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RIePDMA and BP-IDD-IC detection

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Abstract

Pattern division multiple access (PDMA) is a non-orthogonal multiple access (NOMA) scheme which is proposed to meet the demand of massive connection in the future 5G communications. In this paper, we build a random interleaver (RI) enhanced PDMA (RIePDMA) system by bringing the random interleaver into a PDMA system to further improve the overload of PDMA. Furthermore, we analyze several integrated detection and decoding algorithms with interference cancellation (IC) and propose the iterative detection and decoding based on belief propagation and interference cancellation (BP-IDD-IC). Simulation results show that the proposed RIePDMA system can achieve better block error rate (BLER) performance without increasing the complexity of the receiver. Compared with several other integrated detection and decoding algorithms, the proposed BP-IDD-IC algorithm can get better BLER performance with an acceptable complexity.

Keywords: Pattern division multiple access, Random interleaver, Belief propagation, Iterative detection and decoding

1 Introduction

Multiple access (MA) technology is important for wireless communication systems. It creates a connection between users and networks and allows multiple users to access and share resources simultaneously [1]. From 1G to 4G, MA techniques vary accompanying the evolution of wireless communication systems, including frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA). In orthogonal multiple access (OMA) schemes, the radio resources allocated for different users are orthogonal either in time, frequency, or code domain to avoid or alleviate inter-user interference. However, orthogonal resource allocation mechanisms limit the maximum number of supported users with the finite resources.

It is expected that the explosion of data traffic will happen in 5G era. Besides, 5G needs to support massive connectivity of users, due to the emergence of new traffic types and data services [2]. To satisfy these demands, some potential candidates have been proposed to address challenges of 5G, such as ultra dense network (UDN), massive multiple input multiple output (MIMO), device to device (D2D), NOMA, and so on. The major application scenarios for NOMA schemes in 5G systems included enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine type communication (mMTC) [3].

This paper focuses on the NOMA technology, which can improve the spectrum efficiency and accommodate massive connectivity. Different from the conventional OMA, NOMA allows multiple users to share time and frequency resources in the same spatial layer via non-orthogonal resource allocation [4]. Recently, more than 10 NOMA schemes are proposed for new radio (NR) in the contribution of the 3rd generation partnership project (3GPP) RAN1 #85 meeting [5], such as power domain non-orthogonal multiple access (PD-NOMA), sparse code multiple access (SCMA), multi-user shared access (MUSA), PDMA, and so on. In PD-NOMA, users' signals are superimposed in power domain and transmitted in the same time/frequency resources [6]. Advanced receivers (e.g., successive interference cancellation (SIC) receivers) are used to separate users' signals. Utilizing power domain superposition and advanced receivers, PD-NOMA approaches the channel capacity bound of multi-user systems in both uplink and downlink channel. The PD-NOMA can be used in conjunction with MIMO technology to further enhance the system spectral efficiency [7]. SCMA is a novel NOMA technology based on sparse

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codebooks [8]. The core ideas of SCMA are to accommodate more users with identical resources and increase the throughput of networks without affecting user experience, via non-orthogonal spreading and superposition. The authors in [9] proposed a unified framework for the joint design of multi-user codebooks based on multi-stage suboptimal approach. MUSA is based on the enhanced multi-carrier CDMA scheme [10]. At the transmitter, modulated data symbols of each user are firstly spread by a specially designed sequence to facilitate certain SIC processing at the receiver. The design of spreading sequence is crucial to MUSA [11].

PDMA, evolving from SIC amenable multiple access (SAMA) [12], is based on the joint design of the transmitter and receiver to support massive connection [13]. It can achieve multiplexing and diversity gain by designing multi-user diversity pattern matrix. By utilizing multi-domain sufficiently, PDMA enables wider application range, more flexible coding and decoding scheme, and lower processing complexity, compared with other NOMA technologies.

This paper will elaborate on our proposed RIePDMA system and BP-IDD-IC algorithm. The rest of the paper is organized as follows. In Section 2, we introduce the fundamental principle of PDMA and introduce the system model of the RIePDMA uplink system. Different detection algorithms, including maximum likelihood with IC (ML-IC), minimum mean square error with IC (MMSE-IC), iterative detection and decoding based on belief propagation (BP-IDD), and our proposed BP-IDD-IC are illustrated in Section 3. Section 4 shows simulation results, together with the complexities analysis of those above-mentioned algorithms. In Section 5, we discuss the possible future research directions in PDMA briefly. Finally, Section 6 concludes this paper.

