Applications and Applied Mathematics: An International Journal (AAM)

Volume 17
Issue 3 *Special Issue No. 10 (October 2022)*

Article 14

10-2022

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Available at
http://pvamu.edu/aam
Appl. Appl. Math.
ISSN: 1932-9466
Special Issue No. 10 (October 2022), pp. 173 – 187

Applications and Applied Mathematics:
An International Journal
(AAM)

Comprehensive Study On Methodology of Orthogonal Interleavers

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Received: November 20, 2021; Accepted: August 13, 2022

Abstract

Interleaving permutes the data bits by employing a user defined sequence to reduce burst error which at times exceeds the minimum hamming distance. It serves as the sole medium to distinguish user data in the overlapping channel and is the heart of Interleave Division Multiple Access (IDMA) scheme. Versatility of interleavers relies on various design parameters such as orthogonality, correlation, latency and performance parameters like bit error rate (BER), memory occupancy and computation complexity. In this paper, a comprehensive study of interleaving phenomenon and discussion on numerous interleavers is presented. Also, the BER performance of interleavers using IDMA scheme is displayed.

Keywords: Interleaver; Interleave Division Multiple Access (IDMA); Random Interleaver (RI); Tree Based Interleaver (TBI); Prime Interleaver (PI); Master Random Interleaver (MRI); Flip Left-Right Approach Based Inverse Tree Interleaver (FLRITI); Multiplicative Interleaving with Tree Algorithm (MITA)

MSC 2010 No.: 00A06, 11Y16, 65K05, 93A30

1. Introduction

Wireless communication has gained importance with the evolution of technology, but this has an adverse effect on the reliability of wireless channel. The increased number of signals over same bandwidth has increased interference in medium which resulted in error in the received signal. These errors can be rectified by the optimum choice of 3G/4G multiple access technique (Fan (2006); Andrews (2005)) such as Orthogonal Frequency Division Multiple Access (OFDMA), Code Division Multiple Access (CDMA) and Interleave Division Multiple Access (IDMA). OFDMA assists in reducing inter symbol interference (ISI) and intercarrier interference (ICI) (Prasad (2004); Hwang et al. (2008)). CDMA scheme mitigates the effect of fading by employing different spreading codes (Lee (1991); Hara and Prasad (1997)). Recently proposed IDMA scheme helps in nullifying the effect of burst error by employing user defined interleaving sequences (Ping et al. ((2006); Ping et al. (2003)).

The IDMA scheme is a derivative of CDMA technique (Kusume et al. (2011)) and incorporates the advantages of latter. The distinguishing feature of IDMA is that the error-free transmission is feasible by randomizing the data using user specific interleaver sequence. Forward Error Correction (FEC) techniques are effective if the number of errors is less than hamming distance. Sometimes burst error causes greater error in the system making detection difficult thus need for IDMA scheme is felt. The burst error is also referred as group error as it affects a group of consecutive interleaved bits in the signal while passing through the medium. De-interleaving process at the receiver rearranges the bits back to their original positions and thus burst error is dispersed throughout the sample.

Interleavers, heart of IDMA system, have been widely employed in varied environments for numerous applications. The three most commonly used environments are Wireless, Powerline and Underwater. Wireless channel has been an optimum choice for researchers to study the performance of various interleavers and compare them over IDMA (Raje and Markam (2018); Patii and Biradar (2017); Martinez et al. (2019); Sharma et al. (2017)). Some scholars moved a step ahead and analyzed the performance of interleavers on OFDM-IDMA and SC-FDMA-IDMA systems (Yadav et al. (2016)), as the performance is upgraded by employing grouped IDMA schemes. Authors have also implemented and analyzed interleavers over Powerline channel (Shukla et al. (2013); Agarwal and Shukla (2020)) and Underwater channel (Pande et al. (2014); Tripathi and Shukla (2016)), which are emerging as the area of interest for research in terms of communication. Quite recently in Aimer et al. (2017) and Dixit and Shukla (2017), interleaver was employed to reduce peak to average power (PAPR) in OFDM-IDMA and SCFDMA-IDMA systems. Thus, interleavers play an important part in deciding the performance of IDMA system.

