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VLSI Implementation of 4X4 MIMO SC-FDMA Transceiver For Low Power Applications

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Abstract

Single Carrier-Frequency Division Multiple Access (SC-FDMA) is an OFDMA alternative technology. SC-FDMA is the multiuser version of single carrier modulation with frequency domain equalization (SC/FDE). The main objective of SC-FDMA is to introduce transmission with lower PAPR than OFDMA but it is very sensitive to phase noise and carrier frequency offset (CFO), which will break the orthogonality among subcarriers and generate common phase error (CPE) as well as inter-carrier interference (ICI) to distort the received signals. Also this is similar situation in other OFDM communication systems. Thus the BER performance and throughput are seriously degraded. To improve system performance and throughput, it is necessary to analyze the effects of phase noise and CFO and then suppress the interferences. To overcome this problem, the SC-SFBC scheme used here with modified FFT Algorithm. Single Carrier- Space Frequency Block Coding (SC-SFBC) is used to reduce the peak to average power ratio (PAPR) of the multiple-input multiple-output (MIMO) SC-FDMA signal. Modified FFT algorithm is used to reduce the memory references thereby increasing the Throughput. The coding method is different from the Alamouti scheme, the four frequencies involved in SC-SFBC scheme do not use successive subcarriers any longer. Thus it avoids the degrading interactions between phase noise and CFO estimations. The proposed structure is evaluated using performance parameters such as BER & SNR. Structural realization and analysis pertaining to Timing, Power and Throughput are implemented in Virtex-4 and analysis is carried out in Altera respectively

Keywords- Multi Input Multi Output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), Carrier Frequency Offset (CFO), Inter Carrier

Interference (ICI), Single Carrier –Frequency Division Multiple Access (SC-FDMA), Single Carrier - Space Frequency Block Codes (SC-SFBC), Space Time Block Code (STBC), Peak Average Power Ratio (PAPR).

Introduction

Wireless communication has become one of the vibrant areas of research in the communication field today. This is triggered due to increasing demand for their less connectivity, dramatic progress in VLSI technology and the success of the previous generation standards such as 2G, particularly the IS-95 CDMA standards. Today wireless communication is widely used in several exciting applications and areas like cellular telephones, global positioning system, satellite communication, defence and mobile internet.

Multiple Input Multiple Output (MIMO) system consists of multiple antennas at the transmitter and receiver ends to improve link reliability and data rates of the Wireless communication system. Orthogonal Frequency Division Multiplexing is efficient in synchronizing the received signal under fading environment and has been used in past times in applications that require a huge data rate. The advantage of Orthogonal Frequency Division Multiple Access which builds this multi carrier techniques is very useful for wireless communications [1] and it is used in several international standards.

Most of the research in the wireless communication involved Orthogonal Frequency Division Multiplexing [2]. MIMO OFDM (Multiple Input Multiple Output, Orthogonal Frequency Division Multiplexing) is a technology that combines MIMO and OFDM together to transmit data in wireless communications, in order to deal with frequency selective channel effect [3-4]. The OFDM signal on each subcarrier can overcome narrowband fading. Therefore, OFDM can transform frequency-selective fading channels into parallel flat one's. Then by combining MIMO and OFDM technology together, MIMO algorithms can be applied in broadband transmission [3-5]. A MIMO OFDM system is very sensitive to phase noise and carrier frequency offset (CFO), which will break the orthogonality among subcarriers and generate common phase error (CPE) as well as Inter-Carrier Interference (ICI) to distort the received signals [6-8]. Thus the BER performance and Throughput are seriously degraded [9]. Carrier frequency offset (CFO) not only introduce the amplitude distortion in the receiver, but also introduces the inter carrier interference. Several methods have been discussed to the effect of ICI and also reduce the effect of ICI. Based on the effect of ICI, ICI self cancellation is discussed both in time environment and frequency environment [10-12]. However, the ICI self-cancellation method provides low spectrum efficiency and low Throughput. The comb type pilot scheme was discussed in [13], but comb-type pilot is not suitable for SC-FDMA system because it consumes high PAPR. Thus, the block-type pilot is the pilot pattern in SC-FDMA communication system. The method of CPE suppression was discussed in [14], but it does not include influence of ICI. In [15-19], successive interference cancellation as well as parallel interference cancellation methods were discussed but these methods requires perfect CFO estimation, which is not feasible in practical system. Fast Fourier Transform (FFT)/ Inverse FFT (IFFT) processors are proposed for Multiple Input Multiple-Output Orthogonal Frequency Division Multiplexing based IEEE 802.11n. Here the processor not only supports the operation of FFT/IFFT but also provides sufficient throughput rates The drawback of above method is hardware complexity is more, compared with conventional approaches [20]. FFT architecture which is optimized for a processor with a memory system containing a cache is discussed in [21].

The paper is organized as follows. In Section 2, an overview of Spatial block code is discussed. A brief discussion of MIMO SC-FDMA system is presented in Section 3. Section 4 deals with the estimation and suppression of ICI. The performance of the system is analyzed and discussed in Section 5. Finally Section 6 concludes the paper in brief.

Spatial Block Codes

STBC

Space time block coding (STBC) is the most straight forward approach for applying Alamouti coding. In this case, precoding involves four frequency components ($X_k^{(4j)}, X_k^{(4j+1)}, X_k^{(4j+2)}$and $X_k^{(4j+3)}$) to be sent to the antennas over four successive time intervals. As presented in Table 1, Alamouti STBC is performed between k-th frequency component $X_k^{(4j)}$ of FFT output vector $X_k^{(4j)}$ at time 4j, k-th frequency component $X_k^{(4j+1)}$ of FFT output vector $X_k^{(4j+1)}$ at time 4j+1, k-th frequency component $X_k^{(4j+2)}$ of FFT output vector $X_k^{(4j+2)}$ at time 4j+2 and k-th frequency component $X_k^{(4j+3)}$ of FFT output vector $X_k^{(4j+3)}$ at time 4j+3. As a result for each subcarrier, the precoded components are mapped onto four consecutive SC-FDMA blocks and the frequency structure of the signal from one block to another is not altered. Because complex conjugation and or sign changes do not break the low PAPR, the signals sent to the four transmit antennas are single carrier signals.