2 System model

2.1 PDMA principle

PDMA is based on the joint design of the transmitter and the receiver. At the transmitter side, the non-orthogonal characteristic pattern based on the multiple signal domains (including time, frequency, and space domain) is used to distinguish the users. At the receiver side, the advanced multi-user detection algorithm is used to separate the multi-user signals [14].

In order to illustrate the concept of PDMA preferably, the characteristic pattern and PDMA pattern matrix are explained first. The characteristic pattern is a column vector containing binary elements 0 and 1. It shows the mapping method of users in resource blocks (RBs), where the element 1 denotes signals of the user are transmitted in the corresponding RB, while the element 0 means the opposite. The number of 1s in the characteristic pattern is defined as the transmission diversity order [15]. Assuming N RBs are available, therefore, there are $2^N - 1$ different characteristic patterns (except the case that users are not transmitted in those RBs) to be chosen. Assuming K (the number of users multiplexing in these N RBs) is the column number determined by the overloading factor α, $\alpha = K/N$. We can choose different K characteristic patterns out from the $2^N - 1$ candidates to construct the PDMA pattern matrix $\mathbf{H}_{\text{PDMA}}$. The PDMA pattern matrix determines the user's mapping method on RBs. It has a crucial impact on the performance of the PDMA system and the complexity of the detection algorithm. A good PDMA pattern matrix can reach better trade-off among multiplexed users, diversity order, and detection complexity.

A case of six users sharing on four RBs is given as an example, as shown in Fig. 1, and the corresponding PDMA pattern matrix is

$$\mathbf{H}_{\text{PDMA}} = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \tag{1}$$

From the PDMA pattern matrix, the signal of user 1 is transmitted in all four RBs, the signals of user 2 and user 3 are transmitted in 3 RBs (the signal of user 2 is transmitted in RB 1, RB 2, and RB 3, the signal of user 3 is transmitted in RB 2, RB 3, and RB 4), and so on.

The advantages of the PDMA technology are listed as follows:

- *PDMA can get higher multi-user multiplexing and diversity gain via the non-orthogonal signals*

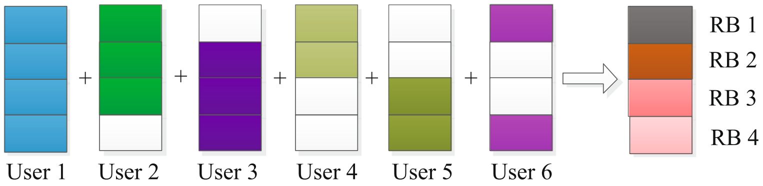

Fig. 1 The resource mapping of six users sharing on four RBs

superposition transmission in time/frequency/ space/power domain.

- *PDMA can adopt low-complexity multi-user detection algorithms to realize high BLER performance because PDMA pattern matrix is relatively sparse.*
- *PDMA can get coding gain and constellation shaping gain at the same time, by joint optimization design with modulation and channel coding.*

2.2 System model of RIePDMA

In order to further improve the overload ability of PDMA, we propose bringing the RI into the PDMA system to form the RIePDMA system. Different from the uplink system of original PDMA, each user in a RIePDMA system is assigned to a unique interleaver after the channel encoder at the transmitter side. And the corresponding de-interleaver is used before the channel decoder at the receiver.

Figure 2 shows the overview of the transmitter and the receiver of the uplink system of the proposed RIePDMA. Assuming there are K single-antenna users sharing on N RBs, and the base station (BS) is equipped with two antennas. The information bit stream from the kth $(1 \leq k \leq K)$ user $\{d\}_k$ is encoded by the channel encoder into b_k, then the coded bits b_k are permuted by the user-specific interleaver π_k to form the chip stream. This interleaving operation can be mathematically formulated as a process by permutation matrix α_I. Assuming the corresponding permutation matrix of the interleaver π_k is α_{Ik}. Thus, the chip stream becomes $C_k = b_k \cdot \alpha_{Ik}$. The chip stream C_k goes through the same processes as the original PDMA system to form the transmitted signal x_k, that is, PDMA mapping and OFDM modulator. It can be seen that the bit-level interleaving randomizes the bit sequence order, which may further bring benefit in terms of combating frequency selective fading and interference.

