= \beta_{k1}x_{kt} + \beta_{k2}y_{kt}. \end{aligned} \tag{5}$$

For simplicity, let $g_{kt} = \lim_{M\to\infty} \frac{1}{M}\mathbf{z}_t^T\hat{\mathbf{h}}_k^*$, the signal detection problem can be formulated as

Problem 1: Find $x_{kt} \in \mathcal{X}_k$ and $y_{kt} \in \mathcal{Y}_k$ for the two users in k-th pair such that

$$\min_{x_{kt}, y_{kt}} |g_{kt} - \beta_{k1}x_{kt} - \beta_{k2}y_{kt}|.$$

$$
\begin{aligned}
\frac{1}{M}\mathbf{z}_{K+1}^T\hat{\mathbf{h}}_k^* =& \frac{1}{M}\big((\mathbf{h}_{k1}+\mathbf{h}_{k2})+\tilde{\mathbf{N}}\boldsymbol{\phi}_k\big)^H\big(\sum_{j=1}^{K}(\mathbf{h}_{j1}x_{jt}+\mathbf{h}_{j2}y_{jt})+\mathbf{n}_t\big)\\
=& \frac{1}{M}|\mathbf{h}_{k1}|^2x_{kt}+\frac{1}{M}|\mathbf{h}_{k2}|^2y_{kt}+\underbrace{\frac{1}{M}(\mathbf{h}_{k2})^H\mathbf{h}_{k1}x_{kt}+\frac{1}{M}(\mathbf{h}_{k1})^H\mathbf{h}_{k2}y_{kt}}_{\Xi_1}\\
&+\underbrace{\frac{1}{M}(\mathbf{h}_{k1}+\mathbf{h}_{k2})^H\sum_{j=1,j\neq k}^{K}(\mathbf{h}_{j1}x_{jt}+\mathbf{h}_{j2}y_{jt})}_{\Xi_2}+\underbrace{\frac{1}{M}(\mathbf{h}_{k1}+\mathbf{h}_{k2})^H\mathbf{n_t}}_{\Xi_3}\\
&+\underbrace{\frac{1}{M}(\tilde{\mathbf{N}}\boldsymbol{\phi}_k)^H\sum_{j=1}^{K}(\mathbf{h}_{j1}x_{jt}+\mathbf{h}_{j2}y_{jt})}_{\Xi_4}+\underbrace{\frac{1}{M}(\tilde{\mathbf{N}}\boldsymbol{\phi}_k)^H\mathbf{n_t}}_{\Xi_5}. \qquad (6)
\end{aligned}
$$

Therefore, the signal detection problem is eventually reduced to such a problem: Under what condition, are x_{kt} and y_{kt} able to be uniquely identified from g_{kt}? This motivates us to introduce the following concept proposed in our previous work [17].

Definition 1: A pair of constellation $\mathcal{U}$ and $\mathcal{V}$ is said to form an absolutely (uniformly) additively uniquely decomposable constellation pair (AAUDCP) if for any given $a>0$ and $b>0$, there exists u, $\tilde{u}\in\mathcal{U}$ and v, $\tilde{v}\in\mathcal{V}$ such that $au+bv=a\tilde{u}+b\tilde{v}$, then, we have $u=\tilde{u}$, $v=\tilde{v}$.

Therefore, if a pair of constellations $\mathcal{X}_k$ and $\mathcal{Y}_k$ constitutes an AAUDCP, then, x_{kt} and y_{kt} can be uniquely identified from g_{kt}. The following proposition provides us with a method for the systematic design of such a constellation pair using two PSK constellation.

Proposition 1: Let $\mathcal{X}_k=\{e^{\frac{j2\pi m}{2^r}}\}_{m=0}^{2^r-1}$ and $\mathcal{Y}_k=\{e^{(\frac{j2\pi n}{2^r}+\frac{\pi}{2^{r+1}})}\}_{n=0}^{2^r-1}$. Then, such a pair of PSK constellations $\mathcal{X}_k$ and $\mathcal{Y}_k$ constitutes an AADUCP.

