MC-CDMA based SDR for Next Generation Wireless Communication

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ABSTRACT

Recent innovations in wireless technology have made a need to propose hybrid systems to achieve excellent data rates and performance. One such system is multi-carrier code division multiple access (MC-CDMA), a combination of direct sequence code division multiple access (DS-CDMA) and orthogonal frequency division multiplexing (OFDM) systems. It offers high data rate, flexible bandwidth allocation and enhanced performance to each user simultaneously. Owing to these advantages, this system is chosen to be interfaced with the physical layer of software defined radio (SDR). SDR is defined as a reprogrammable hardware that suits emerging standards of next generation wireless communication. In MC-CDMA system, when the orthogonality is not maintained in the OFDM part, it leads to multiple access interference (MAI). To overcome the effects of MAI and to reduce complex detection to a great extent, super orthogonal turbo codes is chosen for the system. In this paper, MC-CDMA based SDR system is constructed using super orthogonal turbo codes with log-MAP algorithm. The simulation results show that the performance is remarkable when compared to a turbo system using recursive systematic codes (RSC). The BER performance of both the systems is analyzed for different iterations.

KEYWORDS

MC-CDMA, SDR, SOTC, RSC and MUD

1. INTRODUCTION

The major goal of 4G is the integration of existing systems through a generic architecture. This would be feasible if there is a reprogrammable hardware like SDR. SDR is simply defined as a transceiver, where functions are realized as programs on re-programmable components. It offers compatibility between existing wireless networks and hence it is open to adopt new technologies. Thus it plays an important role in the success and penetration of 4G systems. MC-CDMA belongs to 4G which is a combination of CDMA and OFDM that inherits the benefits of both the systems. It is chosen to be interfaced in the physical layer of SDR to provide excellent performance and good quality of service

(QoS) to each user. Hence MC-CDMA based SDR system would be a well-built candidate that supports existing and future standards.

The 4th generation mobile communication is expected to offer 100 Mbps or higher data rates in downlink. MC-CDMA and OFDM are potential candidates [1] for next generation mobile communication. The performance of CDMA adaptable with SDR is proved [2] to provide high data rates, yet CDMA suffers from multipath fading with increased number of users. As an attempt MC-CDMA system is made adaptable to SDR since it overcomes the effects of multipath fading and thereby satisfies multiple users at the same time. However, it suffers from multiple access interference (MAI) and complex detection. MAI affects the BER performance in MC-CDMA system; hence to mitigate it, joint multiuser detection (MUD) and Turbo decoding [3] are used to improve the system performance. Among all turbo MUD techniques, maximum likelihood (ML) MUD shows better performance [4] by using log-MAP algorithm. Turbo codes are parallel concatenated codes that shown to be near the Shannon's theoretical limit [5]. Super orthogonal turbo codes (SOTC) are low-rate convolutional codes [6,7] chosen since it outperforms other existing codes and reduces complex detection to a great extent. However, the complexity of decoding increases exponentially as the number of users increases [8] and to reduce this problem, MUD techniques such as parallel and serial interference cancellation (PIC & SIC), general minimum mean square error (GMMSE) and polynomial MMSE has been proposed. Signal detection schemes [9] such as minimum mean square error (MMSE), zero forcing (ZF), sphere decoding (SD), Q-less QR decomposition are studied for different modulations to analyze system performance. From the available coding techniques and MUD detection methods, a MC-CDMA based SDR using super orthogonal turbo codes [10] with log-MAP algorithm is constructed and simulated for different iterative values.

The paper is organized as follows: Section II describes the system to be constructed. The importance of using SOTC codes is detailed in section III. Maximum a posteriori algorithm is explained in section IV. Simulation results and discussions are presented in section V and the conclusion is arrived at section VI.

