A Low Power VLSI Implementation of 2X2 MIMO OFDM Transceiver with ICI-SC Scheme

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ABSTRACT
This paper presents a VLSI implementation of 2X2 MIMO OFDM transceiver with self ICI cancellation scheme at very low power. Phase noise and the carrier frequency offset (CFO) are the major problems in Orthogonal Frequency Division Multiplexing (OFDM) that destroys the mutual orthogonality of the sub-carriers over a given time interval. This non-orthogonality between the sub-carriers causes Inter-Carrier Interference (ICI). Interference among the sub-carriers degrades the performance of the system greatly. In the proposed scheme, the space coding is applied over two successive OFDM symbols and neighboring subcarriers simultaneously within single symbol duration. This reduces the delay encountered in space coding and decoding since no OFDM symbol has to be buffered. This leads to the self-cancellation of ICI components in the desired signal. The effects of Phase Noise and CFO in MIMO OFDM are greatly reduced by the space frequency block codes. Matlab simulations are performed prior to the Verilog HDL coding for functional verification. The SFBC coded MIMO OFDM transceiver is designed, implemented and tested in TSMC 180nm technology using Cadence NC Simulator, RTL Compiler and Altera ModelSim with DE2 EP2C35F672C6. The proposed 2X2 MIMO OFDM transceiver with ICI-SC technique has 41,298 numbers in logic gates and consumes 17.92mw in power dissipation at a maximum throughput of 1.13Gbps.

General Terms
Low Power, VLSI, Communication and Computing.

Keywords
Inter carrier interference (ICI), Multiple Input Multiple Output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), Fast Fourier Transform (FFT), Space Frequency Block Codes (SFBC), Phase Noise, Carrier Frequency Offset (CFO) and Inter Carrier Interference Self Cancellation (ICI-SC).

1. INTRODUCTION
The next generation wireless communication systems must be the successor of current generation systems. The several applications of next generation systems includes high speed mobile ultra broadband internet, mobile web access, IP telephony, high definition mobile TV and gaming services at higher data rates than ever before. The rapid need in demands for services with high data rates, high quality and high mobility is driving recent developments in communication technologies for broadband wireless communications [1-2].

Currently, MIMO OFDM is a technology that provides improved spectral efficiency and high diversity gains to achieve a high performance broadband wireless communication system [3-4]. The use of MIMO technology in combination with OFDM becomes an attractive solution for future broadband wireless systems.

A multiple antenna OFDM system is very sensitive to CFO, which introduces ICI. One of the most challenging problems of MIMO OFDM is ICI [5]. In MIMO OFDM system, individual subcarriers in a time invariant multipath model can be made to be orthogonal by the use of guard interval. However this orthogonality is destroyed in time variant channel. The loss of orthogonality reduces the useful signal in each subcarrier and introduces ICI in each subcarrier. The occurrence of ICI leads to an irreducible error floor in conventional OFDM receivers, hence degrading the MIMO OFDM system performance.

Consequently, one of the principal shortcomings of OFDM system is its high sensitivity to phase noise. MIMO-OFDM receiver in the presence of phase noise with even a small fraction of sub-carrier spacing will degrade the performance of MIMO-OFDM receiver greatly [6]. Phase noise and CFO not only causes amplitude degradation of our desired information signal, but also introduces ICI between the successive sub-carriers.

Several methods have been proposed earlier to eliminate the effect of the ICI, which includes, frequency-domain equalization [7], time domain windowing scheme [8], frequency offset estimation [9] and ICI self-cancellation [10].

In despite of loss of bandwidth, the ICI self-cancellation scheme is a very simple way for suppressing ICI in MIMO OFDM system [11]. Its main idea is to modulate one data symbol onto a group of subcarriers with predefined weighting numerical constants. In this way, the ICI components generated within a group of sub-carriers will be “self-cancelled” each other.

To further improve the performance, we may consider space coding across multiple OFDM blocks to exploit all the available diversities in the spatial, temporal and frequency domains. The space coding strategy was first proposed [12] for two transmit antennas and further developed [13-15] for multiple transmit antennas. The performance criteria for space codes were derived and the maximum achievable transmitter diversity order was established in [13]. The result [16] showed that the proposed spatial codes guaranteed to achieve the full spatial, temporal and frequency diversities. So far there is no literature on the performance evaluation of the ICI-SC using space frequency block coding technique in MIMO OFDM. Therefore, in this paper, we propose a real time VLSI implementation of space block coded MIMO OFDM at reduced power employing with low complexity to minimize ICI generated by carrier frequency offset and phase noise.

