Implementation of Pre-FFT Beamforming in MIMO-OFDM

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Abstract

In this study, real-time software defined radio implementation of the point to point multiple input multiple output (MIMO) orthogonal frequency division multiplexing (OFDM) system using pre-fast Fourier transform (pre-FFT) beamforming technique in both the transmitter and the receiver is done for the first time in the literature. By taking benefit of the MIMO system's spatial multiplexing property, the performance of the implemented pre-FFT beamforming approach is demonstrated in terms of bit error rate and error vector magnitude measurements. As a result of the test results, the effect of the beamforming methods on the performance of communication systems are clearly observed.

1. Introduction

Improvement of the wireless communication systems introduces new techniques that offer higher system performance. Orthogonal frequency division multiplexing (OFDM) technique is used in communication technologies such as 802.11a/g/n/ac WLAN standards, power line communications, WIMAX and LTE due to its simplicity of usage and low cost. Moreover, since its introduction in 1996, multiple input multiple output (MIMO) transmission techniques are used for transferring data by using multiple antennas. As well known in the literature, the combination of MIMO-OFDM, used in 4G communication systems, creates efficient solutions for communication networks [1]. Moreover, in next generation communication systems, which have increasing usage of multiple antennas, beamforming applications are of critical importance. Many beamforming techniques are implemented in accordance with communication characteristics.

In our study, pre-Fast Fourier Transform (FFT) beamforming method is implemented in software defined radio (SDR) nodes. Post-FFT and pre-FFT beamforming methods are widely used in such communication system implementations, especially in receiver beamforming studies. Post-FFT beamforming process is very complex especially when the number of subcarriers is large [2]. Furthermore, post-FFT is more complex than pre-FFT process due to need for FFT blocks for every antenna in contrast to need for one FFT block for whole system in pre-FFT [3]. As Lei and Chin pointed out in [2], post-FFT has better theoretical performance than pre-FFT; however, the latter gives better bit error rate (BER) performance in real-time implementations when the system has lack of sufficient pilots for the estimation of frequency domain samples matrix.

Beyond receiver side beamforming studies, few studies handle with two side beamforming applications. For example in [20], authors deal with post-FFT beamforming in both sides and it is shown that two side implementation gives promising performance improvement. In this paper, due to highlighted advantages, the pre-FFT method is chosen and is implemented in both sides for software defined radio (SDR) based point-to-point MIMO-OFDM system using NI-USRP 2921s and LabVIEW. The system performance quality is observed by BER and error vector magnitude (EVM) measurements with respect to different switched beamforming coefficients .

2. Related Works

In [4], the adaptive interleaved beamforming has proposed, showing through simulations that beamforming application based on MIMO-OFDM techniques enhances system capacity and bandwidth efficiency. In [5], orthogonal beamforming that increases system performance with MIMO-OFDM technique has been presented. According to simulation results, signal to interference and noise ratio (SINR) performance of implemented orthogonal beamforming system is greater than a traditional MIMO-OFDMA system. [6] demonstrates computer simulation of implementation of pre-FFT beamforming in an OFDM based communication system. Also, the angular separation between signals is observed. Based on numerical results, this study indicates performance amendment with beamforming. In [7], the authors focused on hardware implementation of smart antenna beamformed networks. Advantages of digital beamformer and analog beamformer are emphasized with test results. In [8], basic ideas of the distributed beamforming implementation by using GNU-radio SDR have been examined. Moreover, [9] demonstrates the implementation of the beamforming by using virtual antenna technique. The performance measurements are observed with simulations on OFDM based system using pre-FFT and post-FFT adaptive arrays for beamforming separately in [10]. The results indicate that pre-FFT array processing is suitable in low multipath situation . In work [11], the simulations of pre-FFT and post-FFT beamforming methods in wireless LANs are compared. The simulation

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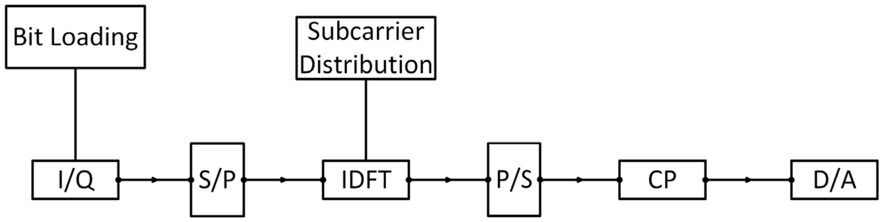


Figure 1. Transmitter structure of the OFDM system.