2. SYSTEM MODEL

2.1 MC-CDMA based SDR Transmitter

SDR consists of three layers; namely, physical layer, data link layer and application layer. The physical layer is enabled with existing systems so that it becomes adaptable to SDR technology. MC-CDMA system is made adaptable to SDR [1] to support future wireless communication systems. The data signal for MC-CDMA is generated by combining CDMA and OFDM systems. The input data signal is spreaded using a spreading sequence followed by inverse fast fourier transform (IFFT) modulation to confirm the orthogonality among the entire signals for excellent transmission with least interference. After passing through the channel, the received signal is down converted and demodulated followed by efficient detection to deliver the appropriate signal to all users.
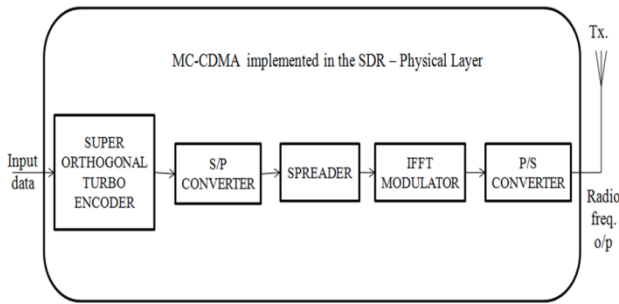
Fig-1: MC-CDMA based SDR Transmitter

The input data along with Hadamard matrix is encoded using SOTC code. The principle of DS-CDMA is to spread the encoded data symbol with a spreading code $c^{(k)}(t)$ of length L,

$$c^{(k)}(t) = \sum_{l=0}^{L-1} c_l^{(k)} \, p \, T_c \, (t - lT_c) \tag{1}$$

assigned to user k, $k = 0, \ldots, K - 1$, where K be the total number of active users. After spreading, the encoded signal $x^{(k)}(t)$ of user k is given by

$$x^{(k)}(t) = d^{(k)} \sum_{l=0}^{L-1} c_l^{(k)} \, p \, T_c \, (t - lT_c) \, , \quad 0 \le t < T_d \tag{2}$$

for each data symbol duration $T_d = LT_c$, where T_c is the chip duration, $d(k)$ be the transmitted data symbol of user k. The multiplication of the information sequence with the spreading sequence is done bit-synchronously and the overall transmitted signal $x(t)$ of all k synchronous users results in

$$x(t) = \sum_{k=0}^{K-1} x^{(k)}(t) \tag{3}$$

Since MAI strongly depends on cross-correlation function (CCF) of the spreading sequences, the CCF should be as small as possible. These multiple sub-carriers follow OFDM modulation with spacing of symbol frequency F_s

$$F_s = \frac{1}{T_s} \tag{4}$$

in order to achieve orthogonality among the signals. However, to completely avoid the effects of ISI and thus, to maintain orthogonality, a guard interval of duration is given by

$$T_g \ge \tau_{\max} \tag{5}$$

The guard interval is a cyclic extension of each OFDM symbol by extending the duration of an OFDM symbol to

$$T_s' = T_g + T_s \tag{6}$$

The signal $x(t)$ after being upconverted and the RF signal is transmitted to the channel.

2.2 MC-CDMA based SDR Receiver

The output of the channel, after RF down conversion is the received signal $y(t)$ obtained from the convolution of $x(t)$ with impulse response $h(t)$ and addition of a noise signal $n(t)$ as follows,

$$y(t) = x(t) * h(t) + n(t) \tag{7}$$

$$= \sum_{k=0}^{K-1} r^{(k)}(t) + n(t) \tag{8}$$

where $r^{(k)}(t) = x^{(k)}(t) * h(t)$ be the noise-free received signal of user k, $n(t)$ be the additive white Gaussian noise (AWGN) and * denotes the convolution operation. After doing analog to digital conversion of the received signal $y(t)$, it is sampled at a rate $1/T_d$ and generates the sequence y_a, $a = -L_l, \ldots, N_c - 1$. The removal of ISI in the sequence is given by, $a = 0 \ldots, N_c - 1$ and it has been demodulated by exploiting fast fourier transform (FFT). The output of the FFT demodulated sequence is

