Hardware Implementation of 802.11ad MIMO-OFDM Transceiver

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Abstract: - Orthogonal frequency division multiplexing (OFDM) is a promising technique that has established a significant presence in the wireless technology market. The combination of high data transfer rates, high spectral performance and multi-path attenuation strength, render OFDM ideal for current and future communication applications, allowing response to high service quality requirements. Multiple input, multiple output (MIMO) OFDM is applied in broadband wireless communication systems for achieving high data rate. It is a combination of MIMO technique, in which different signals are transmitted from different antennas. In this paper a MIMO-OFDM transceiver with QAM modulation scheme is designed based on the IEEE 802.11ad standard. The system design and the simulation were carried out in Matlab/Simulink and implemented in a Field Programmable Gate Array (FPGA) from Xilinx via System Generator tool.

Key-Words: - OFDM**,** MIMO, Transceiver, Multiplexing, Simulation, QAM, FPGA, Implementation.

1 Introduction

OFDM is a form of multi-carrier transmission where all sub-carriers are orthogonal to each other. Multi-carrier transmission idea occurred recently so as to efficiently use the entire spectrum available. This is particularly useful so that telecommunication systems are able to respond to the requirements of high data quality, high data transmission rate, as well as new multimedia. Using this technique, the information remains unaltered and spectrum economy is achieved, given that the sub-carriers transmitted in parallel are rectangles transmitted one adjacent to the other. Each sub-carrier separates data in multi-data flows and it is configured on the basis of a conventional configuration schema (such as QAM configuration) with low symbol rate, preserving a data rate similar to that of single-carrier systems in the same bandwidth.

MIMO-OFDM technology [1] has been adopted by many communication systems due to increasing requirements for high quality services and high data rates. It can improve system capacity, transmission speed in wireless environment and spectrum efficiency without the bandwidth augmentation.

IEEE 802.11ad standard [2] known under the tradename as Wireless Gigabit Alliance (WiGig), allows wireless communication devices providing data rates up to 7 Gbps [3]. To achieve these speeds, the technology uses 60 GHz ISM band to ensure the levels of bandwidth needed and the reduced levels of interference. Due to the use frequencies in the millimeter range, WiGig technology is used to cover short distances as propagation loss is large. The aim is to transfer high performance data, such as video HD and audio applications at very short range.

The article is organized as follows. Firstly, in Section 2, an overview and general description about MIMO-OFDM technology is presented. Secondly in section 3, the 802.11ad standard is described. After that, the MIMO OFDM system model is implemented in a Field Programmable Gate Array (FPGA) from Xilinx using the System Generator tool-flow. Simulation results achieved by using the model for the predefined scenarios are extracted and analyzed in Section 5. Lastly, in Section 6 the article is finalized by giving conclusion remarks.

2 MIMO OFDM Technology

OFDM is based on the orthogonality of signals ensuring that at the points of the sub-channels showing peaks, the adjacent sub-channels show zero. In order for the sub-carriers to be orthogonal, all sub-carrier frequencies must be integer multiples of the same frequency [4]-[6]. Orthogonality amongst the carriers is achieved by separating the carriers by an integer multiples of the inverse of symbol duration of the parallel bit streams. A guard interval (GI) which prevent from Inter Symbol Interference (ISI) is a copy of the last part of an OFDM symbol which is pre-appended to the transmitted symbol. Mathematically, the OFDM signal is expressed in continuous-time notation with the following question for the *k*th OFDM symbol [7].

$$s_{RF,k}(t-kT)=\begin{cases} Re\left\{w(t-kT)\sum_{i=-N/2}^{N/2-1} x_{i,k} e^{j2\pi(f_c+\frac{i}{T_{FFT}})(t-kT)}\right\} \\ kT-T_{win}-T_{guard}\leq t\leq kT+T_{FFT}+T_{win} \quad otherwise \\ 0 \end{cases} \quad (1)$$

where:

