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Progressive pattern orthogonal interleaver set for interleave division multiple access based, non orthogonal multiple access schemes: Beyond 5G perspective

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This communication suggests an orthogonal interleaver set for interleave division multiple access (IDMA) based non orthogonal multiple access (NOMA) schemes from beyond 5G viewpoint to support enormous increase in user count. The method generates an orthogonal interleaver set by providing two mother interleavers as seed to generate other users' interleaving patterns progressively. The key feature of the proposed scheme is that it reduces implementation complexity and memory requirement at the base station, while implementing iterative multiuser detection (MUD), which most of the interlaever designs suggested in literature do not consider. It provides additional security to the user data due to progressively changing mother interleavers' pattern along with the conventional purpose of providing unique identity for individual users in the system. The proposed orthogonal interleaver set is tested through simulations under multiple IDMA system configurations. It has been observed that it preserves the bit error rate (BER) performance of the IDMA scheme along with the optimal implementation complexity and minimal information exchange requirement between base station and mobile station to share the interleaver design.

K e y w o r d s: NOMA, IDMA, MUD, orthogonal interleaver, progressive pattern interleaver, numerical interleaver, tree based interleaver, 5G/6G

1 Introduction

In view of tremendous increase in internet of things (IoT) devices, spectrum sharing will become a challenge in beyond 5G [1, 2] networks. Implementation of orthogonal multiple access (OMA) in terms of time division multiple access (TDMA), frequency division multiple access (FDMA), orthogonal frequency division multiple access (OFDMA) and single carrier frequency division multiple access (SC-FDMA) [3] is incompetent to accomplish the massive multiple access demand of future networks. Non orthogonal multiple access (NOMA) is the suggested multiple access method [4, 5] to fulfill the need of huge number of devices demanding the same band of spectrum simultaneously. Conventional OMA practices orthogonally shared spectrum with simple transmitter and receiver structure, conversely in NOMA, non-orthogonal sharing results in relatively complex transmitter and receiver structures. NOMA allows the non-orthogonal sharing at the transmitter to increase the user count with the associated complex receivers to decode individual user data with the preserved bit error rate. NOMA can be attained through variation in power among users in terms of power domain NOMA, variation in signature codes among users in terms of code domain NOMA or through variation in unique interleavers for different users in terms of interleave division multiple access (IDMA).

According to 3rd Generation Partnership Project (3GPP) Features and Study Items, IDMA has been proposed as NOMA scheme [1, 3] for non-orthogonal spectrum sharing. For the implementation of IDMA [6], each user's spreaded data in terms of chips is interleaved with a unique interleaver resulting in distinguished pattern for the respective user to provide multiple access in a multiuser system. Multiuser detection (MUD) [6] is the strategy in IDMA scheme to detect individual data at the receiver side. In an IDMA based system, chip level interleaving also facilitates need for fewer iterations to consolidate the bit error rate (BER) performance while employing MUD for the detection at the receiver. In IDMA based systems interleaving is performed at chip level after spreading resulting in less correlation among adjacent chips. MUD implementation needs less iteration count if adjacent chips are less correlated due to interleaving. This chip level orthogonal interleaving is performed by an orthogonal interleaver set, which arranges unique and different interleaving patterns for multiple users in a multiple access system.

This work focuses on the design of an orthogonal interleaver set. Few requirements should be satisfied [7] to design an orthogonal interleaver set for an IDMA based system. The design of the orthogonal interleaver set should be such that it provides optimum orthogonality among multiple users to distinguish them from each other. More over orthogonal interleaver set should be easy to generate and should occupy less memory at different stages of communication system. To the best of our knowledge most of the interleaver designs suggested in literature [8-12]

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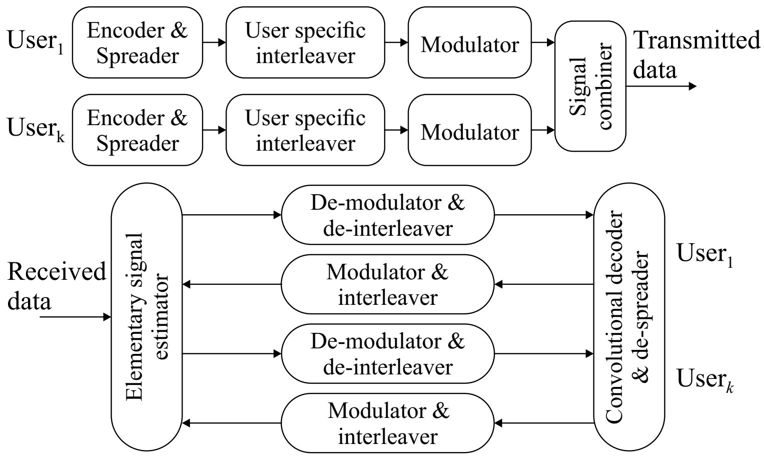


