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# MAI Cancellation in MCCDMA Systems Using Adaptive Chip Interleaving Technique

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## ABSTRACT
The Multi-Carrier Code Division Multiple Access (MC-CDMA) is a powerful candidate for the current and next generation wireless systems. The adaptive interleaving techniques with limited feedback approach have been analyzed for breaking the interference limitation to further enhance the capacity of MCCDMA systems. When the channel is quantized for reducing the number of Channel State Information (CSI) bits and the processing load, the orthogonality of the user signals cannot be perfectly retained owing to inborn quantization error. This results in Multiple Access Interference (MAI). Hence, a novel codebook based adaptive chip interleaving technique is proposed to obtain the optimum interleaving patterns adaptively according to the propagation conditions for mitigating the MAI. As an alternate to the quantized CSI feedback, an algorithm for the codebook design is developed to create the address of the prestored interleaving patterns based on maximum signal to noise ratio criterion. The simulation result shows that the MCCDMA system using the proposed codebook based adaptive chip interleaving technique achieves significant performance improvement in terms of Bit Error Rate (BER) compared to the conventional MCCDMA system and existing chip interleaving techniques. It also shows that this reduces the quantization error and requires limited number of bits as codebook index for the feedback.

**Key words:** Multicarrier code division multiple access, multiple access interference, limited feedback, quantization error, channel state information, interleaving patterns

## INTRODUCTION
In the multipath propagation environment, the signals suffer from frequency-selective fading channel effects. This results in loss of orthogonality of the user codes and increase in Multiple Access Interference (MAI), strongly degrades the performance of the MCCDMA system (Fazel and Kaiser, 2008). Various interference suppression approaches has been developed like beamforming, multiuser detection, adaptive supervised and blind algorithms and transmits processing methods demanding a limited feedback channel (Love *et al*., 2008; Xu *et al*., 2008). The different advanced versions of multiuser detection techniques have been developed for interference suppression in the last decade. Nevertheless, all these methods are unfamiliar in the downlink scenario because of too much power consumption and high complexity in the receiver sections (Zahedi and Bakhshi, 2013). The user capacity of CDMA can be increased substantially by effective system design both at transmitters and receivers through MAI cancellation. Considering the MAI cancellation, a combination of pre-filtering technique in the transmitter side and single user detection technique

such as Equal Gain Combing (EGC) or Maximal Ratio Combining (MRC) schemes in the receiver side was proposed (Chang *et al.*, 2013). In this method, the gain of the each subcarrier is varied in order to reduce the interference and obtain undistorted signal output at the receiver. However, the estimated signal weights for each receiver are not optimum to cancel MAI using pre-filtering technique and it is computation dependent.

The next generation of wireless mobile communication systems is projected to exploit channel adaptive techniques (Sharif and Hassibi, 2005). In this approach, the signals of the transmitter are designed to adjust as per the existing propagation conditions. This requires details of Channel State Information (CSI) for the transmitter so as to modify the signal to be transmitted. The literature on channel adaptive methods for the DS-CDMA systems using adaptive spreading techniques have been analyzed (Rose *et al.*, 2002). An optimization approach has been developed based on evaluation of individual updates for single path channels. Another method (Rajappan and Honig, 2002), applied the alternating update algorithms for joint transmitter-receiver adaptation in the multipath environment. The performance is analyzed based on evaluation of transmitter coefficients where short signature sequences are considered in this case. The signal adaptation in combination of CDMA and MIMO systems is reviewed (Dai *et al.*, 2009) for interference suppression. The suitable signature sequence vector is selected based on signature optimization and beamforming vector selection from the codebook for the specified user and the corresponding index is sent to the transmitter with limited feedback approach.

Besides, the combination of multiple antenna schemes and transmit processing techniques are carried out in the Base Station (BS) (Masouros and Alsusa, 2009) and possibility of simple receiver structures in the Mobile Station (MS). This approach assigns processes of signal precoding and signal adapting to the propagation condition in the BS in order to mitigate the MAI. Another precoder optimization scheme was proposed for the capacity and diversity gains based on the well-known iterative interference leakage minimization scheme (Liu *et al.*, 2014). The computational complexity of this scheme and the effects of imperfect channel state information on the performance are not optimum. In the opposite side, it needs details of the perfect CSI to perform these tasks. This makes extra processing load and feedback of CSI details from the receiver section. Hence, the limited feedback approach (Dabbagh and Love, 2008; Kim *et al.*, 2011) are reviewed for reducing the complexity of processing CSI bits. In particular, the studies in Ding *et al.* (2007) downlink channel states are mapped to quantize the information and feedback these reduced details to the transmitter. On the other hand, estimate of uplink channel states are used by the downlink systems such as TDD/FDD systems. Also, the receivers are designed to process the channel states based on some functions and send these reduced number of CSI bits as feedback to the transmitter. This feedback about channel states is used by the transmitter to process and transmit efficient signal over the channel. In Ding *et al.* (2010), the system based on limited feedback was developed which finds details corresponding to precoding and beamforming for interference suppression. However, prior works (Ding *et al.*, 2007, 2010; Dabbagh and Love, 2008) has considered the channel quantization techniques for limited feedback and performance based on the number of feedback bits. Especially, for time-varying fading channels, this conclude that the sufficient number of feedback bits were required for reasonable performance. The limited feedback approaches in Trivellato *et al.* (2007) and Yoo *et al.* (2007) also provides many improvements. Recently, the combination of MCCDMA techniques and multi-antenna schemes were developed for the enhancement of the system capacity and performance.

