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***Abstract*—In this paper, design and analysis one of the proposed Optical Orthogonal Frequency Division Multiplexing (OFDM) for Visible Light Communication has been conducted. The chosen design is Generalized LED Index Modulation Orthogonal Frequency Division Multiplexing (GLIM-OFDM), with its proposed scheme that avoid Hermitian symmetry and DC bias. Thus, by utilizing the properties of complex data signal and the bipolar index with spatial modulation Multi Input Multi Output (MIMO) configuration. System generator is used to design the GLIM-OFDM. The design is targeted into Arty Board with Xilinx Artix-7 FPGA. Analysis and comparison are covering in the arithmetic option of unscaled and scaled for its effect on precision, performance, and resource usage. The designed system is proven to work according to theory of operation scheme. To verify that, the reversible design has been designed to ensure the processed data in the transmitter side with the origin data signal. The unscaled option performs slightly faster than the scaled option. Both arithmetic option has same precision of data representation. The GLIM-OFDM design used less resource in unscaled option compared with the design in scaled option.**

Keywords*—*Visible Light Communication; Optical OFDM; Signal Processing; FPGA

I. INTRODUCTION

Wireless Communication becomes type of communication that used extensively and the demands of wireless data communication has been increased. Radio spectrum contains 3Hz-3THz becomes insufficient to accept the high demand usage. Electromagnetic spectrum contains visible light spectrum, generally visible light spectrum used as room lighting and illumination, but it is shown that Visible Light Communication (VLC) can transmit at high data rates [1]. Visible light communication is one of solution to solve the insufficient capacity of bandwidth in radio spectrum and one of candidate to support next generation communication and Smart City. Despite the advantages of high capacity and high data rates. Usage of visible light communication can improve the energy efficiency because Light Emitting Diode (LED) is used as transmitter. Even though the optimal usage of visible light communication is only in indoor environment, but it's statically proven that 85% of our activities are in indoor environment [2].

OFDM has been broadly developed in communication systems because of its orthogonally, high data rates and bandwidth efficiency [3]. OFDM is commonly used in Radio Frequency (RF) communication systems, nevertheless several RF OFDM schemes have been adopted in optical domain. DC biased Optical OFDM (DCO-OFDM) [4-6] and Asymmetrical Clip Optical OFDM (ACO-OFDM) [7, 8]. DCO OFDM and ACO OFDM is widely used in VLC systems, moreover combining DCO and ACO together proposed to achieve more performance than conventional scheme [9]. MIMO offer high speed data transmitting. Looking by its name, there are multiple transmitter and multiple receiver meaning that by using multiple transmitter and receiver can improved the link channel and speed performance. There are several MIMO technique that can be used such as spatial diversity, spatial multiplexing, and spatial modulation. Several MIMO OFDM schemes for VLC has been proposed such as GLIM-OFDM [10] and Non-DC-Biased (NDC-OFDM) [11]. Both utilized the spatial modulation to avoid DC bias, unlike NDC-OFDM, GLIM-OFDM completely avoid Hermittian symmetry operation and have better spectral efficiency.

In this paper, we design and analysis the GLIM-OFDM scheme in system generator. We design the system according to GLIM-OFDM theory. We provide a reversible design to verify the transmitted data back to its origin data signal. We analyze the arithmetic option which is affect the performance, precision and resource usage.

This paper is organized as follows. Section II explain theory of Quadrature Amplitude Modulation (QAM) and GLIM-OFDM. Section III describe the methodology of this paper. The designed system and its function are showed and described in Section IV. Section V shows the result and analysis. Future work of this paper are given in Section VI. Section VII provide the conclusion of the paper.

II. SIGNAL PROCESSING THEORY

A. Quadrature Amplitude Modulation (QAM)

QAM is used to mapping a sequence of data into complex data symbols. QAM is combination of two type modulation, Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK). The equation of QAM can be expressed as:

$$s_i(t) = a_i(t)\cos(\theta_i)\cos(\omega_c t) - b_i(t)\sin(\theta_i)\sin(\omega_c t) \quad (1)$$

Where $a_i \cos(\theta_i)$ is In-Phase value and $b_i \sin(\theta_i)$ is Quadrature value. Eq. (1) can be expressed as magnitude and phase

$$s_i(t) = r_i(t)\cos[\omega_c t - \theta_i(t)] \qquad (2)$$

Where $r_i(t)$ is magnitude value and $\theta_i(t)$ is phase value. From Eq. (1), QAM consist two type values, there are In-Phase and Quadrature. Generally, In-Phase can be represented as real value and Quadrature can be represented as imaginary value, each of them ranging from n where M depends on the size of n, $2^n = M$.