In literature various interleavers are proposed such as Random, Master Random, Tree, Prime, etc., each having its own benefits. In this paper, the basic principle and design parameters of interleavers are discussed. A comprehensive study of diverse interleavers and comparative analysis is carried out along with recently proposed MITA interleaver. The paper is divided into sections as follows. Section 2 deals with the description of iterative IDMA model. The importance of interleaving along with the features of optimum interleaver is described in Section 3. Interleavers are discussed along with their algorithms in Section 4. In Section 5 comparative study of interleavers on the basis of computational complexity and memory consumed is presented. Lastly, the paper is concluded in Section 6.

2. Iterative IDMA System Model

The block diagram of IDMA scheme given in Figure 1 is comprised of a transmitter, channel and receiver. The transmitter section has an encoder, spreader which is same for all users, interleaver block, and lastly signal combiner to combine the signals before transmitting over multipath channel. In the paper Additive White Gaussian Noise (AWGN) channel is considered to have more focus on the interleaver behavior.

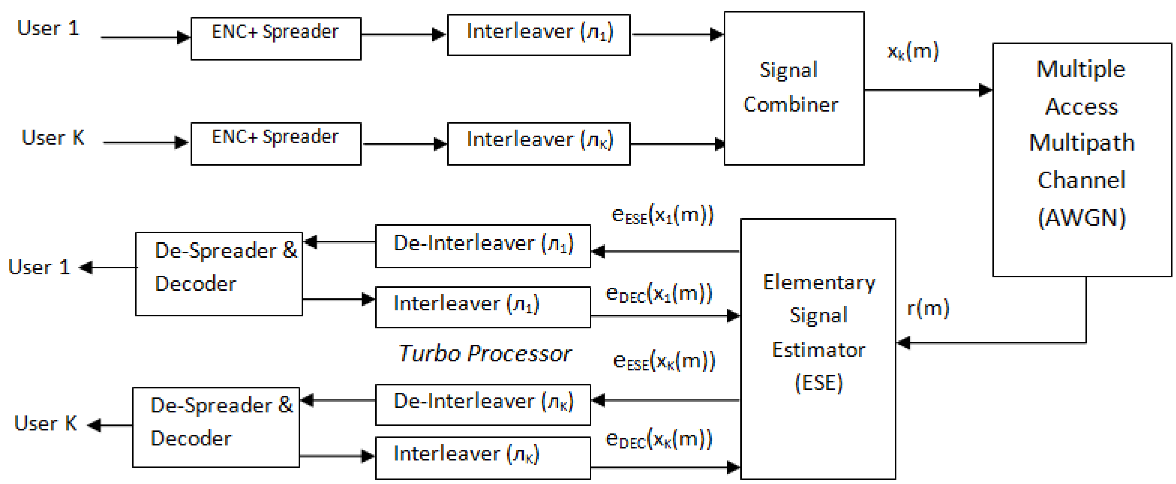


Figure 1. Block Diagram of Iterative IDMA System

The receiver includes elementary signal estimator (ESE), pair of de-interleaver and interleaver, despreader and decoder and functions as a chip by chip detector. The entire assembly at the receiver is also referred as Turbo processor (Cristea (2009); AlRustamani et al. (2001)). The role of ESE is compute the mean and variance of received signal in order to calculate the log likelihood ratios (LLR) which serves as the input to de-interleaver block. The de-interleaved signal is fed to despreader and decoder block which is abbreviated as DEC. The DEC serves to compute the mean and variance of the decoded and de-spread signal which is interleaved and fed back to ESE.

The IDMA system in Figure 1 is designed for K consecutive users having length of data as N. The data of user k, $a_k = [a_k(1), .., a_k(i)..a_k(N)]$ is encoded by employing Convolution Code of rate ½ and memory 2 to $b_k = [b_k(1), .., b_k(j), ..b_k(J)]$, where J is the new data length. Next, spreading operation is performed on the coded bits b_k via a spreading sequence $S = [+1, -1, +1, -1. \ldots \ldots]$ of length sl to produce s_k which is then interleaved using user defined permutation algorithm π_k to produce the chip sequence $x_k = [x_k(1), .., x_k(m), .., x_k(M)]$, where $M = J * sl$. Lastly, signal from all users are combined to transmit over multiple access AWGN channel. The received signal

r_k can be written as:

$$r(m) = \sum_{k=1}^{K} = h_k x_k(m) + \eta(m), \forall m = 1, 2, \ldots, M, \tag{1}$$