On the other side of limited feedback approach, the orthogonality of the user signal is lost due to quantization error when the channel states are quantized for reducing the feedback bits. Large quantization error and the significant number of feedback bits in multiuser preprocessing systems with limited feedback occurs (Islam and Adve, 2011). Unitary codebook design problems for various precoded MIMO scenarios and their interpretation of generalized discretization problems of flag manifolds is considered in Pitaval *et al.* (2013). The limited feedback using Block Diagonalization (BD) was proposed in multiuser MIMO channels (Moon *et al.*, 2014). This finds quantized CSI feedback information for maximum SNR and achieves significant rate gain. The complexity of limited feedback approach is increased further in MIMO systems as analysis considers the multiuser scenario.

A novel codebook based adaptive chip interleaving technique is proposed here to mitigate the MAI for MC-CDMA systems and reduce the quantization error. It is developed based on new limited feedback approach which sends the feedback of the address bits of the interleaver instead of sending the quantized CSI. For this propose, bank of chip-interleavers and codebook with selected interleaving patterns are designed. In order to construct the codebook, mapping function is developed based on maximum SNR (MSNR) criterion for every branch. It finds the interleaving patterns with maximum SNR of quantized CSI among all the users in the receiver while considering the spreading sequences and channel coefficients. These interleaving patterns can be selected from the codebook by the address bits of the interleaver in the transmitter and receiver sections simultaneously. In order to retain the orthogonality of the user signals with respect to the existing channel conditions, the transmitter finds the optimum interleaving pattern adaptively from the codebook to permute with data block.

The main contributions of this study are:

- Adaptive chip-interleaving technique with limited-feedback based on of maximum SINR criterion are proposed for increased robustness against channel variations in downlink MCCDMA systems
- Algorithm for mapping function to obtain address of optimum interleaving
- Interleaving codebook design based on maximum SNR criterion
- Performance improvement of MCCDMA system with proposed technique is evaluated
- Simulation results are discussed to show the capability of the proposed technique and it outperforms the conventional MCCDMA system and existing chip interleaving techniques

## METHODOLOGY

**System description:** Figure 1 describes a simple from of the transceiver construction of MCCDMA system using proposed codebook based adaptive chip-interleaving technique. It considers data block

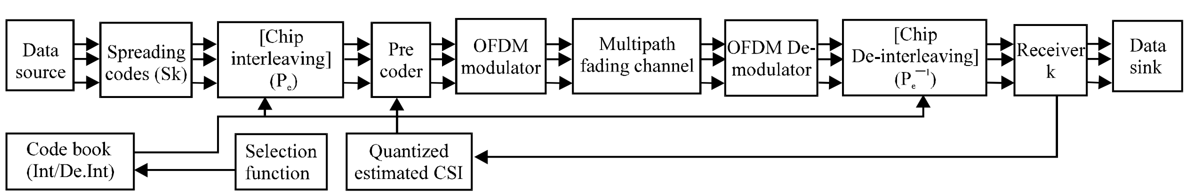


Fig. 1: MCCDMA system with codebook based adaptive chip-interleaving technique

of M symbols, G chips per symbol, spreading codes of $C_1...C_k$ for the K users and $N_t$ transmit antennas. The data $b_k(i) = [b_1^{(k)}(j)... b_M^{(k)}(j)]^T$ represents the j-th block which is assigned to user k and is given by $b_m^{(k)}(j) \in\{\pm 1\}$, where, m = 1 to M, k = 1 to K. The source information of one data bock for each user k is interleaved before the precoding process and is given by:

$$x_k^{(g)} = A_k \ \pi_g \ C_k \ b_k \tag{1}$$

where, $\pi_g$ is the interleaving matrix and $A_k$ is the amplitude associated with user, k.

All the transmitters and the receivers are set up with bank of same chip-interleavers and codebook with selected interleaving patterns. As in Heo *et al.* (2008), the channel characteristics are assumed to be constant per symbol duration and channel coefficients are updated for one block length. In the receiver, the mapping function finds the optimum interleaving patterns corresponding to the maximum SNR of quantized CSI among all the users by considering the spreading sequences and predicted channel coefficients. Also, it indicates the address of the interleaver. This address is updated in block basis in the receiver section and feedback to the transmitter. In the transmitter, the suitable interleaving patterns from the codebook can be selected by these address bits of the interleaver in order to retain the orthogonality of the user signals. Then it is interleaved with incoming data block for signal transmission. On the other hand, the received signal are separated into original data block by the corresponding chip-deinterleaver and then passed to the receivers.