This has been proven in our previous work [18]. In this paper, the transmitted symbols x_{kt} and y_{kt} are randomly chosen from $\mathcal{X}_k$ and $\mathcal{Y}_k$ respectively and they are independent of each other.

B. Analysis of SINR

$$I_1=\frac{2\beta_{k1}\beta_{k2}}{M}; \qquad (7a)$$

$$I_2=\frac{1}{M}(\beta_{k1}+\beta_{k2})\sum_{j=1,j\neq k}^{K}(\beta_{j1}+\beta_{j2}); \qquad (7b)$$

$$I_3=\frac{\sigma^2}{M}(\beta_{k1}+\beta_{k2}); \qquad (7c)$$

$$I_4=\frac{\sigma^2}{M}\sum_{j=1}^{K}(\beta_{j1}+\beta_{j2}); \qquad (7d)$$

$$I_5=\frac{\sigma^4}{M}. \qquad (7e)$$

In the practical scenarios, the number of BS antennas is always finite. Therefore, there will be interference and noise when detecting signals. The received signal can be expressed as (6), in which $\Xi_1+\Xi_2+\Xi_3+\Xi_4+\Xi_5$ represents the interference plus noise. Assuming the transmitted signals have unit power, the expectation of the power of Ξ_i in (6) noted as $I_i=E\{|\Xi_i^2|\}$ can be calculated as (7).

Then, the uplink SINR of the i-th user in the k-th pair (u_{ki}) can be calculated as

$$SINR_{ki}=\frac{\beta_{ki}^2}{I_1+I_2+I_3+I_4+I_5}, \qquad (8)$$

It is clear that thermal noise and small-scale fading effects could be averaged out as M grows to infinity. However, the average uplink capacity is limited by pilot contamination and cannot be improved by the increase of data transmission power. By analyzing the SINR of each user, we find that the user pairing scheme will significantly affect the SINR of users. Therefore, we investigate the user pairing algorithm in the following aiming to improve the signal detection performance of the BS.

There are totally $n=\prod_{k=0}^{\frac{N}{2}-1}\binom{N-2k}{2}/(\frac{N}{2}!)$ different user pairing results. Then orthogonal pilots are allocated to each pair of users. In the traditional pilot allocation scheme, pilots are allocated to users randomly. Since the users with severe pilot contamination are the performance bottleneck of massive MIMO systems. Consequently, we aim to maximize the minimum uplink SINR of all N users, which can be formulated as the following

$$\mathcal{Q}:\max_{\{\psi_s\}}\min_{\forall k,i}SINR_{ki}, \qquad (9)$$

where $\{\psi_s,s=1,\cdots,n\}$ represents all possible n kinds of user pairing results of N users, such as $\{\psi_s\}=\{\{u_{11}^s,u_{12}^s\},\{u_{21}^s,u_{22}^s\},\cdots,\{u_{K1}^s,u_{K2}^s\}\}$ is the s-th user pairing scheme.

To solve the optimization problem $\mathcal{Q}$, we analyze the impact of the user pairing strategy on the SINR firstly. Without loss of generality, consider the two users of the k-th pair.

Proposition 2: For the user u_{ki}, the signal-to-interference-plus-noise-ratio $SINR_{ki}$ is monotonically increasing with the large-scale fading coefficient β_{ki}.

The proof of Proposition 1 is as follows. For simplicity, let $\Gamma=\sum_{k=1}^{K}(\beta_{k1}+\beta_{k2})$,then

$$
\begin{aligned}
SINR_{k1} &= \frac{\beta_{k1}^2}{I_1+I_2+I_3+I_4+I_5} \\
&= \frac{M\beta_{k1}^2}{\Gamma(\beta_{k1}+\beta_{k2})-\beta_{k1}^2-\beta_{k2}^2+\sigma^2(\beta_{k1}+\beta_{k2})+\sigma^2\Gamma+\sigma^4},
\end{aligned} \tag{10}
$$