where h_k is the channel transfer function for k^{th} user and $\eta(m)$ resembles the noise of the AWGN channel with mean $\mu = 0$ and variance $\sigma^2 = No/2$. An assumption is made that channel transfer function is known at the receiver beforehand. The IDMA scheme performs chip by chip detection therefore the received signal for a chip: $r(m) = h_k x_k(m) + \xi(m)$, where $\xi(m) = r(m) - h_k x_k(m) = \sum_{k \neq k} h_k x'_k(m) + \eta(m)$. The $\xi(m)$ is assumed to have Gaussian distribution and $r(m)$ is considered as a conditional PDF (probability density function). The important aspect of ESE is that it helps in suppressing the interference and thus increases BER performance. The output of ESE and decoders are expressed as extrinsic log-likelihood ratios (LLR's) and is given as:

$$e(x_k(m)) = log(\frac{p(y/x_k(m) = +1)}{p(y/x_k(m) = -1))}), \forall k, m, \tag{2}$$

where y is the input to the block. The LLR's are denoted as e_{ESE} and e_{DEC} depending on the generation from ESE or DEC block (Ping (2005)). The steps of the iteration process are as follow:

Step 1: Updating the values of Mean and Variance
Initially, $e_{DEC} x_k(m) = 0$. Then,

$$E(r(m)) = \sum_{k} h_k E(x_k(m)), \tag{3}$$

$$Var(r(m)) = \sum_{k} |h_k|^2 Var(x_k(m)) + \sigma^2. \tag{4}$$

Step 2: Generating LLR's

$$e_{ESE}(x_k(m)) = 2h_k \frac{r(m) - E(r(m)) + h_k E(x_k(m))}{Var(r(m)) - |h_k|^2 Var(x_k(m))}. \tag{5}$$

Step 3: Updating Data

$$e_{DEC}(x_k(\pi(j))) = \sum_{j=1}^{J} e_{ESE}(x_k(\pi(j))). \tag{6}$$

The steps are iterated for specified number of times before performing a hard decision on the output data.

3. Interleaving

In the communication system, interleaving acts as a savior by protecting the signals in the communication channel from burst error which cannot be rectified by error correction methods due to large hamming distance (Fabregas et al. (2008); Herzberg (1998)). It has gained importance as the burst error in the channel affects the consecutive bits making the error correction technique redundant and in some cases the entire symbol might get corrupted. In mathematical terms interleaving is a bijective function (Andrews et al. (1997)) which can be expressed as: $\pi : X \to X \mid b_i = a_{\pi(i)}$, where π is the bijective mapping function, X is the data set, a is the original data sequence, b is the interleaved data sequence. The pictorial representation of interleaving mechanism is laid out in Figure 2.

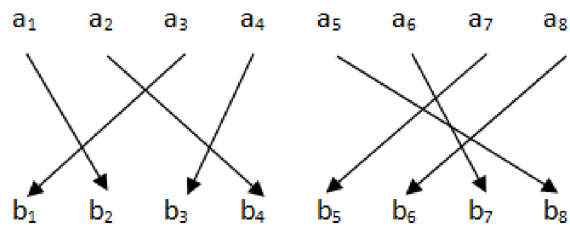


Figure 2. Basic Interleaving Mechanism

From Figure 2 it can be deduced that interleaving is a one-to-one mapping and onto function as each element of sequence a is present in b but at different physical location. Interleaving process is denoted by π and de-interleaving by π^{-1} commonly. The proper combination of interleaving and de-interleaving can result into original sequence and it can be given as: $\pi^{-1}(\pi(i)) = \pi(\pi^{-1}(i)) = i$. The design efficiency of an interleaver in turbo processor plays a vital role in the performance of the system as it can aid in achieving data rates up to Shannon capacity. The selection of an optimum interleaver relies on various factors (Ioachim et al. (2006); Ren et al. (2013); Li et al. (2007)) such as:

