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FPGA Implementation of a WHT-OFDM Modem

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Abstract: *OFDM is one of the most widely used multi-carrier modulation technologies in wireless communication. However, in the case of high mobility, the orthogonality between sub-carriers is destroyed due to the existence of time selective fading, and the performance of OFDM system is greatly affected. In order to reduce this effect, the data can be pre-coding before OFDM modulation. The pre-coding technique adopted in this paper is Walsh-Hadamard transform (WHT). The data are distributed evenly on all sub-carriers by WHT operation, which avoids the problem of data loss caused by some sub-carriers which can't be recovered. In this paper, the design scheme of WHT-OFDM system is first proposed, then the modulation and demodulation module of the system is designed using the Verilog HDL language, and then the simulation verification of the design is completed. The results proved that the designed WHT-OFDM system can be successfully implemented on FPGA.*

Keywords: *OFDM; High mobility; Wireless communication; WHT; FPGA*

1. Introduction

With the continuous development of society, communication technology plays an indispensable role, and people have higher and higher requirements for wireless communication[1]. Under the requirements of high-quality data transmission and a certain bandwidth, multi-carrier modulation schemes that can achieve higher data transmission rates have attracted more and more attention. OFDM technology is a multi-carrier modulation scheme, utilizing IFFT and FFT for its modulation and demodulation processes respectively, resulting in a relatively low implementation complexity of the system[2].The core of OFDM technology is to divide the channel into several quadrature sub-channels, convert the serial data stream of high-speed data into several parallel data streams, and then modulate them to multiple parallel low-speed sub-carriers for transmission[3]. Since the sub-carriers used in OFDM technology are orthogonal, the spectrum zeros of each carrier overlap with the frequency zeros of adjacent carriers, which can reduce the interference between sub-carriers and ensure the correct demodulation of signals[4]. Therefore, compared with other multi-carrier transmission schemes, OFDM system has higher spectrum utilization. However, OFDM technology also has some shortcomings, such as poor ability to resist deep selective fading, and some information transmitted on sub-carriers cannot be recovered, resulting in a high BER; since the OFDM symbol is composed of multiple sine waves, a high peak to average power ratio (PAPR) leads to a decrease in the rate of data transmission[5].

Numerous methods have been suggested to enhance the performance of OFDM system, such as distortion based techniques, pre-coding techniques and probabilistic techniques[6]. Because of the advantages of small distortion and large gain, the pre-coding technique has the best effect[7]. Among the many pre-coding techniques, the most widely used are DFT, DHT and WHT. These methods can improve the BER performance of OFDM system and reduce the PAPR, of which the performance of WHT-OFDM system is better than the other two methods under certain circumstances[8]. In WHT-OFDM system, the information to be transmitted is uniformly distributed in the whole frequency band through the WHT technology before OFDM modulation. In this way, even if some sub-carriers cannot be recovered under the influence of deep selective fading, because some information is carried on other sub-carriers, at the receiver, the information on the received sub-carriers can be combined and recovered through the IWHT technology to obtain the correct transmission data[9]. And the advantages of using WHT technology are: low implementation complexity, no loss of data transmission rate, no bandwidth expansion, and no increase in power. Therefore, the realization of WHT-OFDM system in the digital field will promote the development of digital communication. FPGA technology has been widely used in digital communication systems with its programmability, compatibility, low cost and low power consumption. The effective combination of WHT-OFDM system and FPGA technology is of great help to the mobile communication.

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The remaining portions of the thesis is arranged as follows: In second section, the theory of WHT-OFDM system is introduced. In third part, the scheme and key module design of the system based on FPGA are presented. In fourth section, the design of the the modem is verified. Finally, the paper is concluded in fifth section.

2. The principle of the WHT-OFDM system

At present, the research of WHT-OFDM system in European IST project proves that the system can be good application prospect in the field of wireless communication[10]. In a WHT-OFDM system, the data is uniformly distributed in the whole frequency band by WHT operation, and then IFFT modulation is performed to transmit each data by a separate sub-carrier. The schematic of WHT-OFDM system is shown in Figure 1.