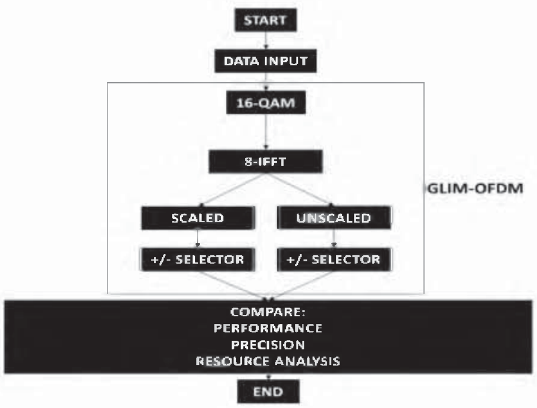

Fig. 1. *Methodology Steps*

B. *Generalized LED Index Modulation-OFDM* (GLIM-OFDM)

The inevitable constraint of transmitting data in optical domain or intensity modulation/direct detection (IM/DD) is, the data signal must be real and positive [3] [12]. GLIM-OFDM is one of many proposed optical OFDM schemes to cover these problems. GLIM-OFDM utilized the properties of complex data signal and LED index, so there is no need to use Hermitian symmetry and DC bias. The rest operation of GLIM-OFDM is like conventional OFDM. First the baseband modulation of QAM is produced. Then the constellation point become an input straight to Inverse Fast Fourier Transform (IFFT). The complex signal of IFFT output separated into real and imaginary signal. While each component signal still contains bipolar value, polar separator is used to separate the polar index and the negative part is inverted into positive signal. The polar separator is expressed in Eq. (3) [10].

$$x_{k,R}^{+} = \begin{cases} x_{k,R} & \text{if } x_{k,R} > 0 \\ 0 & \text{if } x_{k,R} < 0 \end{cases} \quad x_{k,R}^{-} = \begin{cases} 0 & \text{if } x_{k,R} > 0 \\ -x_{k,R} & \text{if } x_{k,R} < 0 \end{cases} \qquad (3)$$
$$x_{k,I}^{+} = \begin{cases} x_{k,I} & \text{if } x_{k,I} > 0 \\ 0 & \text{if } x_{k,I} < 0 \end{cases} \quad x_{k,I}^{-} = \begin{cases} 0 & \text{if } x_{k,I} > 0 \\ -x_{k,I} & \text{if } x_{k,I} < 0 \end{cases}$$

III. Methodology

As mentioned before, the optical OFDM scheme that we choose is GLIM-OFDM. The methodology step and setting parameter are shown in Fig. 1 and Table I respectively.

First, the data input is set to fixed increment of 16 integer value and periodic for analytic purpose later in the analysis section. The number representation is in Fixed-point data type. The baseband modulation we used is 16-QAM. The baseband modulation output can be directly fed into IFFT. We also experimenting and learning IFFT behavior in model-based design by utilizing Xilinx FFT 9.0 block, which contains two arithmetic option of unscaled and scaled. After that, the output from IFFT is driven by selector to divide the polar index into individual data output. The results are analyzed and compared in performance, precision and resource for both arithmetic option.

IV. System Design

The selected optical OFDM schemes are designed in system generator according to theory in section II and methodology in section III, covering the baseband modulation, IFFT, +/- selector and reversible design. The following section will describe each function of the optical OFDM schemes and the complete design is shown in Fig. 2.