Let W represents the denominator of (10), then we can attain the partial derivative of $SINR_{k1}$ to β_{k1} is

$$
\begin{aligned}
\frac{\partial(SINR_{k1})}{\partial\beta_{k1}} &= \frac{1}{W^2}\{M\Gamma\beta_{k1}^2+M\sigma^2\beta_{k1}^2 \\
&+2M\beta_{k1}(\beta_{k2}(\Gamma-\beta_{k2})+\sigma^2\beta_{k2}+\sigma^2\Gamma+\sigma^4)\}.
\end{aligned} \tag{11}
$$

As $\Gamma>\beta_{k2}$, so (11) is always greater than zero. Therefore, for u_{k1}, the relationship between $SINR_{k1}$ and its large-scale fading coefficient β_{k1} is monotonically increasing. The above derivation process is also applicable to the other user u_{k2} of the k-th pair, that is, the relationship between $SINR_{k2}$ and its large-scale fading coefficient β_{k2} is monotonically increasing. The above is the proof of Proposition 1.

Proposition 3: When $\forall\beta_i\in\{\beta_1,\cdots,\beta_N\}\leq\frac{\Gamma+\sigma^2}{2}$ is satisfied, the signal-to-interference-noise ratio of u_{ki} $(SINR_{ki})$ is monotonically decreasing with the large-scale fading coefficient of another user in the same pair (β_{ki^-}), in which $i^-=2$ when $i=1$, and $i^-=1$ when $i=2$.

The proof of Proposition 2 is as follows. The partial derivative of $SINR_{k1}$ in (10) to β_{k2} is

$$
\frac{\partial(SINR_{k1})}{\partial\beta_{k2}}=\frac{M\beta_{k1}^2(\Gamma-2\beta_{k2}+\sigma^2)}{W^2}, \tag{12}
$$

The extreme point of (12) is $\beta_{k2}=\frac{\Gamma+\sigma^2}{2}$, when $\beta_{k2}<\frac{\Gamma+\sigma^2}{2}$, $SINR_{k1}$ is monotonically decreasing with β_{k2}, as $\Gamma=\sum_{i=1}^{N}(\beta_i)$, at most one β_i satisfies $\beta_i>\frac{\Gamma+\sigma^2}{2}$, there is rarely the case when N is large, therefore, we can consider $\forall\beta\in\{\beta_1,\cdots,\beta_N\}<\frac{\Gamma+\sigma^2}{2}$.Therefore, for u_{k1}, the relationship between $SINR_{k1}$ and β_{k2} is monotonically decreasing.

The above derivation process is also applicable to the other user u_{k2} of the k-th pair, that is, the relationship between $SINR_{k2}$ and β_{k1} is monotonically decreasing. The above is the proof of Proposition 2.

C. Smart User Pairing Algorithm

In this subsection, based on Proposition 2 and Proposition 3, the smart user pairing algorithm is proposed to solve the optimization problem $\mathcal{Q}$. The most direct way to solve the optimization problem is the exhaustive search, which tries all possible pairing schemes and chooses the best one. However, the number of all pairing schemes is $n=\prod_{k=0}^{\frac{N}{2}-1}\binom{N-2k}{2}/(\frac{N}{2}!)$, which leads to high computational complexity, especially when N is large. In this paper, the optimization problem $\mathcal{Q}$ is solved in a way with low complexity.

Arrange the large-scale fading coefficients of all users' channels from small to large, $0<\beta_1<\beta_2<\cdots<\beta_N$. Let the user with the large-scale fading coefficient β_i be the u_i. Then let u_{2k-1} and u_{2k} as u_{k1} and u_{k2} respectively. Assuming the proposed smart user pairing scheme is ψ_p, it can be formulated as follows

$$
\begin{aligned}
\psi_p &= \{\{u_{k1}^p,u_{k2}^p\},k=1,2,\cdots,K\} \\
&= \{\{u_{2k-1},u_{2k}\},k=1,2,\cdots,K\}.
\end{aligned}
$$

Apparently, the computational complexity of the proposed smart user pairing scheme comes from the sorting process, which is only $\mathcal{O}(N)$, it is negligible compared with n required by exhaustive search.