The paper is structured as follows. After this introduction, section II explains the MIMO OFDM system concepts and section III shows space frequency block coded multi-user OFDM system model. The section IV discusses with the implementation results using 180nm Cadence NC Simulator, RC compiler and Matlab. The proposed paper finishes with some concluding remarks in section V.

2. MIMO OFDM

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. 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. The OFDM signal on each subcarrier can overcome narrowband fading. Therefore, OFDM can transform frequency-selective fading channels into parallel flat channels. Then by combining MIMO and OFDM technology together, MIMO algorithms can be applied in broadband transmission [17-18]. MIMO OFDM or OFDM based multiple accesses (OFDMA) technique has been proposed for several applications in section I. An example of a MIMO system is given in the figure 1 for N number of transmitter and receiver antennas.

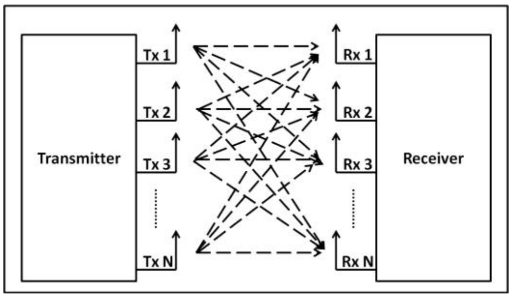


Fig 1: A MIMO system.

OFDM is a technique which is a subset of frequency division multiplexing in which a single channel uses multiple sub-carriers on neighboring frequencies. The sub-carriers of an OFDM system overlap each other. Normally the neighboring channels which overlap may obstruct one another. Since the sub-carriers in an OFDM system are exactly orthogonal to one another, they are capable of overlapping without interfering. As a result, OFDM systems are able to maximize spectral efficiency without causing neighboring channel interference [19]. Since the multiple sub-carriers are used to transmit, an MIMO OFDM communication system must perform several steps as are shown in the figure 2.

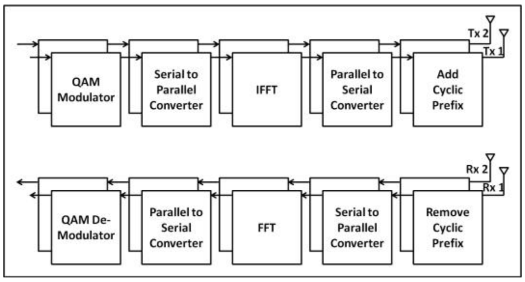


Fig 2: 2X2 MIMO OFDM System.

The incoming input binary bits are modulated using Quadrature Amplitude Modulation (QAM) scheme. Since error probabilities are less in 16-QAM when compared with that of 64 and 256 QAM, we use 16-QAM for our results. The mapping of binary bits in QAM modulation can be expressed mathematically as,

$$s(t) = \sqrt{\frac{2E_s}{T}}\cos(\theta(t))\cos(2\pi f_c t) - \sqrt{\frac{2E_s}{T}}\sin(\theta(t))\sin(2\pi f_c t) \quad \ldots (1)$$

The first and second part of the equation (1) represents the In-phase and Quadrature phase values respectively. We can compute I and Q values depending on the total power we want by a typical constellation diagram shown in figure 3. In our case, we use a look up table function (so called baseband processing) for generating I and Q values. By this way, both the amplitude and phase of the carrier signal is varied according to the incoming information binary bits.

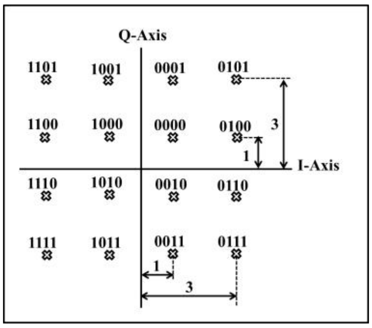


Fig 3: Constellation diagram for 16-QAM

The building blocks of the QAM modulator are shown in the figure 4. The QAM signal mapper divides the incoming bits so as to multiply by the orthogonal carriers. The sine and cosine carriers are normally generated by a Numerically Controlled Oscillator (NCO) which generates accurate In phase and Quadrature phase carriers. For our implementation, these values are stored in a look up table function. Then both the results from multiplier are added to constitute QAM signal.