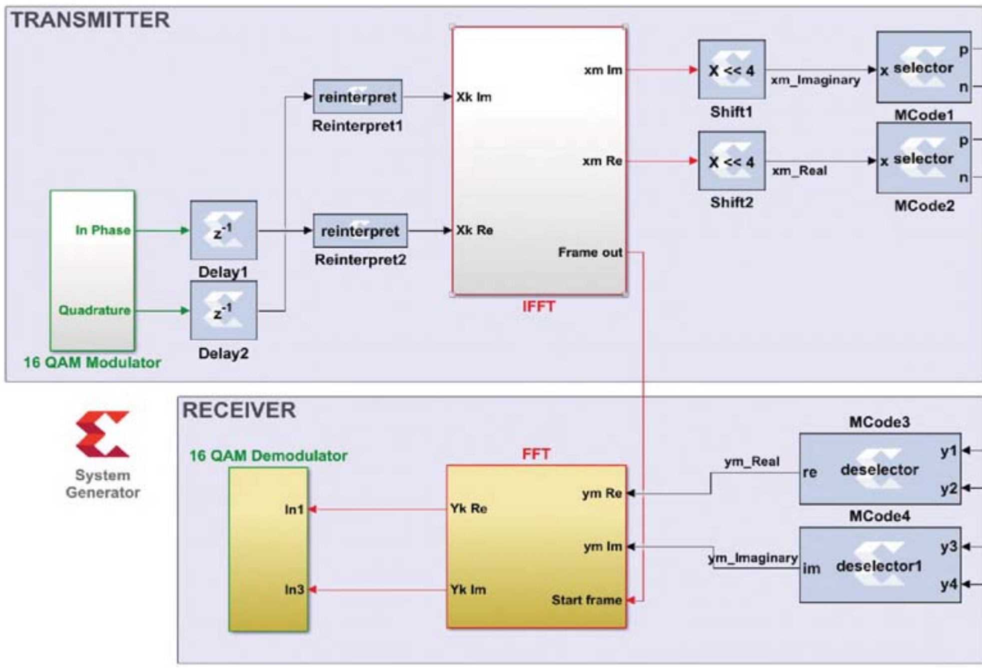

Fig. 2. *Designed GLIM-OFDM scheme*

TABLE I. SETTINGS PARAMETER

Category	Configuration
Data Input	Fixed and periodic
Number Representation	Fixed-point data type
Baseband Modulation	16-QAM
OFDM Method	GLIM-OFDM
FFT length	8 points
Arithmetic Type	Unscaled and Scaled
MIMO Scheme	Spatial modulation
FPGA	Arty Board with Xilinx Artix-7 FPGA

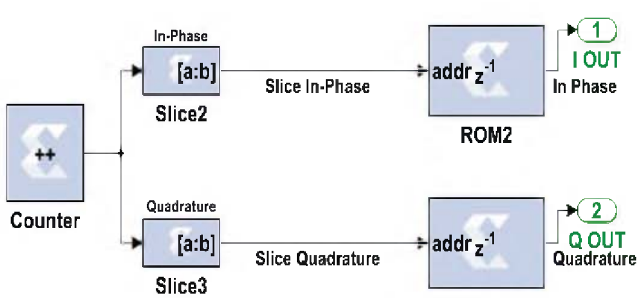

Fig. 3. *16-QAM Modulator Design*

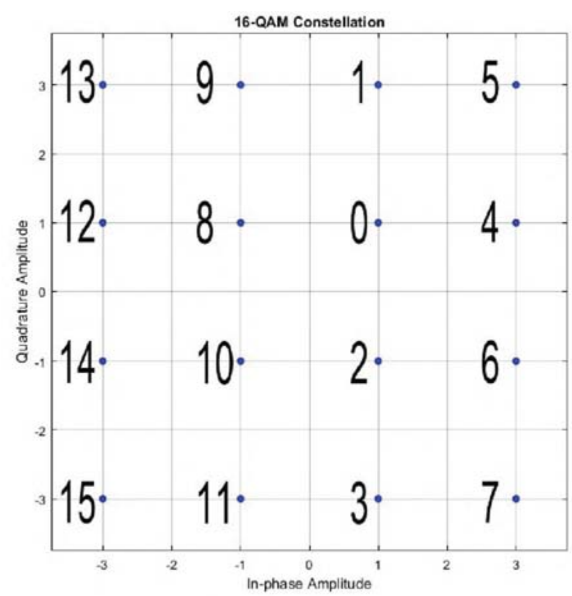

Fig. 4. *16-QAM constellation diagram with gray code.*

A. 16-QAM Baseband Modulation

Baseband modulation is one of primary function in OFDM system. In this design, a baseband modulation of 16-QAM has been designed. The design is based on [13], but in our system design several optimization has been conducted. The design is shown in Fig. 3 with its constellation diagram and gray code configuration in Fig. 4.