Table 1: STBC Precoding

k-th subcarrier	**Time 4j**	**Time 4j+1**	**Time 4j+2**	**Time 4j+3**
Tx1	$X_k^{Tx1,(4j)} = X_k^{(4j)}$	$X_k^{Tx1,(4j+1)}= (-X_k^{(4j+1)})$	$X_k^{Tx1,(4j+2)}=\left(X_k^{(4j+2)}\right)*$	$X_k^{Tx1,(4j+3)}=(-X_k^{(4j+3)})*$
Tx4	$X_k^{Tx2,(4j)}= X_k^{(4j+1)}$	$X_k^{Tx2,(4j+1)} = (X_k^{(4j)})*$	$X_k^{Tx2,(4j+2)}=(-X_k^{(4j+1)})*$	$X_k^{Tx2,(4j+3)}= (X_k^{(4j+2)})*$
Tx3	$X_k^{Tx3,(4j)}= X_k^{(4j+2)}$	$X_k^{Tx3,(4j+1)}=(-X_k^{(4j+1)})*$	$X_k^{Tx3,(4j+2)} = (X_k^{(4j)})*$	$X_k^{Tx3,(4j+3)}= (-X_k^{(4j+1)})$
Tx4	$X_k^{Tx4,(4j)}= X_k^{(4j+3)}$	$X_k^{Tx4,(4j+1)}= (X_k^{(4j+2)})*$	$X_k^{Tx4,(4j+2)}= (-X_k^{(4j+1)})$	$X_k^{Tx4,(4j+3)} = (X_k^{(4j)})*$

SC- SFBC

Since Space frequency precoding scheme does not alter the PAPR of SC-FDMA, SFBC will not be able to achieve diversity gain and improves system capacity in

MIMO SC-FDMA system. The coding scheme of SFBC scheme is described in the Table 2.

Table 2: SFBC Scheme

	Frequency 4k	**Frequency 4k+1**	**Frequency 4k+2**	**Frequency 4k+3**
Tx1	$X_{4k}^{Tx1}=X_{4k}$	$X_{4k+1}^{Tx1}=X_{4k+1}$	$X_{4k+2}^{Tx1}=X_{4k+2}$	$X_{4k+3}^{Tx1}=X_{4k+3}$
Tx2	$X_{4k}^{Tx2}= -(X_{4k+1})$	$X_{4k+1}^{Tx2}= (X_{4k})^*$	$X_{4k+2}^{Tx2}= -(X_{4k+1})^*$	$X_{4k+3}^{Tx2} = (X_{4k+2})^*$
Tx3	$X_{4k}^{Tx3}= (X_{4k+2})^*$	$X_{4k+1}^{Tx3}= -(X_{4k+1})^*$	$X_{4k+2}^{Tx3}= (X_{4k})^*$	$X_{4k+3}^{Tx3} = -(X_{4k+1})$
Tx4	$X_{4k}^{Tx4}= -(X_{4k+3})^*$	$X_{4k+1}^{Tx4}= (X_{4k+2})^*$	$X_{4k+2}^{Tx4}= -(X_{4k+1})$	$X_{4k+3}^{Tx4}= (X_{4k})^*$

SC-SFBC is used in MIMO SC-FDMA system, to overcome the above problem. The coding scheme of SC-SFBC is entirely different from the Alamouti scheme. It is described in Table 3. In SC-SFBC four frequencies are involved, but they does not use successive subcarriers any longer. The subcarriers K, K', K'' and k'''= (p-1-k) mod S

Where p is the even integer and S is the FFT spreading size.

Table 3: SC-SFBC Scheme

	Frequency 4k	**Frequency 4k+1**	**Frequency 4k+2**	**Frequency 4k+3**
Tx1	$X_{k}^{Tx1}=X_{k}$	$X_{k'}^{Tx1} =X_{k'}$	$X_{k''}^{Tx1} =X_{k''}$	$X_{k'''}^{Tx1}=X_{k'''}$
Tx2	$X_{k}^{Tx2}= -(X_{k'})$	$X_{k'}^{Tx2}= (X_{k})^*$	$X_{k''}^{Tx2}= -(X_{k'})^*$	$X_{k'''}^{Tx2}= (X_{4k''})^*$
Tx3	$X_{k}^{Tx3}= (X_{k''})^*$	$X_{k'}^{Tx3}= -(X_{k'})^*$	$X_{k''}^{Tx3}= (X_{k})^*$	$X_{k'''}^{Tx3} = -(X_{k'})$
Tx4	$X_{k}^{Tx4}= -(X_{k+'''})^*$	$X_{k'}^{Tx4} = (X_{k''})^*$	$X_{k''}^{Tx4}= -(X_{k'})$	$X_{k'''}^{Tx4} = (X_{k})^*$

MIMO SC-FDMA

In MIMO SC-FDMA symbols are transmitted sequentially so that the PAPR is reduced by spreading a symbol power over subcarriers. Also, SC-FDMA in one mode introduces localized scheduling in which contiguous subcarriers are assigned to a user. This makes mobile station more robust of frequency offset than OFDMA, but the diversity order becomes lower than OFDMA. The Block diagram of MIMO SC-FDMA is shown in the Fig. 1.