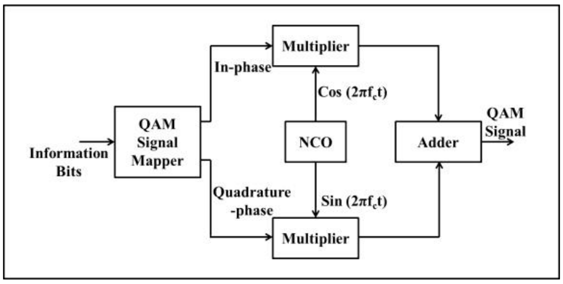


Fig 4: QAM Modulator

After the QAM block the signal is given to serial to parallel converter block so as to facilitate with the Inverse Fast Fourier Transform block in the transmitter and vice versa in the receiver. Let *T* be the duration of the OFDM symbol, *B* be the total bandwidth and the separation between each sub-channel is chosen such that *B* = *N/T*. The complex envelope of the OFDM signal sampled with sampling frequency equal to *B* can be obtained by an Inverse Discrete Fourier Transform of the complex input symbol sequence *sin* (where *i* is the time index and *n* is the sub-carrier index) as:

$$x(k) = \sum_{i=-\infty}^{\infty} DFT^{-1}\{s_{in}\} \prod_N (k - iN) \qquad \ldots (2)$$

Here $\prod_N(k)$ represents a rectangular pulse with *N* sample.
The frequency of the *N* sub channel is given by equation 3.

$$f_n = f_0 + \frac{n}{T},\ n = 0,1, \ldots N-1 \qquad \ldots (3)$$

The Fast Fourier Transform (FFT) is an efficient computation of the Discrete Fourier Transform (DFT) and the Inverse Fast Fourier Transform (IFFT) is an efficient computation of the Inverse Discrete Fourier Transform (IDFT). The IFFT generally needed to transform a signal from the frequency dimension into spatial dimension. The DFT and IDFT transformations are shown in equations 4 and 5.

$$X_k = \sum_{k=0}^{N-1} x_n e^{-i\frac{2\pi nk}{N}} \qquad \ldots (4)$$

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{i\frac{2\pi nk}{N}} \qquad \ldots (5)$$

The operation of Fast Fourier Transform (FFT) and the Inverse Fast Fourier Transform (IFFT) are matched linear pair. So this pair is commutable. So both can be reversed and still they will return the original input which is given in [20]. The operation of Fast Fourier Transform (FFT) and the Inverse Fast Fourier Transform (IFFT) can be mathematically expressed in equations 6 and 7 respectively,

$$x(k) = \sum_{n=0}^{N-1} x(n) \sin\left(\frac{2\pi kn}{N}\right) + j \sum_{n=0}^{N-1} x(n) \cos\left(\frac{2\pi kn}{N}\right) \qquad \ldots (6)$$

$$x(n) = \sum_{n=0}^{N-1} x(k) \sin\left(\frac{2\pi kn}{N}\right) - j \sum_{n=0}^{N-1} x(k) \cos\left(\frac{2\pi kn}{N}\right) \qquad \ldots (7)$$

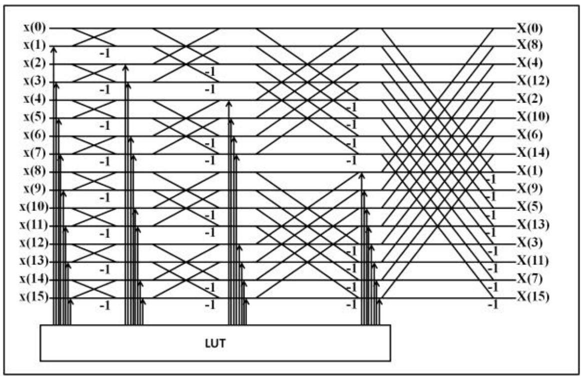


Fig 5: DIT FFT structure for N=16.

Thus by the above equation it is clear that IFFT quickly computes the time domain signal instead of having to do it one carrier at time and then adding [20]. These sub-carriers are orthogonal when we multiply a sinusoid of frequency n by a sinusoid of frequency m/n. The 16 point decimation in time FFT structure is shown in the figure 5. The twiddle factor values are stored and taken from an LUT.