- Generation and Computation Complexity: The interleaver sequence generation for multiple users should not be a cumbersome process. The birth of new interleavers should involve less mathematical computations and less clock cycles thereby having less complexity and latency.
- Correlation: The correlation defines the association between two signals which should be low in case of interleavers, as the interleaved sequences are combined before transmitting over the channel. If the correlation is high, the segregation of combined sequences at the receiver would be difficult. The correlation between two data sets can be evaluated by the scalar product of data sets which can be represented as: $P(\pi_i, a, \pi_j, b) = \langle \pi_i(f(a)), \pi_j(f(b)) \rangle$ in mathematical form, where (π_i, π_j) are two interleaving sequences for data a and b, respectively.
- Orthogonality: The condition for orthogonality for two interleavers (π_i, π_j) for two data a, b can be stated as: $P(\pi_i, a, \pi_j, b) = \langle \pi_i(f(a)), \pi_j(f(b)) \rangle = 0$. Orthogonality condition ensures that the two interleaved sequence will not collide on passing through same channel, thereby exhibiting superior performance.
- Memory and Bandwidth Required: The interleaving sequences applied at the transmitter is required at the receiver for de-interleaving, thus memory occupied and bandwidth consumed plays a major role in selection of interleaver algorithm.
- Bit Error Rate (BER): Bit error rate stands for the ratio of errors to the total number of bits. The BER of the signal should be as less as possible and the interleaver algorithm having least BER is the best.

Interleaver design is evaluated based on the parameters mentioned above and facilitates in the selection of optimum interleaver for a particular application.

4. Interleavers

4.1. Random Interleaver (RI)

Random Interleaver is the most simple and easy to generate and serves as the building block for other interleavers. The principle is to permute the bits according to the random interleaving pattern generated at the transmitter (Darmon and Sadot (1989); Blazek et al. (2001)). The algorithm is quite straightforward but for RI deployment the Base Station (BS) must have huge memory and bandwidth available as all the interleaving sequences have to be transported to receiver de-interleaving. Thus, a trade-off exists, greater the number of users, simplicity of generation but higher is the bandwidth consumption. The algorithm for a single user having data length as dl is given below:

For1 $\forall$ *d, starting from d=1 to dl*
rep=Generate a number randomly between 1 to dl
swap chip position of A(1, d) and A(1, rep)
set d=d+1
End For1

4.2. Master Random Interleaver (MRI)

MRI is a derivative of RI and employs a master random sequence for the generation of multiple interleavers. It is also referred as power interleaver as the subsequent interleaver is the power of the master random interleaver (Wu et.al (2006)). The principle of interleaver (π) generation is explained: Let $\pi = \phi(y)$ be the MRI, then the interleaver for the first user is $\pi_1 = \pi$, second user $\pi_2 = \pi(\pi_1) = \pi^2$, third user $\pi_3 = \pi(\pi(\pi_1)) = \pi^3$ and similarly for n^{th} user is $\pi_n = \pi^n = (\phi(y))^n$, thus the interleavers are power of MRI corresponding to their index numbers. An advantage of MRI over RI is less bandwidth and memory requirement as only master random sequence is necessary for de-interleaving, but at the cost of computation complexity as for generation of interleaving sequences powers of master sequence is to be computed. Additionally time delay increases in the system as for k^{th} user generation of interleaver π_k requires time. The algorithm of generation of MRI for N users and data length dl is shown below:

Generate master interleaving sequence using RI for user 1
For1 $\forall$ *n , n=2*
For2 $\forall$ *d, starting from d=1 to dl*
A(n,d)= A(n-1, A(n-1,d))
Set d=d+1
End For2

Set n=n+1
End For1

4.3. Prime Interleaver (PI)

The prime interleaver relies on a prime number, referred to as seed to generate permuting sequences for users. The seed should be chosen within the data length boundaries. The benefit is that only seed has to be transmitted for regeneration of interleavers thus tremendous reduction in memory occupied is observed (Shukla and Gupta (2010); Gupta et al. (2010)). The permutation sequence is generated by using the formula: $(1 + data * seed) mod (datalength)$. Assume seed to be 5, data length as 8 and data as $(1, 2, 3, 4, 5, 6, 7, 8)$, then the permutation sequence is computed as:

$1 \rightarrow$ (1+1*5) mod 8 =>6	$2 \rightarrow$ (1+2*5) mod 8 =>3
$3 \rightarrow$ (1+3*5) mod 8 =>8	$4 \rightarrow$ (1+4*5) mod 8 =>5
$5 \rightarrow$ (1+5*5) mod 8 =>2	$6 \rightarrow$ (1+6*5) mod 8=>7
$7 \rightarrow$ (1+7*5) mod 8 =>4	$8 \rightarrow$ (1+8*5) mod 8 =>1