B. IFFT Unscaled Configuration

For the IFFT design, we used Xilinx Fast Fourier Transform 9.0 (FFT 9.0) to perform IFFT computation. FFT 9.0 implement an AXI4 configuration and Cooley-Tukey FFT Algorithm which is one of many efficient methods to compute DFT [14]. FFT 9.0 can compute forward and inverse transform to calculate DFT depends on the configuration and system needs.

In order to make FFT 9.0 work like OFDM modulator there are some configurations need to be done in the design and shown in Fig. 5 (a). The input configuration port of FFT 9.0 CONFIG_TDATA_FWD_INV is set to 0 in order to compute IFFT in FFT 9.0 block. The architecture of pipelined streaming I/O has been chosen. The pipelined streaming I/O offer simultaneously transform and continuous data procession [14]. The input complex data for FFT 9.0 which contain constellation point in each vector, needs to be redesigned to meet input data type of FFT 9.0 and to avoid overflow. Reinterpret is use to force the binary point to S-1 of data width, which in this design Fix 8_7 data type is used. There are two options to rescale the input data, the first method by using scaled option in FFT 9.0 configuration and the second method by scaled the data after the data computed in FFT 9.0. In this design, scaling options of unscaled method is designed in order to maintaining the performance. In unscaled method we need to accommodate the estimation of bit growth after the calculation, in order to estimate bit growth, we can use Eq (4) to determine output bit.

$$\text{output bit} : \text{input bit} + \log_2(\text{FFT length}) + 1 \quad (4)$$

For example, considering input data width 8 bits and NFFT length of 8. The output bit width will be 12 bits width, 4 bits wider than the input data. This behavior caused by finite word arithmetic in each butterfly stage. Xilinx shift block is used to rescale the data output, the output data shifted into the initial data type. For example, only 4 bits data needed to represent 16-QAM symbol, in order to fulfill FFT 9.0 data type requirement the data type is need to scale to 8 bits which is 4 bits more than initial data type. Therefore, to rescale the data into initial data type, we need to shift in left direction or to MSB for 4 bits at the output of FFT 9.0 block.

