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Research Article

Joint User Detection and Channel Estimation in Grant-Free Random Access for Massive MIMO Systems

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Grant-free random access (RA) utilizing massive multiple-input multiple-output (MIMO) technology has attracted considerable attention in recent years due to its potential to enhance spectral efficiency. This paper introduces an innovative and advanced approach for the joint detection of users and estimation of channels in grant-free RA. The approach incorporates two distinct preamble structures: the single orthogonal preamble (SOP) and the concatenated orthogonal preamble (COP). The proposed algorithms make full use of the inherent quasiorthogonal characteristic of massive MIMO, thereby enabling the accurate estimation of user channels while effectively avoiding collisions in the preambles. As a result, these algorithms generate highly precise estimations of user channels. To substantiate the effectiveness of the proposed algorithms, this paper provides an extensive theoretical analysis and presents a comprehensive set of experimental results. These findings offer robust evidence for the efficacy of the algorithms in substantially bolstering the performance of grant-free RA. Additionally, we have conducted further research and analysis, which has led to additional insights and refinements in our proposed approach. Moreover, the experimental results validate the statistical significance and reliability of the performance enhancements achieved by these algorithms. Moreover, the proposed approach exhibits robustness in scenarios with different levels of user density and varying channel conditions. Through a thorough analysis of these scenarios, we showcase the versatility and applicability of our algorithms in real-world environments.

1. Introduction

With the continuous advancement of the Internet of Things (IoT), the utilization of machine-to-machine (M2M) communications has become increasingly prevalent in various industrial and academic domains [1–3]. This technological paradigm facilitates intermittent transmission of small-sized data packets from a vast array of machine-type devices. In light of the limited availability of spectral resources, achieving high spectral efficiency is of paramount importance for M2M communications [4–7].

In this context, massive multiple-input multiple-output (MIMO) technology emerges as a promising solution to address this challenge [8–10]. The authors in this study [8] propose a grant-free random access scheme for machine-to-machine (M2M) communication in massive MIMO systems. The authors address the challenges of resource allocation and access scheduling for M2M devices in large-scale MIMO networks. The proposed scheme leverages the advantages of massive MIMO, such as increased connectivity and improved quality of service, to enable efficient and reliable grant-free random access for M2M communication. The paper presents a comprehensive analysis and simulation results to demonstrate the feasibility and benefits of the proposed scheme. Another study [9] provides an overview of massive access techniques for 5G and beyond. It discusses the challenges and opportunities in handling massive connectivity and diverse traffic types. The authors analyze the role of MIMO technology in supporting massive access, highlighting the use of joint detection algorithms and other advanced signal processing techniques to improve spectral efficiency and accommodate a large number of users. The paper presents a comprehensive survey of state-of-the-art techniques and highlights future research directions in massive access for advanced wireless communication systems. The authors in [10] provide an overview of the principles and enhancements of enabling grant-free ultra-reliable low-latency communication (URLLC) using massive MIMO. The authors discuss the challenges and requirements of URLLC that necessitate grant-free transmission techniques. They explore how massive MIMO can be leveraged to meet the stringent requirements of URLLC, such as low latency and high reliability. The paper reviews various enhancements and strategies, including joint detection algorithms, designed to improve the overall performance of grant-free URLLC systems. By leveraging the potential of massive MIMO, significant improvements in spectral efficiency can be achieved. This technology offers numerous advantages. Firstly, the adoption of grant-free random access (RA) schemes minimizes the overhead associated with signaling, as it eliminates the need for a request-grant procedure. Consequently, this streamlined approach enhances the overall efficiency of the communication system. The implementation of grant-free random access (RA) enables a large number of users to access a single channel simultaneously, thereby utilizing the advantages of spatial multiplexing gain. As a result, the spectral efficiency of the communication system is further enhanced, making grant-free RA a highly desirable option for future wireless communication systems. Thus, within the realm of machine-to-machine (M2M) communications, applying grant-free RA within a massive multiple-input multiple-output (MIMO) framework offers a compelling approach to achieving high spectral efficiency and fulfilling the increasing demands of next-generation wireless communication systems. This integration not only allows for the efficient utilization of radio resources but also reduces the signaling overhead associated with traditional random access methods. By optimizing resource allocation and increasing the overall system capacity, grant-free RA significantly enhances the spectral efficiency of the communication system, positioning it as a preferred choice for future wireless communication systems.

In the context of M2M communications, where the demand for ad hoc and sporadic connectivity of numerous devices is prevalent, grant-free RA's capability to handle a massive number of connections in a unified channel facilitates efficient and reliable communication among diverse M2M devices. This aspect holds particular significance for the smooth operation of emerging applications such as smart city infrastructure, industrial automation, and healthcare monitoring. To further elevate spectral efficiency, the incorporation of grant-free RA with a massive MIMO framework harnesses the capabilities offered by large antenna arrays and spatial processing. In doing so, it maximizes the benefits derived from spatial multiplexing gain and enhances resilience against fading and interference. In summary, the adoption of grant-free RA within a massive MIMO framework presents a compelling approach to satisfying the requirements of next-generation wireless communication systems, especially in the domain of M2M communications. By facilitating simultaneous access of multiple users to a single channel and leveraging spatial multiplexing gain, grant-free RA enhances overall spectral efficiency, optimizes resource utilization, and supports seamless connectivity among a plethora of M2M devices. This integration with massive MIMO technology brings forth the advantages of spatial processing and further improves spectral efficiency, providing a promising path toward efficient and reliable wireless communication systems in the future.

The previous research [11] introduces an approach based on a single orthogonal preamble (SOP) structure to facilitate user detection and channel estimation in grant-free RA. The paper addresses the challenges of designing efficient random access schemes for massive MIMO systems. It analyzes the impact of various factors, such as the number of antennas, user density, and interference, on the success probability of grant-free random access. The research provides useful insights into the performance and feasibility of grant-free random access in massive MIMO systems. However, due to the constrained length of the preamble, the occurrence of preamble collision becomes a concern, leading to inaccurate user detection and channel estimation. As a solution to mitigate this issue, subsequent studies [12] propose the utilization of predefined preamble-hopping patterns to support massive random access (RA) schemes. The authors investigate the challenges and opportunities of using random access as a mechanism for MTC in massive MIMO systems. The paper discusses the benefits of random pilot and data access in terms of reduced overhead and improved spectral efficiency. It provides practical insights and advanced signal processing techniques for designing efficient MTC systems based on random access in massive MIMO. Nevertheless, this approach presupposes that the base station (BS) possesses advanced knowledge of the preamble-hopping patterns allocated to all RA users, resulting in the introduction of supplementary signaling overhead. This places a burden on the communication system, necessitating a more efficient strategy for the retrieval and management of preamble-hopping patterns. To address this limitation, further investigations are required to develop alternative methods capable of reducing signaling overhead while effectively mitigating preamble collision in grant-free RA scenarios. By leveraging advanced signal processing techniques and optimizing resource allocation strategies, it may be possible to enhance the accuracy of user detection and channel estimation while also minimizing preamble collision occurrences. Therefore, future research should focus on identifying novel approaches that strike a balance between optimizing system performance and reducing signaling overhead in grant-free RA situations.