The matrix $\pi_g$ represents the gth interleaving matrix of size MG×MG where g = 1...$2^B$ and B is the size of address bits of the interleaver. It is constructed by the selected interleaving patterns of the codebook where the number $2^B$ is size of the interleaver codebook. The quantity $C_k = c_k(X) \ I_M$ is the spreading code of matrix size, MG×M and $I_M$ denotes an M×M identity matrix. The signal of all the users after interleaving with block of permutated chips is represented as $X^{(g)} = [x_1^{(g)}... x_k^{(g)}]^T$, of matrix size, K×MG. The quantity $P_i$ is the gain of precoding for i-th chip of matrix size, G×K and is written as:

$$P_i = [p_1^{(i)}... p_k^{(i)}] \tag{2}$$

where, i = 1... MG and $p_k^{(i)}$ is k-th user precoding vector of size G×1 for the i-th chip. With the aid of the MG-point FFT and IFFT and a cyclic prefix, the multipath fading channel can be divided into MG narrowband channels in frequency domain (Wang and Giannakis, 2000).

Before the deinterleaving process, the received vector, $Q_{i,g}$ of size, K×1 consist of collection of all the users for ith received chips and it is denoted as:

$$q_{i,g} = H_i P_i X^{(g)} \ (:,i \ ) + n_i^{\sim} \tag{3}$$

where, the operation (:,y) is taking the y-th column of a matrix; K×$N_t$ matrix $H_i$ is the equivalent channel matrix for the i-th chip and the K×1 noise vector $n_i^{\sim} = [n_{1,i}^{\sim}... n_{k,i}^{\sim}]^T$. The quantity $Q_g = [q_{1,g}... q_{MN,g}]$ is the collection of received chips of matrix size, K×MG within one block regarding all the subcarriers. After deinterleaving process, the received signal vector for the m-th symbol corresponding to the user $k_0$ is given by:

$$r_{k0,g}^{(m)} = \pi_i^{-1} Q_g^T = \sum_{k=1}^{K} A_k c\sim_{k,k0,g}^{(m)} \ b_m^{(k)} + n_m \tag{4}$$

where, the quantity $\pi_i^{-1}$ is the deinterleaving matrix. The quantity, $n_m$ is the N×1 deinterleaved noise vector with $E[n_m\ n_m^H] = \sigma^2 I_N$. The quantity $c\sim_{k,k0,g}^{(m)}$ is the spreading code of size, MN×1, pertaining to the g-th interleaver and user $k_o$ channel and is written as:

$$c\sim_{k,k0,g} = \pi_i^{-1}[H_i\ (k_0,:)\ p_k^{(i)}\ (\pi_{k,g})_i]^T \tag{5}$$

where, $k_0 = 1...$ K and i = 1... MN for the mth symbol. The MN×1 sized vector of $c_k$ is computed from the M copies of the k-th user's spreading code vector on top of each other.

**Proposed adaptive chip interleaving technique:** The mapping functions are developed to select the best interleaving patterns in the codebook with address corresponding to the maximum SNR of quantized CSI. The SNR of quantized CSI is computed for every branch among all the users in the receiver using the spreading sequences and channel coefficients. Then, the mapping function determines the interleaving patterns for the given users with respect to the maximum SNR.

The received SNR of the gth branch for the given user $k_o$ is given as:

$$SNR_g^{(k0)} = \frac{A_{k0}^2 \| C_{K0,K,g}^{\sim} \|^2}{\sum_{k\neq k0} A_K^2 C_{K0,K,g}^{\sim H} + \sigma^2 \| C_{K0,K,g}^{\sim} \|^2} \tag{6}$$

where, numerator represents the signal component, the first part of denominator represents the interference component and the second part of denominator represents the noise component. The mapping function finds the best address, $g_{opt}$ with respect to the maximum SNR and send to the transmitters. The optimum address is given as:

$$g_{opt} = \arg\max \left\{ \sum_{k=1}^{K} SNR_g^{(k)} \right\} \tag{7}$$

The demodulated output of the m-th symbol is obtained from the correlation between received signal of user, $k_o$ and effective spreading code corresponding to user, $k_o$ channel information and is given by:

$$b_{k_0}^{(m)} = \text{sgn}[R(c\sim_{k_0,k_0,gopt}^{(m)} \cdot r_{k_0,gopt}^{(m)})] \tag{8}$$

where, sgn(.) represents signum function.

