AN EFFICIENT RADIX-2² FFT FOR FIXED & MOBILE WIMAX COMMUNICATION SYSTEMS

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ABSTRACT

The objective of our work is proposing a new Radix-2² Algorithm and its utilization in OFDM based communication system. The modified OFDM communication system has been implemented and the Fixed WiMAX and Mobile WiMAX systems are redesigned for better results. The design has been done in Agilent’s Advanced Design System (ADS) software.

Our proposed work is implemented with Verilog Hardware Description Language (VERILOG). The code is synthesized and targeted into Xilinx Spartan3 Field Programmable Gate Array (FPGA). This FFT module is used in OFDM communication system to improve its performance. The improved OFDM modules are then implemented in fixed and mobile WiMAX communication systems which utilize OFDMA technique for their communication. The advantages, performance, and timing of the communication modules after implementation of the proposed technique are then discussed towards the end, giving a scope for the manufacturing of efficient WiMAX communication modules. A comparison is also made for the implementation of the fixed and mobile WiMAX, with the proposed architecture and that of the Radix ⁴ architecture. The comparison clearly indicates that the WiMAX with the proposed architecture is efficient than the other implementations of its kind.

KEYWORDS: FFT, FPGA, Fixed WiMAX, OFDM, OFDMA, Mobile WiMAX, Radix ²²

I. INTRODUCTION

WiMAX – which stands for Worldwide Interoperability for Microwave Access – is bringing the wireless and Internet revolutions to portable devices across the globe. Just as broadcast television in the 1940’s and 1950’s changed the world of entertainment, advertising, and our social fabric, WiMAX is poised to broadcast the Internet throughout the world, and the changes in our lives will be dramatic. WiMAX is providing the
capabilities of the Internet, without any wires, to every living room, portable computer, phone, and handheld device. The WiMAX modules utilize the OFDMA scheme in their physical layer of communication [1].

OFDM exploits the frequency diversity of the multipath mobile broadband channel by coding and interleaving the information across the subcarriers prior to transmission. After organizing the time and frequency resources in an OFDMA system into resource blocks for allocation to the individual mobile stations, the coded and interleaved information bits of a specific mobile station are modulated onto the subcarriers of its resource blocks [2]. Then OFDM modulation is cost effectively realized by the Inverse Fast Fourier Transform (IFFT) that enables the use of a large number of subcarriers—up to 1024 according to the Mobile WiMAX system profiles—to be accommodated within each OFDMA symbol [3]. Prior to transmission, each OFDMA symbol is extended by its cyclic prefix followed by digital-to-analog (D/A) conversion at the transmitter. At the receiver end, after analog-to-digital (A/D) conversion, the cyclic prefix is discarded and OFDM demodulation is applied through the FFT [4].

The FFT algorithm eliminates the redundant calculation which is needed in computing discrete Fourier transform (DFT) and is thus very suitable for efficient hardware implementation [5]. A high level implementation of a high performance FFT for OFDM modulator and demodulator is presented in this work. The design has been coded in Verilog and targeted into Xilinx Spartan3 field programmable gate arrays. Radix-2^2 algorithm [6] is proposed and used for the OFDM communication system. The design of the FFT is implemented and applied to fixed WiMAX – IEEE 802.16d and mobile WiMAX – IEEE 802.16e communication standards. The results are tabulated and the hardware parameters are compared. The improved OFDM modules is implemented in fixed and mobile WiMAX communication systems which utilize OFDMA technique for their communication, with advantages in terms of performance, and timing of the communication modules [7].