Drawing inspiration from the research conducted in [11, 12], a recent study [13] introduces a concatenated orthogonal preamble (COP) structure as an innovative solution. This approach involves the division of a single preamble into multiple subpreambles, thereby expanding the available preamble space. The consequence of this augmentation is a significant reduction in the likelihood of preamble collision. In the comprehensive investigation presented in [13], a straightforward methodology for user detection and channel estimation was also outlined. While the aforementioned studies demonstrate the capability to facilitate grant-free random access (RA), they fail to address the vital issue of detecting users in cases where preamble collision occurs. Consequently, this limitation calls for further research and development to overcome the challenges associated with preamble collision and devise efficient methods for user detection.

Furthermore, it should be noted that the user detection and channel estimation techniques proposed in these studies are designed as separate entities. To foster a more seamless and integrated communication system, it is imperative to explore approaches that Harmon combines with user detection and channel estimation methodologies. This integration will enable enhanced performance and reliability in grant-free RA scenarios. Given the current state of research, there exists a valuable opportunity to investigate novel strategies that offer a comprehensive solution for detecting users in the presence of preamble collision. Additionally, the development of an integrated framework for user detection and channel estimation will promote more efficient and reliable communication systems in grant-free RA applications. Thus, research should focus on bridging these gaps and devising innovative approaches that conquer the aforementioned limitations.

In this paper, two highly efficient algorithms are presented for the simultaneous implementation of joint user detection and channel estimation in both SOP and COP scenarios. The specific challenge of our research is how to deal with the impact of pilot collision on joint user detection and channel estimation in the SOP and COP, respectively. To address these challenges, the proposed algorithms are devised to leverage the quasiorthogonal characteristic of massive MIMO [14–16], enabling accurate estimation of user channels while effectively avoiding preamble collisions. By excluding users that encounter preamble collisions, the proposed algorithms achieve enhanced performance compared to previous approaches in terms of user detection and channel estimation. The key in our design is that we derive a criterion to judge whether the estimated value is a user channel or not. Another key is that we derive a criterion to judge whether two estimated channels belong to the same user or not. If yes, we propose to compute an average of multiple estimates to output the final estimated channel in the COP, which can further lower the channel estimation error in comparison to the SOP.

To substantiate the efficacy of the proposed algorithms, a thorough theoretical analysis is undertaken, followed by comprehensive experimental evaluations. Through this analysis, the effectiveness of the algorithms is further demonstrated by examining the success rates of user detection and evaluating the errors associated with channel estimation. The results of the investigation provide compelling evidence supporting the effectiveness and superiority of the algorithms in improving user detection and channel estimation in both SOP and COP scenarios.

The algorithms' exploitation of the quasiorthogonality of massive MIMO technology enables precise estimation of user channels, thereby enhancing the overall performance of grant-free random access. By capitalizing on this characteristic, the algorithms achieve more accurate estimates, leading to improved user detection and channel estimation. In conclusion, this research contributes novel algorithms for joint user detection and channel estimation in SOP and COP scenarios within the context of massive MIMO systems. The combination of theoretical analysis and experimental results verifies the remarkable effectiveness of these algorithms, thereby expanding the knowledge and understanding of grant-free random access techniques in the domain of wireless communications.

Considering the ever-evolving demands of the modern digital era, our findings suggest that users in the practical networks may experience access failures due to preamble collision, especially in the case of a large number of RA users accessing at the same time. Comparatively, our research not only improves the success rate of user detection but also reduces the channel estimation error, which can be helpful for high-performance wireless networks in front of a large number of RA users accessing at the same time. The three contributions of this research can be summarized as follows:

(1) Highly efficient algorithms: The proposed algorithms for joint user detection and channel estimation in SOP and COP scenarios offer high efficiency. By leveraging the quasiorthogonal characteristic of massive MIMO technology, these algorithms achieve accurate user channel estimation and effectively mitigate preamble collisions.

(2) Thorough theoretical analysis and comprehensive experimental evaluations: A thorough theoretical analysis is conducted, providing a deep understanding of the algorithms and their underlying principles. Additionally, comprehensive experimental evaluations are performed to evaluate the practical performance of the algorithms. This combination of analysis and experimentation verifies the effectiveness and superiority of the algorithms.

(3) Enhanced user detection and channel estimation: The proposed algorithms demonstrate improved performance compared to previous approaches in terms of user detection and channel estimation. By excluding users who encounter preamble collisions, these algorithms enhance the accuracy and efficiency of user detection and channel estimation in both SOP and COP scenarios.

The remainder of this paper is organized as follows. Section 2 describes the related work. Section 3 describes the system model. Section 4 illustrates how to achieve joint user detection and channel estimation with the help of grant-free RA. Section 5 provides the simulation results of the proposed algorithms. Section 6 gives the conclusion.

2. Related Work

The subject of joint user detection and channel estimation for grant-free random access (RA) in massive multiple-input multiple-output (MIMO) systems has garnered significant attention within academic circles. Extensive research has been conducted on this topic, yielding invaluable insights into this multifaceted area. Therefore, this section aims to furnish a meticulous and thorough synthesis of the crucial discoveries gleaned from the current body of literature, with a specific focus on the seminal work presented in [17–25]. The existing literature has demonstrated a concerted effort to investigate and tackle the challenges associated with joint user detection and channel estimation in grant-free RA within massive MIMO systems. Numerous studies have grappled with these complexities and have offered diverse methodologies and frameworks to address this intricate problem.

Pioneering research conducted in [17–22] has laid a solid foundation for subsequent works and established key principles for joint user detection and channel estimation. This work [17] provides a comprehensive foundation for understanding the mathematical concepts underlying matrix computations. Although not directly related to MIMO and joint detection, this book serves as a valuable resource for understanding the mathematical principles and algorithms used in signal processing and related fields, which are essential for the development of MIMO systems and joint detection algorithms. In [18], the authors propose an expectation propagation-based algorithm for joint active user detection and channel estimation in massive machine-type communication (MTC) scenarios. The authors in [19] propose a joint user identification and channel estimation scheme for massive machine-type communication (mMTC) scenarios. The authors in [20] propose a transmission control-based approach for joint user identification and channel estimation in massive connectivity scenarios. The authors leverage the transmission control parameters to enhance the joint detection performance. The proposed scheme improves the efficiency and reliability of user identification and channel estimation in massive MIMO systems. The authors in [21] introduce a compressive sensing-based algorithm for adaptive active user detection and channel estimation in massive MIMO systems with massive access. The authors utilize the sparsity property of active users in the MIMO system and adaptively estimate both the active user signals and channels. The authors in [22] propose a joint active user detection and channel estimation scheme for massive machine-type communications (MTC). The authors consider the problem of detecting a large number of users in MTC scenarios and jointly estimating their channels. The proposed scheme exploits the inherent sparsity of the active users and leverages the signal statistics to improve the accuracy of detection and estimation. In [23], the authors proposed a joint active user detection and channel estimation approach in massive access systems by exploiting Reed-Muller sequences. In [24], the authors conducted a performance analysis of joint active user detection and channel estimation for massive connectivity. This study focused on investigating the performance limits and trade-offs associated with joint detection and channel estimation in the context of massive connectivity. The authors provided valuable insights into the fundamental limits and achievable performance gains in such systems. Another notable contribution in the field of joint detection and channel estimation with massive MIMO was made in [25]. Their work introduced a grouping-based approach for joint active user detection and channel estimation. By grouping users with similar channel characteristics, the authors improved the performance and computational efficiency of the detection process in massive MIMO systems.