The interleaved data for first user (π_1) is $(6, 3, 8, 5, 2, 7, 4, 1)$. For the second user interleaving sequence of first user is considered as data and so on. This method is profitable for small number of users but for greater number of user, probability of cross correlation becomes high and thus increasing interference in the system. The algorithm for the same N users and data length dl is given below:

Select any prime number; seed
For1 ∀ n , n=1 to N
Initialize array : A(n,:)= serial numbers from 1 to dl
Set k=n
For2 ∀ d, starting from d=1 to dl
*Compute k=1+ (seed*k)*
If k> dl, then divide k by dl and assign it to k
End If
swap chip position of A(n, d) and A(n, k)
Set d=d+1
End For2
Set n=n+1
End For1

4.4. Tree Based Interleaver (TBI)

The Tree based interleaver was proposed by Shukla, M. (Shukla et al. (2008); Shukla et al. (2009)). It was designed to reduce computation complexity and memory requirements as compared to MRI and RI, respectively. The principle of interleaver generation depends on two random interleaver π_1 and π_2 for users 1 and 2, which are tested for orthogonality to ensure less interference. The users in each level are given as $2n$ and the diagram is shown in Figure 3. The users having odd sequence are allotted upper branch, whereas users with even sequence are assigned lower branch. For simplicity interleaver generation up to 14 users (or 3 stages) is shown and from the diagram the tree shape is visible. The most prominent advantage of TBI is the clause of orthogonality which was lacking with existing interleavers along with less memory requirement and reduced computation complexity. The algorithm for N users having data length as dl is given as:

Generate 2 random interleaver π_1 *and* π_2 *for user 1 and user 2*
% Compute the number of levels i
For1 i=1:i
For2 j=1: 2(i-1)
For3 $\forall$ *d, d=1 to dl*
Interleaver (user(j)+ 2(i-1), d)= Interleaver (user(j), π_1*(d))*
Interleaver (user(j)+ 2(i), d)= Interleaver (user(j), π_2*(d))*
End For3, For2, For1

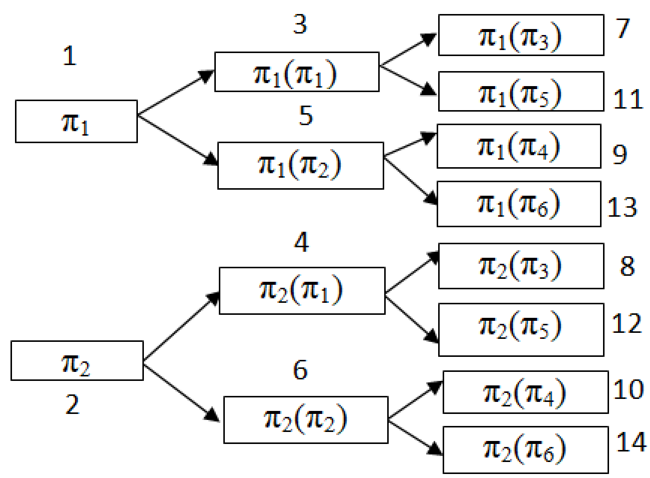


Figure 3. Mechanism of Tree Interleaver

4.5. Flip Left-Right Approach Based Inverse Tree Interleaver (FLRITI)

This interleaver is derived from TBI as is evident from the title and follows tree structure. The modification is, instead of two different random interleaver π_1 and π_2, the second master interleaver is inverse of first, i.e., $\pi_2 = \pi_1^{-1}$ (Yadav et al. (2017); Yadav et al. (2019)) and the operation is performed by employing a shift register. The advantage is reduced memory and bandwidth consumption as only one interleaver has to be transmitted for de-interleaving at the receiver, with same performance as TBI. The algorithm is same as TBI with the only the modification: $\pi_2 = \pi_1^{-1}$.

4.6. Multiplicative Interleaving with Tree Algorithm (MITA) Interleaver

Recently proposed MITA interleaver is derived from TBI and follows its structure (Agarwal and Shukla (2021)) but has significant differences. The users in each stage in MITA are computed as: $3x(n-1)-1$, where $x(n-1)$ are the users in previous stage and in TBI users are given as $2n$, where n is the stage number. The mechanism of MITA interleaver is shown diagrammatically in Figure 4. On comparing Figure 3 and Figure 4, it can be observed that user in each stage in MITA is greater than TBI and also every alternate user is the reciprocal of the previous one thus saving computations. The computation complexity of MITA interleaver is less than TBI and FLRITI but more than RI. However, the memory required by MITA and TBI are same but one interleaver space greater than TBI.