Fig. 1. IDMA transmitter and receiver system

do not consider implementation complexity at the base station while implementing MUD. While implementing MUD at the base station, detection of multiple user data is done sequentially in an iterative manner with multiple cycles of interleaving and de-interleaving, therefore, interleaver generation method should be such that the next user interleaver is generated using the previous user interleaving pattern to decrease complexity of MUD implementation. However, it is also required that the interleaver generation method is strong enough in terms of security, so that any unintended system can-not decode the user data easily. Both the above stated requirements are contradictory and difficult to satisfy simultaneously and have been worked upon through this research.

This work suggests an optimum orthogonal interleaver set named progressive pattern interleaver (PPI) with secure and easy generation method without any sacrifice in memory requirement and BER performance. Orthogonal interleavers are the primary component for any IDMA based system therefore next section describes an IDMA transmitter and receiver system, followed by the motivation for the suggested interleaver. Then PPI generation method is suggested followed by its performance results.

2 IDMA

2.1 System model: Transmitter structure

An IDMA transmitter system [6] for K users is shown in Fig. 1. At the transmitter, convolutional encoding and spreading is used on each user's data, resulting in spread chips. It is followed by the user specific interleaving to distinguish multiple users in an IDMA system. Binary phase shift keying (BPSK) modulation is done over these spread chip sequences of length S for each user. Similar processing is done for all the users and combined signal of all the users' is transmitted through a channel with additive white Gaussian noise (AWGN) channel model. For any individual user, transmitted sequence can be denoted as $x_k(s)$. Here, s is ranging from 1 to S.

2.2 Reciever structure

The MUD receiver system of an IDMA scheme [6] is shown in Fig. 1. At the receiving end of an IDMA system the combined signal of all users can be represented with the expression as follows

$$r(k) = \sum_{k=1}^{K} h_k x_k(s) + w(s), \quad s = 1, 2, \dots S, \tag{1}$$

where, h_k and $w(s)$ are the channel gain parameter and AWGN sample with zero mean and variance σ^2 respectively for an individual user k. Soft information in terms of log-likelihood ratio (LLR) for each chip s of user k is computed by elementary signal estimator (ESE) with the assumption that perfect channel estimates are available at the MUD receiver. Other users' signal is treated as multiple access interference while estimating LLR information for each chip of a particular user. Considering other users' signal $\zeta_k(s)$ as multiple access interference (MAI), the received signal expression (1) for user k can be written, [6], as

$$r(k) = h_k x_k(s) + \zeta_k(s),$$

where

$$\zeta_k(s) \equiv r(k) - h_k\, x_k(s) = \sum_{i \neq k} h_i x_i(s) + w(s).$$

Assuming Gaussian distribution for $\zeta_k(s)$ with mean $E(\zeta_k(s))$ and variance $V\big(\zeta_k(s)\big)$ respectively, the LLR information of each chip

$$e_{\mathrm{ESE}}\big(x_k(s)\big) = \frac{2h_k\big(r(k) - E\big(\zeta_k(s)\big)\big)}{V\big(\zeta(s)\big)},$$

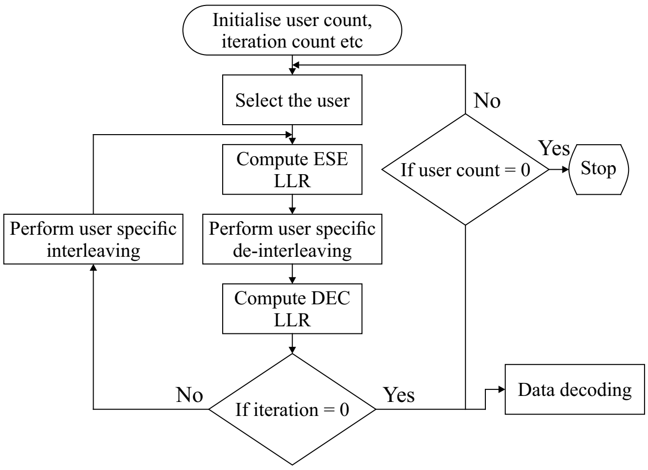


Fig. 2. Iterative IDMA receiver

produced at the output of ESE for user k can be computed, [6].