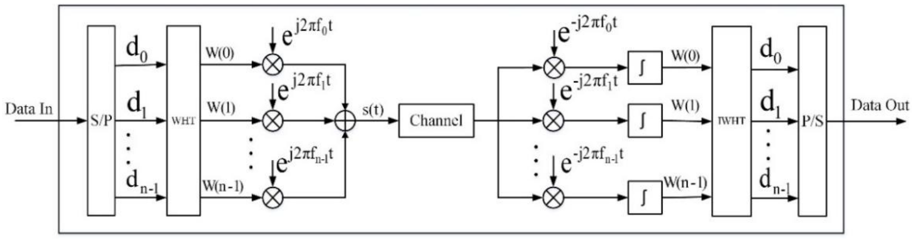


Figure 1: Basic block diagram of the WHT-OFDM system.

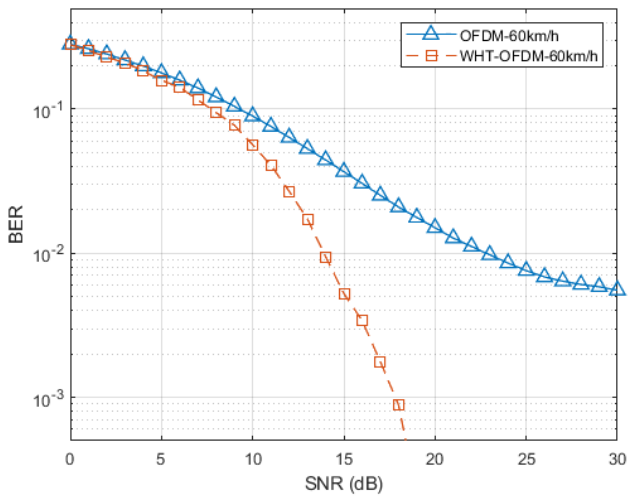
At the transmitter, assume that the input data is $d_i(i=0,1,\cdots,n-1)$, the d_i after WHT operation is

$$W(u)=\frac{1}{n}\sum_{i=0}^{n-1} d_i Wal_H(u,i) \tag{1}$$

where $Wal_H(u,i)$ is Walsh function. So a WHT-OFDM symbol can be expressed as

$$s(t)=\begin{cases}\sum_{i=0}^{n-1} W(u)rect(t-t_s-\frac{T}{2})\exp\left[\frac{j2\pi i}{T(t-t_s)}\right] & t_s \le t \le t_s+T \\ 0 & t<t_s \wedge t>t_s+T\end{cases} \tag{2}$$

where N is the number of sub-carriers, $rect(t)=1,|t|\le T/2$, T is a symbol period, t_s is the initial time of the WHT-OFDM symbol. When $t_s=0$, the eq (1) is the IDFT operation. Therefore, after DFT operation on the signal at the receiver, IWHT conversion is performed, and then the originally transmitted data can be obtained after parallel series conversion.



(a) 60Km/h

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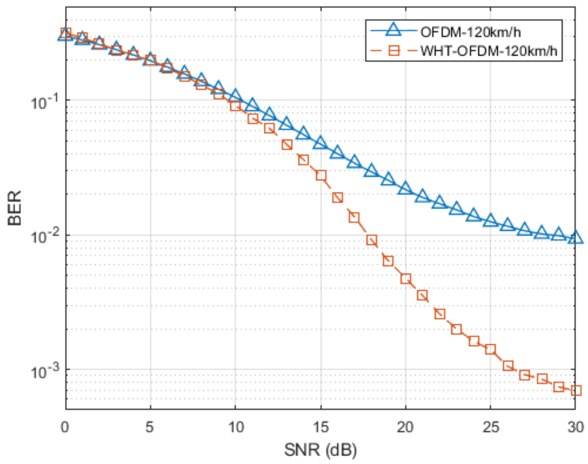

(b) 120Km/h

Figure 2: Comparison diagram of BER of two systems.

Then, the BER performance comparison between WHT-OFDM system and OFDM system at different mobile speeds is simulated and sompared using Matlab over the Rayleigh channel. The simulation parameters are set as follows: the transmission bandwidth is 10MHz, the sub-carrier interval is 15KHz, the number of sub-carriers is 1024, the digital modulation mode is 16-QAM. The simulation results are shown in Figure 2.

As depicted in Figure 2, at different movement speeds, when SNR<15dB, the BER performance of the two systems is close; when SNR>15dB, the BER of the WHT-OFDM system is significantly lower than that of the OFDM system.

3. Hardware design scheme of the WHT-OFDM modem

3.1 Framework of the system

According to the requirements, the scheme of WHT-OFDM system is designed, the system parameters are shown in Table 1, the WHT-OFDM system block diagram is shown in Figure 3.

