A novel random access scheme for M2M communication in crowded asynchronous massive MIMO systems

Huimei Han1 | Wenchao Zhai2 | Ying Li3 | Weidang Lu1 | Jun Zhao4

1 College of Information Engineering, Zhejiang University of Technology, Hangzhou, Zhejiang, P. R. China
2 Key Laboratory of Electromagnetic Wave Information Technology and Metrology of Zhejiang Province, China Jiliang University, Hangzhou, Zhejiang, P. R. China
3 State Key Laboratory of Integrated Service Networks, Xidian University, Xi’an, P. R. China
4 School of Computer Science and Engineering, Nanyang Technological University, Singapore

Abstract
A new random access scheme is proposed to solve the intra-cell pilot collision for M2M communication in crowded asynchronous massive multiple-input multiple-output systems. The proposed scheme utilizes the proposed estimation method of signal parameters to estimate the effective timing offsets, and then active user equipments obtain their timing errors from the effective timing offsets for uplink message transmission. The mean squared error of the estimated effective timing offsets of user equipments and the uplink throughput are analysed. Simulation results show that, compared to the exiting random access scheme for the crowded asynchronous massive multiple-input multiple-output systems, the proposed scheme can improve the uplink throughput and estimate the effective timing offsets accurately at the same time.

1 | INTRODUCTION
The machine-to-machine (M2M) communication is centred on the intelligent interaction of user equipment (UEs) without human intervention, which is the enabler for the Internet of Things (IoT) to achieve the envision of the “Internet of Everything” [1, 2]. In recent years, the M2M communication developments rapidly and has been applied to many scenarios, such as smart medical, smart vehicle, smart logistics, etc. Cisco visual networking index and forecast predicts that there will be around 28.5 billion connected UEs by 2022 [3]. The massive multiple-input multiple-output (MIMO) technology, which achieves significant improvements in energy and spectral efficiency and serve massive UEs in the same time-frequency resource, is well suited for the M2M communication [4, 5].

For the M2M communication in massive MIMO systems, the number of UEs in the cell is envisioned in the order of hundreds or thousands, and the payload data generated by the M2M traffic is usually in small size [6]. Random access procedure is the first step to initiate a data transmission, which is an important step in the M2M communication systems [7]. The connection-oriented random access procedure utilized in the long-term evolution (LTE) network may induce excessive signaling overhead and cannot support massive access [7].
Researchers are exploring new random access schemes for M2M communication in massive MIMO systems, and the grant-based random access schemes have been proposed in recent years. Björnson et al. proposed a strongest-user collision resolution (SUCRe) scheme, which allocates the pilot to the UE with the largest channel gain among the contenders \([8]\). However, the number of successful accessing UEs decreases with the increase of the number of contenders \([9]\). Recently, SUCRe also achieved performance gain for the extra-large massive MIMO systems \([10]\). To ensure the fairness between UEs of the SUCRe scheme, an access class barring with power control (ACBPC) scheme was proposed in \([11]\). To improve the pilot resource utilization of the SUCRe scheme, SUCR combined idle pilots access (SUCR-IPA) scheme was proposed in \([12]\), where the weaker UEs randomly select idle pilots to increase the number of successful accessing UEs. A user identity-aided pilot access scheme was proposed for massive MIMO with interleave-division multiple-access systems, where the interleaver of each UE is available at the BS according to the one-to-one correspondence between UE’s identity number (ID) and its interleaver \([13]\). However, since the grant-based random access schemes require two handshake processes between the base station (BS) and UEs, considering the small packet transmission in M2M communication, such kind of random access scheme will introduce heavy signaling overhead and low data transmission efficiency. To address this problem, the grant-free random access schemes have attracted much attention in recent years, which allow active UEs to transmit their pilots and uplink messages to the BS directly and performs activity detection, channel state information (CSI) estimation, and uplink message decoding in one shot. Ahn et al. proposed a Bayesian-based random access scheme to detect the UE’s activity and estimate the CSI jointly by utilizing the expectation propagation algorithm, considering the BS with one antenna \([14]\). Liu et al. proposed an approximate message passing (AMP)-based grant-free scheme to achieve the joint activity detection and CSI estimation for massive MIMO systems \([15]\). However, this AMP-based grant-free random access scheme requires long pilot sequence to achieve better performance, resulting in heavy pilot overhead. These grant-free random access schemes considers the single pilot structure, and Jiang et al. proposed to concatenate several multiple orthogonal sub-pilots into one pilot sequence, where different UEs are allocated different pilot sequences and the pilot sequence is utilized for activity detection and CSI estimation \([16]\). The performance comparison between these two kinds of pilot structures are made in \([17]\). For the uplink non-orthogonal multiple access (NOMA) system in power domain, a novel random NOMA transmission scheme was proposed to achieve the accurate power control for massive machine-type communications \([18]\).