II. RADIX 2^2 DECIMATION IN FREQUENCY FFT ALGORITHM

A useful state-of-the-art review of hardware architectures for FFTs was given by He et al. [8] and different approaches were put into functional blocks with unified terminology. From the definition of DFT of size N [9]:

\[ X(k) = \sum_{n=0}^{N-1} x(n)W_N^{nk}, 0 \leq k < N \]  

Where \( W_N \) denotes the primitive \( N \)th root of unity, with its exponent evaluated modulo \( N \), \( x(n) \) is the input sequence and \( X(k) \) is the DFT. He [8] applied a 3-dimensional linear index map,

\[ n = \left\lfloor \frac{N}{2} n_1 + \frac{N}{4} n_2 + n_3 \right\rfloor \, \text{mod} \, N \]

\[ k = \left\lfloor k_1 + 2k_2 + 4k_3 \right\rfloor \, \text{mod} \, N \]

And Common factor algorithm (CFA) to derive a set of 4 DFTs of length N/4 as,
$$X(k_1 + 2k_2 + 4k_3) = \sum_{n=0}^{N-1} H(k_1,k_2,n_3)W_N^{m_n(k_1+2k_2)}W_N^{n_3} \quad \ldots \ldots \ldots \ldots (3)$$

where $n_1,n_2,n_3$ are the index terms of the input sample $n$ and $k_1,k_2,k_3$ are the index terms of the output sample $k$ and where $H(k_1,k_2,k_3)$ is expressed in eqn (4).

$$H(k_1,k_2,n_3) = \left[ x(n_3) + (-1)^{k_1}x\left(n_3 + \frac{N}{2}\right) \right] + \left( -j \right)^{(k_2+2k_3)}\left[ x\left(n_3 + \frac{N}{4}\right) + \left( -1 \right)^{k_1}x\left(n_3 + \frac{3N}{4}\right) \right] \ldots (4)$$

Eqn (4) represents the first two stages of butterflies with only trivial multiplications in the SFG, as BFI and BFII. Full multipliers are required after the two butterflies in order to compute the product of the decomposed twiddle factor $W_N^{m_n(k_1+2k_2)}$ in eqn (3). Note the order of the twiddle factors is different from that of radix-4 algorithm [10].

Applying this CFA procedure recursively to the remaining DFTs of length $N/4$ in eqn (3), the complete radix-2$^2$ Decimation-in-frequency (DIF FFT) algorithm is obtained. The corresponding FFT flow graph for $N=16$ is shown in Fig. 1 where small diamonds represent trivial multiplication by $W_N^{N/4} = -j$, which involves only real-imaginary swapping and sign inversion [11].

![Figure 1. Radix-2$^2$ DIF FFT flow graph for $N=16$](image)

III. IMPLEMENTATION OF PROPOSED FFT IN OFDM

The fundamental principle of the OFDM system is to decompose the high rate data stream (bandwidth=$W$) into $N$ lower rate data streams and then to transmit them simultaneously over a large number of subcarriers [12]. The IFFT and the FFT are used for modulating and demodulating the data constellations on the orthogonal subcarriers respectively [13].

In an OFDM system, the transmitter and receiver blocks contain FFT modules as shown in Fig. 2 (a) and (b). The FFT processor must finish the transform within 312.5 ns to serve the purpose in the OFDM system.
Orthogonal Frequency-Division Multiple Access (OFDMA) is a multi-user version of the popular Orthogonal frequency-division multiplexing (OFDM) digital modulation scheme. Multiple accesses is achieved in OFDMA by assigning subsets of subcarriers to individual users as shown in Fig. 3. This allows simultaneous low data rate transmission from several users [14].

The power consumption is measured by the number of times of data transition. The data transition times are proportional to the SRAM access times [15]. Here we assume that the adders and multipliers are active at each clock cycle because of the pipelining architecture. The more the SRAM access times are, the higher the power consumption is.
Fig. 4 shows the SRAM access times versus $N$ points FFT. The SRAM access times are linear to the number of the recursive iterations in FFT as described in equation (5). The SRAM is accessed twice each clock cycle, so equation (5) is multiplied by 2. It shows that the proposed design has less memory access than the radix-4 FFT by 20% to 40%. Therefore, the proposed architecture consumes much lower power.

$$\text{SRAM access times} = N \times \text{(iteration times)} \times 2$$

(5)

With fixed clock frequency, the processing OFDM symbol rate decreases as the FFT point $N$ increases [16].