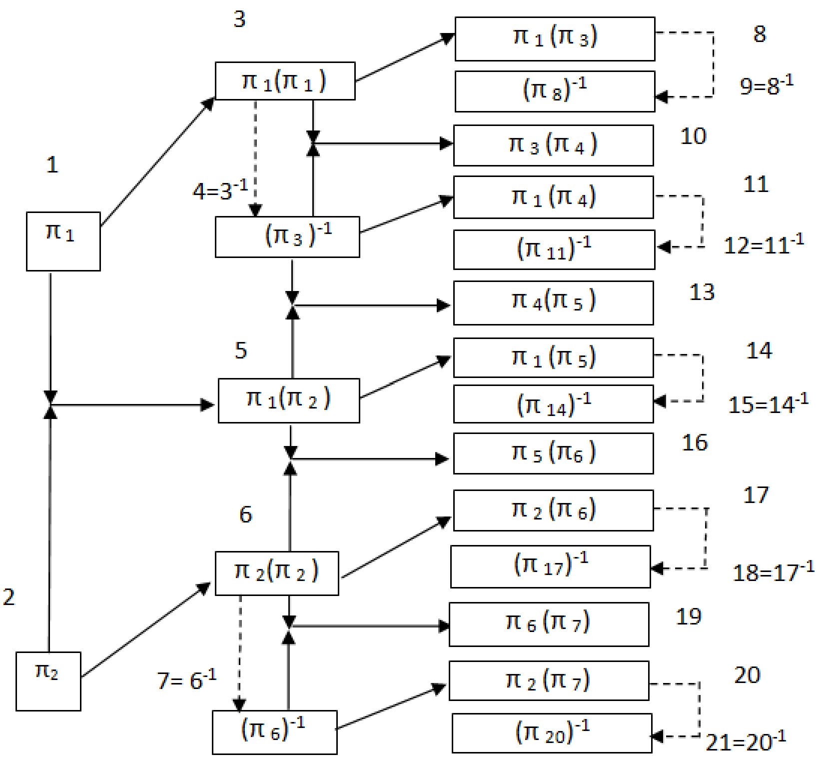


Figure 4. Mechanism of MITA Interleaver

The interleaver for user 1 and 2 is generated randomly first by using the algorithm of RI, the algorithm for remaining users is given below:

Initialize: var=1
For1 $\forall$ *a, a=2 to No. of stages*
p=sum of users till stage a
For2 $\forall$ *b, b=1:3:*$3^{(a-1)}$
Interleaver of $\pi_{user(b+p)} = \pi_1 \pi_{var}; \pi_{user(b+p+1)} = (\pi_b)^{-1}; \pi_{user(b+p+2)} = \pi_{var}\pi_{var+1}$
Set var=var+1
End For2

For3 c= ($3^{(a-1)}$+1):3: (users in current stage)
Interleaver of $\pi_{user(c+p)} = \pi_2\pi_{var}; \pi_{user(c+p+1)} = \left(\pi_{user(c+p)}\right)^{-1};$
If4 c+p+2<= total users till current stage
$\pi_{user(c+p+2)} = \pi_{var}\pi_{var+1}$
End If4
Set var=var+1
End For3, For1

5. Comparison of Interleavers

In this section the interleavers are compared on the basis of memory required, computing complexity and bit error rate (BER). Memory required is defined in terms of number of interleaver sequence that has to be transmitted along with the modulated data for the process of de-interleaving at the receiver. Computation complexity is defined as the number of cycles needed for generation of interleavers for given number of users. Table 1 lists the memory required and Table 2 lists the computation complexity by various interleavers.