$$R_n = \sum_{a=0}^{N_c-1} y_u e^{-j 2\pi n a / N_c}, \quad n = 0, \ldots, N_c - 1. \tag{9}$$

where, R_n be the output of the FFT demodulated sequence, N_c be the complex-valued symbols. Further, assuming that the fading on each sub-channel is flat, a received signal R_n is represented in frequency domain accordingly,

$$R_n = H_n S_n + N_n \, , \quad n = 0, \ldots, N_c - 1 \tag{10}$$

where H_n be the complex-valued flat-fading co-efficient, S_n is the complex-valued source symbols and N_n represents the noise of the nth sub-channel.
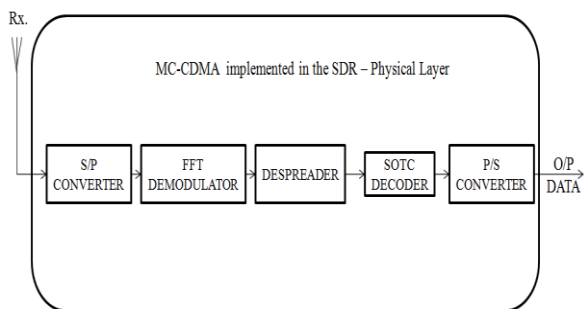
Fig-2: MC-CDMA based SDR Receiver

After serial to parallel conversion, the signal is demodulated using FFT. Then the decoding with SOTC decoder provided with the same spreading sequence used during transmission is done. Finally contented signal is received by appropriate users with high performance.

3. TURBO CONVOLUTIONAL CODES

Turbo codes are a refinement of concatenated encoding structure and it applies an iterative method for decoding the associated code sequence. It has been proved that turbo codes achieves a bit error probability of 10^{-5} using a code rate of ½ over an additive white gaussian noise (AWGN) channel and BPSK modulation [7] at an SNR of 0.7 dB. Turbo decoding passes the soft decision from the output of one decoder to the input of the other decoder and iterates this process several times so as to produce more reliable decisions.

3.1 Recursive Systematic Convolutional (RSC) Codes

RSC codes belong to the class of infinite impulse response (IIR) convolutional codes that serve as building blocks for a turbo code. It results in better error performance compared to non systematic convolutional (NSC) codes by using a feedback loop and setting one of the two outputs equal to d_k. The output a_k is recursively calculated as follows,

$$a_k = d_k + \sum_{i=1}^{K-1} g_i^{'} a_{k-i} \ mod \ 2 \qquad (15)$$

where d_k is the data given as input, the constraint length is K=3, and a_k is the output sequence. Consider a parallel concatenation of two RSC encoders; it produces code words from each component encoders. Turbo code performance is largely influenced by minimum-weight code words; it is the IIR property of RSC codes that protects against the generation of low-weight code words and thus makes turbo code more preferable for budding systems.

3.2 Super Orthogonal Turbo Codes (SOTC)

SOTC is a low-rate convolutional turbo code [7] that can be applied as spreading codes in MC-CDMA system. It is well suited for spread spectrum applications. The idea behind SOTC is to concatenate two component codes i.e. recursive systematic code (RSC) and a Walsh Hadamard (WH) generator. It helps to achieve good performance results for moderate users in uplink as well as in the downlink. This attempt of combining two codes is made to minimize the computational complexity [9] with more number of users.