A notable research direction focuses on enhancing user detection performance in grant-free RA. For instance, the authors in [26] proposed an effective multiuser detection scheme based on the maximization algorithm. This scheme successfully mates interference caused by overlapping transmissions, resulting in significant improvements in user detection rates compared to conventional methods. Similarly, the authors in [27–30] introduced a low-complexity user detection algorithm based on sparse Bayesian learning. By exploiting the sparsity user activity, their algorithm achieves enhanced detection accuracy. Another research area addresses the challenge of channel estimation in free RA. One notable work in the field of joint activity detection and channel estimation in cell-free massive MIMO networks is presented in [27]. Their work proposed an approach to simultaneously detect activities and estimate channels in a cell-free massive MIMO network with massive connectivity. Their study addresses the challenges associated with massive connectivity, providing insights into improving the system's performance. Another interesting contribution in this field is presented in [28]. This work proposed a deep expectation-maximization algorithm for joint MIMO channel estimation and signal detection. Their work explores the integration of deep learning and expectation-maximization algorithms to improve the performance of joint detection and channel estimation. The researchers provided insights into joint iterative time-variant channel estimation and multiuser detection for MIMO-OFDM systems in [29]. They proposed an iterative approach to jointly estimate time-variant channels and detect users in MIMO-OFDM systems. Their study highlights the importance of considering the temporal variation of channels in joint detection and channel estimation algorithms. A double sparsity-based joint active user detection and channel estimation approach is introduced in [30]. This work focuses on massive machine-type communication- (mMTC-) enabled massive MIMO systems and proposes a double sparsity-based algorithm for joint detection and channel estimation. By exploiting the sparsity of the mMTC system, their approach enhances the system's performance. The authors in [31] propose a channel estimation method based on compressed sensing, which takes advantage of the sparsity of user channel responses. This approach demonstrates promising results in terms of channel estimation accuracy, even when limited pilot signaling is available. Expanding on this work, similarly, the authors in [32–35] proposed a noncoherent channel estimation method that leverages the structure of the massive MIMO channel matrix. Their method achieves accurate channel estimates even with a reduced pilot overhead. Furthermore, several studies have explored the joint optimization of user detection and channel estimation grant-free RA [36–42]. For instance, the authors in [42] presented a joint optimization framework based on passing algorithms. By simultaneously estimating the channel state information and detecting the user, their framework effectively considers both channel correlation and interuser interference. Experimental results validate that their approach outperforms conventional methods in terms of detection accuracy and channel estimation quality. In addition to algorithm advancements, researchers have also examined the influence of system parameters on the performance of joint user detection and channel estimation [1, 2, 4, 5, 43]. For instance, the authors in [5] analyzed different pilot designs and their impact on accuracy and user detection performance. Their findings emphasize the significance of optimizing pilot patterns to achieve improved system performance. Notably, in this area, the majority of existing work assumes ideal conditions, such as perfect synchronization and accurate state information at the receiver. However, real-world deployments often present numerous challenges, including imperfect synchronization and inaccurate channel state information. Consequently, there is a pressing need for further research to develop robust algorithms capable of effectively handling such realistic scenarios.

Notably, the study emphasizes the utilization of advanced signal processing techniques to improve the accuracy of user detection and channel estimation. Furthermore, other researchers proposed novel algorithms and schemes that effectively manage the formidable task of joint estimation under the constraints of grant-free scenarios. The works of literature [44–47] demonstrate a prevalent trend toward adopting deep learning approaches to enhance joint user detection and channel estimation in massive MIMO systems. Incorporating powerful deep learning algorithms and neural network architectures has proven to be a promising avenue for surpassing traditional techniques' limitations. These novel approaches can effectively exploit the inherent sparsity and structure in massive MIMO systems, resulting in improved performance in terms of user detection and channel estimation accuracy. It is noteworthy to mention that the literature highlights the significance of considering practical aspects such as low-complexity implementation and computational efficiency when devising joint user detection and channel estimation algorithms. This necessitates striking a balance between achieving performance gains and ensuring practical feasibility for real-world implementations. In [44], the authors introduced a model-driven deep learning algorithm for joint activity detection and channel estimation. Their approach combines deep learning techniques with a model-driven framework to enhance the accuracy and efficiency of joint detection and channel estimation. In this study [45], the authors propose a deep learning-based pilot design method for multiuser distributed massive MIMO systems. The deep learning approach is utilized to optimize the allocation of pilots to user equipment (UE) in a distributed massive MIMO setup. By considering the channel characteristics and pilot assignment constraints, the proposed method achieves improved performance compared to conventional pilot design methods. The study highlights the potential of deep learning in optimizing pilot design for multiuser distributed massive MIMO systems. However, a potential limitation of this research is the lack of extensive evaluation and comparison with traditional pilot design methods. This paper [46] provides an extensive review of deep learning-enhanced nonorthogonal multiple access (NOMA) transceiver designs for massive machine-type communication (MTC). It addresses the challenges and presents the state-of-the-art techniques in NOMA transceiver design for massive MTC. The review discusses the potential of deep learning to optimize NOMA transceiver design, including joint detection algorithms, to deal with the unique requirements and characteristics of massive MTC scenarios. The paper offers insights into future directions for deep learning-assisted NOMA transceiver design for MTC. While the study provides valuable insights into the application of deep learning in NOMA systems, it primarily focuses on the challenges and future directions without providing a comprehensive overview of the state-of-the-art techniques and their performance evaluation. This research [47] proposes an AI-driven blind signature classification approach for IoT connectivity using deep learning. Blind signatures provide privacy and security for IoT applications, but blind signature classification poses challenges due to the heterogeneity of IoT devices and protocols. The deep learning approach presented in this study allows accurate classification of blind signatures by automatically learning discriminative features. The results demonstrate the effectiveness of deep learning in enhancing the security and connectivity of IoT devices in the context of blind signature classification. However, the paper lacks a thorough evaluation of the proposed method's performance, particularly with respect to classification accuracy, computational efficiency, and scalability.

To summarize, the existing research on joint user detection and channel estimation for grant-free random access (RA) in multiple-input multiple-output (MIMO) systems has demonstrated remarkable progress in enhancing the performance of these critical tasks. Numerous algorithms and optimization frameworks have been proposed, aiming to improve user detection rates and enhance channel estimation accuracy. Furthermore, extensive investigations have been conducted to understand the impact of system parameters on these processes. Nonetheless, it is to acknowledge that addressing the practical challenges associated with real-world deployments and developing robust algorithms capable of handling imperfect synchronization and inaccurate channel state information remain primary for future research. These challenges demand innovative approaches and the development of advanced algorithms to effectively tackle the complexities of real-world scenarios. By addressing these limitations, researchers can significantly contribute to the advancement of joint user detection and channel estimation techniques, ultimately facilitating the seamless operation of grant-free RA in MIMO systems.