T: Symbol length

T_{FFT}: FFT time

T_{guard}: GI duration of the cyclic prefix

T_{win}: Window interval duration of windowed prefix for spectral shaping

f_c: Centre frequency of the occupied frequency spectrum

$F = 1/T_{FFT}$: Frequency spacing between subcarriers

N: FFT length; number of FFT points and

$w(t)$ is the transmitter pulse shape defined as

$$w(t)=\begin{cases} \frac{1}{2}\left\{1-\cos\pi(t+T_{win}+T_{guard})/T_{win}\right\} & -T_{win}-T_{guard}\leq t\leq -T_{guard} \\ 1 & -T_{guard}\leq t\leq -T_{FFT} \\ 0 & -T_{FFT}\leq t\leq T_{FFT}+T_{win} \end{cases} \quad (2)$$

Finally, a continuous sequence of transmitted OFDM symbols is expressed as

$$s_{RF}(t)=\sum_{k=-\infty}^{\infty} S_{RF,k}(t-kT) \quad (3)$$

MIMO technique utilizes more than one antenna at the system of the radio link in order to improve the reliability and performance of the channel. By combining of both techniques data transfer rates can be increased up to hundreds Mbps, making them ideal for recent wireless standards, such as IEEE 802.11ad [8].

3. IEEE 802.11ad standard overview

The main features of the IEEE 802.11ad are listed below.

Table 1: Main features of IEEE 802.11ad

Main features	Description
Operating frequency	60 GHz ISM band
Maximum data rate	7 Gbps
Typical distances	1-10m
Antenna technology	Beamforming
Modulation formats	Single carrier and OFDM

In addition the system is compatible with other IEEE 802.11 standards, allowing data transfer between devices operating in the 2.4GHz, 5GHz and 60 GHz. The WLAN system uses frequencies in the unlicensed spectrum of 60 GHz in which restrictions submitted depending on geographic region between 57 GHz and 66 GHz.

Table 2: Band channel plan and frequency location

Region	**Allocation (GHz)**
European Union	57.00-66.00
USA & Canada	57.05-64.00
South Korea	57.00-64.00
Japan	59.00-66.00
Australia	59.4-62.90

Then the ITU-R [9] defines the use of four channels, each 2.16 GHz wide and centre frequency of 58.32 GHz, 60.48 GHz, 62.80 GHz and 64.80 GHz. Therefore only channel 2 is globally available with centre frequency of 60.48 GHz and is recommended as the default channel.

Forward error correction codes proposed for 802.11ad system are Reed-Solomon Block (RS) codes and Low Density Parity Check (LDPC) codes. The generating polynomial for an R-S code over GF(2^k) takes the following form:

$$g(x) = g_0 + g_1 X + g_2 X^2 + ...g_{2t-1} X^{2t-1} + X^{2t} \qquad (4)$$

where t is the symbol-error correcting capability of the code. The degree of the generator polynomial is equal to the number of parity symbols.

The LDPC codes can be represented in two ways. Either through matrices, like the other block codes, or via an alternative method, that of Tanner graphs. The LDPC codes selected are irregular LDPC codes with three code rates: 1/2, 3/4 and 7/8 [10]. The following table defines all the possible LDPC and modulation coding combinations available in the 802.11ad protocol.

Table 3: Main features of IEEE 802.11ad

Control (CPHY)		
Coding	Modulation	Raw Bit Rate
Shortened 3/4 LDPC 32x Spreading	π/2-DBPSK	27,5 Mbps
Single Carrier (SCPHY)		
Coding	Modulation	Raw Bit Rate
½ LDPC, 2x repetition	π/2-BPSK	385 Mbps
1/2 LDPC	π/2-QPSK	to
5/8 LDPC	π/2-16QAM	4620 Mbps
3/4 LDPC		
13/16 LDPC		
Orthogonal Frequency Division Multiplex		
Coding	Modulation	Raw Bit Rate
1/2 LDPC	OFDM-SQPSK	693 Mbps
5/8 LDPC	OFDM-QPSK (DCM)	to
3/4 LDPC	OFDM-16QAM	6756,75Mbps
13/16 LDPC	OFDM-16QAM	
Low-Power Single Carrier (LPSCPHY)		
Coding	Modulation	Raw Bit Rate
RS(224.208)+	π/2-BPSK	625,6 Mbps
Block	π/2-QPSK	to
Code (16/12/9/8,8)		2503 Mbps