3.2.1 SOTC Encoder

An orthogonal convolutional encoder consists of orthogonal output sequences for each user. If the memory of the code is m, there are 2^m different encoder states and a total of 2^{m+1} orthogonal sequences are required. Therefore, to get a set of orthogonal sequences, Walsh functions can be used. SOTC is simply a concatenation of recursive systematic code (RSC) and WH generator [14]. The inner encoder is the walsh-hadamard generator obtained from Hadamard matrices that can be generated as shown below,

$$H_1 = [0] \qquad H_{2i} = \begin{bmatrix} H_i & H_i \\ H_i & H_i^{'} \end{bmatrix} \qquad (11)$$

Thus Hadamard matrices can be easily generated from (11). Fig-3 depicts an example of a SOTC encoder with memory $m = 3$.
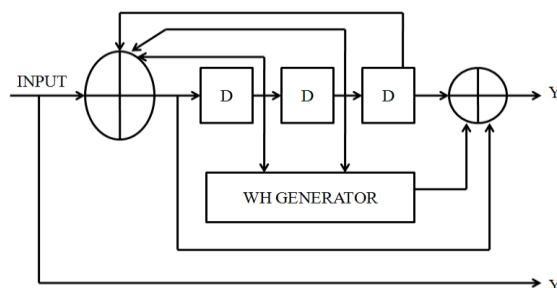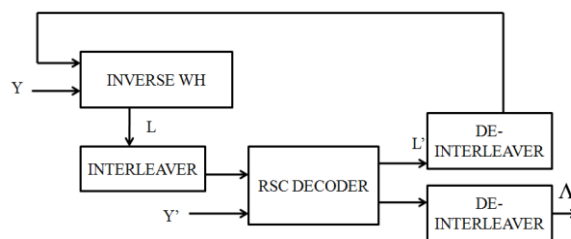

Fig-3: Super Orthogonal Turbo Encoder

The initial data sequence is encoded using RSC code whose systematic output and interleaved output is given as input to the inner encoder i.e. WH generator. WH generator can simply be a look-up table that stores the output sequences [14]; it sends the signal for modulation. Thus the input data is coded using SOTC code and modulated using IFFT and transmitted through the channel.

3.2.2 SOTC Decoder

After transmitting the signal over a fading or AWGN channel, the received signal is represented as Y and Y', where Y is the systematic output and Y' is the parity output. The channel outputs are

$$y_t^i = A_t^i (2x_t^i - 1) + \gamma_t^i \qquad (12)$$

where γ_t^i, $i = 0,1, ..., n-1$ is Gaussian random variables with equal variance. In general, $A_t^i = 1$ for all i and t in an AWGN channel.

Fig-4: Super Orthogonal Turbo Decoder

The channel outputs Y and Y' are decoded using inverse Walsh-Hadamard (IWH) and RSC decoder. The output from IWH is interleaved and sent to inner decoder for iterative decoding. A requirement for iterative decoding is the *a priori* information provided by the previous decoder must remain independent from the other inputs. This is accomplished by interleaving the data sequence before it enters the second component decoder. Λ_t represents the soft decision made by the decoder called log-likelihood ratio which is defined as,

$$\Lambda_t = \log \frac{P(input = 1|observation)}{P(input = 0|observation)} \quad (13)$$

The log-likelihood ratio estimate [14] of a data bit can be expressed as the sum of

$$\Lambda_t = L_t^{(apr)} + L_t^{(ext)} \quad (14)$$

From Fig-4, $L_t^{(apr)}$ is the *a priori* estimate provided by the previous decoder. The next term, $L_t^{(ext)}$ represents the extrinsic information provided by the current decoder, which in turn will be used as *a priori* information by the next decoder. The number of iterations determines the performance of decoder. The iterations can be completed with a predefined value or if a fixed threshold value has been reached.

3.3 Turbo Decoder

A turbo decoder needs to generate the a posteriori probability (APP) or soft decision output for each decoded bit. Unfortunately, the viterbi algorithm is not suited to generate the APP. The Bahl algorithm was proposed for decoding RSC codes. The APP of a decoded data bit d_k can be derived from the joint probability $\lambda_k^{i,m}$ defined by,

$$\lambda_k^{i,m} = P\{d_k = i, S_k = (m|R_1^N)\} \quad (16)$$

Where S_k is the encoder state at time k and R_1^N is a received binary sequence from time $k = 1$ through some time *N*. Thus, the APP for a decoded data bit d_k, represented as a binary digit, is equal to

$$P\{d_k = i|R_1^N\} = \sum_m \lambda_k^{i,m} \quad i = 0,1 \quad (17)$$

The log likelihood ratio (LLR) is defined as the logarithm of the ratio of APPs, as follows

$$L(\widehat{d_k}) = \log \frac{\sum_m \lambda_k^{1,m}}{\sum_m \lambda_k^{0,m}} \quad (18)$$

