Design & Implementation of Optimized DMWT Architecture for OFDM on FPGA

Veena M.B and M.N. Shanmukha Swamy

Abstract—To cater the growing wireless broad band aspirations in the market, new technologies are emerging to take up the challenges. Accordingly requirements for the next generation technologies have started building up and have led to unprecedented demand for high speed architectures for complex signal processing applications. In this work a GHM (Geronimo, Hardian, and Massopust) filter based DMWT and IDMWT is implemented on FPGA optimizing area, power and speed performances. The model is simulated using simulink and tested for its functionality using HDL code and is synthesized using Xilinx ISE targeting Virtex-5 FPGA. The performances of DMWT-OFDM in terms of BER show that DMWT-OFDM achieves higher BER performances compared with DWT-OFDM and FFT-OFDM. The proposed DMWT architecture operates at a maximum frequency of 340MHz and consumes power of 24mW.

Keywords—OFDM, DMWT, FPGA, GHM, BER

I. INTRODUCTION

The communication systems and communication networks of the future will fundamentally improve the way people communicate. One among the services expected to have major impact in the future include wireless communication that will permit mobile telephony and data transfer anywhere on the planet. As we move in to the future there is a rising demand for high performance, high capacity and high bit rate wireless communication systems to integrate wide variety of communication services such as high-speed data, video and multimedia traffic as well as voice signals. As proven by the success of orthogonal frequency division multiplexing (OFDM), it provides an efficient means to handle high-speed data streams over a multipath fading environment. Wireless multicarrier modulation (MCM-OFDM) is a technique of transmitting data by dividing the input data stream into parallel sub-streams that are each modulated and multiplexed onto the channel at different carrier frequencies [1].

The fundamental principle of the OFDM system is to decompose the high rate data stream into N parallel lower rate data streams or channels, one for each subcarrier.

Each sub-carrier is modulated with a conventional modulation Scheme at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth. A sufficiently high value of N makes the individual bandwidth (W/N) of subcarriers narrower than the coherence bandwidth of the channel. The primary advantage of OFDM over single carrier schemes is its ability to cope with severe channel conditions without use of complex equalization filters. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. The choice of individual subcarriers is such that they are orthogonal to each other, which allows for the overlapping of subcarriers because the orthogonality ensures the separation of subcarriers at the receiver end. This approach results in a better spectral efficiency than other types of systems like Frequency Division Multiple Access, where no spectral overlap of carriers is allowed [2].

Inverse fast Fourier transforms (IFFT) and fast Fourier transform (FFT) in a conventional OFDM system are used to multiplex the signals together and decode the signal at the receiver respectively. The major contribution to the OFDM implementation was the application of the Fast Fourier Transform (FFT) to the modulation and demodulation processes. FFT has a major drawback arising from using rectangular window, which creates side lobes. Moreover, the pulse shaping function used to modulate each subcarrier extends to infinity in the frequency domain. This leads to high interference and lower performance levels. Inter carrier interference (ICI) and inter symbol interference (ISI) can be avoided by adding a cyclic prefix (CP) to the head of OFDM symbol. But, this reduces the spectrum efficiency. Another major problem of FFT based OFDM system is the high peak-to-average power ratio (PAPR). Due to this problem other type of modulation scheme based on DWT to generate the carrier is adopted. Many authors have proposed DWT for OFDM [3-11], DWT-OFDM has a high degree of side lobe suppression and the loss of orthogonality leads to lesser inter symbol interference (ISI) and inter carrier interference (ICI) than in conventional OFDM system. By using the transform, the spectral containment of the channels is better since it does not use CP [3-8]. One type of wavelet transform is namely as Discrete Wavelet Transform OFDM (DWT-OFDM). Further performance gains can be made by looking into alternative orthogonal basis functions and finding a better transform.
rather than Fourier and wavelet transform [12],[13],[15].

Multiwavelet is a new concept has been proposed in recent years. Multiwavelets have several advantages compared to single wavelets [21]-[26]. A single wavelet cannot simultaneously possess all the properties of orthogonality, symmetry, short support, and vanishing moments. Multiwavelets are very similar to wavelets but have some important differences. In particular, whereas wavelets have an associated scaling function \( \phi(t) \) and wavelet function \( \psi(t) \), multiwavelets have two or more scaling and wavelet functions. For all the priorities of multiwavelet, a natural thought is applying it on OFDM. GHM based multiwavelet filters for OFDM have proven that the DMWT based OFDM achieves BER 10^{-4} at 11.5 dB [14], the results are based on Software models developed using MATLAB. In this paper, FPGA implementation of DMWT for OFDM is carried out optimizing area and power. Section II discusses Multiwavelet based OFDM, section III discusses design of DMWT architecture and hardware implementation, Section IV results and discussion and section V presents conclusion.