IV. DESIGN IN AGILENT’S ADVANCED DESIGN SYSTEM

After years of development and uncertainty, a standards-based interoperable solution is emerging for wireless broadband. A broad industry consortium, the Worldwide Interoperability for Microwave Access (WiMAX) Forum has begun certifying broadband wireless products for interoperability and compliance with a standard. WiMAX is based on wireless metropolitan area networking (WMAN) standards developed by the IEEE 802.16 group and adopted by both IEEE and the ETSI HIPERMAN group [17].

The IEEE 802.16 group subsequently produced 802.16a, an amendment to the standard, to include NLOS applications in the 2GHz–11GHz band, using an orthogonal frequency division multiplexing (OFDM)-based physical layer. Additions to the MAC layer, such as support for orthogonal frequency division multiple access (OFDMA), were also included. Further revisions resulted in a new standard in 2004, called IEEE 802.16-2004, which replaced all prior versions and formed the basis for the first WiMAX solution. These early WiMAX solutions based on IEEE 802.16-2004 targeted fixed applications, and we will refer to these as fixed WiMAX. In December 2005, the IEEE group completed and approved IEEE 802.16e-2005, an amendment to the IEEE 802.16-2004 standard that added mobility support. The IEEE 802.16e-2005 forms the basis for the WiMAX solution for nomadic and mobile applications and is often referred to as mobile WiMAX [18].
IV.1. DESIGN OF WIMAX 802.16 D TX USING ADS

The proposed OFDM based Fixed WiMAX communication system is designed in Agilent’s Advanced Design System [19]. Fully-coded signal generation Test_WMAN_CodedSignals shows how to build OFDM frame structure for the WMAN frequency division duplex downlink (FDD DL) system in ADS as shown in Fig. 5. Main components in the subsystem level include long preamble generation, frame control header (FCH) and FDD DL data generation, OFDM modulation, multiplexing, RF modulation, and measurements. Signals are fully coded by RS-CC encode based on the 16d standard.

Test_WMAN_CodedSignals is for testing fully coded WMAN 802.16d transmission systems. This signal source is designed according to the specification of IEEE Standard 802.16d 2003 version D2. The test signal generated by using WMAN 802.16d coded Signal Source sends to a device under test (DUT). The output signal from DUT will be measured.

The measurements provided include:
1) RF Signal Spectrum
2) Power and Complementary Cumulative Distribution Function (CCDF)

To understand WMAN FDD DL signal generation, basic components for constructing sub-systems will be described, then sub-system components such as preamble generation, FCH channel, data generation, OFDM modulation, multiplexing, and measurements for WMAN systems will be described.

1) Data Modulation: After bit interleaving, data bits in both FCH and DL data channels are entered serially to the constellation mapper. Gray-mapping is needed for data modulation and the constellations are specified in Section 8.3.3.4 in 802.16d. In the WMAN examples, Mapper (Numeric Advanced Comm library) provides Gray-mapped QPSK, 16QAM and 64QAM modulations.

2) Pilot Modulation: Pilot subcarriers are inserted into each data burst in order to constitute the symbol and these are modulated according to their carrier location within the OFDM symbol. A PRBS generator will be used to produce a sequence. The polynomial for the PRBS generator is \(X^{11} + X^9 + 1\).

The pilot modulation value for OFDM symbol k is derived from \(w_k\). On the downlink, index k represents the symbol index relative to the beginning of the downlink subframe; on the uplink, index k represents the symbol index relative to the beginning of the burst.

3) Signal Sources: IEEE 802.16d FDD DL signal sources are provided in the example workspace. Based on the 16d Standard, a WMAN 16d downlink PHY PDU is defined (see OFDM Frame Structure with FDD DL) that starts with a long preamble for PHY synchronization. The preamble is followed by a frame control header (FCH) burst. The FCH burst is one OFDM symbol long and is transmitted using QPSK rate 1/2 with the mandatory coding scheme.