The above-mentioned two kinds of random access schemes are based on the assumption that the BS has performed accurate time-frequency synchronization. However, in practice, there are frequency errors caused by the Doppler shifts and/or frequency estimation errors during the initial downlink synchronization, and timing errors caused by the locations of UEs in the cell, which impair the pilot orthogonality and further degrade the access performance \([19–21]\). Considering the time-frequency asynchronous massive MIMO systems, Sanguinetti et al. proposed a random access scheme based on orthogonal frequency division multiplexing (OFDM) to solve the pilot collision by exploiting timing offsets and the large number of antennas \([22]\). However, the number of successful detected UEs is less than or equal to the number of subcarriers of the pilot, which cannot meet the massive access requirements of the M2M communication.

To further resolve the pilot collision for the M2M communication in crowded asynchronous massive MIMO systems, we propose a novel random access scheme, where the BS employs a proposed estimation of signal parameters via rotational invariance technique enhanced (ESPRIT-E) method to estimate the effective timing offsets of UEs, and UEs judge whether it is detected in a distributed manner. Then, the detected UE obtains its timing error from the effective estimated timing error, and further compensates the timing error for uplink message transmission. Furthermore, we analyze the mean squared error (MSE) of the estimated effective timing offsets of UEs and the uplink throughput. Numerical results show that, the proposed random access scheme significantly improves the uplink throughput, and provides accurate value of the effective timing offset.

The remainder of this paper is organized as follows: System model is given in Section 2. Section 3 describes the proposed random access process. We present the performance analysis in Section 4. Simulation results and the conclusion are given in Sections 5 and 6, respectively.

**Notation:** Notations utilized throughout this paper are described in Table 1

| Notations | Description |
|-----------|-------------|
| \(T\)     | Transpose operation |
| \(*\)     | Complex conjugate operation |
| \(H\)     | Conjugate transpose operation |
| \(\mathcal{N}(\theta, \varepsilon)\) | A Gaussian distribution with mean \(\theta\) and variance \(\varepsilon\) |
| \(|\cdot||\) | The Euclidean norm of a vector |
| \([x]_n\) | The \(n\)th element of vector \(x\) |
| \(X(i)\) | The \(i\)th column of matrix \(X\) |
| round     | The rounding operation |
| \(\arg(d)\) | The phase of the complex \(d\) |

### TABLE 1: Notation

2 | **SYSTEM MODEL**

We consider the time-division duplexing (TDD) massive MIMO communication system based on OFDM. There is a BS with \(M\) antennas located at the center of the cell and \(K\) single-antenna UEs uniformly distributed in the cell. We assume that each UE becomes active with probability \(p_a\). The number of
UEs residing in the cell is \( K \), and the number of active UEs is \( N_a \).

The pilot with symbol length \( \tau \) consists of \( Q \) consecutive OFDM symbols in the frequency domain (i.e. \( \tau = QN \)). We use \( C_N = \{ f_0, f_1, \ldots, f_{N-1} \} \sim \mathbb{C}^N : f_j = N, W \} \) and \( C_Q = \{ t_0, t_1, \ldots, t_{Q-1} \} \sim \mathbb{C}^Q : t_i = Q, \forall i \) to represent the frequency domain code set and time domain code set, respectively. The time domain code set \( C_Q \) can be any orthogonal sequence set, and the frequency domain code \( f_j \) is the Fourier basis, which is given by [19]

\[
[f_j]_w = e^{j 2\pi \frac{w j}{N}}, \quad n = 0, 1, \ldots, N - 1.
\]

The received pilot signal of UE \( k \) at the BS will introduce frequency error \( w_k \) and timing error \( \theta_k \). Since the value of \( w_k \) is very small in general and its impact can reasonably be neglected if the pilot contains only a few consecutive OFDM symbols [22, 23], we only consider the timing error \( \theta_k = 2D_k/(c T) \) where \( D_k \) is the distance from UE \( k \) to the BS, \( c = 3 \times 10^8 \text{ m/s} \) is the speed of light, \( T_s = 1/(\Delta f N_{\text{FFT}}) \) is the sampling period where \( N_{\text{FFT}} \) is the number of subcarriers with frequency spacing \( \Delta f \). Note that, timing error \( \theta_k \) appears as phase shifts at the output of the receive discrete Fourier transform (DFT) unit [22].