At the receiver side, the received signal of the mth$(m = 1, 2)$ receiving antenna is $\mathbf{y}_m = [y_{1m}, y_{2m}, \ldots, y_{Nm}]^T$. The received signal in the nth$(1 \leq n \leq N)$ RB is denoted as

$$y_{nm} = \sum_{k=1}^{K} \mathbf{H}_{\mathrm{PDMA}}(n,k) h_{nm,k} x_k + n_{nm}. \tag{2}$$

where $\mathbf{H}_{\mathrm{PDMA}}(n,k)$ denotes the element at the nth line and the kth column of $\mathbf{H}_{\mathrm{PDMA}}$, $h_{nm,k}$ denotes the channel between the kth user and BS at the mth receiving antenna, and n_{nm} denotes the additive white Guassian noise in the nth RB at the mth receiving antenna. $\{\hat{d}\}_k$ denotes the decoded information bits of user acquired by detector and decoder. In the following, we will introduce several integrated detection and decoding algorithms.

3 Integated detection and decoding

Compared with the traditional OMA technologies, PDMA provides more access points for users to support massive connections. However, it also brings crucial inter-user interference problem. Therefore, we choose the advanced receiver for multi-user detection to solve it. Herein, we first analyze several integrated detection and decoding algorithms and then propose an iterative detection and decoding algorithm, called BP-IDD-IC.

3.1 ML-IC and MMSE-IC

In this section, we introduce two kinds of the classical multi-user detection algorithms with IC, named ML-IC and MMSE-IC (is shown in Fig. 3a). In ML-IC algorithm, the codeword level soft information, denoted by the log-likelihood ratio (LLR), is output by comparing the two kinds of the nearest combinations that lead to transmitted bit equal to 0 or 1, respectively. The LLR serves as the input to the channel decoder. IC is widely used to improve the performance in multi-user detection. We