Next, we prove that the proposed smart user pairing scheme is one of the solutions to the optimization problem $\mathcal{Q}$. Assume that there is another pairing scheme $\psi_q=\{\{u_{k1}^q,u_{k2}^q\},k=1,2,\cdots,K\}$, which has larger minimum uplink SINR of N users than ψ_p, i.e.,

$$
\gamma_q=\min_{\forall k,i}SINR_{ki}^q>\gamma_p=\min_{\forall k,i}SINR_{ki}^p. \tag{13}
$$

Now we prove that such scheme ψ_q does not exist. For ψ_p scheme, $\beta_{k1}\leq\beta_{k2}$, according to (8), for two users of any pair, there is $SINR_{k1}^p\leq SINR_{k2}^p$, $k=1,2,\cdots,K$. Assume that the user with the minimum uplink SINR in ψ_p scheme is in the t-th pair, i.e., $\gamma_p=SINR_{t1}^p$, the large-scale fading coefficients of $\{u_{t1}^p,u_{t2}^p\}$ are$\{\beta_{t1},\beta_{t2}\}=\{\beta_{2t-1},\beta_{2t}\}$. Then, according to the scheme ψ_q, suppose that the user with large-scale fading coefficient β_{2t-1} is assigned to the v-th pair $(1\leq v\leq K)$ with the user whose large-scale fading coefficient is β_w, i.e., the large-scale fading coefficients of $\{u_{v1}^q,u_{v2}^q\}$ are$\{\beta_{v1},\beta_{v2}\}=\{\beta_{2t-1},\beta_w\}$. Comparing β_w with β_{2t}, there will be two results:

1) $\beta_w\geq\beta_{2t}$: According to Proposition 2, we have $SINR_{v1}^q=SINR_{\beta_{2t-1}}^{\{\beta_{2t-1},\beta_w\}}\leq SINR_{t1}^p=SINR_{\beta_{2t-1}}^{\{\beta_{2t-1},\beta_{2t}\}}$, so

$$
\gamma_q\leq SINR_{v1}^q\leq SINR_{t1}^p=\gamma_p, \tag{14}
$$

which contradicts the assumption in (13).

2) $\beta_w<\beta_{2t}$: According to the order of $0<\beta_1<\beta_2<\cdots<\beta_N$, it is clear that $w\in\{1,2,\cdots,2t-2\}$. Since one user with a large-scale fading coefficient chosen from $\{\beta_1,\beta_2,\cdots,\beta_{2t-2}\}$ has been assigned with the user whose large-scale fading coefficient is β_{2t-1}, there must be a user with $\beta_m(1\leq m\leq 2t-2)$ and a user with $\beta_n(2t\leq n\leq N)$ are divided into a pair, i.e., $\{\beta_{r1}^q,\beta_{r2}^q\}=\{\beta_m,\beta_n\}(1\leq r\leq K)$.

   (i) According to Proposition 2, due to $\beta_{r1}^q=\beta_m<\beta_{2t}=\beta_{t1}^p$, we can have

$$
SINR_{r1}^q=SINR_{\beta_m}^{\{\beta_m,\beta_n\}}<SINR_{\beta_{2t-1}}^{\{\beta_{2t-1},\beta_n\}}.
$$

   (ii) According to Proposition 3, due to $\beta_{r2}^q=\beta_n\geq\beta_{2t}=\beta_{t2}^p$, we can have

$$
SINR_{\beta_{2t-1}}^{\{\beta_{2t-1},\beta_n\}}\leq SINR_{\beta_{2t-1}}^{\{\beta_{2t-1},\beta_{2t}\}}=SINR_{t1}^p.
$$

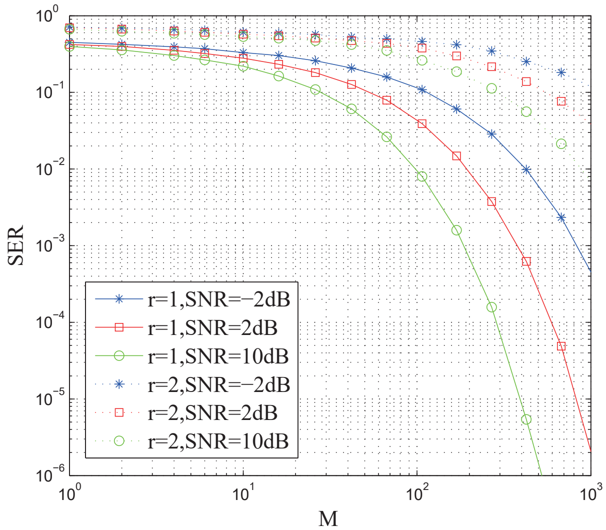

Fig. 1. Average SERs of the proposed scheme with different numbers of BS antennas.