**Codebook design:** The codebook is constructed with entries of interleaving patterns. Generally, the possible number of entries of the interleaving patterns that is size of the codebook is (MG)!. For the simple case of G = 16 and M = 8, the codebook consist of 128! entries. Then, it requires the same number of verifications to find the best pattern which is huge and infeasible. In the literature, many codebook based algorithms such as the Grassmannian and Lloyd algorithms were used for channel adaptation methods like beamforming and precoding techniques in MIMO based systems (Narula *et al*., 1998; Love *et al*., 2003). Due to high complexity of these methods, alternate methods can be developed based on selected entries instead of all entries based on order of complete block chips. Therefore, the codebook is developed to select entries of best interleaving patterns using the interleaving algorithm based on maximum SNR (MSNR) criterion.

In this study, bank of chip-interleavers and codebook with selected interleaving patterns are designed based on MSNR criterion for mitigating MAI. In order to construct the codebook, mapping function is used to find the interleaving patterns with address corresponding to the maximum SNR of quantized CSI. For this, the following algorithm is used (in offline) to find the SNR of exhaustive set of the interleaving patterns among all the users for every branch in the receiver. Then, it selects only $2^B$ number of the interleaving patterns, corresponding to the maximum SNR as entries of the codebook. These address bits, B are feedback to the transmitter and this reduces the required number of CSI bits without quantization error. Thus, the interleaving patterns in the codebook can be selected adaptively by the address bits, B of the interleaver in the transmitter and receiver sections simultaneously as per the existing channel conditions to retain the orthogonality of the user signals. The matrix $S_{SNR}$ of size, $F_i \times F_t$ is used for storing the values of SNRs for practical number of interleaving patterns, $F_i$ out of exhaustive number of tests, $F_t$ instead of all possible (MN)! patterns. The matrix $S_o$ is the space for storing the $F_i$ random order of interleaving patterns.

The algorithm for constructing the codebook with optimum interleaving patterns is explained below:

- Set the number of tests, $F_t$ and the size of the codebook, $2^B$
- Decide practical number of interleaving patterns, $F_i$
- Initialize the matrix $S_{SNR}$, vector $S_{adr}$ and matrix $S_{MaxSNR}$ to null

$$S_{SNR} \leftarrow 0,\ S_{adr} \leftarrow 0,\ S_{MaxSINR} \leftarrow 0$$

- Generate $F_i$ random order of interleaving patterns, assign the entries to the matrix $S_o$
- $S_o \leftarrow$ordering ($F_i$)
- Set $f_t = 1$ and $f_i = 1$

After initial settings, calculate the SNR:

- Create permutation matrix, $\pi_i$ for the $f_i$-th entry of the random interleaving matrix, $S_o$
- Compute the SNR for the $f_i$-th entry based on the permutation matrix, $\pi_i$, spreading sequences $c_k$ and the $f_t$-th test of channel matrix. Update it in the $f_i$-th element of the column vector of the matrix, $S_{SNR}(:,f_t)$
  - Start next iteration, $f_i \leftarrow f_i+1$, repeat SNR calculation for all '$f_i$ ' (until $f_i > F_i$)
    - Start next level of iteration for $f_t \leftarrow f_t+1$, repeat the above two steps with $f_i = 1$ to $F_i$. Update it in the $f_t$-th element of the row vector of the matrix, $S_{SNR}(f_i,:)$. Repeat SNR calculation for all $f_t$ (until $f_t > F_t$)
- Compute vector $S_{adr}$ of size $F_i \times 1$ by taking the average of $S_{SNR}$ based on MSNR criterion over $f_t$ testing channel (row vector). $S_{adr}(f_t) \leftarrow MSNR(S_{SNR})$
- Generate the codebook $S_{MaxSINR}$ by choosing $2^B$ interleaving patterns from random interleaving matrix, $S_0$ with maximum SNR value according to vector $S_{adr}$

## RESULTS

Based on the discussion given in the earlier sections, the performance of MCCDMA systems with the proposed novel codebook based adaptive chip interleaving technique (P-MCCDMA) is evaluated using MATLAB for downlink frequency selective Rayleigh fading channel with AWGN floor. It is compared with conventional MCCDMA system with Walsh code, existing interleaving algorithms and existing channel quantization schemes.

The simulations are conducted to evaluate the Bit Error Rate (BER) performance for different scenarios such as energy per bit over noise ratio ($E_b/N_0$), loads and number of feedback bits. The proposed MCCDMA system uses OCC codes as spreading code. It considers two-ray multipath channel with its delay profile being [1/2, 0, 1/2] and one chip inter path delay. The data packet of 3000 blocks per frame, transmission block of 10 symbols, the symbol length of 64, the modulation of 4-QAM, the number of subcarriers of 128 and the spreading gain (G) of 16 are considered. The key parameters of OCC spreading codes used in the simulations are flock size of 4, element code length of 16.