Table 1: Parameter setting of WHT-OFDM system.

Symbol	3.2us
Cyclic prefix	0.8us
Number of sub-carriers	52
Number of the pilot	4
The spacing of the sub-carriers	312.5kHz
The mode of coding	Convolution coding
The rate of transmission	24Mb/s

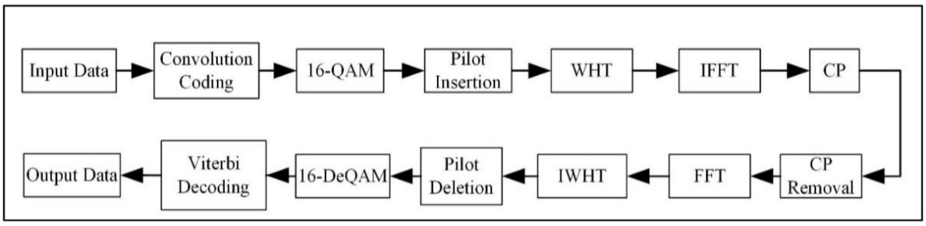

Figure 3: Fundamental schematic of the WHT-OFDM system.

The input data is randomly generated by Matlab and stored in a ROM IP core. At the transmitter, 16QAM modulation and 1/2 convolution coding are used to achieve 24Mb/s data rate. In the modulation module, the data is read out from the ROM IP core, and the read binary data is subjected to 16-QAM modulation after convolution coding. The WHT operation is performed on the digitally modulated data, and the data is modulated to 64 sub-carriers by IFFT operation after pilot frequency is inserted and data sequence is adjusted. After adding cyclic prefix, a WHT-OFDM base-band signal is formed and send to

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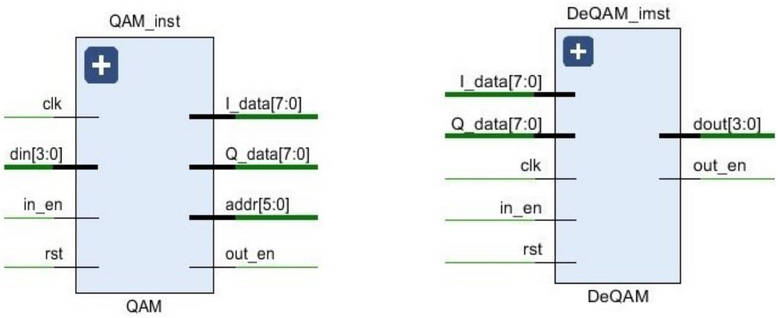
the demodulation module.

In the demodulation module, firstly, removing the cyclic prefix from the received data, then, FFT demodulation, pilot deletion, IWHT operation, 16-QAM demodulation and Viterbi decoding are performed, finally, the demodulated data is obtained.

3.2 QAM modulation and demodulation module

QAM is a vector modulation that maps input bits first onto a complex plane, forming a plural symbol and modulating the real part and imaginary part of the symbol onto two mutually orthogonal carriers respectively. The signal of QAM can be conveniently represented using a constellation diagram. A signal 16-QAM signal has 16 sample points on the constellation diagram, where each point represents a vector state, and each 4-bit binary number specifies one of the 16 states. After the data is mapped into a complex number, the real part and imaginary part need to be normalized to ensure that the power of the data is consistent before and after the mapping.

In the aspect of hardware implementation, the modulation module adopts the design method of look-up table, which first stores 16 states, and then uses the look-up table to complete the mapping of input data. The design of the demodulation module is the same as the modulation module. The amplitude of the real and imaginary parts of the complex data after 16-QAM modulation is 1, -1, 3, -3, after normalization, the corresponding data is 20, -20, 60, -60. The data format is set to 8-bit width: 1-bit symbol bit, 1-bit integer bit, 6-bit decimal place. And negative numbers are expressed in the form of complement. The RTL block diagram of 16-QAM modulation and demodulation is shown in Figure 4, and the simulation plot of 16-QAM modulation and demodulation is shown in Figure 5 and Figure 6.



(a) 16-QAM modulation module *(b) 16-QAM demodulation module*

Figure 4: The RTL block diagram of 16-QAM modulation and demodulation module.