This LLR is processed by a posterior probability (APP) decoder (DEC) after demodulating, de-interleaving, and de-spreading by appropriate methods. Decoder's LLRs are re-applied to ESE after spreading, interleaving and modulating by appropriate methods. This ESE information is upgraded iteratively as shown in Fig. 2 for certain number of iteration loops until an optimized BER is achieved [6].

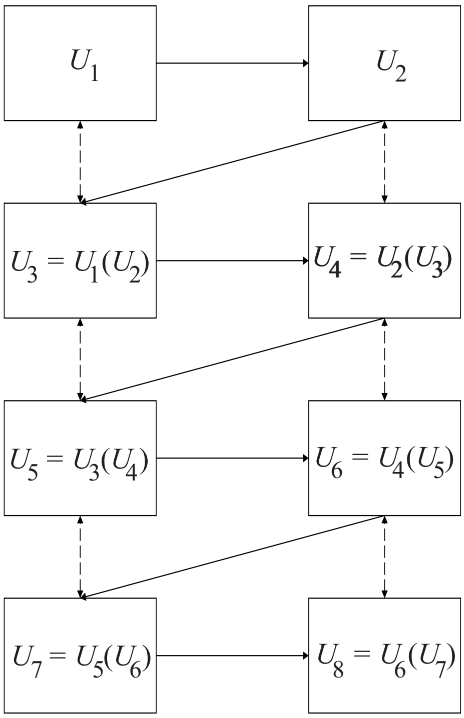
3 Motivation

Numbers of interleavers have been suggested in literature [6, 8 -15] to make IDMA performance better with less complex interleaver structure. Any of the above mentioned orthogonal interleaver set design will actually result in less correlated chips to facilitate almost same BER performance for the same number of iterations to consolidate the required BER. However while executing iterative MUD at the base station; interleaving and de-interleaving process is done multiple numbers of times for each user to optimize the BER as shown in Fig. 2. The further scope of research lies in designing iterative MUD implementation feasible and less complex in terms of interleaver design that has not been considered in the work mentioned in [8-12], [14-15]. The interleaver design should be such that the next user's interleaving pattern is computed from the previous user's interleaving pattern resulting in reduced implementation complexity while implementing MUD. This work focuses specifically on this point to make iterative MUD implementation practical. In addition to this PPI provides additional security due to the requirement of two successive and progressively changing interleaving patterns to decode the patterns of other users.

Random interleaver (RI) assigns random patterns of interleaving to distinguished users. Unique random RI allotment [6] to each user in an IDMA system optimizes BER fast, but resulting in huge memory requirement due to storage requirement of unique random patterns of all the users at multiple stages of communication system. Tree-based interleaver (TBI) as suggested in [8] is easy to implement at user mobile station site as it needs the information about 2 mother interleavers and user number only. Each user's interleaving pattern is generated following the definite interleaving sequence for mother interleavers' which is computed as per tree-based algorithm [8]. As an illustration, first two users have been assigned with two mother interleavers π_1 and π_2. Third user gets its pattern of interleaving by interleaving π_1 with π_1. Fourth user gets its pattern of interleaving by interleaving π_1 with π_2. Fifth user is assigned a pattern by interleaving π_2 with π_1. And sixth user gets a pattern after interleaving π_2 with π_2. Similarly for other incoming users' patterns are assigned with binary tree algorithm after interleaving three times all possible combinations of two mother interleavers. The process is repeated for other incoming users with four times interleaving and five times interleaving, the possible combinations of two mother interleavers. However, TBI implementation becomes very complex while implementing iterative MUD and same is the problem with interleavers suggested in [10-12],[14,15]. This significant requirement is fulfilled by the power interleaver (PI) algorithm [13] which computes the interleaving pattern by re-interleaving the mother interleaver, number of times equal to the user number. For example, second user interleaving pattern will be computed by re-interleaving the mother interleaver and third user pattern is generated by re-interleaving the second user sequence. This results in less complex MUD implementation at the base station since next user's interleaving pattern is computed from the previous user's pattern in single cycle only. However it also makes the system less secure, since for any unintended user it is easy to decode the patterns of interleaving if information about the current pattern of interleaving along with mother interleaving pattern is available. Therefore, the method presented in our work suggests an orthogonal interleaver generation algorithm which is easy to implement as PI and it is relatively difficult for any unintended user to trace the interleaving patterns of other users with this method, thus providing security as well.