II. MULTIWAVELET BASED OFDM

A newer alternative to the wavelet transform is the multiwavelet transform. Multiwavelets are very similar to wavelets but have some important differences. In particular, whereas wavelets have an associated scaling function \( \phi(t) \) and wavelet function \( \psi(t) \), multiwavelets have two or more scaling and wavelet functions. For notational convenience, the set of scaling functions can be written using the vector notation \( \Phi(t) \equiv [\phi_1(t) \phi_2(t) ... \phi_r(t)]^T \), where \( \psi(t) \) is called the multi scaling function. Likewise, the multiwavelet function is defined from the set of wavelet functions as \( \Psi(t) \equiv [\psi_1(t) \psi_2(t) ... \psi_r(t)]^T \). When \( r = 1 \), \( \psi(t) \) is called a scalar wavelet, or simply wavelet. While \( r \) in principle can be arbitrarily large, the multiwavelets studied to date are primarily for \( r = 2 \). The multiwavelet two-scale equations resemble those for scalar wavelets [21]-26

\[
\phi(t) = \sqrt{2} \sum_{k=\infty}^{\infty} H_k \phi(2t-k) \ldots \ldots \ldots \ldots \ldots (1)
\]

\[
\psi(t) = \sqrt{2} \sum_{k=\infty}^{\infty} G_k \psi(2t-k) \ldots \ldots \ldots \ldots \ldots (2)
\]

Note, however, that \( H_k \) and \( G_k \) are matrix filters, i.e., \( H_k \) and \( G_k \) are \( r \times r \) matrices for each integer \( k \). The matrix elements in these filters provide more degrees of freedom than a traditional scalar wavelet. These extra degrees of freedom can be used to incorporate useful properties into the multiwavelet filters, such as orthogonality, symmetry and high order of approximation. The key, then, is to figure out how to make the best use of these extra degrees of freedom. Multifilter construction methods are already being developed to exploit them. Multiwavelet based OFDM architecture is shown in figure below. Input data is converted into parallel data before IDWT processing is performed. For OFDM there are very few multiwavelets reported. A very important Multiwavelets filter is the GHM filter proposed by Geronimo, Hardian, and Massopust. In multiwavelets setting, GHM multiscaling and Multiwavelets functions coefficients are 2X2 matrices and during transformation step they must multiply vectors (instead of scalars). This means that multifilter bank need two input rows. The aim of preprocessing is to associate the given scalar input signal of length \( N \) to a sequence of length-two vectors in order to start the analysis algorithm and to reduce the noise effects. In the one dimensional signals the “repeated row” scheme is convenient and powerful to implement.

The OFDM modulator and demodulator of DMWT-based OFDM are shown in figure 1. The input data is preprocessed and is modulated using Inverse DMWT (IDWMT). In the preprocessing state the input samples are symmetrically extended to the size of the IDMWT coefficients for modulation. At the receiver, DMWT demodulation is performed on the received signals and the post processing logic retrieves the modulated data from the received samples.

Then the computation of IDMWT for 1-D signal is achieved by using an over-sampled scheme of preprocessing (repeated row), the Inverse Discrete Multiwavelets Transform (IDMWT) matrix is doubled in dimension compared with that of the input, which should be a square matrix \( N \times N \) where \( N \) must be power of 2. Transformation matrix dimensions are equal to input signal dimensions after preprocessing. To compute a single-level 1-D discrete multiwavelets transform, the next steps should be followed:

1. Checking input dimensions: input vector should be of length \( N \), where \( N \) must be power of 2.
2. Constructing a transformation matrix, \( W \), using GHM low and high pass filters matrices given in equations (3) and (4), the transformation matrix can be written as equation (5). After substituting GHM matrix filter coefficients values [21], a 2N X 2N transformation matrix results.

\[
H_0 = \begin{bmatrix}
0 & 3 & 1 & 0 \\
1 & 0 & 3 & 1 \\
-10\sqrt{2} & 20 & -10\sqrt{2} & 20 \\
\end{bmatrix} \\
H_1 = \begin{bmatrix}
3 & 0 & 0 & 0 \\
0 & 3 & 0 & 0 \\
0 & 0 & 3 & 0 \\
0 & 0 & 0 & 3 \\
\end{bmatrix}
\]

Fig. 1 DMWT-OFDM modem system

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1. Preprocessing the input signal by repeating the input stream with the same stream multiplied by a constant \( \alpha \), for GHM system functions \( \alpha = 1/\sqrt{2} \).

2. Transformations of input vector which can be done by applying matrix multiplication to the 2Nx2N constructed transformation matrix by the 2Nx1 preprocessing input vector.\[14\]

III. DESIGN OF HIGH SPEED AND LOW POWER ARCHITECTURE FOR DMWT FOR OFDM

In this section, VLSI implementation of DMWT for OFDM is presented. The performances of DMWT-OFDM in terms of BER show that DMWT-OFDM achieves higher BER performances compared with DWT-OFDM and FFT-OFDM. However, the number of coefficients required to compute forward and inverse DMWT are \( 2(2N\times2N) \), where \( N \) is the size of input samples. In order to compute DMWT it is required to perform large number of multiplications and additions. Thus it is required to reduce the computation complexity of DMWT computation to enhance speed, area and Power performances of DMWT-OFDM compared with DWT-OFDM. The transformation matrix based on GHM filters for DMWT is chosen to be of size 8 x 8. This is the minimum size for GHM based filters; higher orders would lead to complexity in hardware.