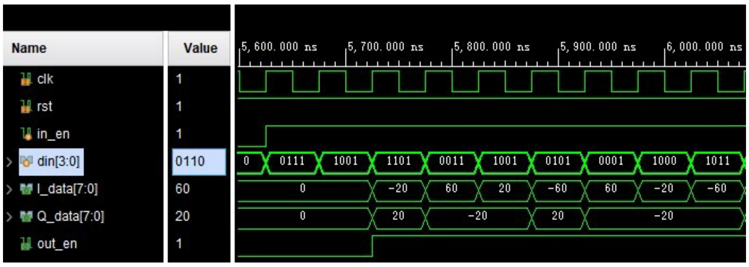


Figure 5: Simulation of 16-QAM modulation.

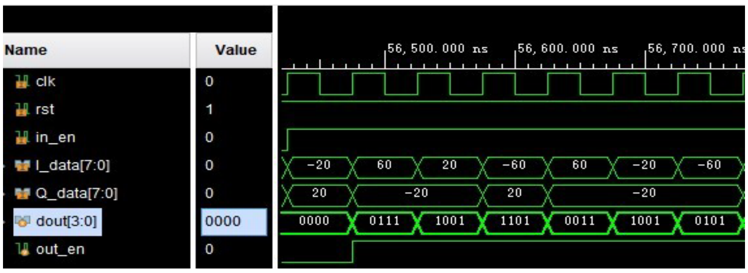


Figure 6: Simulation of 16-QAM demodulation.

In Figure 5, din is the input data, I_data and Q_data are the real and imaginary data after 16-QAM modulation. By comparison with the 16-QAM constellation chart, we can know that the output result is

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correct. Upon comparing Figure 5and Figure 6, it is evident that the data can be successfully demodulated, which demonstrates the successful implementation of the 16-QAM modulation and demodulation module.

3.3 WHT and IWHT module

Hadamard transform is also known as Walsh-Hadamard transform (WHT), it's a typical non-sinusoidal function transformation, using orthogonal rectangular function as the basis function, and has similar properties to the Fourier function. The WHT can be defined as

$$W(u) = \frac{1}{N}\sum_{x=0}^{N-1} f(x) Wal_H(u,x) \tag{3}$$

Where $f(x)$ is the input signal, and $Wal_H(u, x)$ is the Walsh function of Hadamard sort. The IWHT can be defined as

$$f(x) = \sum_{x=0}^{N-1} W(u) Wal_H(u,x) \tag{4}$$

In practical applications, in order to facilitate the transformation and analysis, the Hadamard transform is generally expressed in the form of matrix. The matrix of Hadamard can be written as

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \qquad H_{2^n} = \begin{bmatrix} H_{2^{n-1}} & H_{2^{n-1}} \\ H_{2^{n-1}} & -H_{2^{n-1}} \end{bmatrix} \tag{5}$$

The WHT and IWHT in matrix form can be expressed as

$$W(u) = \frac{1}{N} H_N F(x) \tag{6}$$

$$F(x) = H_N W(u) \tag{7}$$

where H_N is N-order Hadamard matrix, and $F(x)$ is Input matrix[11].

FHT is a fast algorithm for WHT. Its main idea is to factorize the transformation core of Hadamard transform (N-order Hadamard matrix) into several matrix forms with simpler structure. The decomposed matrix usually contains identity matrix and low-order Hadamard matrix. A fast algorithm similar to FFT is derived by combining the decomposed Hadamard matrix with the input matrix. Fig.7 shows the operation process of 8-point FHT.

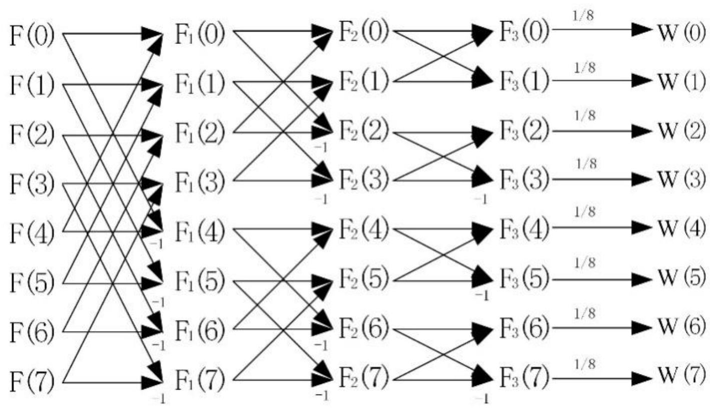

Figure 7: The butterfly transformation process of 8-point FHT.