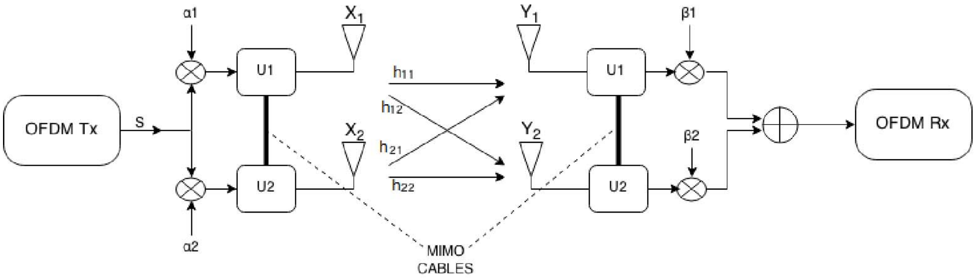


Figure 2. Output of the analog data coming from OFDM transmitter are multiplied with α_1 and α_2 for transmitter beamforming. After, analog data are multiplied with receiver beamforming coefficients β_1 and β_2 to complete beamforming.

results indicate that pre-FFT beamforming is better than post-FFT beamforming in terms of simplicity and cost.

In [12], with combining Least Mean Square (LMS) beamforming method with pre-FFT and post-FFT in OFDM based system, interference is canceled with created beam pattern by post-FFT or pre-FFT methods that form nulls at interfering users. When spatial locations of interfering users change as closer to desired user, post-FFT separates desired user from other users better than pre-FFT but brings important complexity which renders pre-FFT more desirable. In study [13], in spite of same system performance compared to traditional beamforming implementation, pre-FFT beamforming provides substantial reductions in system structure. According to [14], the channel estimator assisted pre-FFT smart antenna algorithms have carried. The simulation results under some scenarios show the improvement of the OFDM system's immunity against multipath fading by using two separate pre-FFT algorithms. The schemes based on LMS algorithm and pre-FFT are simulated in [16] and simulation results show that this adaptive beamforming schemes provide better mean square error (MSE) performance.

In [17], a beamspace-based pre-FFT beamforming algorithm has been presented for OFDM systems and the simulation results shows that pre-FFT beamforming algorithm has better BER performance than conventional adaptive beamforming algorithm. [18] presents pre-FFT adaptive beamformer based on recursive least squares (RLS) for OFDM systems. It is shown that, due to reducing complexity, beamformer has good convergence performance. Low computational complexity and robust BER performance by tracking the channel conditions by using pilot signal can be obtained. Our literature review shows that this study is the first in real-time SDR implementation of the point to point MIMO OFDM system using pre-FFT beamforming method on both the transmitter and the receiver.

3. System Model

3.1. OFDM Transmitter

In this study, OFDM transmission is considered between transmitter and receiver. Transmitter block diagram is shown in the Fig. 1. User's data are passed over I/Q block via bit loading block. For the inverse FFT (IFFT) process, S/P block is used in order to implement serial-parallel conversion. Moreover, IFFT process is handled with subcarrier distribution block. Then parallel-serial conversion is implemented for data transmission by P/S block. Finally, serial digital data are converted to analog data by using D/A block. For protection against the effects caused by multipath channel, cyclic prefix (CP) is added. As MIMO beamforming structure shown in Fig 2, we multiply two same OFDM modulator outputs with two different beamforming coefficients in time domain before the transmission. In MIMO operation, as a part of the beamforming process, output of the OFDM transmitter block are transmitted using two antennas.