3.1 THE PROPOSED RANDOM ACCESS SCHEME

Figure 1 shows the four steps of the proposed random access scheme. UEs first randomly select their pilots, and the BS generates and broadcasts the PRAR information to all active UEs. Then, based on the received PRAR information, if UE judges it has been detected by the BS, it remains silent. Otherwise, it reselects its pilot and sends it to the BS. Finally, the BS generates and broadcasts the PRAR information to active UEs again.

**FIGURE 1** The proposed random access scheme: UEs first randomly select their pilots, and the BS generates and broadcasts the PRAR information to all active UEs. Then, based on the received PRAR information, if UE judges it has been detected by the BS, it remains silent. Otherwise, it reselects its pilot and sends it to the BS. Finally, the BS generates and broadcasts the PRAR information to active UEs again.
where \( g_k^m \sim \mathcal{C}\mathcal{N}(0, 1) \) is the small-scale fading coefficient between UE \( k \) and the \( m \)th antenna of the BS, \( \beta_k \) is the channel gain of UE \( k \) which is known to UE \( k \). The CSI between UE \( k \) and the BS is denoted by \( h_k = (b_{k,1}, ..., b_{k,N})^T \). Then, the received pilot signal at the \( n \)th antenna of the BS can be written as

\[
Y_n = \sum_{k=1}^{N_a} \sqrt{\rho_k} g_k^m ([1, ..., e^{j(2\pi(N-1)\xi_k)}]) \psi_k^T + N_n,
\]

where \( \rho_k \beta_k = 1 \), which can be achieved by the power control mechanism [24]. This ensures that the received signals from UEs have the same power, and thus obtains a fair estimation performance.

**Step 2: Precoded random access broadcasting**

Based on the received pilot signal at the \( m \)th antenna of the BS \( Y_m \), the BS sends the precoded random access response to active UEs. The procedure is described as follows.

1): The number of active UEs estimation

\[
Z = \left[ z_1, z_2, ..., z_M \right]^T.
\]

By utilizing the eigenvectors of \( R_i \) associated to \( \epsilon_i \) is computed by

\[
R_i = \frac{1}{M} \sum_{m=1}^{M} \epsilon_i(z_m(y_m))^H.
\]

By utilizing the eigenvectors of \( R_i \) associated to \( \epsilon_i \) is computed by

\[
\epsilon_i = \frac{\arg(\psi_i)}{2\pi}, \quad s = 1, 2, ..., d^s,
\]

where \( d^s \) is the index of UE among the \( N_a \) active UEs, \( \{\psi_1, \psi_2, ..., \psi_d\} \) are eigenvalues of matrix \( (V_1^{-1} V_1^{-1}) \), and the matrices \( V_1 \) and \( V_2 \) are obtained by taking the first and the last \( N - 1 \) rows of \( V \), respectively.

The ESPRIT method can only estimate the effective timing offsets of \( d^s \leq (N - 1) \) UEs. If the value of \( N_a \) is larger than \( (N - 1) \), Based on Eq. (6), after subtracting these \( d^s \) estimated effective timing offsets from \( \epsilon \), we can obtain the sum of the effective timing offsets of the remaining \( (N_a - d^s) \) UEs, which is given by

\[
\sum_{m=1}^{M} e^{j(2\pi(N-1)i_{\epsilon}^s)}, \quad s = 1, 2, ..., d^s.
\]

By solving Equation (10), we can obtain the effective timing offsets of the remaining \( (N_a - d^s) \) UEs. Thus, the estimated effective timing offsets are \( \{\epsilon_1, ..., \epsilon_2, ..., \epsilon_{d^s}\} \).