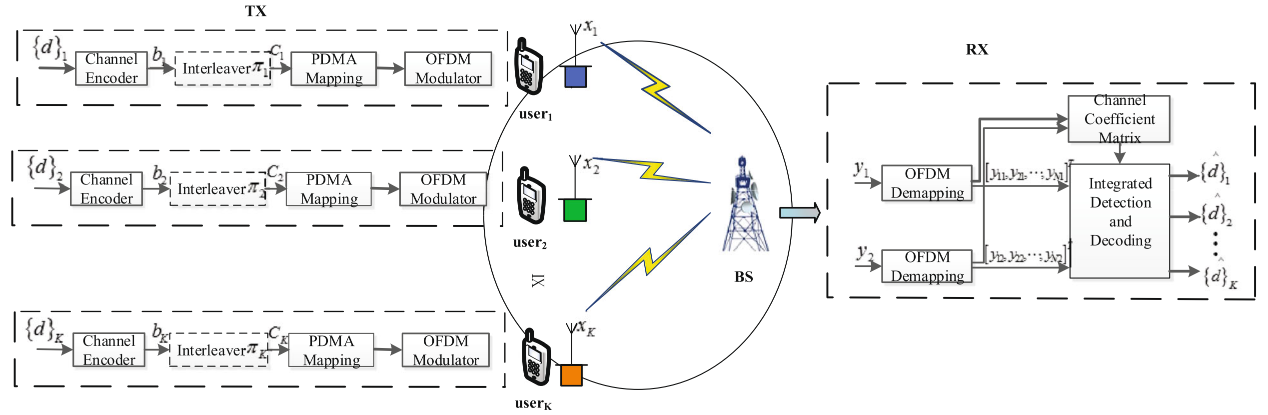

Fig. 2 The system model of RIePDMA

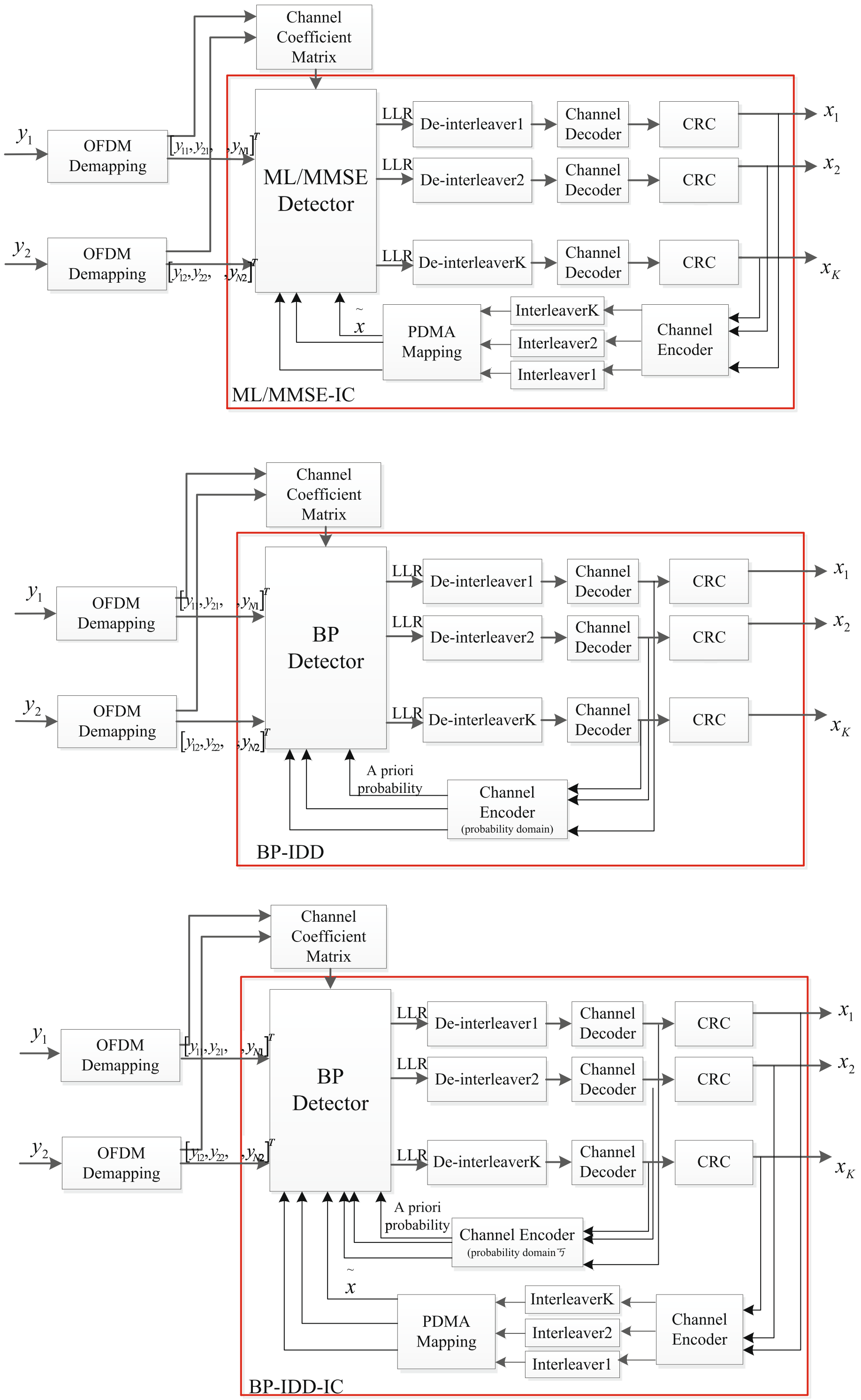

Fig. 3 The block diagram of several detection algorithms: **a** ML/MMSE-IC, **b** BP-IDD, and **c** BP-IDD-IC

use IC to cancel the interferences that have been correctly detected by maximum likelihood (ML) algorithm. According to the results of a cyclic redundancy check (CRC) module, IC is performed, which prevents the propagation of errors and improves the BLER performance of the receiver. By iterating the ML and IC, the ML-IC has a better BLER performance. But due to its prohibitively high complexity (especially when the number of users is large and high order modulation is used), it is hardly applied in practice. Hence, we introduce minimum mean square error (MMSE) to detection and bring out MMSE-IC. Like ML-IC, we utilize MMSE estimation instead of ML for multi-user detection. The codeword level soft information of MMSE-IC can be obtained by the soft MMSE detection [16].

3.2 BP-IDD

In order to illustrate the BP-IDD algorithm, we explain the BP algorithm first. Figure 4 shows a factor graph, which contains variable nodes (VNs) and function nodes (FNs). VNs stand for users, and FNs stand for RBs. If there is a link between the VN and the FN, it means that this RB is shared by the user. BP can realize the multi-user detection by iteratively sending "belief message" between VNs and FNs. In this paper, we refer to the algorithm in [17]. The complexity of this BP algorithm is low because of its implementation in log-domain and Gaussian approximation of interference. The case of six users sharing on four resource blocks with the PDMA matrix (shown in Eq. 1) is given to illustrate the algorithm.

The detailed iterations are shown in Table 1. The message passed from the ith FN to the jth VN is denoted as a_{ij}, and v_{ji} denotes the message passed from the jth VN to the ith FN. s denotes the element of underlying pulse and amplitude modulation (PAM) alphabet $A = \{\pm 1, \pm 2, \ldots, \pm M - 1\}$, and M is the modulation order. After several iterations, the results will be convergent and the accurate marginal function will be produced, especially when the factor graph is cycle-free. However, the factor graph of PDMA is usually not cycle-free, so this BP algorithm is suboptimal.