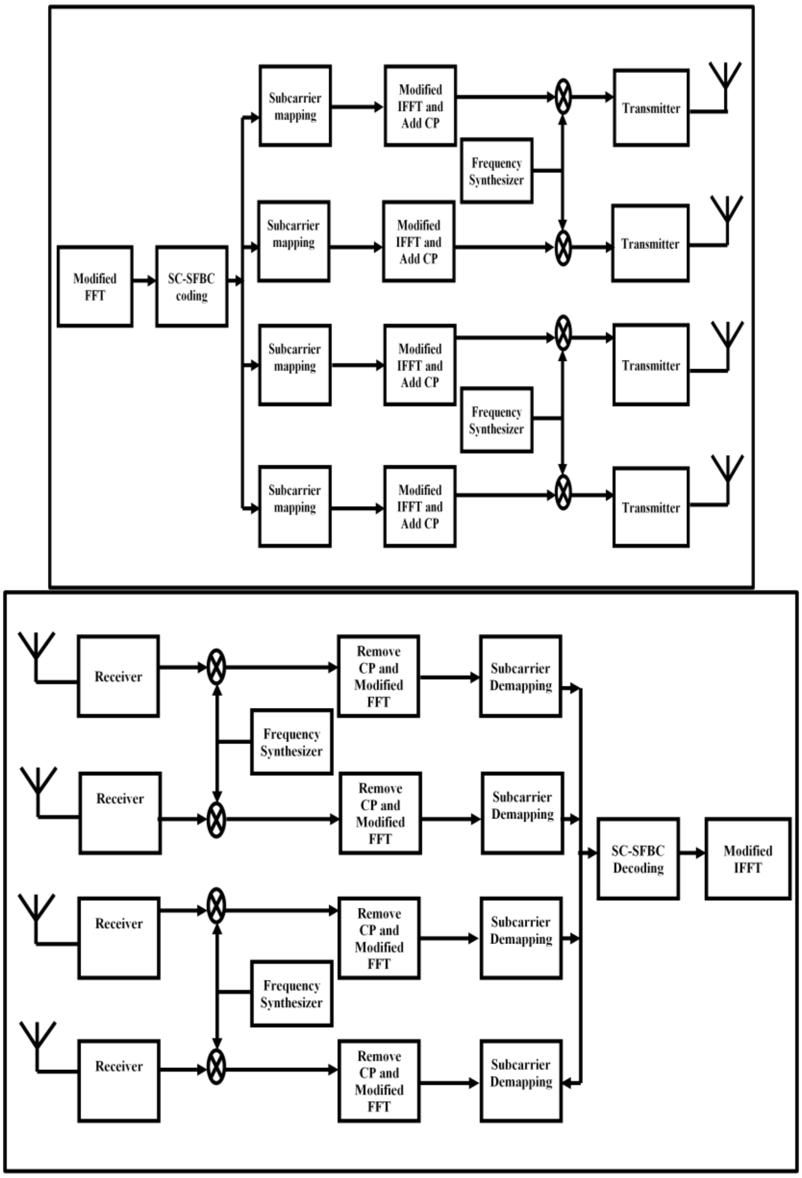

Figure 1: Block diagram of 4X4 MIMO SC-FDMA

The transmitter of an SC-FDMA system converts a binary input signal to a sequence of modulated subcarriers. To do so, it performs the signal processing operations like FFT shown in Fig. 1. The conventional N point FFT, requires $(N/2)\log_2 N$ multiplication operations and $N\log_2 N$ addition operations. If it is N bit multiplier, it will generate 2N partial products. Due to the partial products the delay is increased and it consumes more power. Hence it will affect the throughput of the mobile system. Thus there is a need for reducing the consumed power with decreased delay thereby increase the throughput of the system. The proposed Modified FFT is the combination of memory reference reduction technique, which eliminates the redundant memory references, Binary scaling, converts floating point in to fixed point and Radix 8 Multiplier, generates N/3 partial product.

Signal processing is repetitive in a few different time intervals and resource assignment takes place in transmit time intervals (TTIs). In 3gpp LTE, a typical TTI is 0.5ms. The TTI is further divided into time intervals referred to as blocks. A block is the time used to transmit all of subcarriers once.

Let the Data sequence D= $\{d_0, d_1, d_2...., d_{L-1},\}$ be the input of FFT. The Data spreads after the FFT. It is described in the equation 1.

$$X_k = \sum_{l=0}^{S-1} d_l e^{-j2\pi kl/S} = \sum_{l=0}^{S-1} d_l p_{k,l} \quad (1)$$

To improve the Channel capacity and diversity gain, the symbol undergoes SC-FSBC encoding and it is described in the equation 2.

$$\begin{array}{l} \text{Tx1} \qquad \text{Tx2} \qquad \text{Tx3} \qquad \text{Tx4} \\ \begin{array}{l} \text{Frequency } k \\ \text{Frequency } k' \\ \text{Frequency } k'' \\ \text{Frequency } k''' \end{array} \left\{ \begin{array}{l} X_k^{Tx1} = X_k \; X_k^{Tx2} = (-1)^{k+1} X_{k'} \; X_k^{Tx3} = X_{k''}^{*} \; X_k^{Tx4} = (-1)^{k+3} X_{k'''}^{*} \\ X_{k'}^{Tx1} = X_{k'} \; X_{k'}^{Tx2} = X_k^{*} \; X_k^{Tx3} = (-1)^{k'+2} X_{k'}^{*} \; X_k^{Tx4} = X_{k''}^{*} \\ X_{k'}^{Tx1} = X_{k''} \; X_{k'}^{Tx2} = (-1)^{k'',+1} X_{k'}^{*} \; X_k^{Tx3} = X_k^{*} \; X_k^{Tx4} = (-1)^{k'''+3} X_k \\ X_{k'}^{Tx1} = X_{k'''} \; X_{k'}^{Tx2} = X_{k''}^{*} \; X_k^{Tx3} = (-1)^{k'''+2} X_{k'} \; X_k^{Tx4} = X_k^{*} \end{array} \right\} \end{array} \quad (2)$$

Where X^{Tx1}, X^{Tx2}, X^{Tx3} and X^{Tx4} is the output of the SC-FSBC encoder for Tx1, Tx2, Tx3 and Tx4 respectively

At the input to the transmitter, modulator transforms the binary input to complex number X_n in one of several possible modulation formats including binary phase shift keying (BPSK), quaternary PSK (QPSK) and 16 level quadrature amplitude modulation (16-QAM) The system adapts the modulation format, and thereby increase the transmission bit rate, to match the current channel conditions of each terminal. The transmitter next groups the modulation symbols, X_n into blocks each containing N symbols. The first step in modulating the SC-FDMA subcarriers is to perform an N-point Fast Fourier transform (FFT), to produce a frequency domain representation X_K of the input symbols.

Several approaches for mapping transmission symbols X_K to SC-FDMA subcarriers are currently under consideration. They are divided into two categories namely distributed and localized as shown in Fig. 2.