In an OFDM environment, the individual data carriers are sub divided into a number of sub carriers is determined by IFFT algorithm we have used. For the inherent frequency division nature of the desired signal, FDMA is the best approach. When the OFDM signal is shared in an FDMA basis, different users transmit in different sub-carriers, which become multi-user OFDM.

In the receiver, the composite signal (which is created by IFFT) with the contributions of *N* sub carriers will be an OFDM signal that may be demodulated using a FFT algorithm, which is not much complicated than a set of *N* subsequent FDMA demodulators.

In a multi user MIMO OFDM system, if *n* is the user number and S_n is the information symbol to be transmitted by that user at a given time, each OFDM symbol formed by the composite signal with the contribution of each of the *N* users can be given mathematically as in equation 8.

$$x(k) = \sum_{n=0}^{N-1} S_n e^{j\frac{2\pi}{N}nk} \qquad \ldots (8)$$

After IFFT processing, the signal is fed through a cyclic prefix block. The cyclic prefix serves two significant purposes in OFDM transmission. First, as a guard interval, it eliminates the intersymbol interference from the neighboring OFDM symbol. Second, as a repetition of the end of the same symbol, it allows the linear convolution of a frequency selective multipath channel which can be modeled as circular convolution, given in equation 9 and 10, which in turn may be transformed to the frequency domain using DFT [19].

$$y(n) = \sum_{k=0}^{\mu-1} h(k) x(n-k) N \qquad \ldots (9)$$

$$y(n) = x(n) \otimes h(n) \qquad \ldots (10)$$

This approach allows for simple frequency domain processing such as channel estimation and equalization. The cyclic prefix is more efficient if the length of the cyclic prefix is equal to the length of the multipath channel. The process of cyclic prefix insertion is shown in the figure 6.

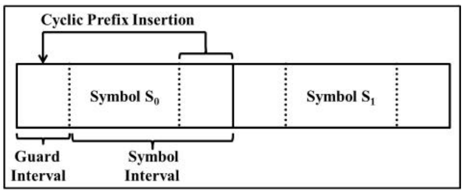


Fig 6: Cyclic Prefix insertion.

Finally, after adding the cyclic prefix, the output OFDM signal is frequency up converted using a frequency synthesizer. Here, the baseband signaling is converted into passband signaling for the purpose of transmission using multiple antennas Tx_1 and Tx_2.

As we discussed the effects of Phase Noise and CFO, the OFDM signal includes Inter Carrier Interference (ICI), which in turn degrades the system performance greatly. Space frequency block codes can reduce such effects of ICI in multi-user system effectively which we will discuss in section III.

3. SPACE FRQEUNCY BLOCK CODES

Space frequency block codes are the subset of space block codes. Space time block coded multi-user OFDM and space frequency block coded multi-user OFDM suffer from time and frequency selective fading channels respectively [21-22]. Table I shows the mapping of the proposed SFBC scheme on subcarriers with two transmit antennas.

Table 1. Mapping Scheme For 2x2 SFBC Codes

Subcarrier	Antenna 1	Antenna 2
N	S_n	$-S_{n+1}^*$
n+1	S_{n+1}	S_n^*

In space frequency block coded MIMO OFDM, different symbols are transmitted from different antenna at the same time. As mapping scheme has shown for 2 transmitter antenna, OFDM symbols are received with an error less than one when those symbols are sent from a one transmitter antenna (without any complex mathematical operations). Here, the space coding is applied across neighboring OFDM subcarriers within a single OFDM symbol duration. This reduces the delay encountered in space coding and decoding since no OFDM symbol has to be buffered. This leads to the self-cancellation of ICI components in the desired signal. The effects of ICI such as system degradation in MIMO OFDM are greatly reduced by the space frequency block codes. Therefore, different subcarrier of one OFDM symbol transmits from different antenna at the same time. If the number of transmit antenna are NTx and the number of frequency slot for transmit NTx subcarrier are L and frequency distance of subcarriers is Δf, optimal performance can be achieved when the spectrum of channel is fixed for frequency range of $L x \Delta f$. This can be expressed mathematically as in equation 11:

$$B_C > L \times \Delta f \qquad \dots (11)$$

Where B_c is the channel coherence bandwidth.

