Abstract— In this paper, we show the measurement results of frequency offset (FO) estimation in Digital Video Broadcasting for Cable version 2 (DVB-C2) receiver which uses orthogonal frequency-division multiplexing (OFDM). Because FO causes inter-carrier interference (ICI) in a multicarrier system, it should be estimated and compensated to improve the performance of a multicarrier receiver. FO can be divided into fractional frequency offset (FFO) and integer frequency offset (IFO) if FO is normalized to subcarrier spacing. The implemented FO estimator consists of FFO and IFO estimator. FFO estimator uses cyclic prefix (CP) in time domain and is implemented using coordinate rotation digital computer (CORDIC) algorithm. IFO estimator uses the correlation with unique synchronization sequence (USS) of preamble in frequency domain. First, we simulate the mean square error (MSE) of FO compensation algorithm w.r.t additive white Gaussian noise (AWGN) channel with computer simulation. Next, we implement FO estimator using in field programmable gate arrays (FPGAs). The implemented FO estimator has the resolution of 1 Hz approximately from measurement results of it.

Keywords— Frequency offset, CORDIC, unique synchronization sequence, FPGA

I. INTRODUCTION

FO is caused by an oscillator of transceiver and dependent on the accuracy of an oscillator. In single carrier system, received QAM symbols are rotated due to FO. However, in multicarrier system such as DVB-C2 using OFDM, FO causes ICI among subcarriers and degrades the performance of a receiver [1]. Because FO of multicarrier system is more serious than single carrier system, it is preferable for FO estimator to have a fine resolution.

When FO is normalized to subcarrier spacing in multicarrier system, it consists of IFO and FFO. FFO estimator using CP in time domain can extract only the FFO of FO. Thus, IFO is estimated in frequency domain using USS after FFT.

We simulate the MSE of the FO estimation algorithm under AWGN with computer simulation and implement it with FPGAs. In addition, we measure the implemented FO estimator.

II. FOC

First, we introduce the implemented of OFDM system. Next, we explain the algorithm and simulated MSE of FO estimation. Last, we show the results of hardware measurement.

A. OFDM System

Figure 1 shows the OFDM system we implement.
made of FFO estimator and IFO estimator. $\epsilon$ is normalized FO, $\epsilon_f$ is FFO and $\epsilon_i$ is IFO.

Table 1 shows the system parameters for 6MHz channel bandwidth [2], [3].

<table>
<thead>
<tr>
<th>TABLE 1. SYSTEM PARAMETERS OF OFDM TRANSMITTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of total subcarriers per OFDM symbol, $N$</td>
</tr>
<tr>
<td>Number of used subcarriers per OFDM symbol, $N_{\text{used}}$</td>
</tr>
<tr>
<td>Number of CP, $L$</td>
</tr>
<tr>
<td>Number of pilot subcarriers per OFDM symbol in preamble, $N_{\text{PRP}}$</td>
</tr>
<tr>
<td>Subcarrier spacing, $\Delta f$</td>
</tr>
<tr>
<td>DAC and ADC bit resolution</td>
</tr>
<tr>
<td>IFFT/FFT period, $T_{\text{FFT}}$</td>
</tr>
<tr>
<td>Sampling frequency, $f_s$</td>
</tr>
<tr>
<td>Tx IF frequency, $f_{\text{TX}}$</td>
</tr>
<tr>
<td>DDC IF frequency, $f_c$</td>
</tr>
</tbody>
</table>

B. DDC

Figure 2 shows the block diagram of DDC which consists of NCO, low pass filter (LPF) and Decimator.

![Figure 2. The block diagram of DDC](image)

As shown in Figure 2, from ADC to decimator, they operate at eight times the sampling frequency. The 3dB frequency of LPF is 3.42MHz. The signal spectrum after ADC is shown in Figure 3.

![Figure 3. The spectrum after ADC](image)

As shown in Figure 3, the image of ADC input spectrum, indicated by dotted line, for downconversion of input signal is used. In other words, $\sin(2\pi f_c t)$ is used instead of $-\sin(2\pi f_c t)$ shown in Figure 2. The factor of decimator is 8.