2): The effective timing offsets estimation

By utilizing \( \epsilon_i \), we utilize the proposed ESPRIT-E method to estimate the effective timing offsets of UEs, which is described as follows:

The sample covariance matrix \( R_i \) is computed by

\[
R_i = \frac{1}{M} \sum_{m=1}^{M} \epsilon_i(z_m(y_m))^H.
\]

By utilizing the eigenvectors of \( R_i \) associated to \( \epsilon_i \) is computed by

\[
\epsilon_i = \frac{\arg(\psi_i)}{2\pi}, \quad s = 1, 2, ..., d^s,
\]

where \( d^s \) is the index of UE among the \( N_a \) active UEs, \( \{\psi_1, \psi_2, ..., \psi_d\} \) are eigenvalues of matrix \( (V_1^{-1} V_1^{-1}) \), and the matrices \( V_1 \) and \( V_2 \) are obtained by taking the first and the last \( N - 1 \) rows of \( V \), respectively.

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By solving Equation (10), we can obtain the effective timing offsets of the remaining \( (N_a - d^s) \) UEs. Thus, the estimated effective timing offsets are \( \{\epsilon_1, ..., \epsilon_2, ..., \epsilon_{d^s}\} \).

3): CSI estimation

By utilizing \( \epsilon_i \), we employ the least squares (LS) method to estimate the CSI of UE \( i \) between UE \( i \) and the \( m \)th antenna.
at the BS
\[
\hat{h}_i' = \frac{c(\varepsilon)_i^1}{c(\varepsilon)_i^1} \frac{c(\varepsilon)_i^1}{c(\varepsilon)_i^1}, \quad \varepsilon = 1, 2, \ldots, N_u^i.
\] (11)

Based on procedures (1)–(3), the BS obtains estimated CSIs of UEs selecting other time domain codes. Then, the precoded random access response is given by
\[
V_i' = h_i' t_i^T, \quad (i = 0, \ldots, Q - 1, \varepsilon = 1, \ldots, N_u^\varepsilon).
\] (12)

Finally, the BS broadcasts the precoded random access response \(V_i'\) and the corresponding effective timing error \(\varepsilon_i'\) to all active UEs.

**Step 3: Pilot reselection**

The received signal \(R_k'\) at UE \(k\) is written as
\[
R_k' = h_k' V_i' + W_k
\] (13)

\[= h_k' h_i' t_i^T + W_k, \quad i = 0, \ldots, Q - 1, \varepsilon = 1, \ldots, N_u^\varepsilon.\]

UE \(k\) first correlates the received signal \(R_k'\) with its selected time domain code to obtain
\[
r_k' = R_k' h_i' t_k^* \frac{1}{||t_k||M\sqrt{\beta_k}}
\]
\[= h_k' h_i' t_k^* \frac{1}{||t_k||M\sqrt{\beta_k}} + W_k \frac{t_k^*}{||t_k||M\sqrt{\beta_k}}, \quad (14)\]

where (a) is derived by \(h_i' h_i' = 1, W_k t_k^* = 0\) when \(h_i' \approx h_k', \) otherwise \(h_i' h_i' = W_k t_k^* = 0.\)

Then, UE \(k\) uses the following rule to judge whether it is detected in a distributed manner, which is given by
\[
D_k : \text{if } \sum_{j=1}^{N_u^\varepsilon} \text{round}(r_k') = 1 \quad \text{(Detected)}
\] (15)

\[U_k : \text{otherwise (Undetected).}\]

If UE \(k\) is a detected UE, it uses the effective timing error \(\varepsilon_k'\) corresponding to \(h_i'\) that makes round\((r_k')\) = 1 to obtain its timing error as follows
\[
\varepsilon_k' = \text{round}(l_k - C_k' N_\text{FFT}) = \text{round}(l_k - C_k' N_\text{FFT}) - 1
\] (16)

Finally, UE \(k\) employs \(\varepsilon_k'\) to compensate its timing error for uplink message transmission. Otherwise, UE \(k\) randomly selects a frequency domain code from set \(C_N\) and a time domain code from set \(C_Q\) to obtain its pilot, and send it to the BS, as we described in step 1.