3. System Model

Figure 1 presents an illustration of a single-cell massive multiple-input multiple-output (MIMO) system, showcasing its key components and their interaction. The system

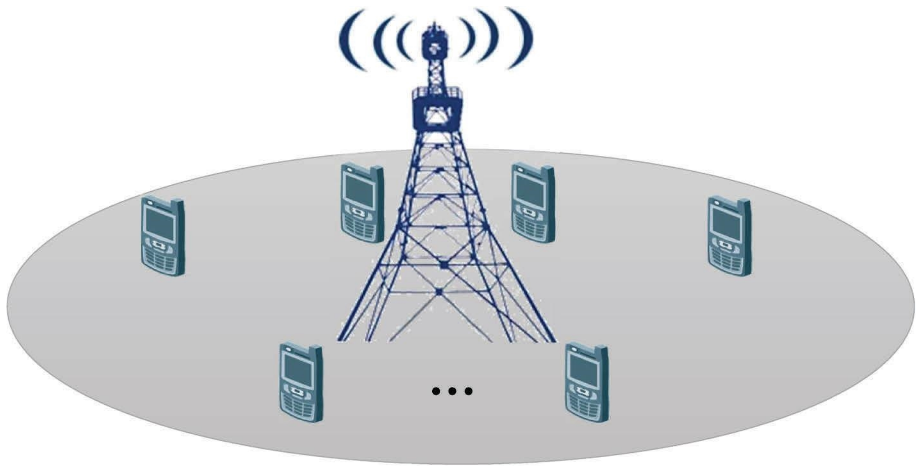

Figure 1: The system of a single-cell massive MIMO.

revolves around the base station (BS), which serves as the communication provider, catering to a multitude of users uniformly distributed within the cell. This arrangement forms the foundation of our investigation, focusing on the scenario where N single-antenna users concurrently attempt to access the BS while the BS itself is equipped with M antennas. By adopting this configuration, the system is able to facilitate improved transmission and reception processes, thereby enhancing overall performance.

By visualizing a single-cell massive MIMO system in Figure 1, we emphasize the pivotal role played by the BS as the central communication provider, ensuring seamless connectivity for a diverse range of users uniformly dispersed within the cell. It is important to note that the notion of a single-cell system encompasses the dynamics and interactions within a confined spatial region, where the BS operates as the primary hub for communication processes, and users are evenly distributed. With N single-antenna users simultaneously accessing the BS and the BS equipped with M antennas, we harness the potential for heightened performance and efficiency within this system.

To facilitate comprehension and provide a comprehensive overview of the notations employed in this study, we summarize them in Table 1.

We consider a single-cell massive MIMO system, in which a BS is equipped with M antennas, and a large number of users are uniformly distributed in this cell. Without loss of generality, we assume N single-antenna users are attempting to access the BS simultaneously. In the diagram of grant-free RA, users directly transmit their RA preambles along with data blocks. Up to now, two preamble structures of grant-free RA were proposed, which are SOP and COP as depicted in Figure 2. In SOP, the length of an RA preamble is supposed to be U. Each preamble is selected from a public set $\mathbf{P}$, which satisfies $\mathbf{P}\mathbf{P}^H = \mathbf{I}_U$. In COP, an RA preamble is composed of $L(L \geq 2)$ subpreambles with the length of $V = U/L$. Each subpreamble is chosen from a public set $\mathbf{Q}$, satisfying $\mathbf{Q}\mathbf{Q}^H = \mathbf{I}_V$. It can be observed that the number of available preambles in COP increases with L and can up to V^L. These two preamble structures have their advantages and disadvantages, respectively [48].

The principal advantage of COP over SOP lies in its substantial ability to reduce the probability of preamble collision, primarily achieved through the augmentation of the preamble space. By expanding the available range of preambles, COP minimizes the likelihood of multiple nodes transmitting identical preambles simultaneously. This enhancement in collision avoidance significantly improves the efficiency and reliability of data transmission in wireless communication systems.

However, it is important to note that the adoption of nonorthogonal preambles in COP comes at the expense of its channel estimation performance. The nonorthogonality introduces interference and correlation among preambles, leading to a degradation in the accuracy of channel estimation. Consequently, this may adversely impact the overall quality of signal reception, potentially affecting the system's ability to effectively decode transmitted information.

It is crucial to acknowledge this trade-off between collision avoidance capability and channel estimation performance when considering the implementation of COP in practical scenarios. While the expanded preamble space of COP contributes to a substantial reduction in the occurrences of preamble collision, the compromised channel estimation accuracy may introduce potential challenges in maintaining adequate communication reliability. Thus, careful consideration must be given to system requirements and constraints, ensuring that the benefits and drawbacks of COP integration are thoroughly evaluated and aligned with the desired objectives of the wireless communication system.

The channel response from N users to the BS is modeled by $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_N] \in \mathbb{C}^{M\times N}$, where $\mathbf{h}_i \in \mathbb{C}^{M\times 1}$ is the channel response from the i-th user to the BS. In addition, the propagation channel $\mathbf{H}$ is assumed to be constant in an RA slot. We also assume that the perfect power control is adopted to keep the transmit power of all RA users equal to 1 [49]. Then, the received preambles at the BS can be represented as follows:

Table 1: Notations.

Notation	Description
$\mathbf{a}$	An arbitrary vector $\mathbf{a}$
$\mathbf{A}$	An arbitrary matrix $\mathbf{A}$
$\mathbf{I}_M$	An $M \times M$ identity matrix
$\mathbf{A}^T$	The transpose of a matrix $\mathbf{A}$
$\mathbf{A}^H$	The conjugate transpose of a matrix $\mathbf{A}$
$\|\mathbf{a}\|$	The Euclidean norm of a vector $\mathbf{a}$
$\mathbb{C}^{M\times N}$	The space of all $M \times N$ complex matrices
$CN(0, \Sigma)$	A normal complex Gaussian distribution with zero mean and Σ variance

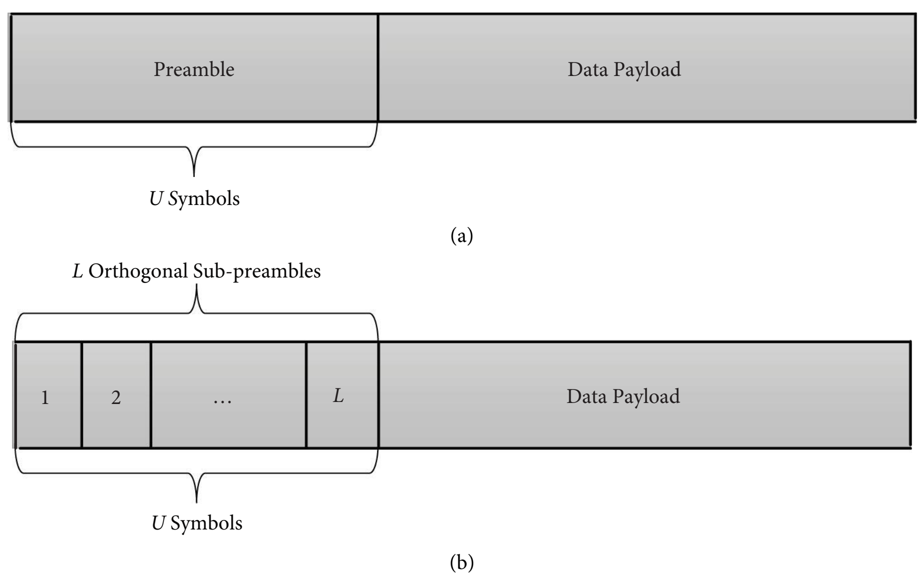

Figure 2: Two preamble structures of grant-free RA: (a) SOP; (b) COP.

$$\mathbf{Y} = \mathbf{HX} + \mathbf{Z}, \tag{1}$$

where $\mathbf{X} = [\mathbf{p}_1^T, \mathbf{p}_2^T, \ldots, \mathbf{p}_N^T]^T \in \mathbb{C}^{N\times U}$ is the transmit preambles of N users and $\mathbf{Z} \in \mathbb{C}^{M\times U}$ is the noise matrix, whose elements are distributed as $\mathscr{CN}(0, \sigma^2)$.