First, the BER performance of the adaptive chip interleaving algorithm (P-MCCDMA) is compared in Fig. 2 with the general chip interleaving algorithm (G-CI) and the random interleaving method (random CI) with respect to number of feedback bits. In this case, let $G = 16$, $M = 10$, $K = 16$, $E_b/N_0 = 8$ dB and $N_t = 2$. It is assumed that predicted channel information for one block length is available for every user and channel coefficients are independent. The graph shows that the BER decreases as number of feedback bits increases. It is observed that the number of feedback bits required to achieve the BER performance level of $10^{-2.8}$ are 1.5 bits for the proposed

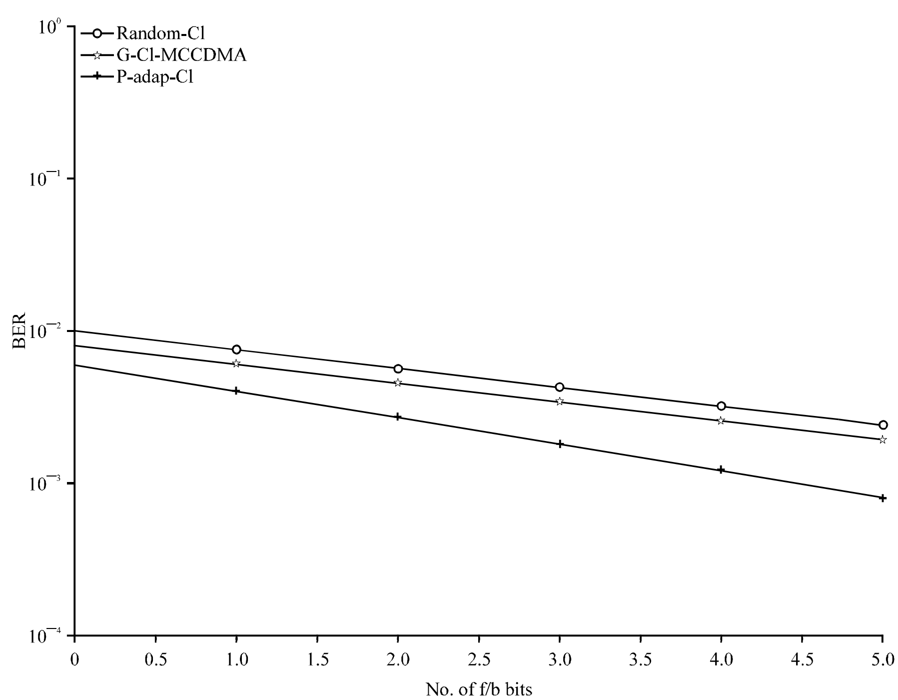


Fig. 2: BER performance of MCCDMA systems with different interleaving algorithms with respect to the number of feedback bits

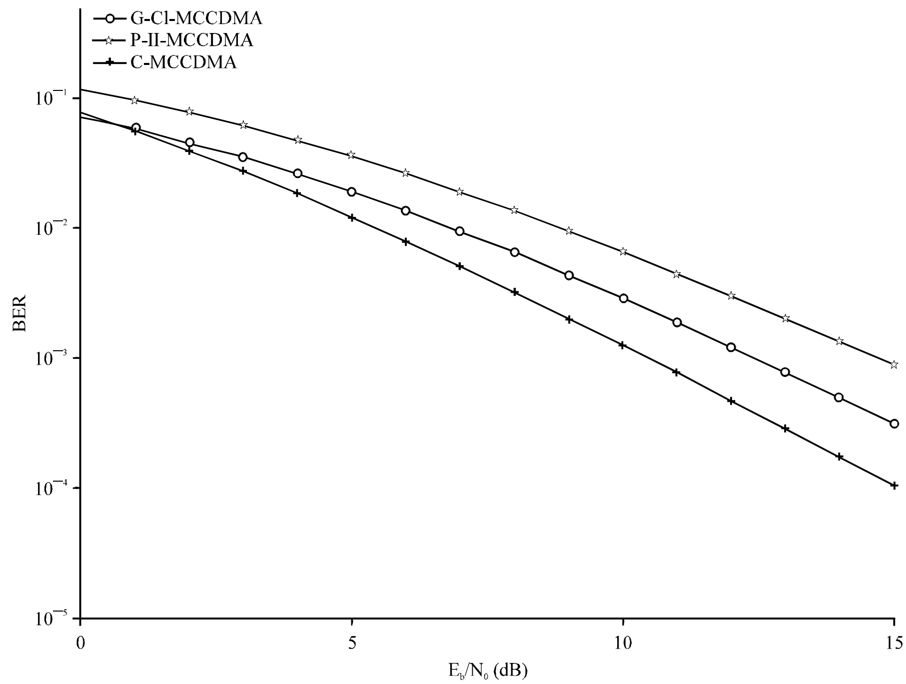


Fig. 3: BER performance among the MCCDMA systems with respect to $E_b/N_0$

algorithm (P-MCCDMA), 3 bits for the G-CI and 4 bits for the random CI. It is clear that the proposed adaptive chip interleaving algorithm outperforms the general chip interleaving algorithm and the random interleaving method.