The average coherence bandwidths were assessed numerically from a large number of realizations [23]. As in SFBC MIMO OFDM system, space codes are placed on subcarriers of a single OFDM symbol and in MIMO OFDM, frequency hopping occurs in the end of OFDM symbol, therefore, frequency hopping does not affect the functionality of this system. Figure 7 shows blocks after the modulator, in the transmitter of SFBC multi-user OFDM system.

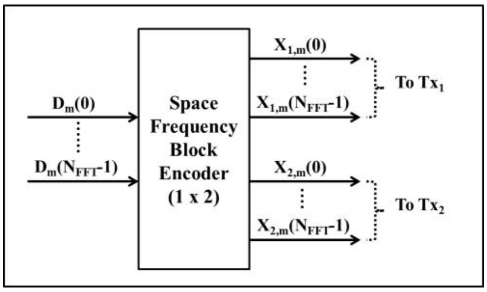


Fig 7: SFBC Encoder.

The data from the QAM modulator can be mathematically represented as,

$$D_m = [D_m(0), D_m(1), \dots, D_m(N_{FFT}-1)]^T \qquad \dots (12)$$

In equation 12, m is multi-user OFDM symbol number, D_m is the modulator output and N_{FFT} is the size of FFT/IFFT algorithm used in our system. Then, the modulator output D_m enters space frequency block encoder and symbols $X_{l,m}(k)$ are coded output which indicates *m*th transmitted OFDM symbol in the *l*th antenna and *k*th subcarrier, where k ranges from 0 to $N_{FFT}-1$.

The space frequency block encoder uses the code vector given in equation 13 is passed to the IFFT block.

$$X_{l,m} = [X_{l,m}(0), X_{l,m}(1), \dots, X_{l,m}(N_{FFT}-1)] \qquad \dots (13)$$

The code matrix for $NT_x = 2$ is given as,

$$G = \begin{bmatrix} X_{1,m}(2r) & X_{1,m}(2r+1) \\ X_{2,m}(2r) & X_{2,m}(2r+1) \end{bmatrix} \qquad \dots (14)$$

$$G = \begin{bmatrix} D_m(2r) & -D_m^*(2r+1) \\ D_m(2r+1) & D_m^*(2r) \end{bmatrix} \qquad \dots (15)$$

In equation 15, $r = 0, 1 \dots (N_{FFT}/2 - 1)$ that represents the index number of subcarriers (it is assumed that the N_{FFT} is even). Figure 7 shows the clarified function of the space frequency block encoder to overcome this issue. The transmitted signals from both the antenna are then passed into the different individual channels [24-25]. In receiver, the signal with maximum power will be processed down to get the information bits by using Maximal Ratio Combining (MRC) technique.

As discussed above, the space frequency block coding is to be applied across the sub-carriers of OFDM. In order to achieve this, encoding is done immediate after the mapping operation in OFDM. Therefore, space frequency block coding will effect on IFFT, where sub carriers for OFDM will be generated. So the SFBC encoder is placed in between the modulator and IFFT blocks in the transmitter. The block diagram for the space frequency block coded MIMO OFDM is shown in the figure 8.

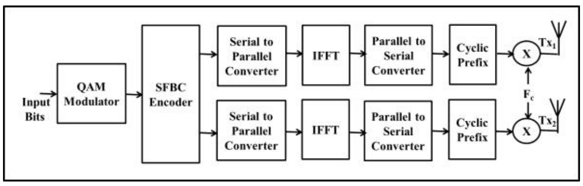


Fig 8: SFBC coded MIMO OFDM block diagram.

Even though the output from the QAM modulator is a complex one, the encoding is carried out in an efficient way such that it maps the output to the both transmitting antennas Tx_1 and Tx_2 as shown in the figure 7.

Since the implementation is carried out in real-time FPGA, the serial to parallel conversion, IFFT algorithm, parallel to serial conversion and the insertion of cyclic prefix must be simultaneously applied to the both real and imaginary values from the space frequency block encoder [26].

The frequency synthesizer used here is to convert the baseband signaling from MIMO OFDM to passband signaling in order for transmission. The same technique is used in the receiver to generate the carriers in accurate frequencies to eliminate CFO.

4. RESULTS AND DISCUSSIONS

The SFBC coded 2X2 MIMO OFDM transceiver is designed, implemented and tested in TSMC 180nm technology using Cadence NC Simulator, RTL Compiler and Altera ModelSim with DE2 EP2C35F672C6 FPGA. The simulations of SFBC coded 2X2 MIMO OFDM transceiver is implemented in Altera Quartus II. Analysis pertaining to timing, area and power are accomplished in Cadence RTL compiler under 180nm technology. The SFBC coded 2X2 MIMO OFDM structure for determination of constellation points and BER were coded & simulated in MATLAB. The experimental results and analysis obtained using Matlab, Cadence simulator and Altera are presented and discussed in succeeding sub-section.