Upon reception of the preambles by the base station (BS), the subsequent steps involve the intricate processes of user detection and channel estimation. Within the scope of this research, we introduce two distinct algorithms, each tailored to facilitate the joint implementation of user detection and channel estimation in both SOP and COP frameworks.

Acknowledging the constraints imposed by the finite preamble length, our design methodology takes into account the recurring issue of preamble collision. This consideration becomes particularly relevant as it pertains to the interrogation of preambles that may overlap and coincide with the received signals. Inherent to our proposed algorithms is their ability to examine and analyze these preambles, generating outputs that solely comprise the estimated channels of users devoid of any preamble collision.

By effectively addressing the challenges posed by preamble collision and the limited length of preambles, our algorithms provide a comprehensive solution encompassing the joint detection and estimation of user channels. These algorithms hold the potential to significantly enhance the overall performance and reliability of wireless communication systems, showcasing their efficacy across both SOP and COP frameworks. As demonstrated in subsequent sections of this paper, our algorithms exhibit superior performance in terms of accurate user detection and precise estimation of channel characteristics, thereby allowing for improved signal reception and data decoding in practical scenarios.

4. Joint User Detection and Channel Estimation of Grant-Free RA

In this section, we propose to implement joint user detection and channel estimation of grant-free RA with SOP and COP, respectively. Then, we analyze the computational complexity of the proposed algorithms.

4.1. Joint User Detection and Channel Estimation in SOP. We start from the simple case that all RA users select the different preambles, i.e., no preamble collision occurs in the grant-free RA. For ease of description, let $\mathbf{P}_s$ and $\mathbf{P}_n$ denote the sets of the selected and nonselected preambles. Due to the orthogonality of the preambles in the $\mathbf{P}$, we can have

$$\mathbf{Y}\mathbf{p}_i^H = \begin{cases} \mathbf{h}_k + \mathbf{Z}\mathbf{p}_i^H, & \mathbf{p}_i \in \mathbf{P}_s, \\ \mathbf{Z}\mathbf{p}_i^H, & \mathbf{p}_i \in \mathbf{P}_n, \end{cases} \tag{2}$$

where k is the index of the user selecting the i-th preamble, and $1 \leq k \leq N$. Since $\mathbf{Z}$ is independent from $\mathbf{p}_i$, the elements in $\mathbf{Z}\mathbf{p}_i^H$ are distributed as $\mathscr{CN}(0, \sigma^2)$. Thanks to the power control, the background noise $\mathbf{Z}\mathbf{p}_i^H$ in (2) is relatively small. Hence, $\mathbf{Y}\mathbf{p}_i^H$ is approximately equal to $\mathbf{h}_k$ in the case of $\mathbf{p}_i \in \mathbf{P}_s$, which means that we can utilize (2) to estimate user channels. In addition, due to the quasiorthogonality of massive MIMO [50], we can have

$$\left\|\mathbf{Y}\mathbf{p}_i^H\right\|^2 \approx \left\|\mathbf{h}_k\right\|^2 = \mathbf{h}_k^H\mathbf{h}_k \approx M, \tag{3}$$

where $\mathbf{p}_i \in \mathbf{P}_s$. Thus, the BS can detect whether a user is trying to access by comparing the square of Euclidean norm on its estimated channel with a predefined threshold αM, where $0 < \alpha < 1$. Note that α is an adjustable coefficient balancing the miss-detection and false-detection. After traversing all preambles in the $\mathbf{P}$, the BS can utilize (2) to estimate the channels of all RA users.

Next, we consider joint user detection and channel estimation in the case of preamble collision. Let $\mathbf{U}_c$ denote the indices of users selecting the same preamble $\mathbf{p}_c$, and N_c denote the length of $\mathbf{U}_c$, where $1 \leq c \leq U$. Similar to (2), we can have

$$\mathbf{Y}\mathbf{p}_c^H = \sum_{j=1}^{N_c} \mathbf{h}_{i_j} + \mathbf{Z}\mathbf{p}_c^H \approx \sum_{j=1}^{N_c} \mathbf{h}_{i_j}, \tag{4}$$

where $i_j \in \mathbf{U}_c$. It is hard for the BS to reconstruct the user channels $\mathbf{h}_{i_1}, \mathbf{h}_{i_2}, \ldots$, and $\mathbf{h}_{i_{N_c}}$ from the mixed value $\sum_{j=1}^{N_c}\mathbf{h}_{i_j}$. As a result, the BS can hardly utilize (4) to estimate the channels of users with preamble collision. The unsolvability of user channels would lead to an incorrect beamforming pattern [51]. Thus, the BS should have the ability to identify all the users with preamble collision. To this end, we propose a simple algorithm as follows. Considering the propagation channel $\mathbf{H}$ is quasiorthogonal in massive MIMO systems [15], i.e., $\mathbf{H}^H\mathbf{H} \approx M\mathbf{I}_N$, we can have

$$\begin{aligned} \left\|\sum_{j=1}^{N_c} \mathbf{h}_{i_j}\right\|^2 &= \left(\sum_{j=1}^{N_c} \mathbf{h}_{i_j}\right)^H \sum_{j=1}^{N_c} \mathbf{h}_{i_j}, \\ &= \sum_{j=1}^{N_c} \mathbf{h}_{i_j}^H\mathbf{h}_{i_j} + \sum_{j=1}^{N_c}\left(\sum_{k=1,k\neq j}^{N_c} \mathbf{h}_{i_j}^H\mathbf{h}_{i_k}\right), \\ &\approx N_c M. \end{aligned} \tag{5}$$

Combining (4) with (5), we can directly have

$$\left\|\mathbf{Y}\mathbf{p}_c^H\right\|^2 \approx N_c M. \tag{6}$$

Comparing (3) with (6), it can be observed that there is a clear gap between M and $N_c M$, where $N_c \geq 2$. Thereafter, the BS can detect whether the estimated channel is the mixture of multiple user channels by comparing the square of its Euclidean norm with a predefined threshold βM, where β is in the range from 1 to 2 due to $N_c \geq 2$.

Based on the above discussion, the BS can find out the estimated channels of all RA users without preamble collision, which is summarized in Algorithm 1.