The input is taken into group of 4 samples, and is repeated with scaled values. The input matrix which is of size 4 x 1 is resized to 8 x 1 after extension and scaling as shown in equation 4. The input matrix is transformed to output using the GHM filter. After matrix multiplication we get equations for computing the output matrix of size 8 x 1. From the equations, there are redundant factors between samples \( y_0 \) and \( y_7 \), in order to eliminate redundancies and reduce computation time; the equations are regrouped by reducing the common factors. The simplified constants are scaled by 128 to convert the fractions to nearest integers. Due to rounding effect the loss is restricted to less than 2%.

The simplified expression for GHM filters are rewritten in matrix form, from the two matrices it is found that the input samples are of size 4 x 1 and are used simultaneously to compute the output samples \( y_0 \) to \( y_7 \). The filter coefficients are obtained from the simplified equations. Reducing the above equations into matrix form

\[
\begin{bmatrix}
G_0 & G_1 & G_2 & G_3 \\
\end{bmatrix}
\]

are used in design of multiwavelet architecture. Figure 2 shows the optimized data flow diagram for DMWT. The optimized architecture consists of a FIFO of size 4, that stores the input samples, and the FIFO are accessed to compute the output samples as per the simplified equations. The optimized architecture is modeled using HDL and is simulated using ModelSim. In this work a GHM based DMWT and IDMWT is implemented on FPGA optimizing area, power and speed performances.

IV. RESULTS AND DISCUSSION

In this section, VLSI implementation of DMWT for OFDM is presented. The performances of DMWT-OFDM in terms of BER show that DMWT-OFDM achieves higher BER performances compared with DWT-OFDM and FFT-OFDM in AWGN channel. This is a reflection to the fact that the orthogonal bases of the multiwavelets is much significant than the orthogonal bases used in FFT-OFDM and DWT-OFDM.
The modeled HDL is simulated and tested for its functionality; the functionally verified HDL code is synthesized using Xilinx ISE targeting Virtex-5 FPGA (XC5VLX110T-FF1136-2). The design consists of 110 million gates and has 1136 I/Os. The synthesized net list and synthesis report are analyzed for the performance of designed DMWT architecture. The results obtained are compared and discussed in this section.

### Table I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Reference</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Multipliers</td>
<td>6N+2</td>
<td>18</td>
</tr>
<tr>
<td>No. of Adders</td>
<td>4N+2</td>
<td>17</td>
</tr>
<tr>
<td>Through Put</td>
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<td>1</td>
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<tr>
<td>Latency</td>
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<td>4</td>
</tr>
<tr>
<td>Memory Usage</td>
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<td>3N^2+2</td>
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<tr>
<td>ALU Type</td>
<td>Floating Point</td>
<td>Fixed Point</td>
</tr>
</tbody>
</table>

From the optimized architecture shown in figure 2, the number of multipliers and adders are minimized as compared with the actual GHM filter design. Apart from reduction in multipliers and adders, it is also found that the throughput and latency of the optimized design is also improved. The arithmetic unit designed works on fixed point number system and thus introduces loss when compared with floating point number system.

As the literature referred does not report on FPGA implementation of DMWT architecture for OFDM, in this work a generic DMWT architecture is modeled based on references and is synthesized. The results obtained are considered as reference design for DMWT architecture on FPGA. The proposed DMWT model based on novel architecture using GMH filters are synthesized using the same FPGA and the results are compared with the reference design. The comparison results are reported in Table II.

### Table II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DMWT</th>
<th>Modified DMWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Elements</td>
<td>3902</td>
<td>2985</td>
</tr>
<tr>
<td>No of Slices</td>
<td>2695</td>
<td>1996</td>
</tr>
<tr>
<td>Clock Speed</td>
<td>301 MHz</td>
<td>340 MHz</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>51mW</td>
<td>24mW</td>
</tr>
</tbody>
</table>

The proposed DMWT architecture operates at a maximum frequency of 340MHz and consumes power of 24mW. The power consumption is reduced by adopting various low power techniques as recommended for FPGA implementation. The OFDM model along with the IDMWT and DMWT can be further realized on FPGA and can be configured for reconfigurability.

### V. CONCLUSION

In this work, BER performance DMWT based OFDM is designed and modeled. From the software simulation results it is found that the DMWT model achieves better BER (10^{-3}), as compared with DWT (10^{-1}), FFT (10^{-0}) at 10dB SNR. The FPGA implementation of GHM based multiwavelet filters operate at 340MHz frequency and consumes power of less than 24mW. The developed OFDM model can be reconfigured with respect to various modulation schemes.

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### REFERENCES

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