4.1 VLSI Implementation

4.1.1 Synthesis output

The SFBC coded 2X2 MIMO OFDM structure was synthesized in TSMC 180nm technology using Cadence NC Simulator and RTL Compiler. The proposed system achieves a total of 41,298 instances which includes 5,805 of sequential, 8,538 of inverters and 26,955 of logic elements. The RTL output of SFBC coded 2X2 MIMO OFDM system is shown in the figure 9.

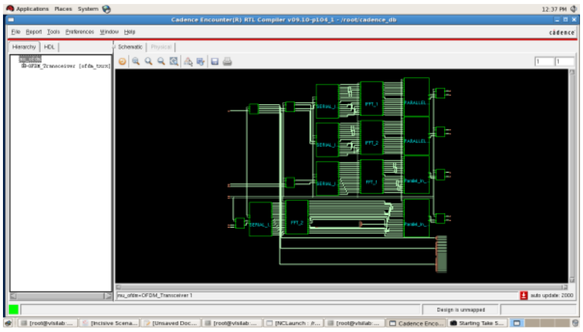


Fig 9: RTL schematic Output.

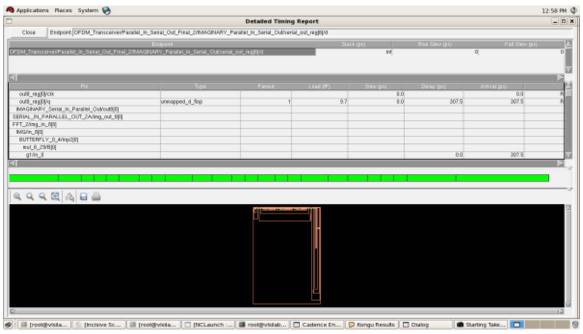


Fig 10: Timing analysis output.

4.1.1.1 Timing analysis

The proposed system with ICI-SC scheme achieves a maximum clock set up time 11.696ns (85.50MHz) and a maximum delay of 307.5ps. The timing analysis report for SFBC coded 2X2 MIMO OFDM is shown in the figure 10.

4.1.1.2 Power analysis

The proposed system consumes a total power of 17.92mW which includes a leakage power of 0.029mW, internal power of 5.88mW, a net power of 3.06mW and a switching power of 8.95mW. The power analysis report for SFBC coded 2X2 MIMO OFDM is shown in the figure 11.

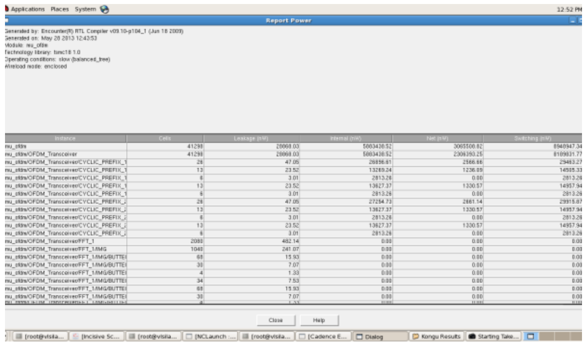


Fig 11: Power analysis output.

The net power usage and instance power usage by the proposed SFBC coded 2X2 MIMO OFDM transceiver are shown in the figure 12 and 13 respectively.

The different performance considerations were taken from three different MIMO OFDM processors [27,28,29]. The total power consumption, area, throughput, operating frequency and the CMOS technology used for simulations are detailed in the table II.

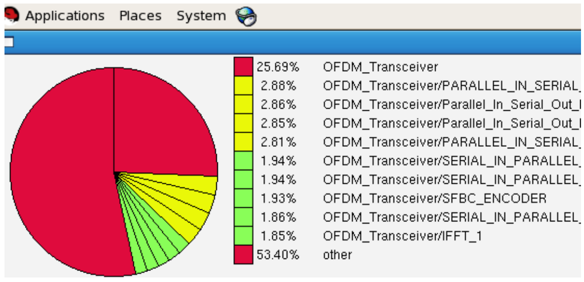


Fig 12: Net power usage.