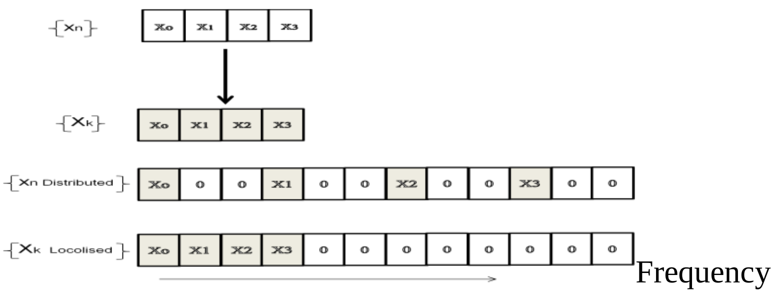

Figure 2: Distributed and Localized Mapping

In the distributed subcarrier mapping mode, FFT outputs of the input data are allocated over the entire bandwidth with zeros occupying the unused subcarriers resulting in a non-continuous comb-shaped spectrum. As mentioned earlier, interleaved SC-FDMA (IFDMA) is an important special case of distributed SC-FDMA. In contrast with IFDMA, consecutive subcarriers are occupied by the FFT outputs of the input data in the localized subcarrier mapping mode resulting in a continuous spectrum that occupies a fraction of the total available bandwidth. Distributed mapping make use of bandwidth spreading factor to introduce a parameter for interleaving the allocated subcarriers of a user. Localized mapping maps the subcarriers allocated to user, which are adjacent to each other.

X_K then maps each of the N FFT outputs to one of the subcarriers that can be transmitted. If all terminals transmit N symbols per block, the system can handle Q simultaneous transmissions without co-channel interference(where Q is the bandwidth expansion factor of the symbol sequence and N=(No of subcarriers)/Q. The result of the subcarrier mapping is the set of X_K (K=0,1,2,…..,M-1) complex subcarrier amplitudes. As in OFDMA, an M-point inverse FFT (IFFT) transforms the subcarrier amplitudes to a complex time domain signal X_M. Each X_M when modulates a single frequency carrier and all the modulated symbols are transmitted sequentially. The transmitted signal of each transmitter can be written as

$$x^1(n) = \frac{1}{N}\sum_{k=0}^{N-1} x'^{Tx1}_k e^{j2\pi kn/N} = \frac{1}{N}\sum_{k=0} x'^{Tx1}_k e^{j2\pi kn/N}$$

$$= \frac{1}{N}\sum_{k\epsilon Sc} \sum_{l=0}^{s-1} d_l p_{k,l} e^{j2\pi kn/N} \quad (3)$$

$$X^2(n) = \frac{1}{N}\sum_{k=0}^{N-1} x'^{Tx2}_k e^{j2\pi kn/N} = \frac{1}{N}\sum_{k\epsilon Sc} x^{Tx1}_k e^{j2\pi kn/N}$$

$$= \frac{1}{N}\sum_{k\epsilon Sc}(-1)^{k+1} \sum_{l=0}^{s-1} d_l^* p_{k,l}^* e^{j2\pi kn/N} \quad (4)$$

$$X^3(n) = \frac{1}{N}\sum_{k=0}^{N-1} x'^{Tx3}_k e^{j2\pi kn/N} = \frac{1}{N}\sum_{k=0} x'^{Tx1}_k e^{j2\pi kn/N}$$

$$= \frac{1}{N}\sum_{k\epsilon Sc}(-1)^{k+2} \sum_{l=0}^{s-1} d_l\, p_{k,l}^* e^{j2\pi kn/N} \quad (5)$$

$$X^4(n) = \frac{1}{N}\sum_{k=0}^{N-1} x'^{Tx4}_k e^{j2\pi kn/N} = \frac{1}{N}\sum_{k\epsilon Sc} x^{Tx1}_k e^{j2\pi kn/N}$$

$$= \frac{1}{N}\sum_{k\epsilon Sc}(-1)^{k+3} \sum_{l=0}^{s-1} d_l^* p_{k,l} e^{j2\pi kn/N} \quad (6)$$

At the receiver, the received signal can be described in the equation 7.

$$y(n) = \sum_{t=1}^{4} [x^t(n)*h^{t,r}(n) + v(n)]\, e^{j[\varphi(n)+2\pi\Delta fn]} \quad (7)$$

The receiver transforms the received signal into the frequency domain via FFT de-maps the subcarriers, and then performs SC-SFBC decoding. Since SC-FDMA uses single carrier modulation, it suffers from inter-symbol interference (ISI). The equalized symbols are transformed back to the time domain via IFFT, detection and decoding take place in the time domain.

Estimation and Suppression of ICI

In MIMO SC-FDMA systems training based estimation is carried out. In training based channel estimation algorithms, training symbols or pilot tones that are known prior to the receiver, are multiplexed along with the data stream for channel estimation. They rely on a set of known symbols interleaved with data in order to acquire the channel estimate. The estimation can be performed by either inserting pilot tones into all of the sub carriers of SC-FDMA symbols, with a specific period, or inserting pilot tones into each SC-FDMA symbol. This is accomplished with the help to two types of pilot carriers. They are 1. Block type pilots 2. Comb type pilots

For a slow fading channel, where the channel is constant over a few SC-FDMA symbols, the pilots are transmitted on all subcarriers in periodic intervals of SC-FDMA blocks. This type of pilot arrangement is depicted in Fig. 3 is called the block type pilot arrangement.

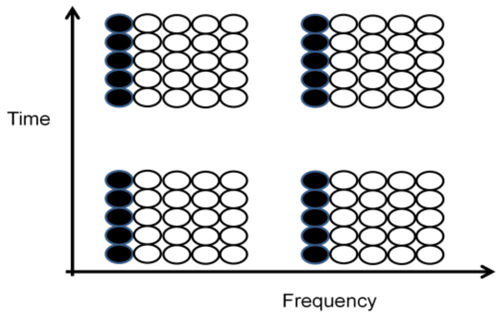

Figure 3: Block type Pilot arrangement

In this some sub-carriers are reserved for pilots for each symbol. The channel estimates form the pilot subcarriers are interpolated to estimate the ICI. The pilot arrangement we have used here is block type pilot arrangement because channel is assumed to be constant over a single sub-carrier which is very small. Based on block type pilot arrangement, ICI is estimated and suppressed. ICI is calculated directly from the received pilot block by reconstructing the ICI matrix and Least Square method, instead of estimating ICI from the phase noise and CFO. Finally ICI is suppressed by taking the inverse for ICI matrix.