The FCH is followed by one or multiple downlink bursts, each transmitted with different burst profiles. Each downlink burst consists of an integer number of OFDM symbols, and its burst profiles are specified by a 4-bit DIUC in the DL-MAP. DIUC encoding is defined in the DCD messages.
4) Preambles: All preambles are structured as either one of two OFDM symbols as specified in IEEE 802.16d. The first preamble in the downlink PHY PDU (as well as the initial ranging preamble) consists of two consecutive OFDM symbols (the combination of the two OFDM symbols is referred to as the long preamble). The first OFDM symbol uses only subcarriers indices that are a multiple of 4. As a result, the time domain waveform of the first symbol consists of 4 repetitions of 64-sample fragment, preceded by a cyclic prefix (CP). The second OFDM symbol uses only even subcarriers, resulting in a time domain structure with 2 repetitions of a 128-sample fragment, preceded by a CP. The time domain structure is illustrated below. Long Preamble Generation shows generation of the long preamble for a WMAN FDD downlink transmitter.

5) OFDM Modulation: The WMAN physical layer is based on OFDM modulation. An OFDM symbol is made up of subcarriers, the number of which determines the FFT size as illustrated in OFDM Symbol. WMAN subcarriers types include:

- Data subcarriers for data transmission.
- Pilot subcarriers for various estimation purposes.
- Null subcarriers (no transmission at all) for guard band and DC subcarrier.

The guard band (illustrated in OFDM Symbol Time Structure) enables the signal to naturally decay and create FFT brick wall shaping.

6) Measurements: Measurements are provided for waveforms, spectrum, power, and time. The Power CCDF measurement for Fixed WiMAX with Radix-4 FFT is shown in Fig. 6. The same measurement with the modified FFT is shown in Fig. 7. Timed Sink models are directly used to display waveforms for preamble, FCH, medium access control data, and whole framed signals. Signal power is measured in the region that does not include signal idle. Fig. 8 & 9 show the simulation timing for Fixed WiMAX with Radix-4 FFT and modified FFT respectively.
Figure 6. Power measurements for 802.16d Fixed WiMAX for N=256

<table>
<thead>
<tr>
<th>MeanPower_dBm</th>
<th>PeakPower_dBm</th>
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<tbody>
<tr>
<td>6.116</td>
<td>14.333</td>
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</tbody>
</table>

Figure 7. Power measurements for 802.16d Fixed WiMAX with modified FFT for N=256

<table>
<thead>
<tr>
<th>MeanPower_dBm</th>
<th>PeakPower_dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.124</td>
<td>12.648</td>
</tr>
</tbody>
</table>
Figure 8. Simulation Time for Fixed Wimax 802.16d design with Radix-4 FFT for N=256

Figure 9. Simulation Time for Fixed Wimax 802.16d design with proposed FFT for N=256
IV.2. DESIGN OF WIMAX 802.16E TX USING ADS

The proposed OFDM based Mobile WiMAX communication system is designed in Agilent’s Advanced Design System [19]. WMAN_OFDMA_DL_FDD_Tx Waveform shows WMAN OFDMA FDD downlink measurement results with CCDF, waveform and spectrum. The schematic is shown below in Fig. 10.

The Power CCDF measurement for Mobile WiMAX with Radix-4 FFT is shown in Fig. 11. The same measurement with the modified FFT is shown in Fig. 12. One complete downlink FDD RF source consists of two WMAN_M_DL_Src_FDD_RF. One WMAN_M_DL_Src_FDD_RF is assigned to the first DL subframe (DL1) by setting ActiveDLSubframe = DL1; the other is assigned to the second DL subframe (DL2) by setting ActiveDLSubframe = DL2.