4 PPI generation method

Through this work we propose a progressive pattern interleaver generation method which generates user specific orthogonal interleavers for an IDMA system with K number of users represented by U_k. As per the method two random mother interleavers π_1 and π_2 are assigned to the first two users (U_1 and U_2, respectively) as is shown in Fig. 3(a). The third user gets (U_3) interleaving pattern after interleaving π_2 with pattern of π_1 represented as $U_3 \equiv \pi_1(\pi_2) \equiv U_1(U_2)$. In sequence with this U_4 is assigned a pattern $U_4 \equiv \pi_2(\pi_1(\pi_2)) \equiv U_2(U_3)$. Further, the two interleaving patterns of U_3 and U_4 are



(a)

Algorithm of Interleaver generation at different stages of communication system:

Interleaver Generation at base station:

First user 1 is given Interleaver pattern U_1

Second user 2 is given Interleaver pattern U_2

Third user 3 is given Interleaver pattern $U_3 \equiv U_1(U_2)$*ie* interleaving U_2 with pattern of U_1.
Fourth user 4 is given Interleaver pattern $U_4 \equiv U_2(U_3)$*ie* interleaving U_3 with pattern of U_2, and so on for next users.

Interleaver Generation at mobile station:

Ifi nterleaving patterns are available for all 2^n-1 and 2^n users for each value of $n \geq 1$,

Get the user number k

Compute n such that $2^n < k < 2^{n+1}$

At most $2^n - 1$ interleaving cycles are needed to compute interleaving pattern for the largest value of k.

Interleaver Generation while implementing MUD:

Single cycle is needed only, since next user pattern is generated using previous 2 users patterns.
For example interleaving pattern of $U_3 \equiv U_1(U_2)$ and interleaving pattern of $U_4 \equiv U_2(U_3.)$

(b)

Fig. 3. PPI generation: (a) – for 8 users, (b) – at different stages of communication system

assigned as mother interleavers for the next two users resulting in the interleaving pattern of U_5 as $U_5 \equiv U_3(U_4)$ and U_6 as $U_6 \equiv U_4(U_5)$ respectively. Starting with two orthogonal mother interleavers, sequentially other users patterns are computed which are also orthogonal in nature. In this method mother interleaver's patterns are modified progressively for upcoming users that provide more security to the system at base station site. In PI, current user's interleaving information and mother interlaever's information is sufficient to decode all other users' interleaving pattern. Here with the suggested PPI method, knowledge of two successive interleaving patterns is required to decode other users' interleaving pattern, in addition to this mother interleavers' patterns are also changing progressively resulting in an overall more secured system.

At mobile station, the interleaving pattern for each user is computed as per the user number assigned by the base station. This results in very less information exchange between mobile and base station to share interleaver's information. Few intermediate interleaving patterns are also broadcasted along with mother interleavers to reduce the computational complexity at mobile station. While computing interleaving pattern at the mobile station, the number of interleaving cycles required are less if interleaving pattern generation method for $2^n - 1$ and 2^n user is also broadcasted from base station for all possible values of $n \geq 1$. Considering a user k, where $2^n \leq k \leq 2^{n+1}$, at most $2^n - 1$ more interleaving cycles are needed for the largest possible value of k to compute its interleaving pattern. As an illustration, for user $k = 31$, where $2^4 \leq k \leq 2^5$ and is the largest possible value lying between these limits, n can be concluded as 4. Therefore if interleaving patterns for $(2^n - 1)$ and 2^n (15 and 16) users are available then at most $2^n - 1$ (15) more cycles are needed to compute the interleaving pattern for 31-st user. The method of interleaver generation at different stages of communication system is also shown in Fig. 3(b).

Progressive pattern interleaving reduces the memory requirement at base station also as compared to RI and TBI while implementing MUD at the base station. This method facilitates the next users' interleaving pattern generation from the previous two users' interleaving patterns in a sequential manner. Therefore, at any stage only two interleaving patterns are needed to be stored in memory in contrast to RI where all random patterns are needed to be stored or in tree-based where the whole tree-based algorithm is repeated to compute the interleaving pattern. Simulation results have been shown in the following section to justify the BER performance of PPI. Results provided in terms of memory requirement, implementation complexity and security feature of different interleavers have also been discussed in the following section.