Least Square Method

The method of least squares is a standard approach for the approximate solution of over determined systems, i.e., sets of equations in which there are more equations that unknowns. Least square means that the overall solution minimizes the sum of the squares of the errors made in the results of every single equation.

4.1 A regression model is a linear one when the model comprises a linear combination of the parameter, i.e.,

$$f(x_{i,\beta)} = \sum_{j=1}^{m} \beta_j.\Phi_j(x_i) \quad (8)$$

Where the coefficients, Φj are function of (xi)

Letting

$$X_{ij} = \frac{\partial f(xi,\beta)}{\partial \beta j} = \Phi_j (x_i) \quad (9)$$

We can then see that in that case the least square estimate (or estimator, in the context of a random sample), β is given by

$$\beta = (X^T X)^{-1} X^T y \quad (10)$$

Estimation of ICI

Matrix representation of frequency domain signal vector is

$$Y = Q_M R_v + N \quad (11)$$

Where Q_M is ICI matrix, Rv is received pilot block, N is AWGN noise.

$$R_v = [R_0, R_1, R_2, \ldots\ldots, RN\text{-}1]^T \quad (12)$$

The ICI Matrix is given by

$$Q_M = \begin{pmatrix} Q_0 & Q_1 & Q_2 & \cdots & Q_{N-1} \\ Q_{-1} & Q_0 & Q_1 & \cdots & Q_{N-2} \\ Q_{-2} & Q_{-1} & Q_0 & \cdots & Q_{N-3} \\ . & . & . & \cdots & . \\ . & . & . & & . \\ . & . & . & & . \\ Q_{-(N-1)} & Q_{-(N-2)} & Q_{-(N-3)} & \cdots & Q_0 \end{pmatrix} \quad (13)$$

By using FT property

$$\begin{aligned} Q\text{-}k &= \frac{1}{N}\sum_{n=0}^{N-1} e\ j[2\pi(-k+\varepsilon)n/N + \varphi(n)] \\ &= \frac{1}{N}\sum_{n=0}^{N-1} e\ j[2\pi(-k+\varepsilon)n/N + \varphi(n) + 2\ \pi.n] \\ &= \frac{1}{N}\sum_{n=0}^{N-1} e\ j[2\pi((N-k)+\varepsilon)n/N + \varphi(n)] \\ &= QN\text{-}k \end{aligned} \quad (14)$$

Now the ICI matrix is

$$Q_M = \begin{pmatrix} Q_0 & Q_1 & Q_2 & \cdots & Q_{N-1} \\ Q_{N-1} & Q_0 & Q_1 & \cdots & Q_{N-2} \\ Q_{N-2} & Q_{N-1} & Q_0 & \cdots & Q_{N-3} \\ . & . & . & \cdots & . \\ . & . & . & & . \\ Q_1 & Q_2 & Q_3 & \cdots & Q_0 \end{pmatrix} \quad (15)$$

Q_M is a circular matrix with only n different values. Frequency domain signal vector of the received signal in matrix form is

$$Y = Q_M . R_v + N \quad (16)$$

$$Q_M = \begin{pmatrix} Q_0 & Q_1 & Q_2 & \cdots & Q_{N-1} \\ Q_{N-1} & Q_0 & Q_1 & \cdots & Q_{N-2} \\ Q_{N-2} & Q_{N-1} & Q_0 & \cdots & Q_{N-3} \\ \cdot & \cdot & \cdot & \cdots & \cdot\,\cdot \\ \cdot & \cdot & \cdot & & \cdot\,\cdot \\ Q_1 & Q_2 & Q_3 & \cdots & Q_0 \end{pmatrix} \begin{pmatrix} R0 \\ R1 \\ R2 \\ \\ \\ R_{N-1} \end{pmatrix} + N \qquad (17)$$

Q_M consists of N unknown values, these values are easily calculated by solving the equation set 17 and Q_M matrix can be reconstructed. By multiplying the inverse Q_M matrix with the received signal, we can suppress the interference caused by phase noise and CFO.

The above matrix equation can be rewritten as

$$Y = Q_M . R_v + N$$
$$= R_M . Q_v + N \qquad (18)$$

Where

$$R_M = \begin{pmatrix} R0 & R1 & R2 & \cdots & RN-1 \\ R1 & R2 & R3 & \cdots & R0 \\ R2 & R3 & R4 & \cdots & R1 \\ \cdot & \cdot & \cdot & \cdots & \cdot\,\cdot \\ \cdot & \cdot & \cdot & & \cdot\,\cdot \\ \cdot & \cdot & \cdot & & \cdot \\ RN-1 & R0 & R1 & \cdots & RN-2 \end{pmatrix} \quad Q_v = \begin{pmatrix} Q0 \\ Q\,1 \\ Q\,2 \\ \\ \\ \cdot \\ Q\,N-1 \end{pmatrix} \qquad (19)$$

N is the AWGN

Where R_M is a full rank matrix and Q_v is the ICI vector, which contains the N components in Q_M. Since the pilot carrier is known to the receiver, it can be easily estimated from the received signal. Assuming that the channel information known to the receiver, we can calculate matrix R_M and inverse matrix R_M^{-1}. Thus the ICI vector Q_v can be obtained by least square method

$$Qv = (R_M^T R_M)^{-1} R_M^T Y \qquad (20)$$

After that, the ICI matrix Q_M can be reconstructed form the estimated Q_v by very simple mapping process.

Suppression of ICI

During the pilot block Mapping the phase noise and CFO is highly correlated, since the symbol period and frame size are usually very short. Therefore phase noise and CFO of data block can be easily suppressed by least square method

$$Y_{suppressed} = (Q_M^H . Q_M)^{-1} . Q_M^H . Y$$
$$= R_v + (Q_M^H . Q_M)^{-1} . Q_M^H . \qquad (21)$$

Results and Discussion

Code development and simulation was carried out on a system running on Intel i3 configuration having 4GB RAM working in windows 7 Platform. The MIMO SC-FDMA Transceiver structure for determination of constellation points and BER were coded & simulated in MATLAB the results of which are presented & discussed in succeeding section. Structural realisation of MIMO SC-FDMA Transceiver is implemented in Xilinx. Analysis pertaining to timing and frequency is done in Altera. The experimental results and analysis obtained using Matlab, Xilinx and Altera are presented and discussed below.