Characteristics of wireless standard IEEE 802.11ad are the frequencies at millimeter wave spectrum and the use multiple antennas both at the transmitter and receiver. Also, because of the high propagation loss that is presented in the millimeter band is necessary to provide more beamforming gain [11],[12]. This is achieved with the control signal both in amplitude and in phase. MIMO technology (Fig.1) makes use of multiple antennas at the transmitter and receiver, which combined with a digital signal processing modulation scheme allows the system to create multiple data streams in the same channel, increasing the channel capacity with a specific bandwidth. Through this process, it can reduce fading effects and optimize the data throughput without adding bandwidth or extra transmission power. Nowadays, the algorithms applied in MIMO system are divided into 3 main categories: beam forming, space time coding and spatial multiplexing.

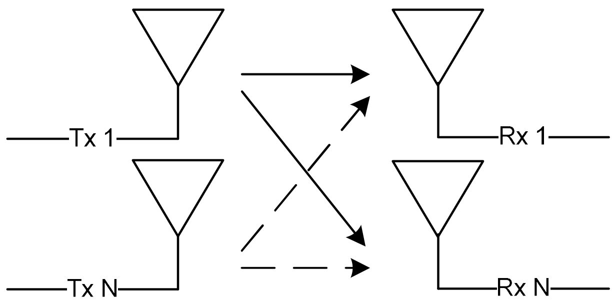

Fig. 1: MIMO system

The beam forming technology (Fig.2) uses multiple antenna elements to form a direction beam with increased power signal. This is achieved by transmitting phase shifted signals from the multiple antenna elements. The signal phase shift is done in such a way as to maximize the signal to the desired target.

A space time coding is a method which rely on transmitting multiple, redundant copies of a data stream to the receiver in order to improve the reliability of data transmission in wireless communication systems using multiple transmit antennas [13].

A technique that takes advantage of MIMO is called spatial multiplexing, or spatial diversity multiplexing. Using this technique, an Access Point will use multiple radios to transmit separate segments of a message to a receiver, effectively increasing throughput. Using this technique, multiple unique streams of data can be sent between the transmitter and receiver [14].

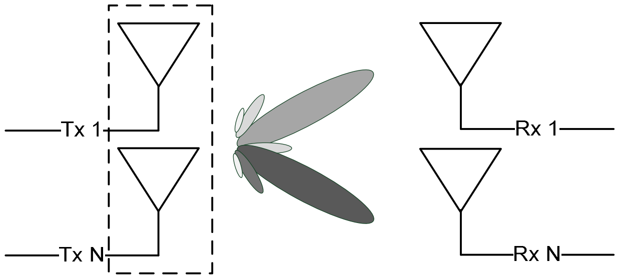

Fig. 2 Beamforming system

4. Methodology design & FPGA implementation

First is the system verification by simulation in Matlab environment. Then, the system is implemented in Simulink via Xilinx System Generator that will create the hardware model with the code for programming the FPGA. The System Generator of Xilinx, is a tool for the design of Digital signal processing or DSP systems using the Simulink environment of Mathworks for the design in FPGA. The drawings are formed through modeling in the Simulink using the blocks availed by the System Generator libraries. The system generator allows full simulation of the designed system, control, evaluation of the results and HDL code generation. All stages of implementation in FPGA are performed automatically, including the compilation, placement and routing, generating an FPGA programming file. During design in System Generator, it is necessary to define the margins of the designed system. This separates the elements composing the system and which shall be depicted in the hardware, from the elements used for its simulation.

OFDM Transmitter

The standard implementation of OFDM transmitter with its standard constituting parts is depicted below.