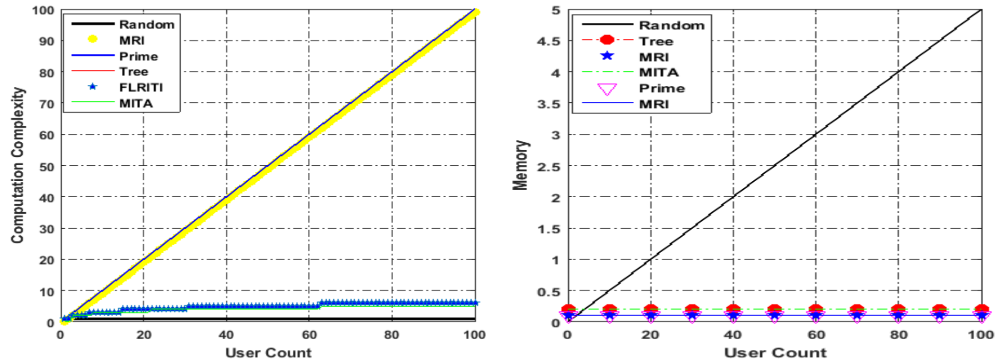
Table 1. Comparison of Interleavers on the basis of Memory required

S. No.	Users	Random Interleaver	Master Random Interleaver	Prime Interleaver	Tree Based Interleaver	FLRITI	MITA Interleaver
1	2	2	1	1	2	1	2
2	6	6	1	1	2	1	2
3	14	14	1	1	2	1	2
4	30	30	1	1	2	1	2
5	62	62	1	1	2	1	2
6	126	126	1	1	2	1	2

Table 2. Comparison of Interleavers on the basis of Computation Cycles required

S. No.	Users	Random Interleaver	Master Random Interleaver	Prime Interleaver	Tree Based Interleaver	FLRITI	MITA Interleaver
1	2	1	1	1	1	1	1
2	6	1	5	5	2	2	2
3	14	1	13	13	3	3	3
4	30	1	29	29	4	4	4
5	62	1	61	61	5	5	4
6	126	1	125	125	6	6	5

From Table 1 and Table 2, it can be observed that RI has highest memory requirement and lowest complexity and MITA has low memory requirement and computation cycles depend on number of user. In comparison to TBI and FLRITI, as the user count increases the clock cycles required in MITA is less, thus MITA can be preferred for large number of users. However, if both memory required and computational complexity are considered the most probable option would be MITA interleaver as with slightly more memory, it provides the benefit of reduction in computation complexity. The comparison of both parameters is plotted graphically and is shown in Figure 5(a) and 5(b).



(a) Computation Complexity

(b) Memory Required

Figure 5. Graphical Representation of Computational Complexity and Memory Required by Various Interleavers

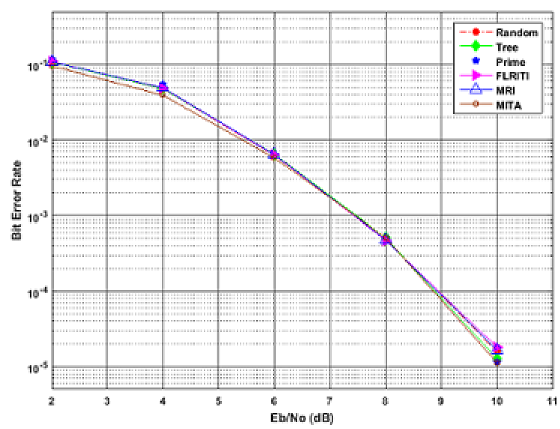


Figure 6. Comparison of Interleavers over IDMA System in AWGN Environment

Next, comparison of interleavers has been carried out on the basis of BER in MATLAB environment. For better understanding of the performance of interleaver simple BPSK modulation and AWGN channel is assumed. For simulation the number of users was taken as 16, data length as 1024 and iterations in IDMA receiver were taken as 10. The graph is shown in Figure 6. From Figure 6, it can be observed that MITA interleaver behaves at par with the other interleavers, thus for applications requiring low computation complexity and simple memory requirement MITA interleaver can be preferred. The next simulation demonstrates the performance of multiple interleavers for variation in user count. From Figure 7, it can be deduced that MITA interleaver performs at par with Random and Tree interleaver for user count $= 16$, but the performance improves as the user count was increased to 32, thus in scenarios with large number of user MITA interleaver is viable candidate.