In the BP algorithm, all possible transmitted symbols are considered to be equal possibility, i.e., there is no prior information. If BP detector can get the prior information before the iterations, the BLER performance of BP algorithm can be improved. For BP-IDD, the prior information of the BP detector is provided by the channel decoder. The block diagram of BP-IDD is shown in Fig. 3b. In our case, we choose turbo code for channel encoding. The turbo decoder outputs bit level soft information. The soft information is transmitted to BP detector as the prior information by turbo recoding at probability domain. By iterating the prior information between BP detector and turbo decoder, the BLER of BP detector will be reduced.

Table 1 BP detection algorithm

BP detection
Step 1: Initialize the posterior probability values
$v_{ji}(s) = 1/\sqrt{M}$
Step 2: Iterative message passing along edges
a) The messages passed from the i^{th} FN to the j^{th} VN
$a_{ij}(s) = \frac{1}{\sigma_{ij}\sqrt{2\pi}} \exp\left(\frac{-(y_i - u_{ij} - h_{ij}s)^2}{2\sigma_{ij}^2}\right)$
b)The message passed from the j^{th} VN to the i^{th} FN
$v_{ji}(s) = \prod_{l=1, l \neq i}^{N} a_{lj}(s)$
where u_{ij} and σ_{ij} denote the mean and variance of the interference, respectively.
Step 3 LLR output of the j^{th} VN after the iteration
$LLR_j = \log(P_{x_j}(s)/P_{x_j}(s_0))$
where $P_{x_j}(s)$ denotes the probability of the symbol s, s_0 means the symbol corresponding to 0.

3.3 BP-IDD-IC

To reduce the complexity and improve the BLER performance of BP-IDD, we implement IC technique and CRC module into BP-IDD and bring out self-adaptive BP-IDD-IC.

In this new scheme, the output of BP will be sent to turbo decoder firstly. The hard information from turbo decoder goes through CRC module. We denote C as a set to record the correctly decoded users. If all users' signals are correct, IDD iteration and IC will not run. Otherwise, turbo decoder will send soft information to turbo encoding at probability domain and then send the coded soft information back to BP as prior information. We also reconstitute the signal of users which are the element of C. IC module cancels the reconstituted signal $\tilde{x}$ from the received signal y to get a new received signal $\tilde{y}$ (see in Eq. 3) and sends the new signal $\tilde{y}$ to BP module. The block diagram is shown in Fig. 3c.

$$\tilde{y} = y - \sum_{k \in C} h_k \tilde{x}_k \tag{3}$$

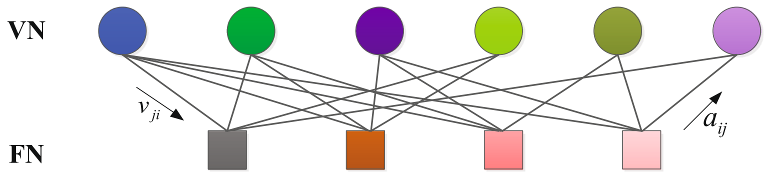

Fig. 4 The factor graph and vector messages of BP

Since some of the PDMA patterns are sparse, the complexity of BP is reduced and the convergence of iteration is guaranteed. Moreover, with the implementation of CRC module, our receiver scheme becomes self-adaptive. The number of iterations can be reduced, especially in high signal-to-noise ratio (SNR) region, and will not affect the BLER performance of the receiver. With the implementation of IC technology, the correctly decoded information can be canceled, and the inter-user interference will be reduced. Therefore, the BLER performance can be improved.

4 Simulation results and analysis

4.1 Performance analysis

In this section, we present the simulation results of evaluating the performance of abovementioned several integrated detection and decoding algorithms and the proposed RIePDMA scheme. We set up a link-level simulation platform for PDMA uplink system. The detailed simulation parameters are shown in Table 2, which are referenced in [18]. Figure 5 shows the average BLER curves of several integrated detection and decoding algorithms with six users sharing on four RBs. With the IC technique, BP-IDD-IC achieves a better BLER performance than BP-IDD getting about 1 dB gain. It should be noted that, the degree of improvement of BLER performance is affected by the value of SNRs. The BP-IDD and BP-IDD-IC can get the similar performance at -2 and 8 dB. While, the performance of BP-IDD-IC can obviously get gain at the other points. It is because that when the certain interferences are cancelled by IC iteration, the correct decoded probability of users are improved. However, with the increasing of the SNR, the high BLER performance can be obtained without the IC iteration. So the gain of the BP-IDD-IC becomes lower. Compared with MMSE-IC, BP-IDD-IC outperforms slightly as well. Obviously, BP-IDD-IC is an approximation of ML-IC.