Further, maximum a posteriori (MAP) decision rule is applied by comparing $L(\widehat{d_k})$ to a zero threshold and decision is made by the decoder. The conditions for comparison is as follows,

$$\widehat{d_k} = 1 \text{ if } L(\widehat{d_k}) > 0 \quad (19)$$

$$\widehat{d_k} = 0 \text{ if } L(\widehat{d_k}) < 0 \quad (20)$$

4. TURBO MULTIUSER DETECTION (MUD) TECHNIQUES

Detection techniques can be classified as either single-user detection or multi-user detection (MUD). Generally, single-user detection is not preferred in MC-CDMA system since it is sub-optimal. It detects the user signal of interest by not taking into account any information about multiple access interference and therefore it is sub-optimal. This has been rectified in multi user detection by using *a priori* knowledge of the spreading codes but at the expense of receiver complexity. The problem of MAI and remedies to overcome are explained below.

4.1 Multiple Access Interference (MAI)

In MC-CDMA system, the spreaded signal is passed through a frequency selective channel to the receiver. When the received codes are not orthogonal to each other, in other words, if the cross-correlation is non-zero, there arises multiple access interference (MAI). There are many techniques to overcome MAI among which multi user detection technique [11] is well suited for MC-CDMA systems. The design of spreading codes is considered to remove the effects of MAI completely [12]. In order to transmit MAI free signals, a basic concept is explained. Consider a Walsh-Hadamard (WH) sequence of length *M*, say $WH = d_k$; $k = 1,2, \ldots, M$. Each user transmits a sequence of *M* samples which are uniformly spaced at a distance *R*. These *M* samples are obtained by spreading the data by a specified element of *WH* sequence. The calculated frequency domain sequence as follows,

$$c_k(i) = \frac{1}{\sqrt{N}} \sum_{m=0}^{M-1} d_k(m) e^{-j\frac{2\pi}{M}(im)} \quad 0 \le iN - 1. \quad (21)$$

where $c_k(i)$ be the spreaded signal without MAI, *M* is the different codes used for spreading and *i* is the user.

4.2 Log-MAP Algorithm

For any kind of iterative decoding algorithms, the basic tool is the log likelihood ratio (LLR). It is defined as the ratio between the required data and the transmitted data. For a convolutional code, the LLR information about sequences is calculated using MAP receiver. The MAP algorithm [13] also known as BCJR algorithm provides the exact LLR value for a bit rather than an approximate one, but this is achieved at the expense of complex detection. The LLR ratio is written as,

$$\Lambda_1 (d_k) = \log \frac{Pr(d_k = (1|R_1^N))}{Pr(d_k = (0|R_1^N))} \quad (22)$$

$Pr(d_k = (1|R_1^N))$ is the a posteriori probability (APP) of the information input data at time k (d_k) when it is equal to 1 given the entire received data. R_1^N is the block data sequence and the state of the encoder S_k is represented as,

$$S_k = (a_k, a_{k-1}, \ldots\ldots, a_{k-v+1}) \quad (23)$$

where a_k is the output of the first shift register in the RSC encoder. The APP of d_k is thus equal to

$$Pr(d_k = (j|R_1^N)) = \sum_s \Gamma_k^j (s), \quad j = 0,1 \quad (24)$$

The MAP algorithm defines the joint probabilities of in terms of three parameters,

$$\alpha_k = Pr(S_k = s|R_1^k) \quad (25)$$

$$\beta_k(s) = \frac{Pr(R_{k+1}^N | S_k = s)}{Pr(R_{k+1}^N | R_1^k)} \qquad (26)$$

$$\gamma_j(R_k, s', s) = Pr(d_k = j, S_k = s, R_k | S_{k-1} = s') \quad (27)$$

The LLR is now described in terms of these parameters as,

$$\Lambda_1(d_k) = \log \frac{\sum_s \sum_{s'} \gamma_1(R_k, s', s) a_{k-1}(s') \beta_k(s)}{\sum_s \sum_{s'} \gamma_0(R_k, s', s) a_{k-1}(s') \beta_k(s)} \quad (28)$$