The second experiment compares the BER performance among the MCCDMA system with proposed adaptive chip interleaving technique (P-MCCDMA), the general chip interleaving algorithm (G-CI) and the conventional MCCDMA system with Walsh codes (C-MCCDMA). It is assumed that the perfect CSI is available for the receivers. The channel fading is generated independently between fading blocks. Here, the BER performance curves are shown in Fig. 3 and 4 for the variability of $E_b/N_0$ and total number of users over processing gain (K/G). Notably from the Fig. 3 for the case of G = 16, M = 10, K = 16, 3 feedback bits and $N_t = 2$, the proposed adaptive chip interleaving technique (P-MCCDMA) achieves the SNR gain of 3 dB compared with the C-MCCDMA and achieves the SNR gain of 1.5 dB compared with the G-CI at the BER level of $10^{-3}$. Also, notably from the Fig. 4 for the case of G = 16, M = 10, $E_b/N_0$ = 8 dB, 3 feedback bits and $N_t$ = 2, the proposed technique (P-MCCDMA) achieves the normalized K/G gain of 0.4 compared with the C-MCCDMA and achieves the normalized K/G gain of 0.2 compared with the G-CI at the BER level of $10^{-3}$. It is evident that the best BER performance is achieved with the MCCDMA system with proposed adaptive chip interleaving technique, followed by the MCCDMA system with generalized chip interleaving algorithm and then the conventional MCCDMA with Walsh codes.

In the next scenario, the BER performance of the MCCDMA system using proposed codebook based indexed CSI technique is compared with other CSI techniques namely precoding with quantized estimated CSI (Qnt. CSI), the general chip interleaving with predicted CSI (G-CI-CSI) and random interleaving with estimated CSI (rand-Est-CSI). Here, the BER performance curves are shown in Fig. 5 for the variability of $E_b/N_0$. In this case, let G = 16, M = 10, K = 16,

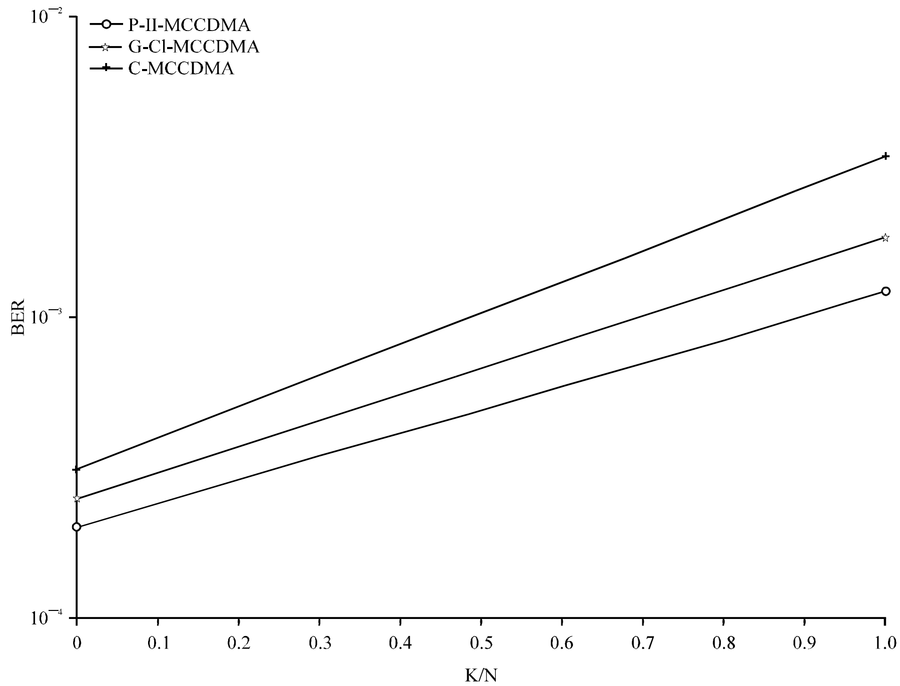


Fig. 4: BER performance among the MCCDMA systems with respect to normalized number of users (K/G)