The design of the WHT module is done according to the theory of FHT, perform N butterfly transformations on the 2^N (N=1,2,3,…,) data entered. When implemented in hardware, the WHT module uses a sequential processing architecture to design the butterfly transformation framework, the next butterfly transformation will only take place once the previous one has been completed. After the input data is fully butterfly transformed, the result of the WHT operation can be obtained by dividing the output

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result by 2^N. The hardware design can be implemented by shifting the output result to the right by $\log_2(N)$ bits to achieve the division calculation. The RTL block diagram of WHT module is shown in Figure 8, Figure 9 shows the output results of 8-point WHT.

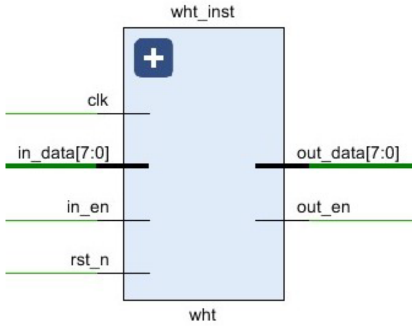

Figure 8: The RTL block diagram of WHT module.

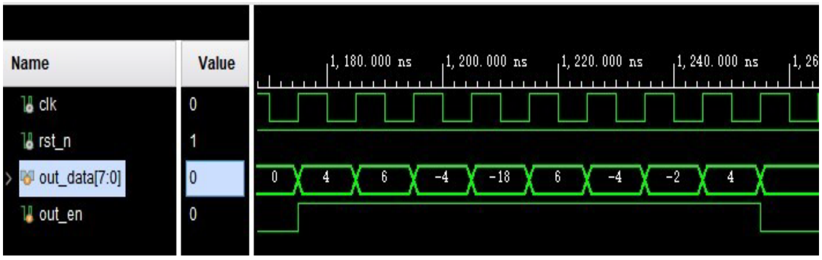

Figure 9: Simulation of WHT.

In Matlab, WHT operation is performed on the same data, the simulation result is shown in Figure 10.

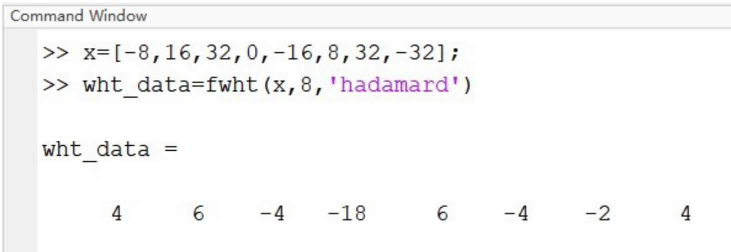

Figure 10: The result of simulation in Matlab.

In Figure 9, out_data is the data after WHT operation. By comparing the data in Figure 9 and Figure 10, it can be found that the output results are completely consistent, which verifies the correctness of WHT module. By comparing eq (6) and eq (7), it can be seen that the WHT module can be converted to an IWHT module by simply removing the division step of the WHT module. The output data from the WHT module is fed into the IWTH module and the simulation results obtained are shown in the Figure 11.

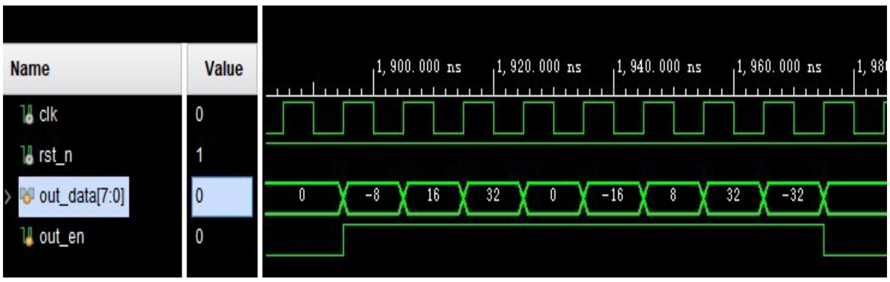

Figure 11: Simulation of IWHT.

By comparing the data in Figure 9 and Figure 11, the output data is the same as the input results, which proves the successful implementation of WHT module and IWHT module.