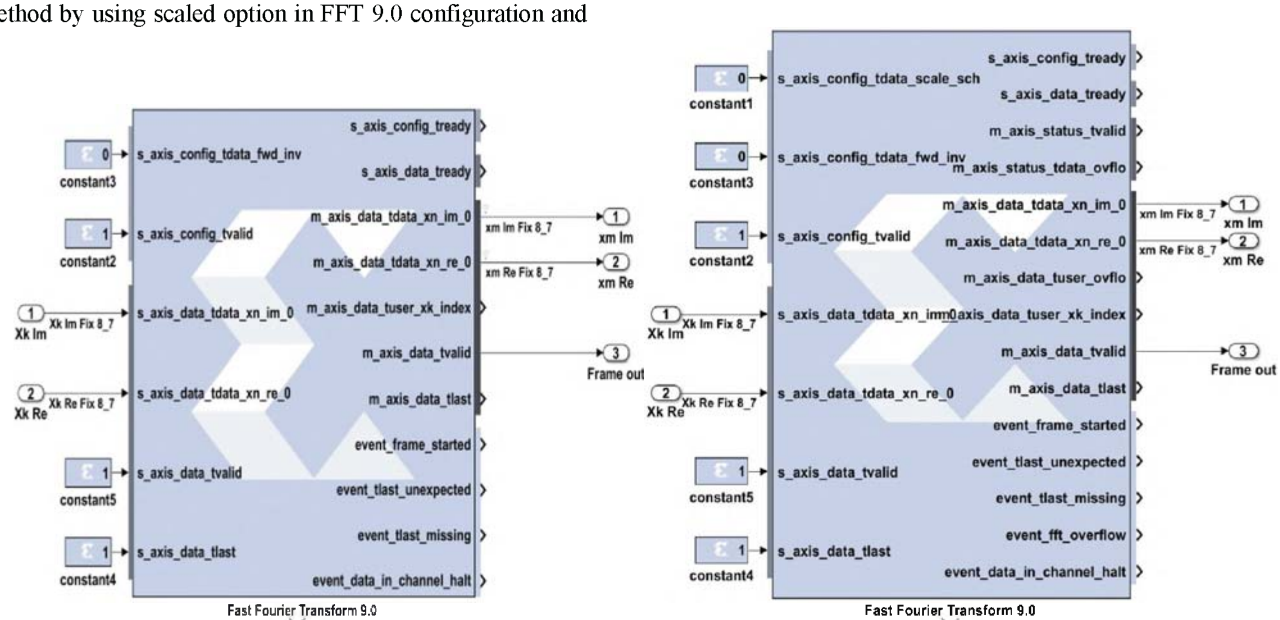

Fig. 5. *FFT 9.0 configuration for (a) Unscaled and (b) Scaled.*

C. IFFT Scaled Configuration

In this configuration, scaling option of scaled method has been designed and most of all configuration is still same like unscaled configuration and the configuration is shown in Fig. 5 (b). Scaling option is used to reduce the bit growth in butterfly computation transform from FFT 9.0 block. But when using scaled method, FFT 9.0 block will add more input and output port configuration such as STATUS_TDATA_OVFLO, DATA_TUSER_OVFLO, EVENT_FFT_OVERFLOW, and CONFIG_TDATA_SCALE_SCH. STATUS_TDATA_OVFLO, DATA_TUSER_OVFLO, and EVENT_FFT_OVERFLOW is a useful port to identify where the overflow occurs which caused by addition, subtraction, multiplication and divide operation inside FFT 9.0 computation, which is later the output signal from overflow output port can determine and configure how the scaling schedule in CONFIG_TDATA_SCALE_SCH port. CONFIG_TDATA_SCALE_SCH is an input configuration port to configure how the scaling schedule work. Pipelined streaming I/O has possible scaling schedule with 5 bits width configuration. For scaled configuration design, CONFIG_TDATA_SCALE_SCH is set 0, which mean there is no rescale bits inside butterfly stage because in small FFT length there is no overflow at the output of FFT

9.0 as observed in all of overflow port since in this design we used 8-FFT length. But in large FFT length such as 64 to 65536 the overflow may occur so the CONFIG_TDATA_SCALE_SCH cannot set to 0. The output data type from FFT 9.0 block is same with input data type, Fix 8_7. Unlike unscaled option where the input and output data type are not same that caused by bit growth and need more operation to rescale the data type outside FFT 9.0.

D. LED Index Selector

In transmitter front end, GLIM-OFDM utilize the LED index to transmit in bipolar signal value. From Fig. 6 it can be seen that MCode is used to separate each input index value resulting positive value and negative value. MCode operates simple condition according Eq. (3) to separate the index. First it will compare the input value with 0, then when the statement is fulfilled it will address to output port positive or negative. Since the positive value can be sent directly to output port, but not with negative value. Extra operation is needed to convert the negative value into positive value by addressing the output port negative as an absolute value of the input.