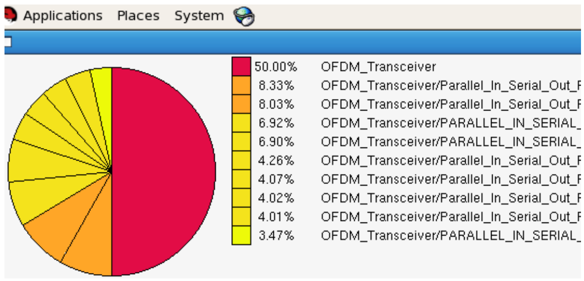
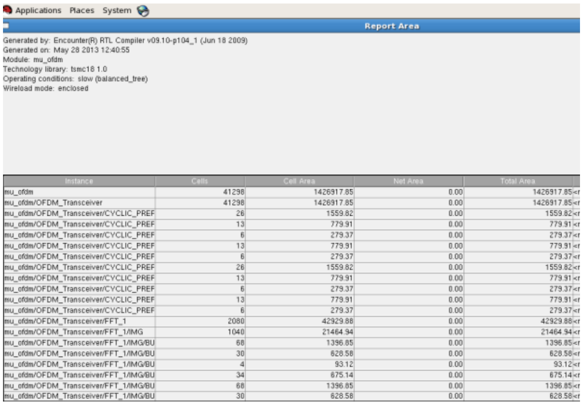


Fig 13: Instance power usage.

4.1.1.3 Area analysis

The SFBC coded 2X2 MIMO OFDM consumes an area of 10426μm^2 for a total of 41,298 cells. The area analysis report for each cell are shown in the figure 14.



Applications Places System

Report Area

Generated by: Encounter(R) RTL Compiler v09.10-p104_1 (Jun 18 2009)
Generated on: May 28 2013 12:40:55
Module: mu_ofdm
Technology library: tsmc18 1.0
Operating conditions: slow (balanced_tree)
Wireload mode: enclosed

Instance	Cells	Cell Area	Net Area	Total Area
mu_ofdm	41298	1426917.85	0.00	1426917.85
mu_ofdm/OFDM_Transceiver	41298	1426917.85	0.00	1426917.85
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	26	1559.82	0.00	1559.82
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	13	779.91	0.00	779.91
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	6	279.37	0.00	279.37
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	13	779.91	0.00	779.91
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	6	279.37	0.00	279.37
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	26	1559.82	0.00	1559.82
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	13	779.91	0.00	779.91
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	6	279.37	0.00	279.37
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	13	779.91	0.00	779.91
mu_ofdm/OFDM_Transceiver/CYCLIC_PREF	6	279.37	0.00	279.37
mu_ofdm/OFDM_Transceiver/FFT_1	2080	42929.88	0.00	42929.88
mu_ofdm/OFDM_Transceiver/FFT_1/IMG	1040	21464.94	0.00	21464.94
mu_ofdm/OFDM_Transceiver/FFT_1/IMG/BU	68	1396.85	0.00	1396.85
mu_ofdm/OFDM_Transceiver/FFT_1/IMG/BU	30	628.58	0.00	628.58
mu_ofdm/OFDM_Transceiver/FFT_1/IMG/BU	4	93.12	0.00	93.12
mu_ofdm/OFDM_Transceiver/FFT_1/IMG/BU	34	675.14	0.00	675.14
mu_ofdm/OFDM_Transceiver/FFT_1/IMG/BU	68	1396.85	0.00	1396.85
mu_ofdm/OFDM_Transceiver/FFT_1/IMG/BU	30	628.58	0.00	628.58

Fig 14: Area analysis report.

4.1.2 Simulation output

The SFBC coded 2X2 MIMO OFDM simulation was carried out in Altera ModelSim and the waveforms are shown in the figure 15. The signed decimal inputs are given to the constructed SFBC-OFDMA unit through the input pin ofdm_input. Similarly, clock pulse and reset are given through clk and reset pins respectively. Laterally, the real and imaginary outputs for antenna T_{x1} are taken from real_ofdm_out_1 and img_ofdm_out_1 pins respectively.