3.2. MIMO-OFDM and Beamforming Process

2×2 MIMO-OFDM and beamforming process is shown in Fig. 2. In the receiver side, two signal components received by two receiver antennas after channel interaction are obtained as

$$y_1(n) = \alpha_1 \cdot s_1(n) * h_{11}(n) + \alpha_2 \cdot s_2(n) * h_{21}(n) + \eta_1(n) \quad (1)$$

$$y_2(n) = \alpha_1 \cdot s_1(n) * h_{12}(n) + \alpha_2 \cdot s_2(n) * h_{22}(n) + \eta_2(n) \quad (2)$$

$y_1(n)$ and $y_2(n)$ represent time domain beamformed OFDM signals received by two destination node antennas, $s_1(n)$ and $s_2(n)$ represent transmitted OFDM symbols by two source node antennas, α_1 and α_2 symbolize transmit beamforming coefficients, $h_{11}(n)$, $h_{12}(n)$, $h_{21}(n)$ and $h_{22}(n)$ represent channel components in four different MIMO paths, $\eta_1(n)$ and $\eta_2(n)$ symbolize AWGN components in the links. Afterwards, these received signals are multiplied with two receive beamforming coefficients β_1 and β_2 and summed to conclude MIMO process

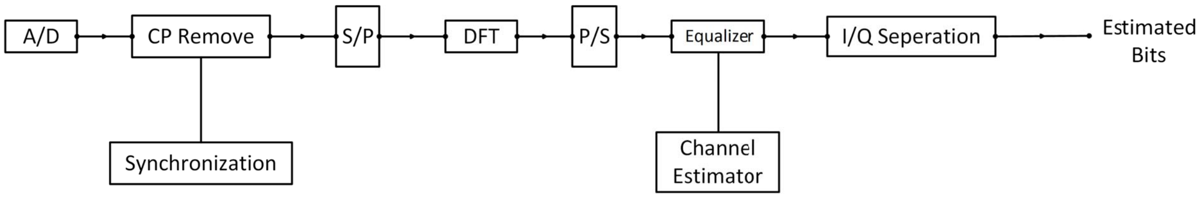


Figure 3. Receiver structure of the OFDM system.

as in 3.

$$z(n) = \beta_1 \cdot y_1(n) + \beta_2 \cdot y_2(n) \quad (3)$$

$z(n)$ is output time domain signal after beamforming that is fed into OFDM receiver. OFDM Receiver. The block diagram of receiver side of the MIMO-OFDM system is shown in the Fig. 3. Analog data that are coming from source nodes are converted to digital data. Next, removing cyclic prefix (CP) process is handled in accordance with data coming from symbols in order to prevent synchronization shift. Then serial-parallel conversion is implemented to digital data for FFT process. Equalization and channel estimation are implemented to FFT process' output as in [19]. The channel estimation on pilot symbols is implemented with least square method, and then channel estimation for data subcarriers is implemented with one dimensional linear interpolation by using channel estimation on pilot symbols. The equalization process is applied to obtain transmitted data using estimated channel coefficients. In our frame structure, as indicated in Table 1, we used 40 pilot subcarriers with order as one reference symbol for every 8 data symbols. By proposed frame structure and proper selection of beamforming coefficients, channel coefficients for MIMO paths are estimated separately.

4. Test Setup

The testbed of the implementation of point to point MIMO OFDM system using pre-FFT beamforming is shown in Fig. 4. The testbed consists of two source and two destination nodes. USRP devices are used for implementation of source-destination pairs.

4.1. Hardware and Software Components

In the point to point MIMO OFDM system using beamforming's testbed, LabVIEW is used as software component. System program was created in LabVIEW using virtual instruments (VI) which are the core elements of LabVIEW. NI USRP 2921 nodes of ITU Wireless Communication Research Laboratory (WCRL) are used as the source and destination nodes. These USRP nodes are software defined radio nodes and their operating frequency includes 2.4-2.5 and 4.9-5.9 GHz frequency bands. Each USRP node's instantaneous bandwidth is up to 20 MHz and it can receive 100 million samples per second in the destination channel.