Figure 6 shows the BLER performance of the OMA, PDMA, and the proposed RIePDMA under different overloading factors with the BP-IDD-IC algorithm. From the figure, PDMA achieves better BLER performance, compared with OMA at high SNR region, and the gain exceeds 1 dB when the BLER is 10^{-2}. In addition, the proposed RIePDMA achieves better BLER performance, compared with the PDMA system. The higher the overload is, the greater BLER performance gains RIePDMA gets. There are two reasons for the results. On the one hand, the interleavers used in RIePDMA can resist the channel fading; on the other hand, the interleaver disrupts the order of the encoded information bits, so the consecutive errors caused by the small interference can be avoided to some extent. Since the proposed RIePDMA can get higher BLER performance when the overload is higher, it is expected to support more connections, compared with PDMA. The comparison of BLER performance of the OMA, PDMA, SCMA, and the proposed RIePDMA is shown in Fig. 7. From the figure, NOMA technologies get better BLER performance than the OMA. RIePDMA achieves better BLER performance, compared with PDMA and SCMA. Besides, SCMA can support 150% overload at most when the available PRB is 4. However, the proposed RIePDMA can support higher overload.

Table 2 Simulation parameters

Parameter	Value
Carrier frequency	2 GHz
Length of information bits	432 bits
System bandwidth	10MHz
Modulation coding rate	QPSK; 1/2 Turbo
Carrier modulation	OFDM
Antenna configuration	1Tx;2Rx
Channel model	Uma
Channel estimation	Ideal
Overloading factor	150%; 200%; 300%
Number of BP iterations	4

4.2 Complexity analysis

As mentioned in [17], the approximate computational complexity of the BP is $O(\lambda_2 NK(13\sqrt{M}+4K))$, where λ_2 stands for the times of inner iteration also known as the iteration of BP. By taking the overloading factor α, it can be rewritten as $O(\lambda_2 K^2(13\sqrt{M}+4K)/\alpha)$. We ignore the complexity of the channel recoding at probability domain. And the complexity of BP-IDD is $O(\lambda_1(\lambda_2 K^2(13\sqrt{M}+4K)/\alpha+T))$, where λ_1 stands for the times of IDD iteration also known as the outer iteration and T stands the complexity of the channel decoding. In this paper, we assume that the value of λ_1, λ_2, and M are 4, 4, and 4, respectively. So the complexity of BP-IDD can be rewritten as $O(\frac{1}{\alpha}(416K^2+64K^3)+4T)$. According to the self-adaption of BP-IDD-IC described in Section 3, the complexity of BP-IDD-IC can drop to $O(\frac{1}{\alpha}(104K^2+16K^3)+4T)$ with ignoring the complexity of the process of signal reconstituted. The worst complexity of MMSE is around $O(K^3)$ to execute matrix inversion. In our case, the worst complexity of MMSE-IC is $O(3(K^3+T))$. Compared with MMSE-IC, BP-IDD-IC has a higher complexity. For the ML detector algorithm, its total complexity reaches $O(2^{MK})$ by searching all of the possible constellation combination. If a soft output is required, the LLRs at bit level of K users should be calculated separately, so the complexity of ML-IC would increase to $O(3(K2^{MK}+T))$. In conclusion, the complexity of BP-IDD-IC is acceptable in low SNR region, and the complexity of BP-IDD-IC is low in high SNR region. We measure the experiment time of the abovementioned