5 Results

5.1 BER performance

To justify the appropriateness of the interleaving scheme, BER performance of the PPI is simulated and compared along with other orthogonal interleavers including PI, TBI, and RI. Multiple simulation environments have been generated and tested for the overall validation of the performance. Simulation parameters have been fixed as follows, except if pointed out individually in respective simulations. An IDMA system with 32 users has been simulated for data length of 128 bits, spread length 16, rate – 1/2 convolutional code and 10 or 5 iteration counts for 100 blocks. First, BER versus bit energy to noise ratio (Eb/N0) performance has been simulated for different data lengths specified as 32, 128 and 256 for all four interleavers including PI, PPI, TBI and RI as presented in Fig. 4 for 5 iteration count. As can be concluded from the results that for small data length of 32 performance deteriorates for all interleavers. Small data length results in more correlation among adjacent chips resulting in inferior MUD implementation. However, the suggested PPI interleaver performs equally well as other interleavers even for small data length. The simulations have also been performed for different iteration counts set at 5, 8 and 10 with all four interleavers as shown in Fig. 5. Performance of suggested PPI interleaver is similar to other interlaevers at low iteration counts as well. Moreover, subsequent increase in iteration count decreases the BER performance of all four interleavers including PPI interleaver as presented in Fig. 5. Additionally results have also been simulated for variable block lengths of 20, 50 and 100 to optimize the BER performance for 5 iteration counts and it can be observed from Fig. 6 that PPI interleaver performs identical to other interleavers when BER results are averaged for smaller block lengths. Fig. 7 includes the BER performance of all four interleavers for variation in user count as 16, 32 and 40 for 10 iteration count. It is observed that results of PPI interleaver are equally efficient as other interleavers at higher user count also.

5.2 Performance comparison of different orthogonal interleavers

Memory requirement of the presented interleaver at different stages of communication system has been shown and compared with other interleavers in Tab. 1 for n number of users.

Table 1. Memory requirement for n number of users

	RI[6]	TBI[8]	PI[13]	PPI
Base station	n	2	1	2
Mobile station	n	2	*)	*)
MUD Implementation	n	2	1	2

*) proportional to but less than n

Memory requirement of RI is huge at every stage of communication system since random patterns of interleaving are needed to be stored for all users. It increases in proportion to user count in a system. As an illustration, to store patterns for three users three memory locations are required at every stage of communication system. This is primarily undesirable for any multiple access system design. TBI interleaver needs only two memory locations to store interleaving patterns of two mother interleavers, rest of the patterns are computed with these two mother interleavers. Least memory is required with TBI implementation whereas PI and PPI need reasonable amount of memory.

Table 2 compares implementation complexity for different interleavers. In TBI generation whole tree algorithm runs to compute interleaver design for every new user in a system. This leads TBI implementation very complex and impracticable. RI has already stored interleaving patterns leading to nil implementation complexity. PI and PPI have practical and reasonable implementation complexity.

Table 2. Implementation complexity for n number of users, in terms of number of interleaving cycles

	RI[6]	TBI[8]	PI[13]	PPI
Base station	0	$\propto n$	1	1
Mobile station	0	$\propto n$	$\propto n$	$\propto n$
MUD Implementation	0	$\propto n$	1	1

Table 3. Overall performance

	RI[6]	TBI[8]	PI[13]	PPI
BER	same	same	same	same
Memory requirement	highest	lowest	$\surd$	$\surd$
Implement complexity	lowest	highest	very low	very low
Security	highest	$\surd$	lowest	high

$\surd$ – reasonable

Table 3 compares all interleavers considered in this work in terms of overall performance. BER performance of all the interleavers is approximately same. RI is not suitable for practical IDMA systems due to its huge memory requirement. TBI implementation becomes complex and unreasonable as user count increases in a system. When it comes to the security feature of the interleaver design, PI offers least. Therefore the suggested PPI interleaver is the optimal solution for any IDMA integrated NOMA system due to its concrete overall performance.