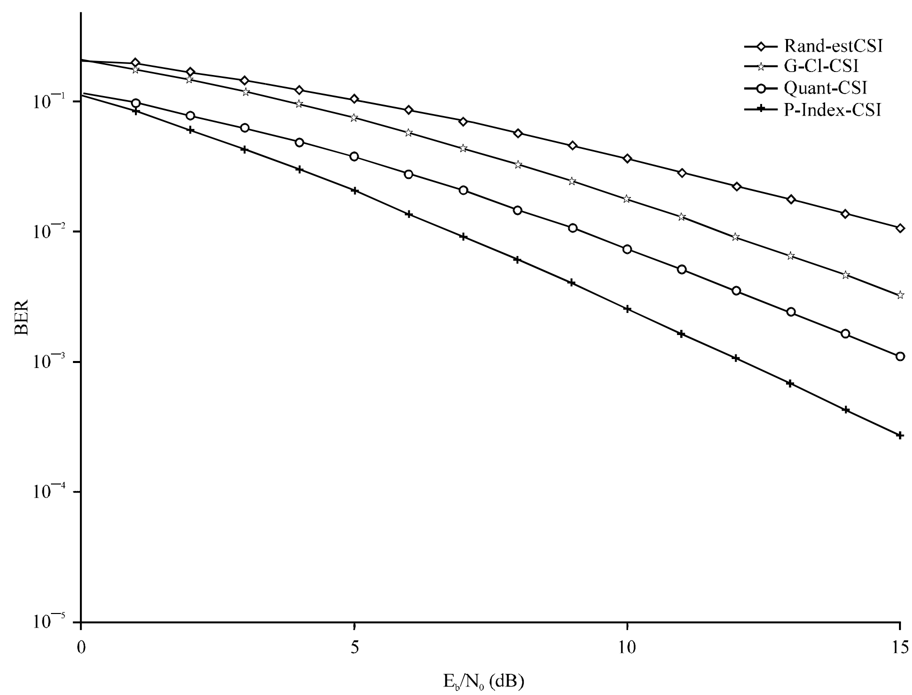


Fig. 5: BER performance of the MCCDMA systems with codebook based CSI technique and other channel quantization schemes

$E_b/N_0 = 10$ dB, 5 feedback bits and $N_t = 2$. It is observed that the values of energy per bit over noise ratio ($E_b/N_0$) are 7 dB for the proposed codebook based indexed CSI technique (P-MCCDMA), 9 dB for Qnt. CSI, 12 dB for G-CI-CSI and 15 dB for rand-Est-CSI at the BER performance level of $10^{-2}$. It is seen that the MCCDMA system using proposed codebook based indexed CSI technique outperforms other CSI techniques which are compared in this scenario.

## DISCUSSION

The results of proposed adaptive chip interleaving algorithm (P-MCCDMA) had been compared with the general chip interleaving algorithm (Xu *et al*., 2008) and the random interleaving method (Masouros and Alsusa, 2009) in Fig. 2. Considering the performance of the random interleaving method (random CI) based on random spreading sequences, it is affected by the amplitude and phase shift caused by the multipath propagation effects because of loss of orthogonality of user codes. The P-MCCDMA shows improvement due to the good orthogonality among the user signals based on OCC code and adaptive to propagation conditions. Next, in the general chip interleaving algorithm (G-CI), mutual orthogonality between different users' codes is preserved even after multipath propagation due to chip interleaving and zero padding at the transmitter and hence it gains 2.5 feedback bits at the BER performance level of $10^{-2.8}$ compared to the random CI. However, the G-CI is affected by channel variations and cannot be improved further. For the same scenario, the P-MCCDMA provides the superior performance than G-CI because it is adaptive to the channel condition and robustness to the channel variations in addition to good orthogonal properties. Thus, the P-MCCDMA saves the number of feedback bits of 4 bits and 1.5 bits compared to the random CI and G-CI, respectively and shows the efficiency in terms of BER performance with reduced feedback bits.

From the results of the second experiment, the BER performance of the MCCDMA system with proposed adaptive chip interleaving algorithm (P-MCCDMA) had been compared with the general chip interleaving algorithm (Xu *et al*., 2008) and the conventional MCCDMA system with Walsh codes (Chang *et al*., 2013) for the variability of $E_b/N_0$ and total number of users over processing gain (K/G) in Fig. 3 and 4. Considering the performance of conventional (C-MCCDMA) system, it is degraded due to loss of orthogonality of user codes by the detrimental effects of MAI and shows the inferior performance. The generalized chip interleaving algorithm (G-CI) achieves the performance gain in terms of normalized K/G of 0.2 and SNR gain of 1.5 dB compared with the C-MCCDMA because the mutual orthogonality between different users' codes is preserved even after multipath propagation. But, the G-CI is degraded when the number of multipath increases owing to the randomization effect of burst errors, the performance cannot be improved further. For the same scenario, the P-MCCDMA achieves the best performance than the G-CI and the C-MCCDMA due to good orthogonal properties of OCC codes and interleaving mechanism against time and frequency variations. Thus, the P-MCCDMA achieves the SNR gain of 1.5 and 3 dB and normalized K/G gain of 0.2 and 0.4 compared with the G-CI and the C-MCCDMA, respectively and proves in terms of these performance gains that it can support system with higher loads.