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3.4 IFFT module

IDFT is the most important step in OFDM system. The frequency-domain data is transformed into time-domain symbol after IDFT operation, in which each sample value of symbol is generated by superposition of all sub-carrier signals[12]. The signal after IDFT operation can be written as

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k)e^{\frac{2\pi jnk}{N}}, \qquad n = 0,1,\ldots,N-1 \tag{8}$$

At receiving end, the correct data can be recovered by DFT operation. The DFT can be expressed as

$$X(k) = \sum_{k=0}^{N-1} x(n)e^{\frac{-2\pi ynk}{N}}, \qquad k = 0,1,\ldots,N-1 \tag{9}$$

FFT is a fast algorithm of DFT. Compared with DFT, FFT can reduce the amount of computation complexity, and improve the operation speed. In terms of hardware implementation, the FFT and IFFT Module is realized by calling the FFT IP-core provided by Xilinx. The IP-core performs the FFT operation when the lowest bit of the input port s_axis_config_tdata of the FFT IP-core is configured to 1, and the IFFT operation when it is configured to 0.

The parameters for FFT IP-core are set as shown in Table 2, Figure 12 shows the RTL block diagram of IFFT module.

Table 2: The parameter of FFT IP-core

Parameter	Value/Option
Architecture Choice	Radix-4, Burst I/O
Data Format	Fixed Point
Scaling Option	Block Floating Point
Rounding Mode	Convergent Rounding
Input Data Width	8
Phase Factor Width	16
Output Ordering	Natural Order

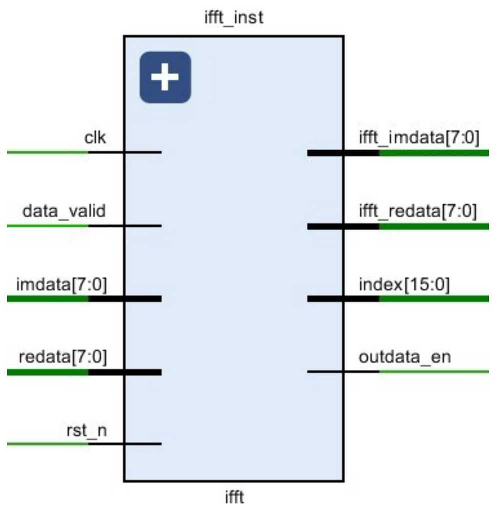

Figure 12: IFFT module.

The IFFT module was tested with 64 data inputs and the simulation results obtained are shown in the Figure 13, Figure 14 shows the results of the IFFT operation in Matlab for the same data.

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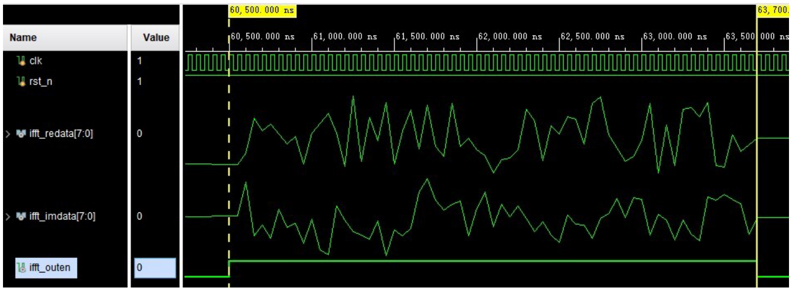

Figure 13: Simulation of IFFT.

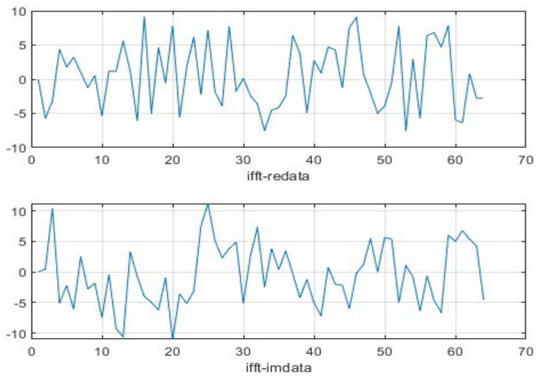

Figure 14: The simulation waveforms in Matlab.

In Figure 13, ifft_redata and ifft_imdata are the real and imaginary parts of the input data after the IFFT operation. By comparing the simulated waveforms in Figure 13 and 14, it can be seen that they are identical, proving that the design of the IFFT module is correct.

4. Results

According to the design of the WHT-OFDM system, the system is simulated and verified on the Vivado. In the absence of interference and noise, the simulation results are shown in Figure 15, Figure 16 and Figure 17.