6 Conclusions

In this work we proposed an orthogonal interleaver generation method employed for NOMA-IDMA systems

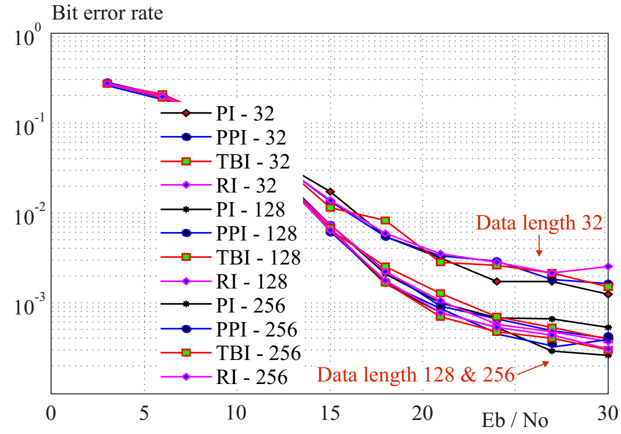


Fig. 4. BER performance for data length of 32, 128 and 256

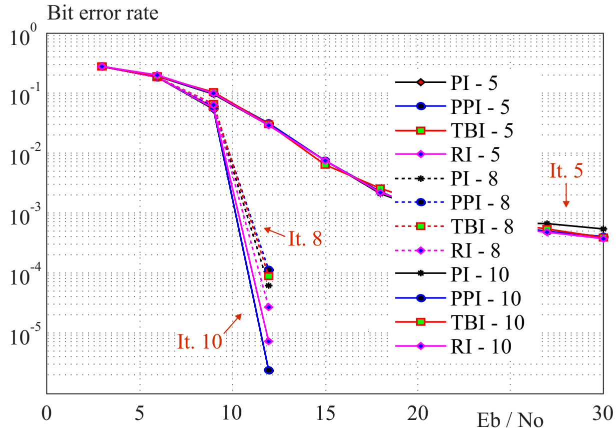


Fig. 5. BER performance for iteration count of 5, 8 and 10

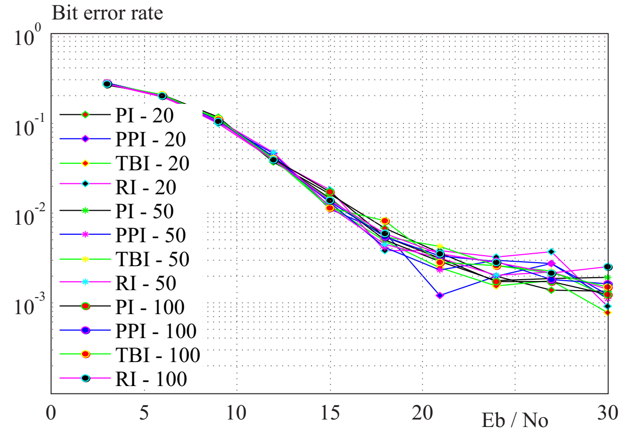


Fig. 6. BER performance for block length of 20, 50 and 100

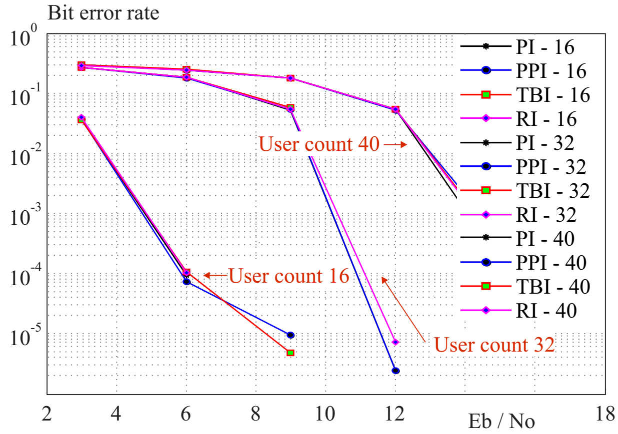


Fig. 7. BER performance for user count of 16, 32 and 40

in 5G and beyond networks. The work compares the performance of the suggested method of interleaving with other significant interleavers available in literature to justify the findings for the appropriateness of the method for future generations of the networks. The main feature of this method is that the patterns of mother interleavers are continuously changing resulting in more secure system as compared to PI method.

Moreover, this method requires relatively less information exchange between base station and mobile station to exchange information about the interleaver design specifically in comparison to RI. In contrast to TBI, generation of interleaving pattern at user station is also modest along with effective generation of interleaving patterns while implementing MUD at the base station. Further BER performance has been evaluated and compared with other interleavers and it has been found equally competent. BER performance, memory requirement and implementation complexity justifies the appropriateness of the method for NOMA based IDMA systems for future advanced mobile networks. Although the focus of this work was on the design of orthogonal interleaver set for NOMA-IDMA systems, further interesting work would be to analyze the performance of PPI for other applications such as interleaver based multidimensional concatenated codes and space-time codes.

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