In the next graph, Figure 8 was plotted for variation in user count using MITA interleaver having data length as 128 and iteration count as 15. With increase in number of users BER performance de-

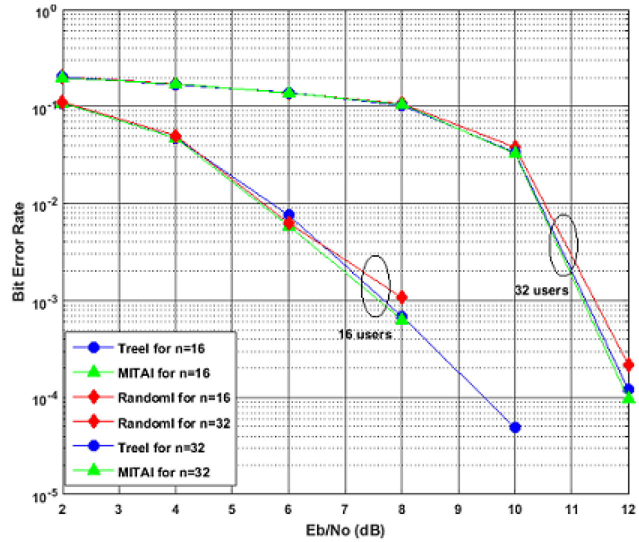


Figure 7. Simulation results for Random, Tree and MITA interleaver for user count 16,32

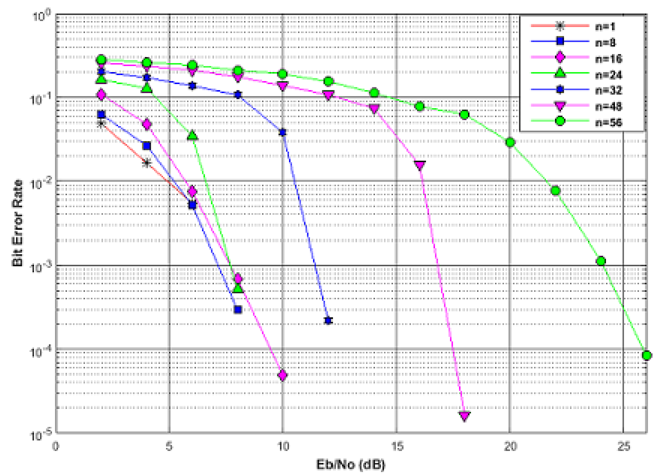


Figure 8. Performance of MITA interleaver for various users count in AWGN Environment

grades as interference in channel increases. Lastly, performance of MITA interleaver was evaluated for varying data lengths and is shown in Figure 9. The BER performance improves with increase in data length, as higher the data length, larger is the probability of orthogonality in interleavers and thus low interference.

6. Conclusion

Interleavers are widely deployed in IDMA system as it reduces burst error and it forms the heart of scheme. In this paper, algorithms of multiple interleavers and comparison on the basis of computational complexity, memory required and BER is presented. On analyzing memory consumption, RI has the highest requirement and the other mentioned interleavers have almost the same need, whereas for computing cycles RI and MITA interleaver has the least demand. Overall, MITA interleaver outshines all the other interleavers as it has same memory requirement but low com-

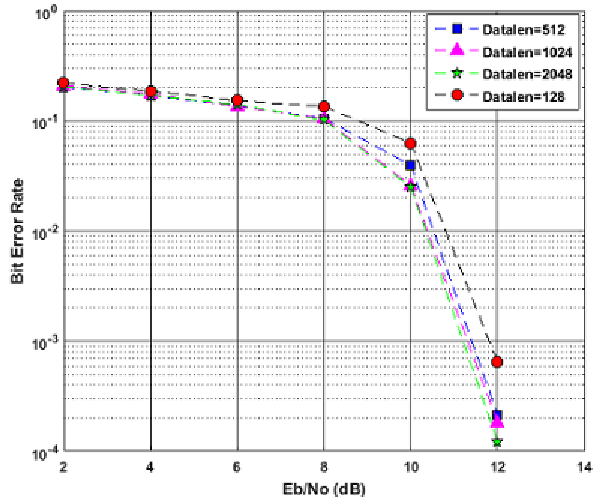


Figure 9. Simulation of MITA interleaver for variation in data length

putational complexity which is an important parameter in IDMA systems. Next comparison of interleavers in terms of BER was performed over MATLAB environment, where MITA interleaver performed comparable to RI and TBI but for higher user count MITA interleaver performed better. Thus with reduced computation complexity and better performance for large user count MITA interleaver can be substituted in place of TBI. In future, comparison of interleavers could be performed on grouped IDMA scheme for different modulation schemes.

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