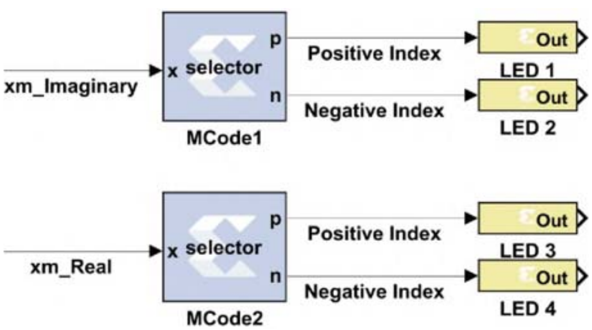

Fig. 6. *LED Index Selector*

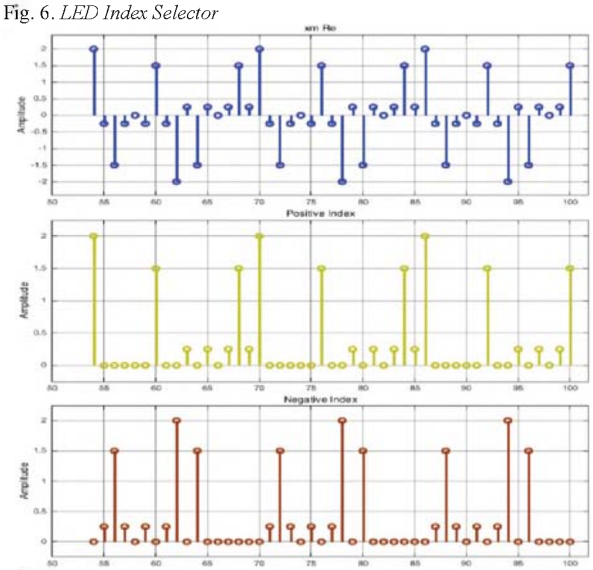

Fig. 7. *Real Selector Output*

Fig. 7 shows an example of real selector output from our design. It can be seen that, the separator is able to divide the polar index and invert the negative value.

E. Reversible Design

In order to ensure the processed data in the transmitter side with the origin data signal. Reversible design has been conducted. In contrast, we have to do the reverse operation as the transmitter do, the design is shown in Fig 4 on receiver side. Assuming the transmitted data is directly sent into reversible design and in perfect condition without adding wireless channel noise with simplified MAP estimator [10].

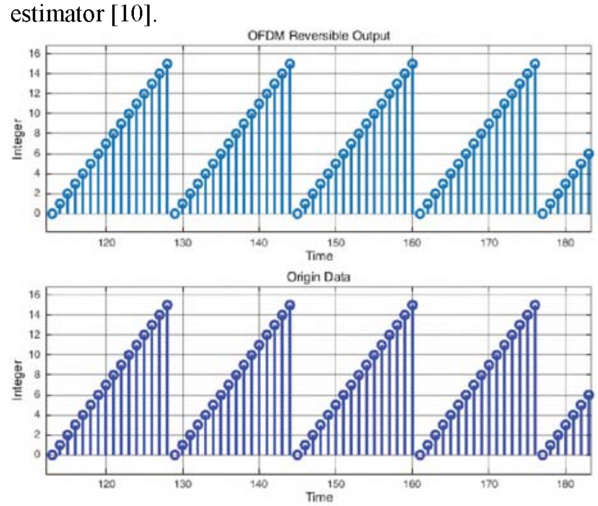

Fig. 8. *Comparison Of OFDM Reversible Output and Data Input*

Fig. 8 shows the result from our reversible design and compared with aligned data input for easier analyze. The output is match with origin data signal, which in this design we used 4 bits to produce 16 possible integer values.

V. RESULT & ANALYSIS

In this section, result and analysis are conducted in performance, precision and resource usage with the following system design in section IV.

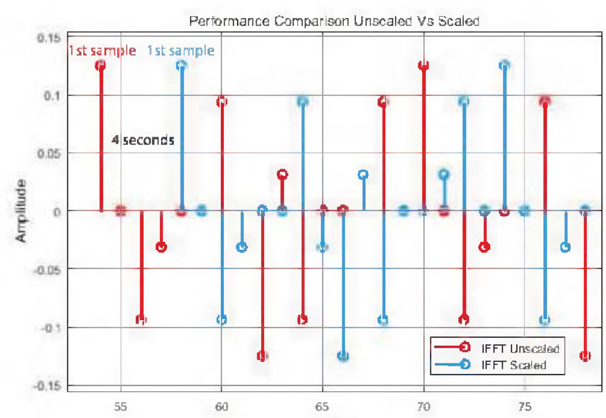

Fig. 9. *Performance Comparison with Different Arithmetic of Unscaled and Scaled*

A. *Performance Analysis*

Performance comparison is to show how the scaling option affect the time computing inside FFT 9.0 block. Fig. 9 shows the performance timing differences for unscaled and scaled arithmetic.