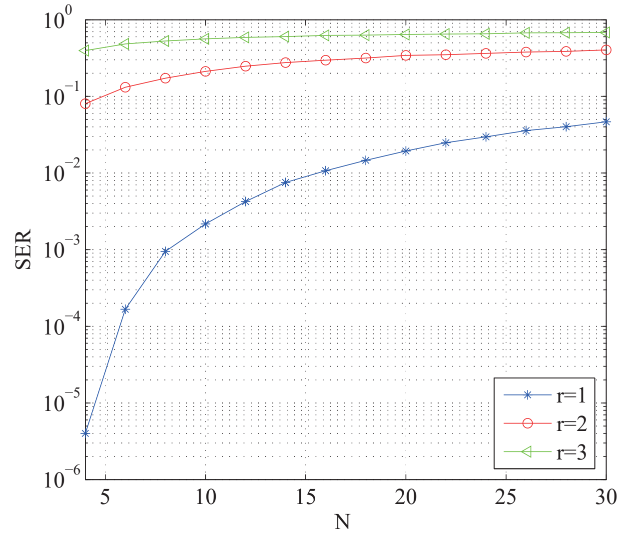

Fig. 2. Average SERs of the proposed communication scheme with different N.

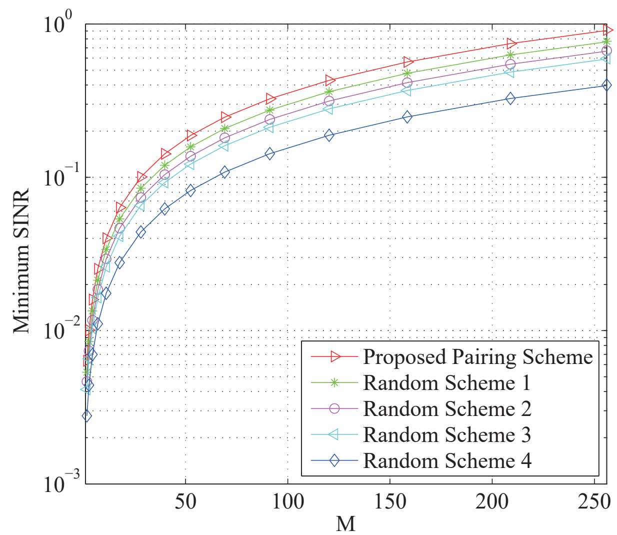

Fig. 3. Minimum uplink SINR of different user pairing scheme.

As a result of (i) and (ii), we have

$$\gamma_q \leq SINR_{r1}^{q} < SINR_{\beta_{2t-1}}^{\{\beta_{2t-1},\beta_n\}} \leq SINR_{t1}^{p} = \gamma_p,$$

which contradicts the assumption in (13). This completes the proof.

It is concluded that the scheme ψ_p is one of the solutions to the optimization problem $\mathcal{Q}$. Note that there may be more than one optimal solution, for example, there are two users with the same channel quality, i.e., $\beta_{n_1} = \beta_{n_2}$, $n_1 \neq n_2$. However, the exchange of the two users makes no difference to the minimum uplink SINR.

IV. Simulation Results

In this section, computer simulation results are presented to show the performance of the proposed communication scheme. In simulations, the transmission period T is set to $N/2+1$ for clarity. The SNR is defined as the ratio of transmitting power of each user to the noise power at the BS.