**Step 4: Precoded random access response broadcasting again**

Similar to step 2, based on the received pilot signal, the BS generates and broadcasts the precoded random access responses again, and each UE reselecting its pilot during step 3 employs the rule in Equation (15) to judge whether it is detected. If UE \(p\) is a detected UE, it compensates its timing error for uplink message transmission. In the following, all detected UEs send their uplink messages to the BS, and thus the BS can utilize any blind detection method to obtain their uplink messages, such as the proposed EICA method proposed in [27], which is not the focus of this paper.

Remark 1 (Why we utilize Equation (15) as the detection rule). Equation (14) indicates that, if the estimated channel response \(h_i'\) is approximately equal to the CSI of UE \(k\), the value of \(r_k'\) equals 1 with large value of \(M\). Furthermore, based on Equation (11), we observe that multiple similar effective timing offsets lead to multiple estimated CSIs being approximately equal to the CSI of UE \(k\), resulting in \(\sum_{j=1}^{N_u^\varepsilon} \text{round}(r_k') = 1\). However, we cannot determine the timing error of UE \(k\) for such case, because of \(\varepsilon_k = \frac{l_k - \varepsilon_k'}{N_\text{FFT}}\), which means that UEs with different selected frequency domain codes and different timing errors may have similar effective timing offsets. To obtain the timing error of UE \(k\), if multiple estimated CSIs are approximately equal to the CSI of UE \(k\), that is, \(\sum_{j=1}^{N_u^\varepsilon} \text{round}(r_k') = 1\), we claim that UE \(k\) is not detected. Obviously, the case of \(\sum_{j=1}^{N_u^\varepsilon} \text{round}(r_k') = 0\) means that UE \(k\) is not detected. The case of \(\sum_{j=1}^{N_u^\varepsilon} \text{round}(r_k') = 1\) indicates that there are no similar effective timing offsets with UE \(k\), and thus we can obtain its timing error based on Equation (16).

Remark 2 (Random access schemes comparison). Both our work and [22] focus on the problem of massive access in time-frequency asynchronous massive MIMO systems. The differences between our work and [22] are threefold. First, [22] proposed to utilize minimum description length (MDL) algorithm to estimate the number of UEs selecting the same time domain code, which can only be estimated accurately when the number of UEs selecting the same time domain code is less than or equal to the number of frequency codes. By utilizing the characteristic of the massive MIMO channel, we proposed a method of estimating the number of UEs selecting the same time domain code, which independently on the
number of frequency codes. Second, [22] proposed to employ the estimation of signal parameters via rotational invariance technique (ESPRIT) to recover the timing error of each UE, while the number of recovered UEs is less than the number of frequency codes. We proposed to utilize an ESPRIT-enhanced (ESPRIT-E) method to recover more UEs’ timing errors. Third, in [22], the BS judges whether a UE is successfully detected by utilizing a final performance criteria. However, this performance criteria depends on two thresholds which should be properly designed and is non-adaptive. By utilizing the characteristic of the massive MIMO channel, we proposed to allow each UE to judge whether it is detected in a distributed manner without any parameter adjustment, which is adaptive.

4 PERFORMANCE ANALYSIS

In this section, we analyze the performance of the proposed random access scheme, including the MSE of the estimated effective timing offset, and the uplink throughput.

4.1 MSE of the estimated effective timing offset

In the proposed random access scheme, we utilize the ESPRIT-E method to estimate the effective timing offsets of UEs. Specifically, for the active UEs selecting the same time domain code, we first utilize the ESPRIT method to estimate the effective timing offsets of \( N - 1 \) active UEs. Then, after subtracting the \( N - 1 \) estimated effective timing offsets from the sum of effective timing offsets of all active UEs, we obtain the effective timing offsets of the remaining active UEs by solving the polynomial equations in Equation (10). Obviously, the procedure of Equation (10) will introduce noise. Furthermore, based on Equation (6), the sum of effective timing offsets of all active UEs selecting the same time domain code is accurate when \( M \) goes to infinity. Hence, given \( N_s, Q, \) and \( N, \) the MSE of the estimated effective timing offset of the proposed ESPRIT-E method is greater than or equal to that of the estimated effective timing offset when \( M \) goes to infinity, which is given by

\[
\text{MSE} = \frac{1}{N_s} \sum_{k=1}^{N} \left( \theta_k - \hat{\theta}_k \right)^2 \geq \text{MSE}_{\text{ESPRIT-E}},
\]

where \( N_s \) is the number of UEs being detected. We utilize the Monte Carlo simulation method to obtain the value of \( \text{MSE}_{\text{ESPRIT-E}} \), which is the lower bound of the MSE of the estimated effective timing offset of the ESPRIT-E method.