The results of the MCCDMA system using the adaptive chip interleaving based on proposed codebook based indexed CSI technique (P-MCCDMA) had been compared with other CSI techniques namely precoding with quantized estimated CSI (Dabbagh and Love, 2008), the general chip interleaving with predicted CSI (Xu *et al*., 2008) and random interleaving with estimated CSI techniques (Masouros and Alsusa, 2009) in Fig. 5. Taking into account of the estimation error and spreading sequence mismatch error, the random interleaving with estimated CSI techniques (rand-Est-CSI) attains the $E_b/N_0$ of 15 dB at the BER performance level of $10^{-2}$. The general chip interleaving with predicted CSI (G-CI-CSI) using 5 feedback bits without feedback delay can save up to 3 dB of $E_b/N_0$ compared with rand-Est-CSI due to optimization of signature sequence against estimation errors. However, the G-CI-CSI degrades when channel prediction error increases due to the number of multipath owing to the randomization effect of burst errors. As an alternate to these techniques to collect the CSI bits, the precoding with quantized estimated CSI (Qnt. CSI) perfectly estimates quantized details of channel states at the receiver and maps to the precoder. Because of this feedback technique, the Qnt. CSI can save $E_b/N_0$ up to 3 and 6 dB compared with the G-CI-CSI and rand-Est-CSI, respectively. However, the gains are significantly reduced due to lack of perfect CSI at the transmitter and large quantization error. So, Qnt. CSI needs additional feedback bits to achieve the perfect CSI. For the same scenario, the proposed codebook based indexed CSI technique (P-MCCDMA) achieves the best performance than Qnt. CSI, the G-CI-CSI and rand-Est-CSI because of reduced quantization error due to codebook based approach which sends the feedback of the address bits of the interleaver instead of sending the quantized CSI and of optimum interleaving patterns selected based on maximum SNR due to perfect CSI. Thus, the P-MCCDMA provides the best performance and can save $E_b/N_0$ up to 3, 6 and 8 dB compared with the Qnt. CSI, the G-CI-CSI and rand-Est-CSI, respectively. Thus, the proposed scheme is more adaptive against channel variations and achieves improvement in BER performance with reduced feedback bits.

## CONCLUSION

A novel codebook based adaptive chip interleaving technique was developed to mitigate the MAI for MC-CDMA systems and reduce the quantization error based on new limited feedback approach. For this, bank of chip-interleavers and codebook with selected interleaving patterns were constructed. As a result, the proposed adaptive chip interleaving technique retains the orthogonality of the received signal without quantization error. Furthermore, the new algorithm is demonstrated based on MSNR criterion and mapping function to select the best interleaving patterns in the codebook. It achieves improvement in BER performance with reduced CSI feedback bits and low processing load. The simulation results show that the BER performance of the proposed scheme outperforms the conventional MCCDMA systems with Walsh codes, existing channel quantization schemes and existing chip-interleaving schemes. The results show that the developed system is adaptive to multipath frequency-selective fading channel conditions with higher loads and support the system with more number of users due to increased MAI mitigation efficiency.

## NOMENCLATURE

$A_k$ = Amplitude associated with user, k
$b_k(j)$ = Data of the jth block for user k
B = Size of address of the interleaver in bits
$C_k$ = Spreading codes
$E_b/N_0$ = Energy per bit over noise ratio
$F_i$ = Number of interleaving patterns
$F_t$ = Number of tests
G = Chips per symbol
$H_i$ = Equivalent channel matrix for ith chip
$I_M$ = Identity matrix (of size M×M)
i = Interleaved chip (1 to MG)

| | |
|---|---|
| K | = Number of users |
| K/G | = Number of users over processing gain |
| M | = Number of symbols |
| $N_t$ | = Number of transmit antennas |
| $\mathbf{n}_l^{\sim}$ | = Noise vector |
| $n_m$ | = Deinterleaved noise vector |
| $P_i$ | = Precoder gain for ith chip |
| $\pi_g$ | = Interleaving matrix |
| $\boldsymbol{\pi}_i^{-1}$ | = Deinterleaving matrix |
| q | = Received signal vector (before the deinterleaving process) |
| r | = Received signal vector (after deinterleaving process) |
| $S_o$ | = Space for storing the random order of interleaving patterns, $F_i$ |
| $S_{adr}$ | = Address vector |
| sgn(.) | = Signum function |
| $S_{MaxSINR}$ | = Codebook |
| $S_{SNR}$ | = Matrix for storing the values of SNRs |
| x | = Source or signal |
| $\sigma^2$ | = Noise variance |
| G-CI | = General chip interleaving algorithm |
| G-CI-CSI | = General chip interleaving with predicted CSI |
| P-MCCDMA | = MCCDMA systems with the proposed novel codebook based adaptive chip interleaving technique |
| Qnt. CSI | = Precoding with quantized estimated CSI |
| random CI | = Random interleaving method |
| rand-Est-CSI | = Random interleaving with estimated CSI |

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