First, we study the average symbol error rates (SERs) of the proposed scheme with different numbers of BS antennas in Fig. 1, in which $N = 10$, $\beta_1, \cdots, \beta_{10}$ randomly selected from $\{0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95\}$. It observes that the SERs of the proposed scheme exponentially decrease as M increases. This phenomenon is mainly because that the interference and noise exponentially descend. Also, the error performance of the system degrades with the modulation order increasing from 2 to 4. It is mainly because the larger the modulation order, the smaller the distance between the constellation points of $\mathcal{X}_k$ and $\mathcal{Y}_k$.

Fig. 2 studies the relationship between the SERs of the proposed scheme with the number of users. To compare fairly and avoid the channel quality difference caused by the number of users, the large-scale fading coefficients of all users are set to be a fixed value 0.8dB. It illustrates that when N is small, the proposed scheme has a better SER performance. However, the error performance decreases as N increases. This is mainly because the demodulation scheme highly depends on the gradual orthogonality between multi-user channels. With N increasing, the orthogonality will be destroyed. As a result, the interference between multiple users increases, which leads to poor SER performance.

Fig. 3 shows the minimum uplink SINR among all N users of proposed user pairing scheme and four other schemes. And the 4-th random scheme is $\{\{0.5, 0.95\}, \{0.55, 0.9\}, \{0.6, 0.85\}, \{0.65, 0.8\}, \{0.7, 0.75\}\}$.

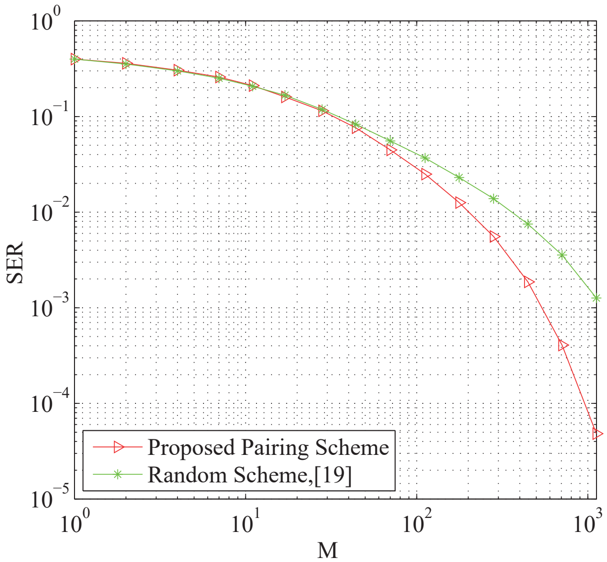

Fig. 4. Average SERs of different user pairing scheme.

It is seen that the proposed smart user pairing scheme improves the minimum SINR, which is more obvious as the number of BS antennas increases. Specifically, when the typical parameter $M = 256$ is considered, the minimum uplink SINR in the proposed smart user pairing scheme is larger than that of the 4-th random scheme by about 0.5.

The impact of user pairing scheme on the average SERs is shown in Fig. 4, in which $N = 10$. Compared with the traditional random pilot allocation scheme [19], we observe that the proposed smart user pairing scheme improves the system's error performance significantly. Besides, the performance gap becomes larger as M increases.

V. Conclusion

In this paper, we have considered the uplink of an IIoT communication system. For such systems, a smart user pairing scheme based on PSK modulation division has been proposed by carefully investigating the impact of the user pairing strategy on the SINR. The proposed scheme performs user pairing in a sequential way with low complexity, it can reduce the pilot overhead and mitigate the pilot contamination effectively. The computer simulation results have shown that the proposed scheme works well and the smart user pairing scheme can decrease the average SER significantly.

References

[1] R. Chaudhary, G. S. Aujla, S. Garg, N. Kumar, and J. J. P. C. Rodrigues, "SDN-Enabled multi-attribute-based secure communication for smart grid in IIoT environment," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 6, pp. 2629–2640, June 2018.

[2] H. Ji, S. Park, J. Yeo, Y. Kim, J. Lee, and B. Shim, "Introduction to ultra reliable and low latency communications in 5G," *CoRR*, 2017.

[3] I. Budhiraja, S. Tyagi, S. Tanwar, N. Kumar, and J. J. P. C. Rodrigues, "DIYA: Tactile Internet driven delay assessment NOMA-based scheme for D2D communication," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 12, pp. 6354–6366, Dec 2019.