4.2. Joint User Detection and Channel Estimation in COP. Different from SOP, multiple subpreambles in each preamble need to be taken into consideration in COP. For the j-th subpreamble phase, the received signal at the BS can be represented as

$$\mathbf{Y}_j = \mathbf{H}\mathbf{X}_j + \mathbf{Z}_j, \tag{7}$$

where $\mathbf{X}_j = [\mathbf{q}_{j_1}^T, \mathbf{q}_{j_2}^T, \ldots, \mathbf{q}_{j_N}^T]^T \in \mathbb{C}^{N\times V}$ is the set of the j-th subpreamble of all RA users, $\mathbf{Z}_j \in \mathbb{C}^{M\times V}$ is the noise matrix, and $1 \leq j \leq L$. With the input of $\mathbf{Y}_j$, $\mathbf{Q}$, and V, the BS can utilize Algorithm 1 to generate the estimated channels of the users without preamble collision in the j-th subpreamble phase, denoted as $\widehat{\mathbf{H}}_j$. After traversing all L subpreambles in the COP, the BS can obtain the estimated channels of all RA users without preamble collision through computing $\widehat{\mathbf{H}} = \widehat{\mathbf{H}}_1 \cup \widehat{\mathbf{H}}_2 \cup \cdots \cup \widehat{\mathbf{H}}_L$, where $\cup$ denotes the union operator. However, the estimated values of the same channel are likely to be unequal in the different subpreamble phases, which is caused by the randomness of background noise in (7). Then, $\widehat{\mathbf{H}}$ might contain the repeatedly estimated channels of the same user, which would result in the incorrectness of beamforming pattern [51]. Thereafter, the BS has to eliminate the repeatedly estimated channels in $\widehat{\mathbf{H}}$, which can be implemented as follows.

Let $\widehat{\mathbf{h}}_i$ and $\widehat{\mathbf{h}}_j$ denote the i-th and j-th estimated channels in $\widehat{\mathbf{H}}$. If these two channels are of the same user, the difference between them is only the background noise, and thus $\|\widehat{\mathbf{h}}_i - \widehat{\mathbf{h}}_j\|^2$ is relatively small. Otherwise, the difference between them contains both the actual channels and the background noise and then $\|\widehat{\mathbf{h}}_i - \widehat{\mathbf{h}}_j\|^2$ becomes

$$\begin{aligned} \left\|\widehat{\mathbf{h}}_i - \widehat{\mathbf{h}}_j\right\|^2 &= \left(\widehat{\mathbf{h}}_i - \widehat{\mathbf{h}}_j\right)^H\left(\widehat{\mathbf{h}}_i - \widehat{\mathbf{h}}_j\right), \\ &\approx \mathbf{h}_i^H\mathbf{h}_i - \mathbf{h}_i^H\mathbf{h}_j - \mathbf{h}_j^H\mathbf{h}_i + \mathbf{h}_j^H\mathbf{h}_{j,} \\ &\approx 2M. \end{aligned} \tag{8}$$

As a result of the prior processes, the base station (BS) is equipped with the capability to discern the similarity or dissimilarity between two estimated channels, effectively determining whether they originate from the same user or not. This determination is accomplished by comparing the square of the Euclidean norm with the difference between the estimated channels with a predefined threshold, denoted as γM, where $0 < \gamma < 2$. Through this comparative analysis, the BS can effectively discern whether the estimated channels belong to distinct users or a single user.

Subsequently, with the identification of repeatedly estimated channels, the BS proceeds to calculate their aggregate value, represented as the average. This average value serves as the final estimation for the channel characteristics associated with a specific user. Thus, by integrating multiple estimations, the BS accomplishes the task of joint user detection and channel estimation within the COP framework.

Require: The received signal $\mathbf{Y}$, the preamble set $\mathbf{P}$ and its length U.
Ensure: $\widehat{\mathbf{H}}$.
(1) **for** $i = 1$: U **do**
(2) The BS calculates the estimated channel as $\mathbf{Y}\mathbf{p}_i^H$.
(3) **if** $\alpha M < \|\mathbf{Y}\mathbf{p}_i^H\|^2 < \beta M$ **then**
(4) The BS accepts $\mathbf{Y}\mathbf{p}_i^H$ as the estimated channel of a certain RA user, and appends it into $\widehat{\mathbf{H}}$.
(5) **end if**
(6) **end for**

Algorithm 1: Joint detection and estimation in SOP.

It is worth noting that users in the COP have lower channel estimation compared to users in the SOP because COP's final estimated channel is an average of multiple estimates. The reason is that background noise might be mistakenly judged as user pilot signals during user detection, which will further result in incorrect channel estimation in the SOP. But in the COP, even though some falsely detected subpreamble signals of a user are actually background noise, the channel of this user can still be estimated using other correctly detected subpreamble signals of this user. In such a way, the average of multiple channel estimates in the COP can effectively mitigate the impact of mistaking background noise for user preamble signals.

To summarize the aforementioned procedures, all steps involved in achieving the joint detection and estimation of users in the COP framework are consolidated and concisely outlined in Algorithm 2. This algorithmic representation further reinforces the systematic and reproducible nature of the proposed methodology. By following this algorithmic framework, the BS can efficiently and reliably accomplish the dual objectives of user detection and channel estimation, thereby enhancing the overall efficacy and performance of wireless communication systems within the COP framework.

4.3. Performance Analysis. We conduct the performance analysis from the perspectives of the success rate of user detection and channel estimation error, respectively. Suppose that there are K instances of multiple users selecting the same subpreamble, and $N_{c,i}$ users selecting the same subpreamble for each instance $i\,(1 \le i \le K)$. For ease of description, we introduce P_i denoting the probability of differentiating the i-th multiuser mixed subpreamble from a single-user subpreamble, and P_z denoting the probability of differentiating a single-user subpreamble from the background noise. The detailed analysis is as follows.

4.3.1. Success Rate of User Detection. The probability of successful user detection can be computed as

$$\mathcal{P}_d \ge 1 - \left(1 - \prod_{i=1}^{K} \mathcal{P}_i \mathcal{P}_z^{\,N - \sum_{i=1}^{K} N_{c,i}}\right)^L, \qquad (9)$$

where L is the number of subpreambles in a pilot and N is the number of users. According to (9), it can be observed that (1) P_d is proportional to P_z, which means that P_d can be increased by using the power control to reduce the disturbance of background noise; (2) P_d increases as L increases, which is because that even though a user cannot be identified using some subpreamble signals are falsely detected, this user can still be identified using other correctly detected subpreamble signals; (3) P_d increases with the growth of $N_{c,i}\,(1 \le i \le K)$, which is mainly caused by the fact that the more users choose the same preamble, the less likely the mixed signal of multiple users retrieved through this preamble is to be misinterpreted as a single-user signal.

4.3.2. Channel Estimation Error. The probability of falsely estimating the channel for a specific user can be computed as

$$\mathcal{P}_c \le \left(\prod_{i=1}^{K} \left(1 - \mathcal{P}_i\right) \left(1 - \mathcal{P}_z\right)^{N - \sum_{i=1}^{K} N_{c,i}}\right)^L, \qquad (10)$$

where L is the number of subpreambles in a pilot and N is the number of users. According to (10), it can be observed that (1) P_c is inversely proportional to P_z, which implies that P_c can be decreased by using the power control to lower the influence of background noise; (2) P_c decreases as L increases, which is because that more subpreambles in a slot will bring the BS more chances to obtain the correctly-estimated user channels; (3) P_c decreases with the growth of $N_{c,i}\,(1 \le i \le K)$, which is due to the fact that the more users select the same preamble, the smaller the likelihood that the mixed signal of multiple users recovered through this preamble is to be used for estimating user channel.

4.3.3. Further Discussion. According to the quasiorthogonal characteristic of massive MIMO, one can see that as the number of base station antennas increases, interuser interference becomes less and less. After that, the detection of different users from the received pilot signal will become increasingly accurate, and likewise, the estimation of the data channels will also become increasingly precise.