The Modified FFT processor has been implemented using Xilinx Virtex-4 FPGA. Based on the analysis, Device utilization summary is tabulated in the Table 4. From the results, we can observe that the Modified FFT Algorithm requires only 10 percentage of slices, 11 percentage of flip flops and 7.5 percentage of LUTs compared to the conventional FFT Algorithm.

Table 4: Device utilization summary

	Modified FFT Algorithm		**Conventional FFT Algorithm**	
Logic Utilization	**Used**	**Available**	**Used**	**Available**
No of Slices	74	6144	782	6144
No of Slices Flip Flop	92	12288	1040	12288
No of 4 Input LUTS	142	12288	1080	12288
No of bonded IOBs	187	240	321	240
No of GCLKS	1	32	1	32

The MIMO SC-FDMA described in section 3 has been implemented using Xilinx Virtex-4 FPGA. Based on the analysis, Device utilization summary is tabulated in the Table 5. From the results, we can observe that the Modified FFT + MIMO SC-FDMA requires only 24% percentage of slices, 5% percentage of flip flops and 21% of LUTs.

Table 5: Device utilization summary

	Modified FFT +MIMO SC-FDMA		
Logic Utilization	**Used**	**Available**	**Utilization**
No of Slices	1489	6144	24%
No of Slices Flip Flop	684	12288	5%
No of 4 Input LUTS	2691	12288	21%
No of bonded IOBs	25	240	21%
No of GCLKS	1	32	3%

The MIMO SC-FDMA described in section 3 has been analysed using Altera Quarts II FPGA. Based on the results, the performance of the system is compared and tabulated in the Table 6. Throughput of the mobile system entirely depends on the power consumption and delay. The proposed system consumes less power and short delay. Hence the Throughput of the mobile system is increased.

Table 6: Performance Comparisons

S.No	Parameter	MIMO OFDM	Mixed Radix FFT + MIMO OFDM	Modified FFT + MIMO OFDM	Modified FFT + MIMO OFDM +CSD Input	Modified FFT + MIMO SC-FDMA
1	Power Dissipation	597mW	540mW	121mW	111mW	100mW
2	No of Memory Reference	32	24	15	12	12
3	Storage space in Bytes	32	30	12	12	12
4	No of clock cycle	698	600	540	520	480
5	Throughput	600Mbps	700Mbps	1.4Gbps	1.6Gbps	1.9Gbps
6.	Delay	9.43ns	8.89ns	4.04ns	3.79ns	3.13ns
7.	Logic Elements	9940	9813	5844	3128	1096

MATLAB Simulation Output

The constellation points before ICI is shown in the Fig. 4 and the constellation points after ICI is shown in the Fig. 5. Both the results are obtained when Signal to Noise ratio is 15dB and the normalised frequency offset is ϵ=0.1. From the results it is observed that the constellation points will be distorted by the interference.

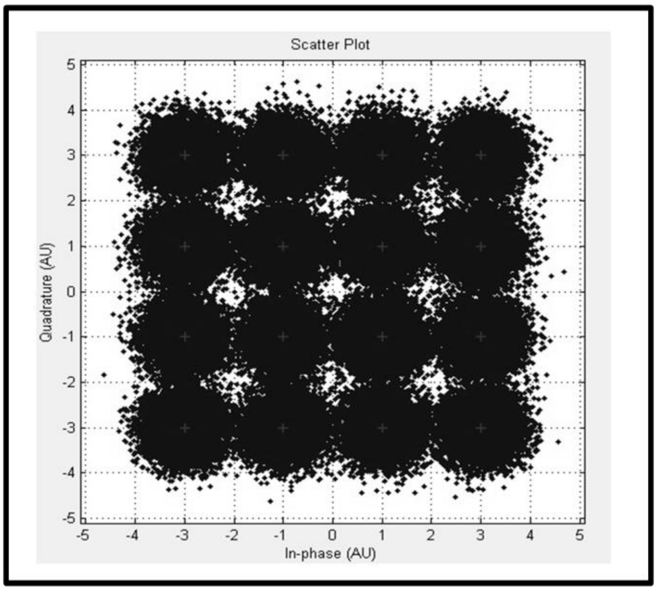

Figure 4: Constellation points before ICI

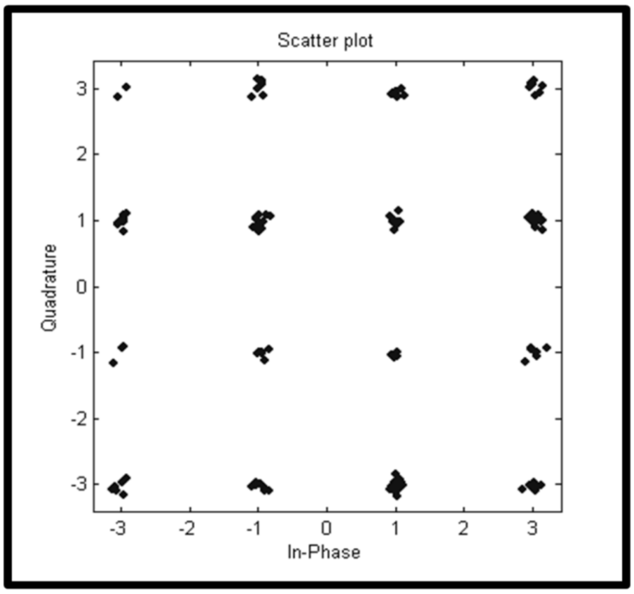

Figure 5: Constellation points after ICI

Fig. 6 shows the BER performance of Rayleigh channel. From the results we can observed that BER of the proposed method is zero when SNR is around 15dB and the Inter carrier interference is completely eliminated.

When the SNR is 12.5dB, BER of 4X4 MIMO SC-FDMA Transceiver is almost zero compared with other scheme is shown in the Fig .7.