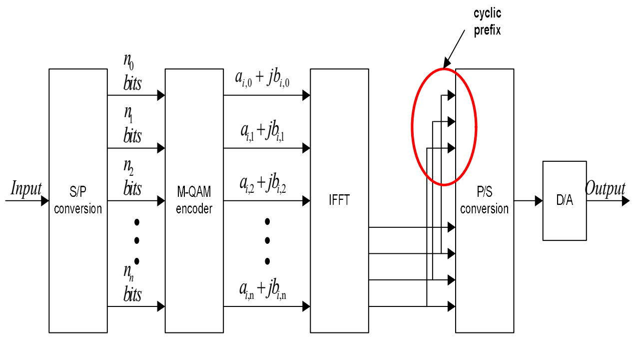

Fig. 3 OFDM transmitter

- Serial to parallel format converter
- QAM configuration
- Inverse Fourier conversion (IFFT)
- Parallel to serial format converter
- Digital to analog conversion

Initially the incoming binary data pulse sequence is converted from serial to parallel, where the bits are divided into n sub-groups consisting of M bits each. These n sub-groups shall be mapped as per the selected constellation using Gray encoding, and this way, a $a_i + jb_i$ value shall be received at the modulator constellation.

QAM modulator converts input data to complex values and depicts them on points in accordance with the given constellation, 4-QAM, 16-QAM, 32-QAM etc. The number of data transmitted by each sub-carrier depends on the constellation, i.e. 4-QAM configuration transmits two data bits, 16-QAM transmits four data bits per sub-carrier. The configuration to be used depends on the quality of the communication channel. On a channel with great interference, it is optimal to use a small configuration scheme such as BPSK, given that the signal to noise ratio (SNR) required at the receiver shall be low, while on a channel without interference it is preferred to use a larger constellation due to the higher rate of binary digits.

The inverse Fourier transformation (IFFT) converts the signals from the frequency field to the time field. An IFFT converts a group of data whose length is a power of 2, within the same number of data but in the time field. The sub-carriers number determines the sub-zones into which the available spectrum is divided.

The cyclic prefix (CP) having length ν, greater than length L of the discrete, equivalent, Channel Impulse Response (CIR), is a copy of the last n samples of the output of IFFT and is placed at the beginning of the OFDM frame. It is converted from discrete to analog signal, which is then transmitted.

OFDM receiver

The standard simplification of OFDM receiver, with its key components is depicted in the following figure 4.

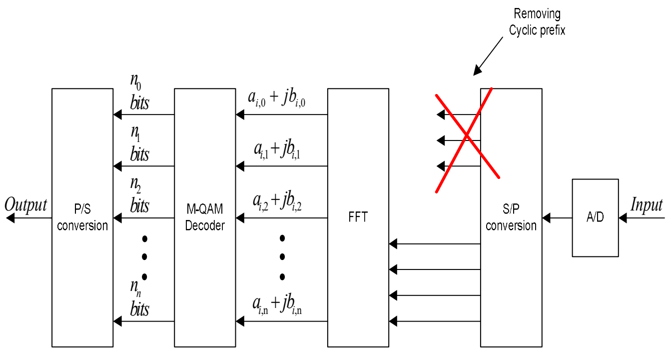

Fig: 4. OFDM receiver

- Analog to digital format conversion.
- Serial to parallel format conversion.
- Cyclical prefix removal.
- Fourier transformation (FFT).
- M-QAM demodulation.
- Parallel to serial format conversion.

The symbol received is in the time field and due to its extension with the cyclical prefix the result may be altered. Thus, the signal received is converted from parallel to serial and then the cyclical prefix is removed. Following removal of the cyclical prefix, the signals are converted from the time field to the frequency field through the FFT of n points. The FFT output firstly forms the M output samples. FFT transformation is followed by the demodulation of symbols so that they are decoded as per the respective symbol of the constellation with which they were transmitted. The constellation point of the transmitted symbol may have changed due to the additional noise on the communication channel, an erroneous adaptation of the sampling time with the receiver, or for various other reasons. Therefore, it is necessary to define a threshold for the reception of decisions on the receiver's constellation. This operation is performed by the M-QAM decoder.