5. SIMULATION RESULTS

The proposed system is simulated using MATLAB version 7.14.0. The frame size for RSC codes is 518 and for SOTC it is generally in multiples of 2. The transmission takes place through additive white gaussian noise (AWGN) channel for both the systems since it shows improved performance. The parameters required to execute the code is specified in table-1 shown below.

Table-1: Parameter Specifications

| PARAMETER	SPECIFICATION
Codes used	Super Orthogonal Turbo Codes (SOTC) and Recursive Systematic Codes (RSC)
Code rate used	1/2 and 1/3
Frames Size	512 and 1024
SNR	1 to 3 (dB) for code rate 1/2 and 1/3 1 to 6 (dB) for code rate 1/2
No. of Iterations	5, 10, 15 and 20
Channel	AWGN
Interleaver	Punctured and Un punctured

The performance curves for different iterative values is made and shown from Fig-5 to 13 below. The two different frame size chosen are 512 and 1024 respectively. The signal to noise (SNR) ratio is given as 3 dB for all the iterative values. The graph is plotted for number of iterations along x-axis and bit error rate (BER) along y-axis for all the following outputs.
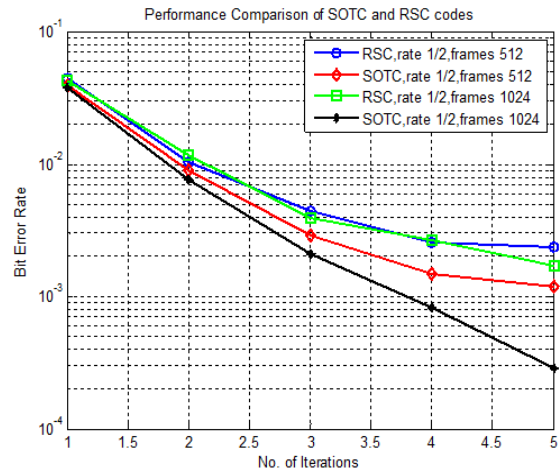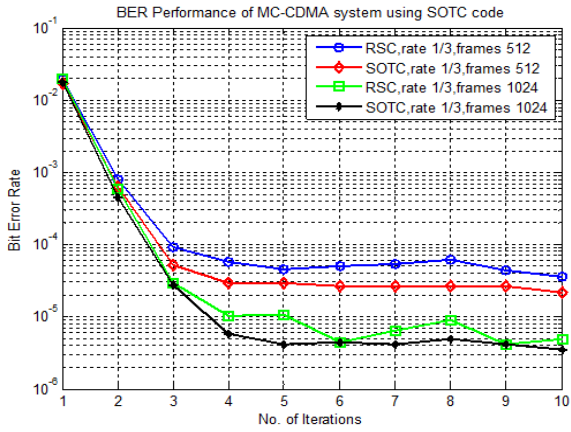