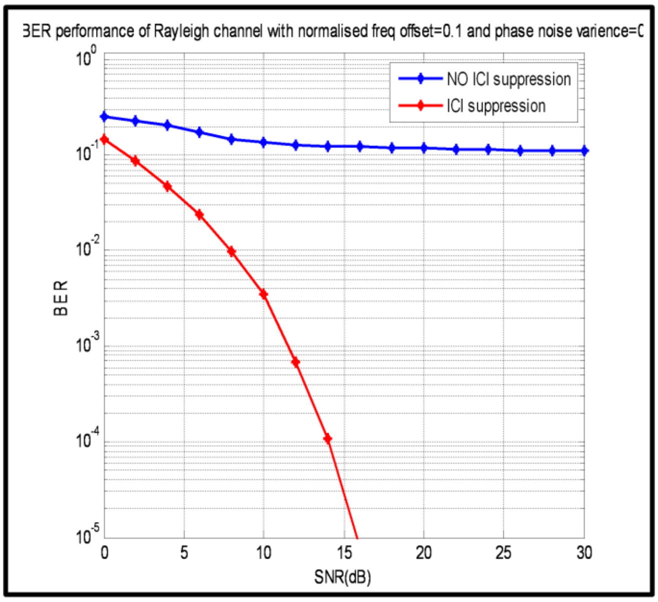

Figure 6: BER Vs SNR of Rayleigh channel

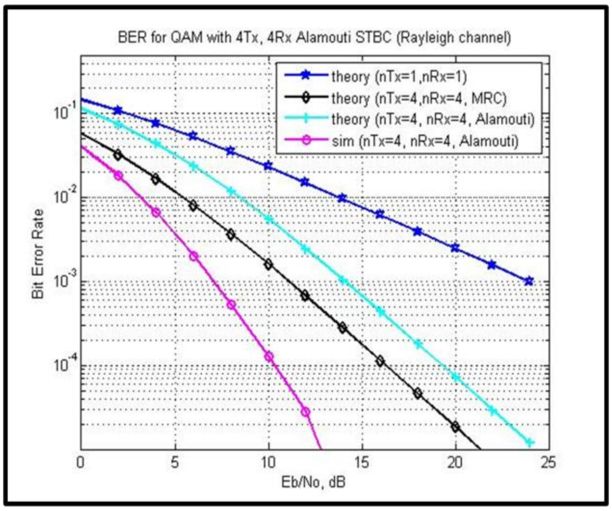

Figure 7: BER Vs Eb/No of MIMO SC_FDMA

FPGA Implementation output

Simulation Output of MIMO SC-FDMA

The Binary inputs i1 are passed through the modified FFT algorithm and the FFT output is mapped using QAM technique, finally the frequency of the bit is synchronized in the transmitter section. The transmitted outputs are spatially multiplexed and the transmitted data are received by receiver using MRC (Maximum Ratio Combining) Techniques. Finally the outputs are taken from s7out. Simulation Output of MIMO SC-FDMA transceiver is shown in the Fig. 8.

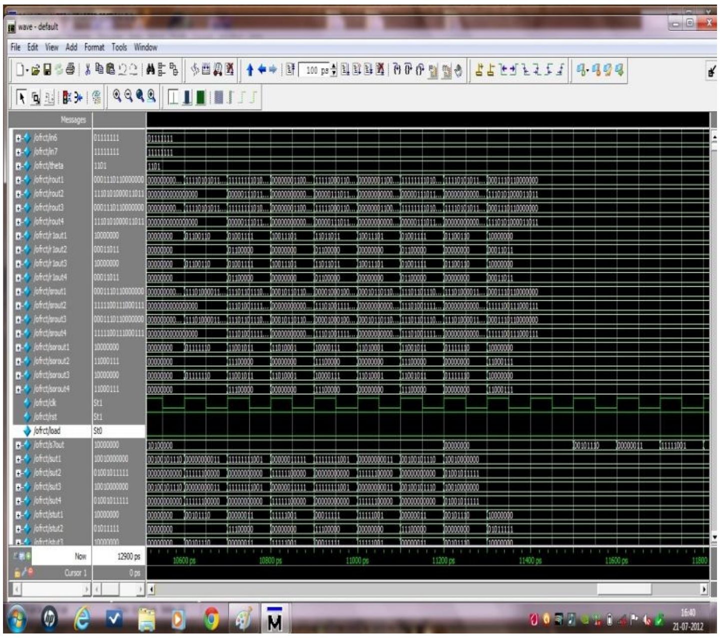

Figure 8: Simulation output of MIMO SC-FDMA

Synthesize output of MIMO SC-FDMA

MIMO OFDM Structure was synthesized and simulated in Vertex-4 FPGA as shown in the Fig 9. The proposed structure was constructed using four transmitting and four receiving antennas. Transmitter outputs and receiver inputs are combined using spatial multiplexing Technique. From the results we can observed that the proposed method can achieve average of 24% Number of slices, 5 % of Flip Flops and average of 21 % of LUTs.