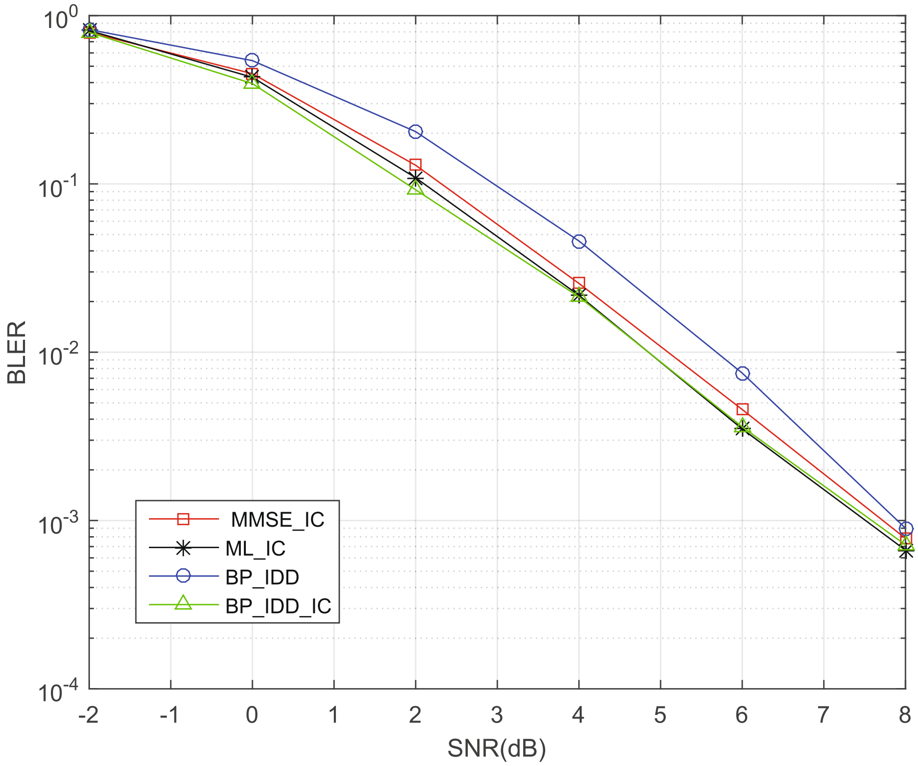

Fig. 5 Performance comparison of different integrated detection and decoding algorithms

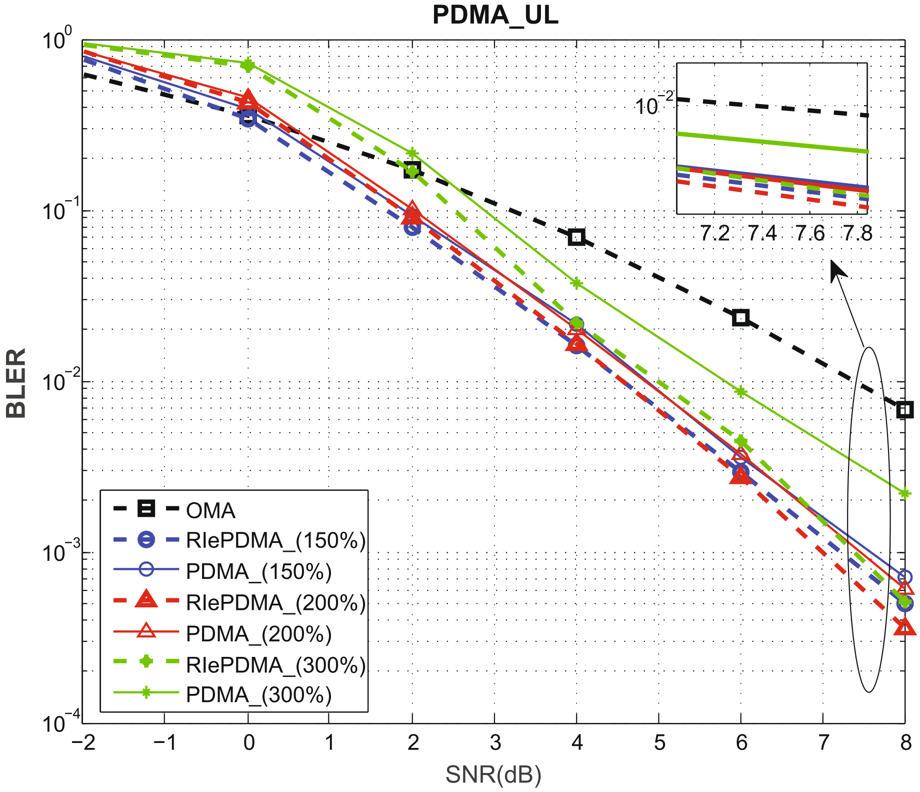

Fig. 6 Performance comparison of RIePDMA and PDMA with different overloading factors