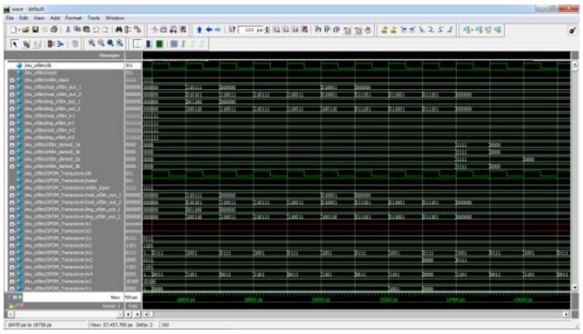


Fig 15: Simulation output.

Table 2. Performance Comparisons of different 2x2 MIMO OFDM Transceivers.

OFDM Processors	ICI-SC Scheme	Technology (nm)	Gate Count	Frequency (MHz)	Area (mm^2)	Throughput (Gbps)	Power (mW)
This Work	Yes	180	41,298	85.5	1.426	1.13	17.92
Shingo [27]	No	90	3,069,957	80	9.209	0.60	674.80
Shingo [28]	No	90	3,906,152	80	11.718	0.60	730.16
Shingo [29]	No	250	NA*	80	NA*	0.60	1638.8

*NA – Not Available

In a similar way, the real and imaginary outputs for antenna T_{x2} are taken from real_ofdm_out_2 and img_ofdm_out_2 pins respectively. The demodulated output values for both of the antennas can be taken from the pins ofdm_demod_1a, ofdm_demod_1b, ofdm_demod_2a and ofdm_demod_2a.

4.1.3 Chip Layout

The chip layout for SFBC coded 2X2 MIMO OFDM transceiver was generated in Cadence Encounter using 180nm technology. The floorplan view is shown in the figure 16.

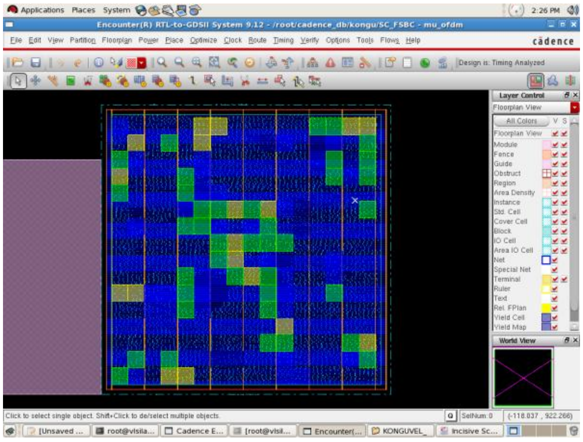


Fig 16: Floorplan view.

4.2 MATLAB Implementation

The proposed system is implemented in MATLAB to show the bit error rate (BER) performance of 2X2 MIMO OFDM system with and without SFBC coding. BER is defined as the ratio of number of error bits and total number of bits. There are many ways of reducing BER. Here, we focused on self ICI cancellation using space frequency block codes.

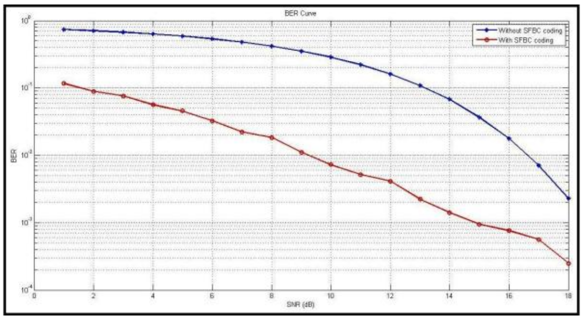


Fig 17: SNR vs BER comparision.

In this paper, we have taken AWGN channel where noise gets spread over the entire spectrum of frequencies. BER has been calculated by comparing the transmitted signal with the received signal and computing the error over the total number of bits. The BER is normally expressed in terms of Signal to Noise Ratio (SNR). The bit error rate is approximately improved from $10^{-1}$to 10^{-3} at a range of 6dB to16dB of SNR as shown in Figure 17.

5. CONCLUSION

In this article, a complete 2X2 MIMO OFDM transceiver with ICI-SC ASIC targeting low power broadband communications is described. We have designed a MIMO OFDM processor core consists of 26,955 gates in 180nm CMOS technology with a lower power dissipation of 17.92mW. Simulations showed a greater improvement in the bit error rate for the

MIMO OFDM schemes with and without ICI-SC technique. This processor can execute the transmitting as well as receiving operations in 11.696ns at a frequency of 85.50MHz. The reduction of circuit scale is left for future work.

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