Fig.5 and Fig. 6 shows the system block diagrams for the transmitter and receiver respectively, which were implemented in Simulink using Xilinx System Generator. Fig. 5 includes elements, such as convolutional encoder, scrambler, QAM modulator and OFDM modulator and Fig. 6 includes elements that perform the opposite process from that of the transmitter, such as OFDM demodulator, QAM demodulator, descrambler and decoder. All stages of implementation in FPGA Xilinx Virtex 7 VC707 are performed automatically, including the compilation, placement and routing, generating an FPGA programming file. The System Generator symbol allows selecting the FPGA implementation device, as well as the type of translation to machine language, depending on the programming file generated. At the end of the process, System Generator creates the files necessary for the implementation of the programming of the default device materialized through Xilinx ISE. The use of ISE tool achieves the generation of the Bitstream file from the VHDL code of the system.

Table 4 depicts results related to the resources of the overall OFDM system and the surface occupied in the FPGA. It is derived that the overall system uses 4% of the Flip Flop slices, 5% of the LUTS and 8% of the occupied slices of Virtex7 VC707 xc7vx485t 1ffg1761 [15].

Table 4: Device (Xilinx Virtex 7 VC707 xc7vx485t1ffg1761) utilization summary of MIMO OFDM 802.11ad System

Slice Resource Utilization	Used	Available	Utilization
Flip-Flop Slices	24,888	607,200	4%
4 input Lookup Tables	16,824	303,600	5%
Occupied Slices	6,457	75,900	8%
Bonded Input/Output Buffers	2	700	1%
Number of RAMB16s	2	1,030	1%
Multiplexed global clock buffer (BUFGMUXs)	4	32	12%