We observe the first sample produced from IFFT operation for both unscaled and scaled option. Unscaled option performs 4 second faster in normalized time or 40ns compared to scaled option. Because scaled option uses extra operation to rescale the data inside FFT 9.0 block.

B. *Precision Analysis*

The result showed data signal of fixed point data type for real and imaginary value with different arithmetic configuration and compared with accurate Matlab result. Fig 10 shows the comparison result for real value and Fig. 11 shows the comparison result for imaginary value.

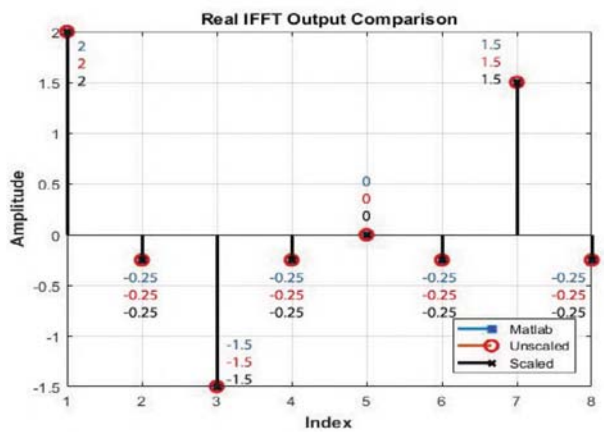

Fig. 10. *Compared precision results for real value with Matlab, unscaled and scaled option.*

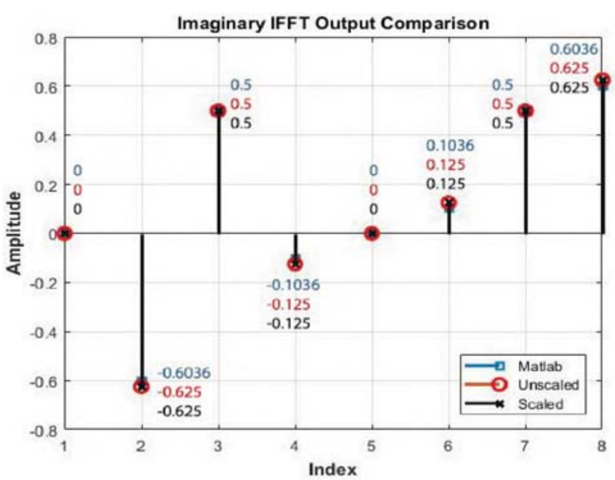

Fig.11. *Compared precision results for imaginary value with Matlab, unscaled and scaled option*

Both unscaled option and scaled option have same precision output, because the finite word arithmetic behavior. Precision loss in fixed point data type, is caused by the inability to represent precise fractional number. Using floating point data type is far more precise than using fixed point data type, but in exchange of lack computation performance and use more resource when being implemented.

C. *Resource Analysis*

FPGA board from Arty Artix 7 is used in Hardware Utilization to observe the usage resource inside FPGA. The system is needed to be efficient, since the resource of FPGA is limited and different over another. The resource utilization is shown in Table II.

TABLE II. RESOURCE UTILIZATION

	BRAMs (50)		**DSP (90)**		**LUTs (20800)**		**Registers (41600)**	
SYSTEM DESIGN	Used	%	Used	%	used	%	used	%
GLIM-OFDM UNSCALED	3	6	18	20	1167	5.61	1624	3.9
GLIM-OFDM SCALED	3	6	18	20	1305	6.27	1732	4.16

VI. FUTURE WORK

This paper only design one optical OFDM method covering transmitter side and simplified receiver side. For further work, implementing the design and getting real test result is needed to analyze the MIMO channel, spectral efficiency, Peak-to-Average Power Ratio (PAPR) and the complexity. Comparing one into another Optical OFDM scheme can be useful to decide the best Optical OFDM that is suitable for Visible Light Communication especially for implementation.

VII. CONCLUSION

Using the results and analysis from previous section, it can be concluded that different arithmetic option such as unscaled and scaled affects resource usage while being implemented in FPGA. Finite word representation in fixed point affect the precision representation, for integer values are 100% accurate but it less accurate when represent the fractional numbers. Arithmetic option such as unscaled performs 4 seconds (normalized time) faster than scaled option.

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