When implementing a MIMO based SDR, the most probable difficulty is the synchronization of the nodes. Multiple nodes should work in coordination with each other to provide robust system performance. Especially if OFDM technique is implemented with MIMO configuration, the robust synchronization between nodes becomes more important to gain from OFDM functionality. In our system, the synchronization problem is solved by multiple steps which contain both hardware and software configurations. We used the NI PXI-6683 module as a synchronization source. NI PXI-6683 module can provide 10 MHz synchronization clock source from GPS module that is connected to main clock . Two external 10 MHz and one PPS signals are transmitted through cables to one source and one destination nodes. Other source and destination nodes that are not connected to these synchronization sources are synchronized through MIMO cables by using other source or destination node pairs as synchronization sources. Moreover, we changed some configurations in software to transmit synchronization signals correctly. We also configured a LabVIEW code for the accurate synchronization correlation between software and hardware components. Thus system synchronization is provided by the joint configuration of the software and hardware components. Testbed components that are used in the system are shown in Fig. 4.

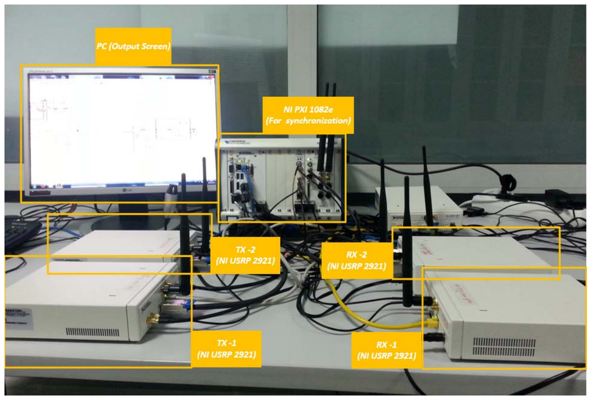


Figure 4. Our test setup in Istanbul Technical University WCR.

4.2. Data Processing Method

Point to point MIMO-OFDM system using pre-FFT beamforming implemented in the LabVIEW software. Our code consists of two VIs which are for the source and destination functions separately.

In the source part, we first added necessary USRP VIs for the coordination between the USRP hardware and the LabVIEW. These VIs are responsible for start or end of the session, configuration of the USRP parameters and configuration of the transmitting signal properties. Moreover, MIMO configuration is done for the two source nodes by changing USRP settings. After addition of the USRP VIs, Data SubVI is implemented which includes OFDM frame structure. Firstly, pseudonoise data bits are produced using MT Generate Bits VI. Then these bits are mapped to symbols with the 4-QAM modulation scheme. Array functions in the LabVIEW are used for the subcarrier assignment and frame structure constitution. Reference symbols that are determined as constant are combined with data symbols as one reference symbol per 8 data symbols with the interleaving process by using the Array VIs. Zero padding is also implemented and sequence of the zero subcarriers are added into the frame.

After preparation of the frame structure, inverse discrete Fourier transform is implemented using IDFT VI. Then CP is added to the beginning of the frame by copying $\%25$ end portion of the frame by using Array VIs and with some other configurations Data SubVI is created. After this, by using Data SubVI, two OFDM signal outputs are multiplied with switched beamforming coefficients α_1 and α_2. Then these two beamformed signals are sent to the necessary USRP VI's. Thus, source node VI is created

In the destination node part, USRP VIs are used which are responsible for the reception process, for the session process and parameter configuration. As similar to source part, MIMO configuration is done for the two destination nodes by changing USRP settings. Firstly, received two OFDM signals are multiplied with other switched beamforming coefficients β_1 and β_2; furthermore; the result of these products are summed and one beamformed OFDM signal is created. Based on the algorithm in [21] which utilizes maximum likelihood estimation of carrier frequency offset (CFO) using cyclic prefix portion of the frame, CFO is estimated and fixed. Then CP is removed and DFT is implemented. At the end of the process; zero padding is removed, data portions are decomposed and information symbols are decomposed from reference symbols for every data part respectively. Channel estimation and equalization is implemented. Afterwards, data portions are obtained, thus destination node's VI is implemented. Moreover, BER and EVM measurements are obtained in all the necessary parts. As a result, point to point MIMO OFDM system using pre-FFT beamforming is implemented successfully.

5. Results

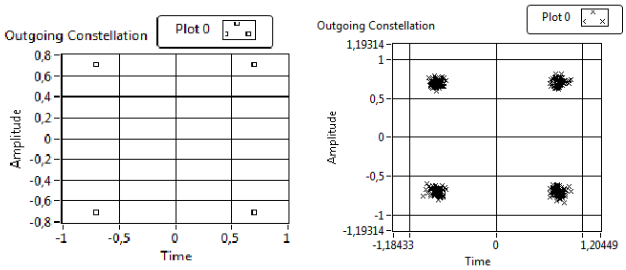
Table 1. Values of tesbed's parameters .