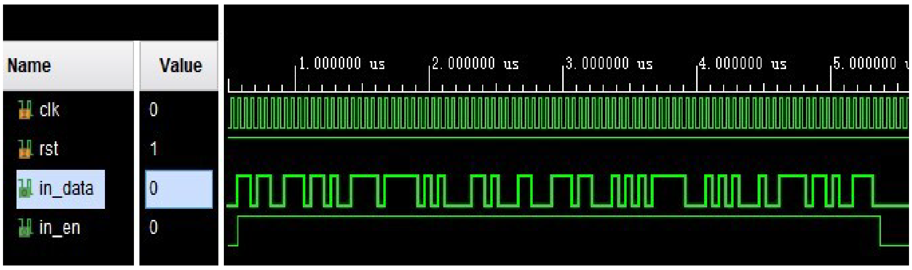

Figure 15: The waveform of input data.

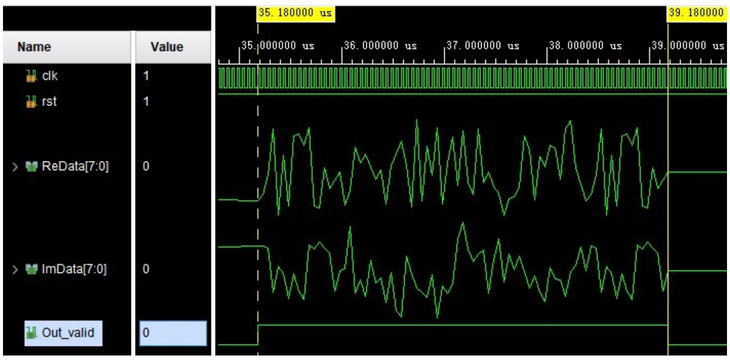

Figure 16: The waveform of data after WHT-OFDM modulation.

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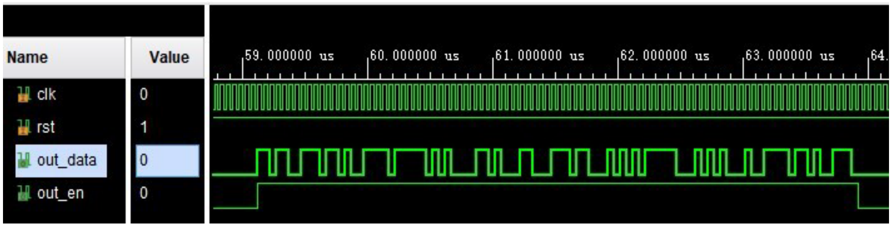

Figure 17: The waveform of output data

In Figure 15, in_data is the test data entered into the WHT-OFDM system. In Figure 16, out_redata and out_imdata are the real and imaginary data waveforms of the output data after the test data has been modulated by the WHT-OFDM system. In Figure 17, by feeding out_redata and out_imdata into the demodulation module of the WHT-OFDM system, the final output is out_data. As can be seen from Figure 15 and Figure 17, in_data are the same asout_data after modulation and demodulation of the WHT-OFDM system. Therefore, it can be proved that the modulation and demodulation modules of the designed WHT-OFDM system have correct functions and can work normally.

The model of WHT-OFDM system was targeted to a Artix-7 XC7A100T, the implementation of the system model requires approximately 40% of the available resources. Detailed area results are shown at Table 3.

Table 3: Area results

Area metrics for a Artix-7 XC7A100T device		
Resource	**used**	**%**
LUT	25327	39.95
FF	24225	19.10
BRAM	12.50	9.26
LUTRAM	524	2.76
IO	4	1.40
BUFG	3	9.38
DSP	18	7.50

5. Conclusion

In order to enhance the BER performance of OFDM system in the case of high mobility, WHT is used as pre-coding technology in OFDM system. The simulation results indicate that the performance of WHT-OFDM system has been enhanced when compared to OFDM system. In this paper, the base-band processing of the WHT-OFDM system is realized by FPGA technology, the implementation scheme of modem module is given. The modem module of the system is tested on the FPGA, and the test results are compared with the simulation results on the Matlab. The results prove that the functions of modem module of the WHT-OFDM system can be correctly realized and can work normally. The successful implementation of WHT-OFDM baseband processing system using FPGA technology provides a solid foundation for the implementation of WHT-OFDM system in high mobility communication systems.

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