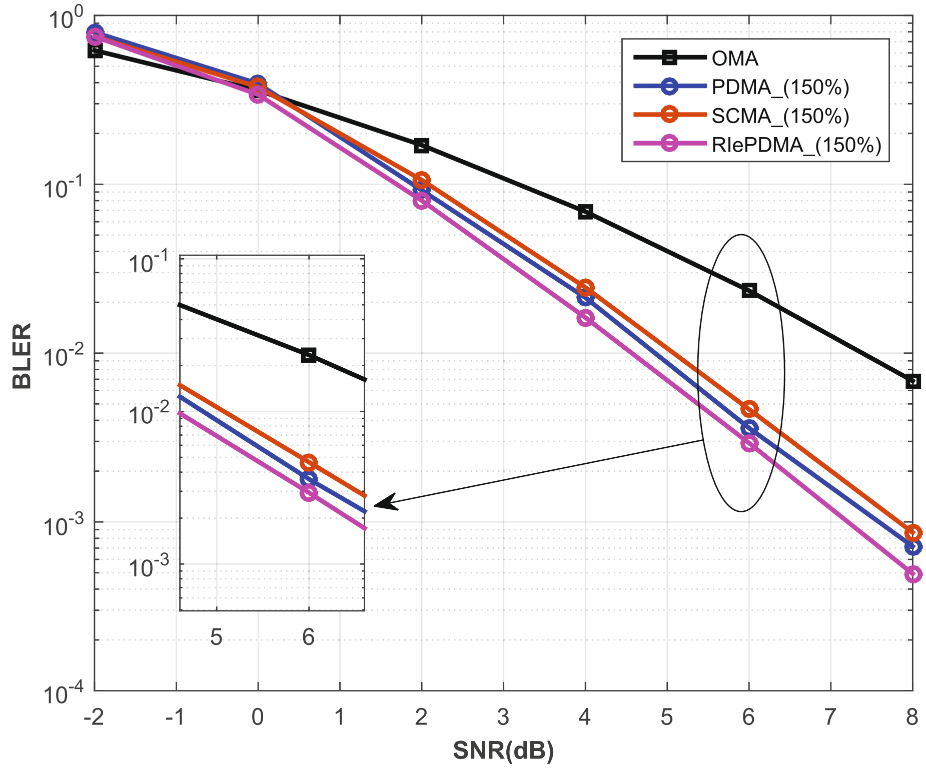

Fig. 7 Performance comparison of different multiple access technologies

algorithms with 1000 packages and list the detailed experimental time consumption in Table 3. From Table 3, with the same simulation condition, MMSE-IC uses the least time, ML-IC uses the longest time. The experimental time of ML-IC is nearly 40 times of MMSE-IC. BP-IDD can reduce the experimental time compared with ML-IC. The experimental time of BP-IDD is nearly 11 times of MMSE-IC. With the increasing of the SNR, the experimental time of the proposed BP-IDD-IC has been cut down (especially in high SNR region). The experimental time of BP-IDD-IC is nearly 13 times of MMSE-IC in −2 dB, while it is nearly 3 times of MMSE-IC in 8 dB. The results of the time consumption correspond with our conclusion.

5 Future research

Based on our current exploration and consideration, the further research can be conducted from the following possible directions.

5.1 Power domain pattern design

In the current studies, the PDMA pattern only consists 0 or 1 elements, which leaves out the effect of the amplitude and the phase. The joint design of the amplitude and the phase, called the power domain pattern design, will be studied in future research.

5.2 Space domain pattern design

The space domain pattern design can be explained as the combination of PDMA and MIMO. Specially, the quasi-orthogonal space-time block code (Q-OSTBC) in space domain can be adopted when designing the PDMA pattern. And the ordered successive interference cancellation (OSIC) can be used at the receiver side to improve the overall performance of system. And the pattern design with joint Q-OSTBC scheme in space domain and power allocation in power domain will be studied in the future work.

Table 3 Time consumption of several integrated detection and decoding algorithms (unit: s)

SNR(dB)	−2	0	2	4	6	8
ML-IC	97,875	97,991	99,837	97,755	97,717	96,947
MMSE-IC	2386	2394	2400	2422	2425	2425
BP-IDD	28,508	27,471	27,838	27,577	29,760	28,278
BP-IDD-IC	31,055	29,642	20,911	12,919	9091	8145

6 Conclusions

PDMA technology is of vital importance as a candidate multiple access technology in future 5G wireless communication system. In this paper, RIePDMA is firstly proposed in PDMA uplink system to further improve the overload ability and the BLER performance of PDMA. We evaluate the BLER performance of the proposed RIePDMA and BP-IDD-IC with the link-level simulation. The simulation results show that the proposed RIePDMA scheme can obviously improve the BLER performance without increasing the complexity of the receiver remarkably. The higher the overload is, the greater BLER performance gains RIePDMA can get. At the same time the proposed BP-IDD-IC can get better BLER performance with an acceptable complexity increment of the receiver.

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Authors' contributions
The work presented in this paper corresponds to a collaborative development by all authors. JZ defined the research line, guided and organized the study, and wrote the paper. DK and BL detailed some parts of the paper. XS and TL gave many modification suggestion about the paper. All authors have read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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