Fig. 13 & 14 show the simulation timing for Mobile WiMAX with Radix-4 FFT and Modified FFT respectively. The following illustration shows the measurement results.
Figure 11. Power measurements for 802.16e Mobile WiMAX for N=256

Figure 12. Power measurements for 802.16e Mobile WiMAX with modified FFT for N=256
IV.3. COMPARISONS

The FIXED WiMAX 802.16d and MOBILE WiMAX 802.16e were implemented in ADS for different values of N. The power measurements and the timing measurements are tabulated in the previous chapter for N=256. A random signal was applied to the design of FIXED WiMAX as well as MOBILE WiMAX design. Initially the design is implemented and synthesized with Radix-4 FFT, after that the design is modified with proposed FFT.

The power measurements, as shown above in the previous section, also show a considerable decrease in the total power consumption of the system, which shows the system efficiency increases for the modified FFT.

The timing measurements have shown a noticeable decrease which in turn will help in increasing the efficiency of the overall system in terms of time taken for processing a complete signal.
The spectrum measurements have also been shown in the previous section which does not show much difference. This indicates that the performance of the system in terms of other factors (except the power and timing) does not get affected by the modification done in the system. This clearly indicates that, with the modified OFDMA, the system increases its speed and decreases its power consumption, keeping the other constraints unvaried.

Table 1 and Fig. 15 below tabulate the timing measurements for both the conventional Radix-4 FFT, as well as the proposed FFT for Fixed WiMAX. Table 2 and Fig. 16 show the same for Mobile WiMAX. The graphs clearly indicate that the timing measurement almost double for higher values of N.

Table 1. Design Timing Comparison For Fixed Wimax

<table>
<thead>
<tr>
<th></th>
<th>N=256</th>
<th>N=512</th>
<th>N=1024</th>
<th>N=2048</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radix-4 FFT</td>
<td>5.24</td>
<td>5.91</td>
<td>9.18</td>
<td>15.96</td>
</tr>
<tr>
<td>Proposed FFT</td>
<td>3.24</td>
<td>4.18</td>
<td>5.9</td>
<td>9.39</td>
</tr>
</tbody>
</table>

Figure 15. Fixed WiMAX ADS Design Synthesis Timing Comparisons (in Secs)

Table 2. Design Timing Comparison for Mobile Wimax

<table>
<thead>
<tr>
<th></th>
<th>N=256</th>
<th>N=512</th>
<th>N=1024</th>
<th>N=2048</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radix-4 FFT</td>
<td>18.59</td>
<td>31.83</td>
<td>58.84</td>
<td>113.37</td>
</tr>
<tr>
<td>Proposed FFT</td>
<td>14.76</td>
<td>24.46</td>
<td>43.68</td>
<td>81.46</td>
</tr>
</tbody>
</table>

Figure 16. Mobile WiMAX ADS Design Synthesis Timing Comparisons (in Secs)
V. CONCLUSION

Both Fixed and Mobile WiMAX communication systems have been designed using the proposed FFT in Agilent’s Advanced Design Systems software. The accurate power and timing measurements have been made for various values of N. The results have been tabulated and compared for the same design using Radix-4 FFT and for proposed FFT. The observations clearly indicate that the communication system with proposed FFT is almost two times faster for higher values of N. Also, there is a considerable change in the overall power consumption of the system. Since the system design in AGILENT’s ADS is presented, the outcome of this thesis can be directly used for manufacturing the prototype.

The outcome of this work has several potential applications in the field of communication systems. This efficient OFDM communication module, after its physical implementation, can be effectively utilized in the manufacturing of the Fixed and Mobile WiMAX communication systems as discussed in this work. Further, the implementation can also be extended to any other communication standards that use OFDM technique in the architecture. Apart from implementation into the OFDM communication module, the proposed Radix $2^2$ algorithm can be implemented in other communication modules that utilize FFT, and increase their efficiency to a great extent.

REFERENCES