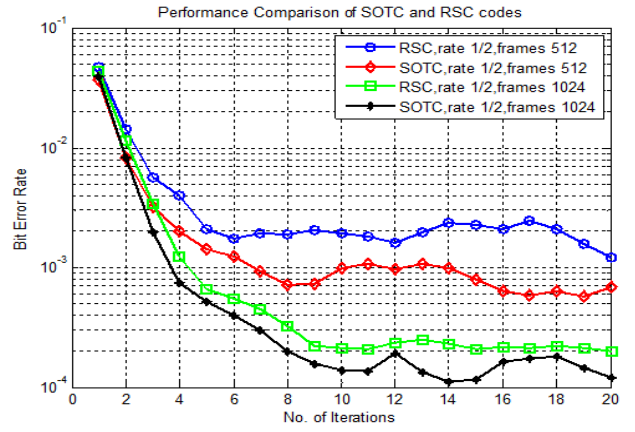**Fig-5: BER performance of MC-CDMA based SDR system for 5 iterations**
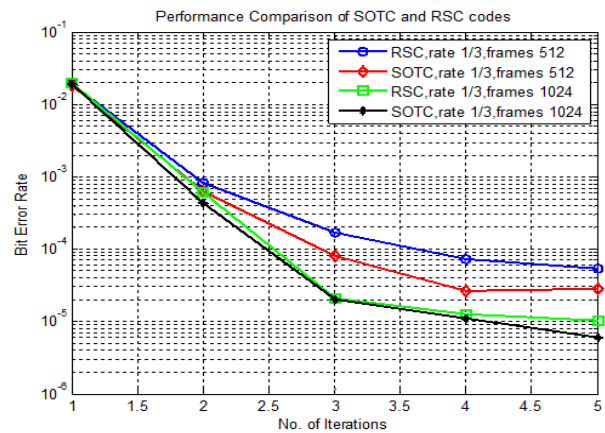
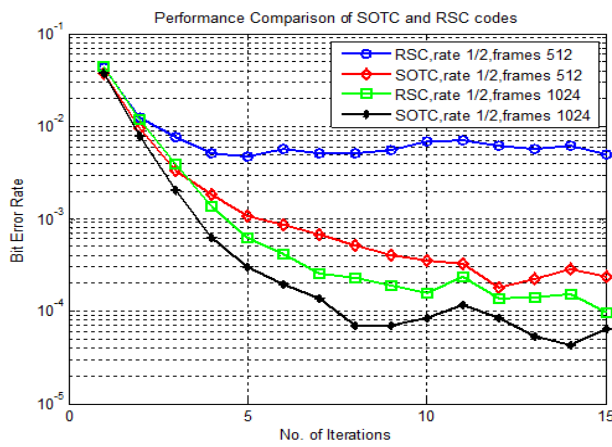**Fig-6: BER performance of MC-CDMA based SDR system for 5 iterations**
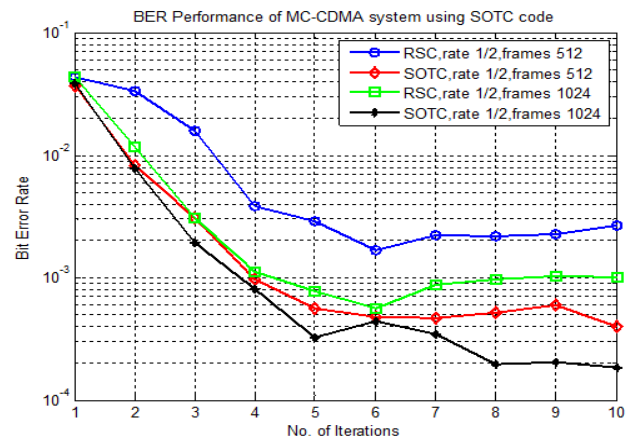
Fig-7: BER performance of MC-CDMA based SDR system for 10 iterations