Carrier frequency	2.45 GHz
Transmit gains	10 dB
Receiver gains	10 dB
I/Q data rate	1 MS/sec
Number of bits used in one frame	640
Number of 4-QAM symbols	320
Total number of subcarriers in the information portion	320
Number of reference subcarriers	40
Zero padding length	120
FFT length	480
CP length	120
Total number of subcarriers in the frame	600

System performance of the point to point MIMO OFDM system using pre-FFT beamforming which was described in Test Setup Section is observed by tests with different configurations. Some parameters in the LabVIEW code are changed for performance observation. Every source data are transmitted using 4-QAM modulation. BER and EVM values are measured for received beamformed data. System parameters are determined as shown in Table 1. EVM values are the measures of the modulation quality and error performance for the communication systems. EVM plays an important role on the measurement of the whole potential phase and amplitude distortions or on the determination of the one circuit's quality. If distortions exist, EVM quantifies the demodulator's performance, by comparing the ideal symbol vector's and real measurement vector's size and position difference by using phasors in the I-Q plane. The difference between these vectors equals to EVM. As I_k is the real part and Q_k is the imaginary part of the k^{th} symbol, EVM values can be calculated as

$$EVM = \frac{\sqrt{\frac{1}{T}\sum_{k=1}^{T}\left[\left(I_k - \hat{I}_k\right)^2 + \left(Q_k - \hat{Q}_k\right)^2\right]}}{|v_{max}|}, \quad (4)$$

where $\hat{I}_k$ and $\hat{Q}_k$ are the real and imaginary parts of the k^{th} received symbol, $|v_{max}|$ is the maximum value of the received ideal symbol. Moreover; the total number of the transmitted symbol is denoted by T.



(a) a

(b) b

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Figure 5. Constellation diagrams of the source node and destination node respectively.

System performances are measured to show how beamforming improves system performance. These measurements are repeated with different beamforming coefficient pairs. Furthermore, constellation diagrams are obtained for both source and destination VI's to show the transmission quality. As demonstrated in Fig. 5, 4-QAM constellation diagrams are obtained successfully.

EVM and BER values are measured with 16 combinations of coefficient pairs as shown in Table 2. Best values are obtained with combinations of the β coefficients when $\alpha_1 = j$ and $\alpha_2 = 1$. Optimum error performance can be obtained when $\alpha_1 = j$, $\alpha_2 = 1$, $\beta_1 = j$ and $\beta_2 = 1$. System's performance becomes worse when coefficient combinations of $\alpha_1 = 1$ and $\alpha_2 = 1$ are used. Worst one is observed when $\alpha_1 = 1$, $\alpha_2 = 1$, $\beta_1 = j$ and $\beta_2 = 1$ which increase BER to $1,85 \times 10^{-6}$ from 0 . It is clear that beamforming affects system performance and can cause dramatic changes of performance results.

6. Conclusion

In this paper, pre-FFT beamforming is investigated in constituted SDR based MIMO-OFDM system. According the results, optimum error performance can be obtained when the beamforming coefficients are used at the appropriate angle, affecting BER and EVM performance. As future work, we plan to extract channel estimates and then perform quantization to design physical layer aided encryption schemes.

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Table 2. EVM and BER values that are obtained with different beamforming coefficients.

α_1	α_2	β_1	β_2	EVM	BER
1	1	1	1	7,305	0
1	1	1	j	8,722	0
1	1	j	1	10,392	$1,85 \times 10^{-6}$
1	1	j	j	8,104	0
1	j	1	1	6,543	0
1	j	1	j	7,117	0
1	j	j	1	6,308	0
1	j	j	j	7,062	0
j	1	1	1	5,987	0
j	1	1	j	6,231	0
j	1	j	1	5,908	0
j	1	j	j	6,286	0
j	j	1	1	9,883	0
j	j	1	j	9,406	0
j	j	j	1	8,366	0
j	j	j	j	9,86	0

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