Require: The received signal $\mathbf{Y}$, the number of subpreambles L, the preamble set $\mathbf{Q}$ and its length V.
Ensure: $\widehat{\mathbf{H}}$.
The BS initializes $\widehat{\mathbf{H}}$ to an empty set.
for $i = 1: L$ **do**
  The BS runs Algorithm 1 to generate $\widehat{\mathbf{H}}_i$ with the input of $\mathbf{Y}_i$, $\mathbf{Q}$ and V.
  The BS counts the numbers of elements in $\widehat{\mathbf{H}}$ and $\widehat{\mathbf{H}}_i$, denoted as μ and ν.
  The BS computes $\widehat{\mathbf{H}} = \widehat{\mathbf{H}} \cup \widehat{\mathbf{H}}_i$.
  for $i = 1: \mu$ **do**
    for $j = +1: \mu + \nu$ **do**
      if $\|\widehat{\mathbf{h}}_i - \widehat{\mathbf{h}}_j\|^2 \leq \gamma M$ **then**
        The BS appends the average of $\widehat{\mathbf{h}}_i$ and $\widehat{\mathbf{h}}_j$ to $\widehat{\mathbf{H}}$.
        The BS eliminates the original $\widehat{\mathbf{h}}_i$ and $\widehat{\mathbf{h}}_j$ from $\widehat{\mathbf{H}}$.
      end if
    end for
  end for
end for

ALGORITHM 2: Joint detection and estimation in COP.

4.4. Complexity Analysis. According to [17], the complexity of the proposed algorithms in SOP and COP is illustrated as follows.

In Algorithm 1, the computation on $\mathbf{Y}\mathbf{p}_i^H$ and $\|\mathbf{Y}\mathbf{p}_i^H\|^2$ has to be repeated U times. Since the complexity of computing $\mathbf{Y}\mathbf{p}_i^H$ and its Euclidean norm is $O(MU)$ and $O(M)$, the total complexity of the proposed algorithm in SOP is $O(MU^2)$.

In Algorithm 2, the complexity of generating $\widehat{\mathbf{H}}_i$ is $O(MV^2)$. Since both μ and ν are no more than the total number of RA users N, the complexity of aggregating $\widehat{\mathbf{H}}$ and $\widehat{\mathbf{H}}_i$ is $O(MN^2)$. Considering that $N \leq V$ and $U = VL$, the total complexity of the proposed algorithm in COP can be represented as $O(\mathrm{MUV})$. Based on the above discussion, we can observe that both of these two algorithms are highly efficient. In addition, the execution of these two algorithms is a burden only on the powerful BS not on the resource-limited RA users.

5. Simulation Results

In this section, we provide extensive experimental results to validate the effectiveness of the proposed algorithms. In our experiments, the signal-to-noise ratio (SNR) is 10 dB, and the propagation channels are independent Rayleigh fading, whose entries are distributed as $\mathscr{CN}(0,1)$. The total number of RA users is $N = 40$. The number of preambles selected by multiple users is set to 5. The detecting parameters α, β, and γ are set as 0.5, 1.5, and 1, respectively. Two representative indicators are adopted to evaluate the performance of the proposed algorithms, i.e., the success rate of user detection and the channel estimation error. The former indicates the probability that all users without preamble collision are successfully detected, which is denoted as $\mathscr{P}_s$. The latter is defined as $\mathscr{C}_e = \underset{i}{\mathrm{mean}}(\|\widehat{\mathbf{h}}_i - \mathbf{h}_i\|^2/\|\mathbf{h}_i\|^2)$, where $\widehat{\mathbf{h}}_i$ is the i-th estimated channel in $\widehat{\mathbf{H}}$ and $\mathbf{h}_i$ is the actual channel corresponding to $\widehat{\mathbf{h}}_i$. In addition, each experimental result is the average of 10^5 Monte Carlos trials.

In Figure 3, we present the success rates of user detection as functions of the number of BS antennas, denoted as M. Several key observations can be made from the results:

(i) The success rate, denoted as $\mathscr{P}_s$, gradually converges to 1 as the number of BS antennas increases. This can be attributed to the fact that as the number of antennas at the BS grows, the user channels tend to approach quasiorthogonality. As a result, the level of interuser interference is significantly reduced.

(ii) Users in the COP scenario exhibit higher success rates ($\mathscr{P}_s$) compared to users in the SOP scenario. The disparity arises from the differing number of access subpreambles available in each scenario. COP facilitates multiple access subpreambles, whereas SOP only provides a single access preamble. Thanks to the augmented preamble space, the probability of preamble collision in the COP is lower than that in the SOP. Recalling that preamble collision makes it impossible to distinguish channels from different users, which thus leads to user detection failure, COP has a superiority over SOP in terms of $\mathscr{P}_s$. Note that there are some potential methods to improve $\mathscr{P}_s$ in the SOP considering its limitation of having only a single access preamble, such as enlarging the size of the candidate pilot set and reducing the number of users accessing simultaneously, etc.

(iii) $\mathscr{P}_s$ in COP exhibit an increasing trend with the number of subpreambles, denoted as L. This can be attributed to the fact that a larger number of subpreambles in COP enables users to have more access opportunities, thereby enhancing the overall success rate of user detection.

(iv) $\mathscr{P}_s$ displays an increasing trend with the number of users selecting the same preamble, denoted as N_c. For users experiencing preamble collision, the square of the Euclidean norm on their estimated channel can be approximated to $N_c M$, as indicated

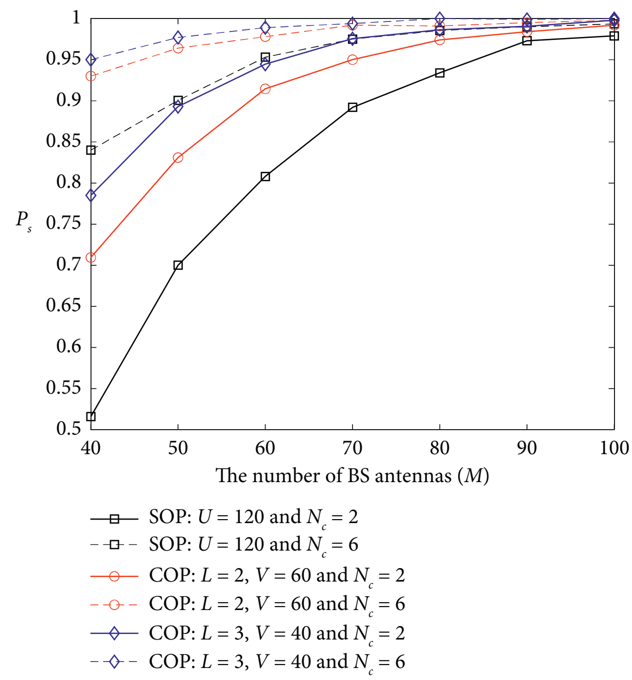

Figure 3: The success rates of user detection in SOP and COP.