Fig-8: BER performance of MC-CDMA based SDR system for 10 iterations

Fig-11: BER performance of MC-CDMA based SDR system for 20 iterations

Fig-9: BER performance of MC-CDMA based SDR system for 15 iterations

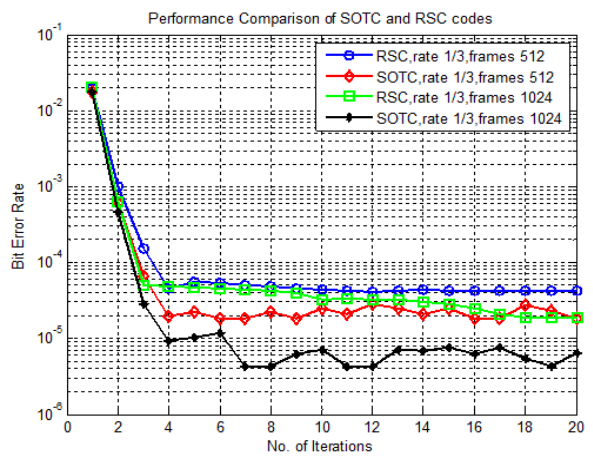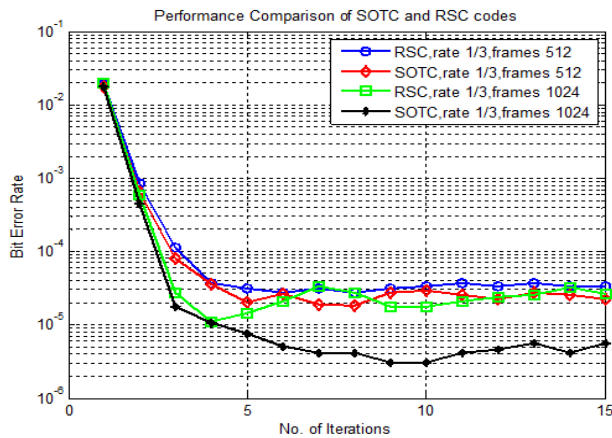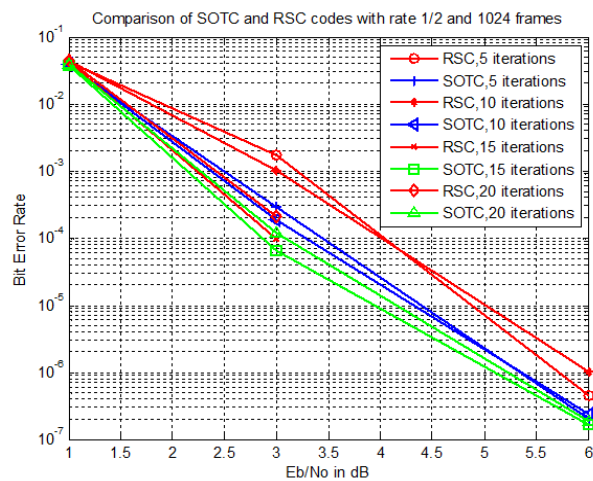**Fig-12: BER performance of MC-CDMA based SDR system for 20 iterations**

Fig-10: BER performance of MC-CDMA based SDR system for 15 iterations

Fig-13: BER performance of MC-CDMA based SDR system

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From the results obtained, the performance of MC-CDMA based SDR using SOTC is outstanding as the number of iterations increases and it outperforms RSC codes. Table-2 shows the improved range in numerical values as follows,

Table-2: Performance Comparison of MC-CDMA system using SOTC and RSC codes

No. of Iterations	MC-CDMA using SOTC code	MC-CDMA using RSC code
5	0.0004293	0.00206
10	0.0001305	0.0003472
15	9.148e-005	0.0002777
20	9.707e-005	0.000127

6. CONCLUSION

MC-CDMA based SDR system using super orthogonal turbo code with log-MAP algorithm is proposed in this paper. Simulation is done using MATLAB version 7.14.0. The results show that the proposed system outperforms MC-CDMA using RSC codes. The simulations are made with various iterative values for comparison of both systems. Its observed that as the number of iterations increases, the performance in terms of BER is excellent using SOTC with log-MAP algorithm. This improvement is more evident from the outputs obtained over AWGN channel. Thus completely removing the effects of MAI and mitigating complex detection to a great extent, the proposed system would be preferable for next generation wireless communication. In future, complex detection can further be reduced when the number of users increases by using combinations of concatenated turbo codes and efficient decoding algorithms.

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