[4] G. J. Sutton, J. Zeng, R. P. Liu, W. Ni, D. N. Nguyen, B. A. Jayawickrama, X. Huang, M. Abolhasan, and Z. Zhang, "Enabling ultra-reliable and low-latency communications through unlicensed spectrum," *IEEE Network*, vol. 32, no. 2, pp. 70–77, March 2018.

[5] P. Popovski, J. J. Nielsen, C. Stefanovic, E. d. Carvalho, E. Strom, K. F. Trillingsgaard, A. Bana, D. M. Kim, R. Kotaba, J. Park, and R. B. Sorensen, "Wireless access for ultra-reliable low-latency communication: Principles and building blocks," *IEEE Network*, vol. 32, no. 2, pp. 16–23, March 2018.

[6] T. K. Vu, C. Liu, M. Bennis, M. Debbah, M. Latva-aho, and C. S. Hong, "Ultra-reliable and low latency communication in mmWave-enabled massive MIMO networks," *IEEE Communications Letters*, vol. 21, no. 9, pp. 2041–2044, Sep. 2017.

[7] Y. Hori and H. Ochiai, "A low PAPR subcarrier hopping multiple access with coded OFDM for low latency wireless networks," in *2015 IEEE Global Communications Conference (GLOBECOM)*, Dec 2015, pp. 1–6.

[8] M. Serror, C. Dombrowski, K. Wehrle, and J. Gross, "Channel coding versus cooperative ARQ: Reducing outage probability in ultra-low latency wireless communications," in *2015 IEEE Globecom Workshops (GC Wkshps)*, Dec 2015, pp. 1–6.

[9] M. Bennis, M. Debbah, and H. V. Poor, "Ultrareliable and low-latency wireless communication: Tail, risk, and scale," *Proceedings of the IEEE*, vol. 106, no. 10, pp. 1834–1853, 2018.

[10] J. Zeng, T. Lv, R. P. Liu, X. Su, N. C. Beaulieu, and Y. J. Guo, "Linear minimum error probability detection for massive MU-MIMO with imperfect CSI in URLLC," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 11, pp. 11 384–11 388, Nov 2019.

[11] G. Durisi, T. Koch, and P. Popovski, "Toward massive, ultrareliable, and low-latency wireless communication with short packets," *Proceedings of the IEEE*, vol. 104, no. 9, pp. 1711–1726, 2016.

[12] B. Lee, S. Park, D. J. Love, H. Ji, and B. Shim, "Packet structure and receiver design for low-latency communications with ultra-small packets," in *2016 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2016, pp. 1–6.

[13] F. Fernandes, A. Ashikhmin, and T. L. Marzetta, "Inter-cell interference in noncooperative TDD large scale antenna systems," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 2, pp. 192–201, February 2013.

[14] A. Ashikhmin, L. Li, and T. L. Marzetta, "Interference reduction in multi-cell massive MIMO systems with large-scale fading precoding," *IEEE Transactions on Information Theory*, vol. 64, no. 9, pp. 6340–6361, Sep. 2018.

[15] Mingmei Li, Shi Jin, and Xiqi Gao, "Spatial orthogonality-based pilot reuse for multi-cell massive MIMO transmission," in *2013 International Conference on Wireless Communications and Signal Processing*, Oct 2013, pp. 1–6.

[16] X. Zhu, Z. Wang, L. Dai, and C. Qian, "Smart pilot assignment for massive MIMO," *IEEE Communications Letters*, vol. 19, no. 9, pp. 1644–1647, Sep. 2015.

[17] S. Li, J. Zhang, and X. Mu, "Noncoherent massive space-time block codes for uplink network communications," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 6, pp. 5013–5027, June 2018.

[18] ——, "PSK-based space time modulation for two-user two-way massive MIMO relay systems," *IEEE Signal Processing Letters*, vol. 25, no. 2, pp. 184–188, Feb 2018.

[19] L. Sanguinetti, A. A. D'Amico, M. Morelli, and M. Debbah, "Random access in uplink massive MIMO systems: How to exploit asynchronicity and excess antennas," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec 2016, pp. 1–5.