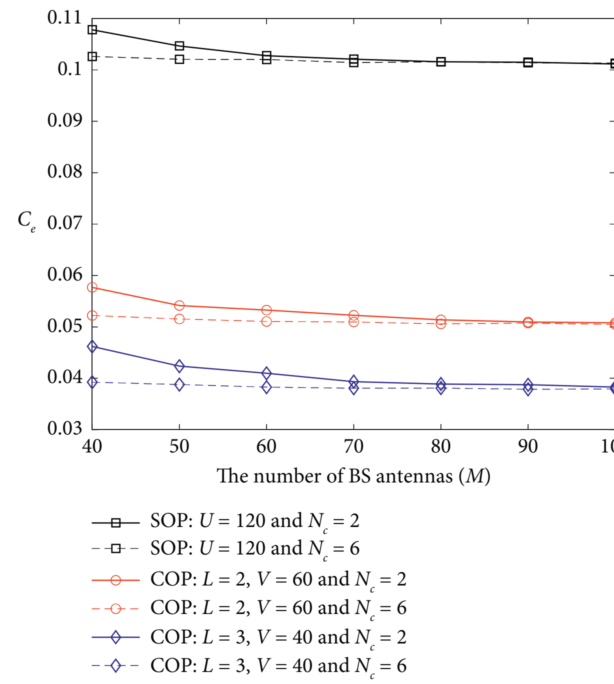

Figure 4: The channel estimation errors in SOP and COP.

by (6). Taking into consideration the upper detection threshold, βM, a higher value of N_c reduces the probability of the BS accepting the mixed channel of multiple users as the estimated channel of a specific user.

In summary, the findings in Figure 3 reveal valuable insights into the success rates of user detection in grant-free RA with massive MIMO systems. Increasing the number of BS antennas leads to improved success rates due to the quasiorthogonality achieved in the user channels. Moreover, the choice between COP and SOP, the number of subpreambles, and the number of users selecting the same preamble significantly impact the overall success rates of user detection. These observations contribute to a deeper understanding of the performance characteristics of massive MIMO systems in the context of grant-free RA.

In Figure 4, we also present the channel estimation errors as functions of the number of BS antennas, denoted as M. Several key observations can be made from the results:

(i) The channel estimation error, represented by $\mathscr{C}_e$, maintains a consistently small value throughout. This can be attributed to the fact that the difference between the estimated and actual channels is primarily determined by the background noise when the interuser interference has been effectively suppressed through accurate user detection.

(ii) Users in the COP scenario exhibit lower channel estimation errors ($\mathscr{C}_e$) compared to users in the SOP scenario. The reduced error in COP is a result of the final estimated channel being an average of multiple estimated values. This averaging process effectively reduces the power of the channel noise.

(iii) $\mathscr{C}_e$ in COP demonstrates a decreasing trend with the number of subpreambles, denoted as L. This can be explained by the inverse relationship between the number of subpreambles and the effect of background noise and interuser interference on channel estimation. As L increases, the impact of background noise and interuser interference on channel estimation diminishes accordingly.

(iv) $\mathscr{C}_e$ exhibits a decreasing trend with both N_c and M. This can be attributed to the fact that when the values of N_c and M are small, channels with lower noise levels become more challenging to detect compared to those with higher noise levels. This difficulty arises due to the lower detection threshold αM.

To summarize, the observations presented in Figure 4 shed light on the characteristics of channel estimation errors in grant-free RA with massive MIMO systems. The consistently small values of $\mathscr{C}_e$ indicate the efficacy of the estimation process, which primarily relies on minimizing the impact of background noise and interuser interference. Furthermore, the choice between COP and SOP, the number of subpreambles, and the number of users selecting the same preamble all influence channel estimation errors. These findings contribute to a comprehensive understanding of the channel estimation performance in the context of grant-free RA with massive MIMO systems.

6. Conclusion

This paper provides a comprehensive investigation into joint user detection and channel estimation techniques for grant-free random access (RA) in the context of massive multiple-input multiple-output (MIMO) systems. To exploit the inherent quasiorthogonal characteristic of massive MIMO, we have derived both lower and upper user detection thresholds. These thresholds serve as important reference points to assess the reliability of user detection. By considering the statistical properties of the received signals, we can determine the optimal detection thresholds that strike a balance between false alarm and miss-detection probabilities.

In addition, we propose two efficient algorithms to facilitate joint user detection and channel estimation in both SOP and COP scenarios. These algorithms take advantage of the overlapping nature of RA transmissions to improve the accuracy and efficiency of detection and estimation processes. To evaluate the performance of our proposed algorithms, we adopted a meticulous approach that combines rigorous theoretical analysis with comprehensive experimental evaluations. Through extensive simulations and measurements, we demonstrate the efficacy of our algorithms in achieving high success rates of user detection and minimizing channel estimation errors within massive MIMO systems. One noteworthy aspect of our algorithms is their robustness in scenarios where a substantial number of RA users experience preamble collision. Preamble collision, which arises when multiple users select the same preamble index during the RA process, can significantly degrade the system's performance. However, our algorithms effectively mitigate this issue by leveraging the characteristics of the received signals, achieving remarkable performance even under challenging conditions. Overall, our research contributes to the advancement of joint user detection and channel estimation techniques in grant-free RA with massive MIMO systems. The proposed algorithms offer enhanced performance, especially in scenarios with preamble collision, and pave the way for improved reliability and efficiency in future wireless communication systems.

Our research aims to make significant strides in the field of joint user detection and channel estimation in grant-free RA with massive MIMO systems. These systems pose unique challenges, and our study addresses these challenges head-on. By harnessing the distinctive characteristics of MIMO technology, we have developed algorithms that effectively enable efficient and reliable user detection while simultaneously mitigating the negative impact of channel estimation errors. The outcomes of our research hold great importance in ensuring the seamless operation of massive MIMO systems, which in turn supports their potential deployment in high-capacity wireless networks. These networks are becoming increasingly vital in meeting the escalating demands for enhanced data rates, improved spectral efficiency, and enhanced wireless connectivity.

Moving forward, there are several promising avenues for future research in this area. One potential direction is to further optimize the performance of our algorithms by considering additional factors. For instance, incorporating interference mitigation techniques could enhance the robustness of our algorithms under various interference scenarios. Additionally, exploring resource allocation strategies that are tailored to grant-free RA in massive MIMO systems could potentially yield further performance improvements. Scalability is another aspect that warrants attention. Investigating how our techniques scale with the number of users and antennas in a massive MIMO system would be valuable, as it would shed light on the feasibility of deploying these techniques in practical scenarios. Moreover, examining the applicability of our techniques in real-world settings is a crucial stepping stone toward their adoption. Validating the performance of our algorithms in field trials or experimental setups that mirror practical conditions would provide valuable insights into their effectiveness and potential limitations. Furthermore, it is essential to keep a pulse on the evolving landscape of communication standards and protocols. Exploring the compatibility of our techniques with emerging standards and protocols, such as those for 5G and beyond, would contribute to the continual development of grant-free RA techniques in massive MIMO systems.

In conclusion, our research not only enhances the understanding of joint user detection and channel estimation in grant-free RA with massive MIMO systems but also paves the way for practical implementation. By addressing the challenges in this domain, we bring closer the realization of high-performance wireless networks that can support the growing demands of the modern digital era.

Data Availability

No underlying data were collected or produced in this study. Our experiment is conducted in a simulation mode, and the settings of the data used to support the findings of this study are available from the corresponding author upon request. The main parameters are set as follows: In our experiments, the signal-to-noise ratio (SNR) is 10 dB, and the propagation channels are independent Rayleigh fading, whose entries are distributed as CN (0, 1). The total number of RA users is $N = 40$. The number of preambles selected by multiple users is set to 5. The detecting parameters α, β, and γ are set as 0.5, 1.5, and 1, respectively.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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