4.2 Uplink throughput analysis

We define the uplink throughput as the number of the successfully detected active UEs. When given the number of active UEs selecting the same time domain code, based on Equation (10), the larger the value of \( M \), the more accurate the estimated effective timing offsets. This leads to the increase of the number of the detected active UEs. Hence, given \( N_s, Q, \) and \( N, \) we can obtain the upper bound of the uplink throughput of the proposed random access protocol by setting the value of \( M \) to infinity. Since it is hard to derive the analysis result of the uplink throughput, we utilize the Monte Carlo simulation method to obtain the upper bound, denoted by \( T_u \).

5 SIMULATION RESULTS

In this section, we compare the performance of the proposed random access scheme with the random access scheme in [22], including the MSE of the estimated effective timing offset and the uplink throughput.

In the simulation, we consider a cellular network operating over a bandwidth \( B=20 \text{ MHz} \) and the radius of the cell is 250 m and all UEs locate uniformly at the place farther than 25 m from the BS. Table 2 shows the simulation parameter setting.

![Table 2: System parameters](attachment:table2.png)

Figure 2 shows how the MSE of the estimated effective timing offset changes with the number of subcarriers under \( Q = 2, M = 200, \) and \( N_s = 6, \) to verify the proposed effective timing offset estimation method. The simulation results show that the MSE of the estimated effective timing offset takes small value, and decreases with the number of subcarriers \( N \). The reason is that, the increase of the number of subcarriers \( N_s \) means the increase of the number of pilots, resulting in the decrease of the pilot collision probability and the interference between UEs. We can also note that the MSE of the estimated effective timing offset is close to the lower bound.

Figure 3 shows how the uplink throughput changes with the number of antennas at the BS under \( Q = 2, N = 8, \) and \( N_s = 14. \) We can observe from the simulation results that the uplink throughputs of the proposed random access scheme and the random access scheme in [22] increase dramatically.
The proposed random access scheme
Lower bound

**FIGURE 2** MSE versus the number of subcarriers

![MSE versus the number of subcarriers](image)

**FIGURE 3** Uplink throughput versus the number of antennas at the BS

![Uplink throughput versus the number of antennas at the BS](image)

from $M = 20$ to $M = 50$, and increases at a slower pace when $M \geq 50$. We also note that the uplink throughput of the proposed random access is significantly higher than that of the random access scheme in [22], and much close to the upper bound $T_u$. The reason is that the random access scheme in [22] utilizes the ESPRIT method to estimate the effective timing offsets, and thus the number of detected effective timing offsets is limited by the number of subcarriers $N$. However, to address this problem, our proposed random access scheme proposed an ESPRIT-enhanced (i.e. ESPRIT-E) method to estimated the effective timing offsets.

Figure 4 shows how the uplink throughput changes with the number of active UEs under $Q = 2$, $M = 200$, and $N = 8, 12$. We can observe from the simulation results that the uplink throughput of the proposed random access scheme is significantly higher than the random access scheme in [22] with the increase of the number of active UEs, and close to the upper bound $T_u$. We also see that, with the increase of the number of active UEs, the uplink throughput of the proposed random access scheme increases almost linearly, whereas that of the random access scheme in [22] increase almost linearly from $N_a = 6$ to $N_a = 8$, and increases at a slower pace when $N_a \geq 8$. The reason is the same as we described for Figure 3; that is, the number of detected UEs is limited by the number of subcarriers $N$.

## 6 Conclusion

This paper proposes a new random access scheme for M2M communication in crowded asynchronous massive MIMO systems to resolve the intra-cell pilot collision. The proposed random access scheme estimates the effective timing offsets
by utilizing the proposed ESPRIT-E method, and then the UE can obtain its timing errors for uplink message transmission. We also analyze the performance of the proposed random access scheme, including the MSE of the estimated effective timing offset and the uplink throughput. Simulation results show that compared to the exiting random access scheme for the crowded asynchronous massive MIMO systems, the proposed random access scheme can improve the uplink throughput and provide accurate effective timing offsets at the same time.

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ORCID
Wenchao Zhai © https://orcid.org/0000-0002-7469-1487

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