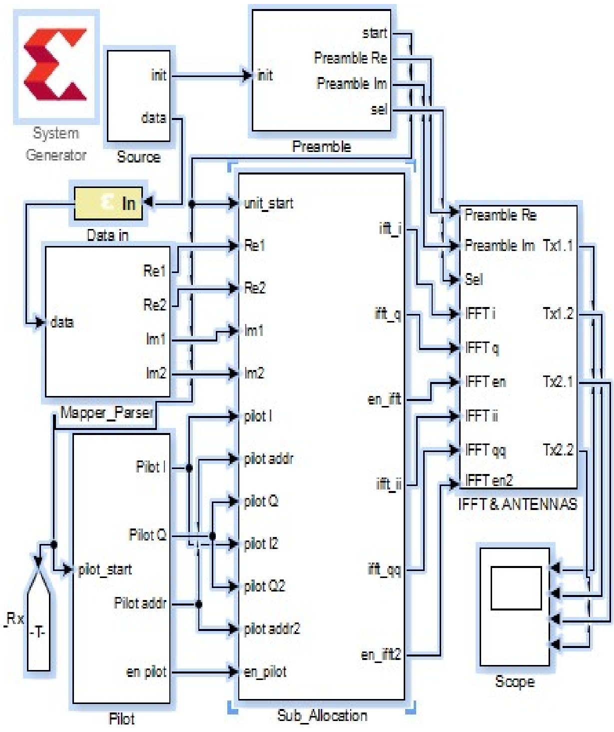

Fig. 5: MIMO-OFDM 802.11ad Transmitter implementation

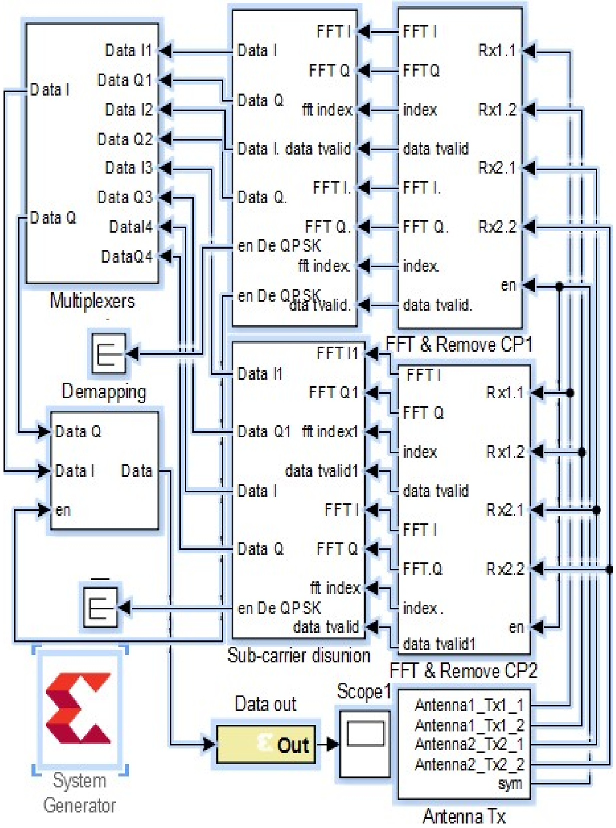

Fig. 6: MIMO-OFDM 802.11ad Receiver implementation

5. Simulation results

Simulation results of the system are depicted in Fig. 7, for a different number of antennas at the transmitter. This figure shows the BER performance curve of the MIMO-OFDM system for 2, 4 and 8 transmitting antennas, while the receiver comprises one receiving antenna. For the performance results are considered and losses from other mobile users in wireless environment. In the system is used 16QAM modulation and beamforming technology for all three cases. Indicatively, Fig. 8 shows the constellation diagram with SNR 36 dB and 14 dB respectively, for 8 transmitting antennas and one receiving antenna. From the images, it can be proved that by increasing the SNR decreasing BER providing better results.

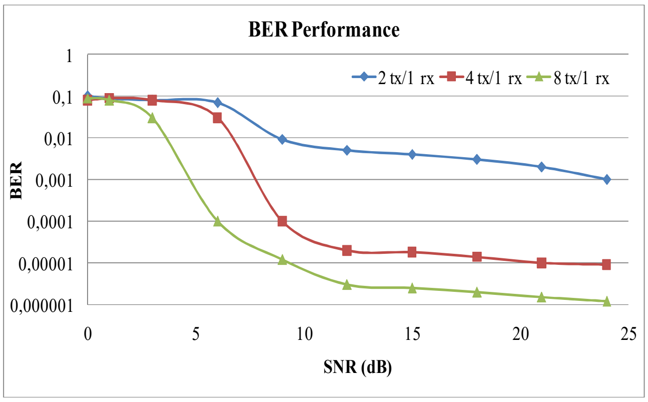

Fig. 7: BER performance of MIMO-OFDM 802.11ad system

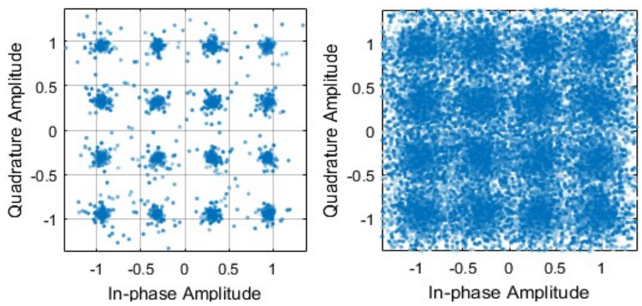

Fig. 8: Receiver constellation with SNR=36(dB) and 14(dB)

6. Conclusion

In this paper, there was a theoretical analysis and performance evaluation results of a MIMO-OFDM system based on typical IEEE 802.11ad standard. Furthermore, implementation issues in XILINX

FPGA were conducted. The results obtained were made using 16QAM modulation for a different number of antennas at the transmitter. By comparing the results, it was concluded that by increasing the number of antennas in the transmitter the receive signal is improved and reduces the bit error rate. This outcome is particularly important in the context of wireless personal networks. Regarding the implementation experiments conducted so far show that the implementation of the 802.11ad in FPGAs does not impose any significant performance or resource usage overhead.

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