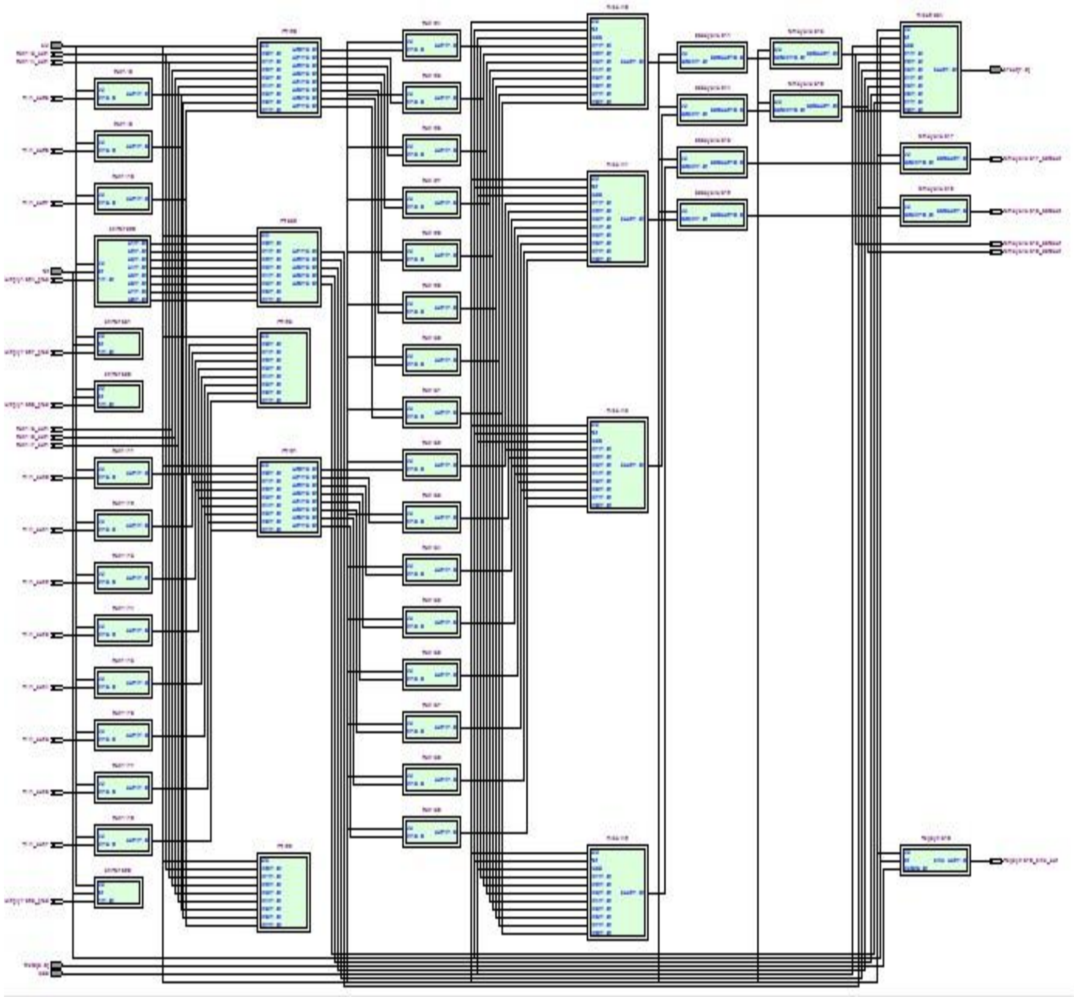

Figure 9: Synthesize output MIMO SC-FDMA

Performance Analysis

Power Dissipation Vs Throughput

Maximum throughput is obtained at minimum power which is 100mW. When power increases more and more correspondingly throughput of the system gradually decreases as shown in the Fig. 10. From the graph we conclude that the proposed system consumes less power and transmits maximum number of bits per second.

Memory Reference Vs Performance parameters of Different MIMO OFDM Systems
The main objective of this paper is to estimate and suppress the ICI and also to reduce the power and increase the throughput. Memory reference in FFT is costly due to the long delay and high power consumption. Memory reference reduction method is used in FFT to eliminate redundant memory references. Based on the result the graph is plotted in Fig. 11. From the graph we conclude that the proposed method delivers 1.9 Gbps maximum throughput with minimal number of memory references of 12 with the corresponding delay of 3.13ns at 100mW power.

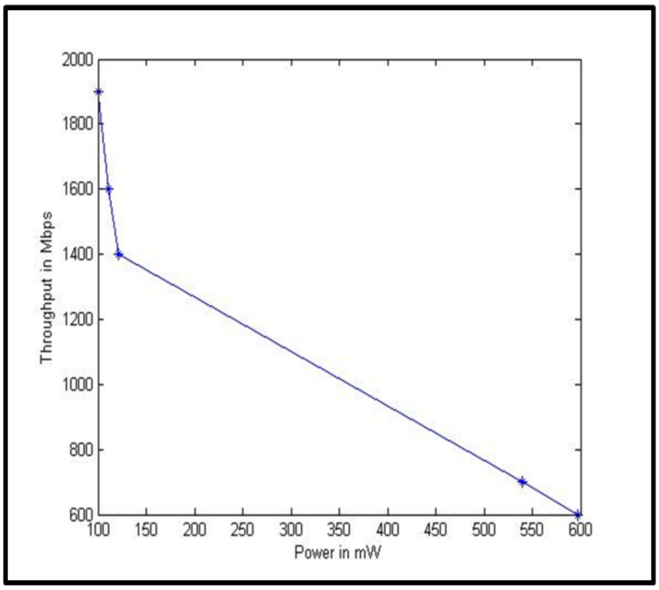

Figure 10: Power Vs Throughput parameters of Different Systems

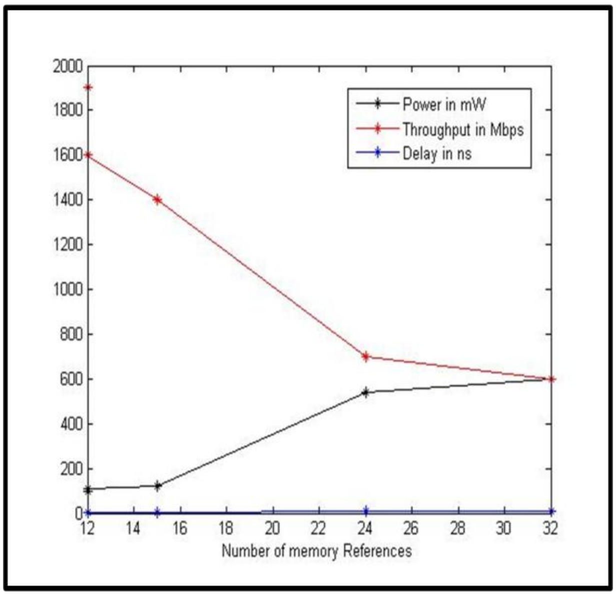

Figure 11: Memory Reference Vs Performance parameters of Different Systems

Conclusion

In this work we have presented a VLSI Implementation of 4X4 MIMO SC-FDMA transceiver for low power applications which achieves 1.9 Gbps throughput. The circuit was implemented in a 28 nm library with less circuit area and evaluated under lower power dissipation. This can be achieved by optimizing FFT architecture (Memory reference reduction and Binary Scaling Methods are used to minimize redundant memory references) and Radix-8 Booth Multiplier Algorithm (Radix-8 Multiplier technique is used to reduce the power dissipation) which reduces number of partial products. Also the block type arrangement used to suppress the interference between the carrier caused by phase noise and CFO. Our future work will be focused on VLSI implementation of the above mentioned concept in channel synchronization and OFDM environment.

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