C. Estimation of FFO and IFO

FO can be normalized to $\Delta f$ and is expressed as equation (1).

$$\frac{\text{FO}}{\Delta f} = \epsilon = \epsilon_f + \epsilon_i$$  \hspace{1cm} (1)

where $\epsilon$ is normalized FO, $\epsilon_f$ is FFO and $\epsilon_i$ is IFO.

Figure 4 shows FFO estimator [4], [5], [6], [7], [8], [9], [10].

![Figure 4. FFO estimator](image)

The estimation of $\epsilon_f$ in Figure 4 can be expressed as equation (2) and estimated in time domain using CP of OFDM symbol.

$$y(n) = x(n) e^{\frac{j2\pi \epsilon n}{N}} + z(n),$$

$$c(n) = y^*(n)y(n - N)$$

$$= x^*(n)x(n - N) e^{\frac{j2\pi \epsilon n}{N}} e^{\frac{j2\pi \epsilon (n-N)}{N}} + z^*(n)$$

$$v(n) = e^{-j2\pi \epsilon} \sum_{n=0}^{L-1} |x(n)|^2 + z^*(n)$$

$$= Ae^{-j2\pi \epsilon} + \text{noise}$$

$$-2\pi \epsilon = \tan^{-1}\left(\frac{\text{Imag}(v)}{\text{Real}(v)}\right) < \pm \pi \to |\epsilon| < 0.5$$

where $x(n)$ is IFFT output, $z(n)$ and $z^*(n)$ are noise.

As shown in equation (2), the estimation of FO using CP can extract only the FFO ($\epsilon_f$) of FO ($\epsilon$) and is affected with CP length.

The function of $\tan^{-1}(\ )$ is implemented by CORDIC algorithm shown in Figure 5.
As shown in Figure 5, PH_LUT is a phase lookup table and generated in as equation (3).

\[ PH_{LUT}[X] = \tan^{-1}(2^{-X}) \text{ radian} \quad X = 0, 1, \ldots, N \quad (3) \]

where \( N \) is the iteration number.

As \( N \) increases, the error of estimated phase (\( p \)) decreases. The red dotted line shown in Figure 5 is a basic cell. If \( N \) increases, the basic cell is added.

Figure 6 shows the estimated phase error when input (\( v \)) have a value of between \( e^{-j\pi} \) and \( e^{j\pi} \) and \( N \) is 16.

As shown in Figure 6, the estimated phase error is very small. IFO (\( \epsilon_i \)) of FO (\( \epsilon \)) is estimated in frequency domain after FFT and IFO estimator is shown in Figure 7 [3].

\[ MSE = \frac{1}{M} \sum \left| \epsilon_{given} - \epsilon_{estimated} \right|^2 \quad (5) \]

where \( M \) is the number of simulation iteration, \( \epsilon_{given} \) is given frequency offset and \( \epsilon_{estimated} \) is the estimated frequency offset.

Figure 10 shows the MSEs under AWGN.
As CP length and $E_b/N_0$ increase, the MSEs decrease monotonically.

### III. Measurement Results

Figure 9 shows the spectrum of ADC input whose center frequency is 44 MHz and channel power is -14.43 dBm/6 MHz.

![Figure 9. The spectrum of ADC input](image)

Figure 10 shows the spectrum of DDC output and DDC+LPF output when the IF center frequency ($f_c$) of DDC is 10.85 MHz.

![Figure 10. The spectrum of DDC and DDC+LPF output](image)

As shown in Figure 10, the spectral line corresponds to the IF center frequency of DDC and is removed by LPF. The estimated FO (nco_phi) from FFO and IFO estimator is shown in Figure 11.

![Figure 11. The measurement of the estimated FO when IF center frequency is 10.85 MHz](image)

Table 2 lists several IF center frequency.

<table>
<thead>
<tr>
<th>IF center frequency</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$ + ($\Delta f$ x 1) + ($\Delta f$ x 0.286875) = 10.85 MHz + 2.1568 kHz</td>
<td></td>
</tr>
<tr>
<td>$f_c$ + ($\Delta f$ x 2) + ($\Delta f$ x 0.286875) = 10.85 MHz + 3.8308 kHz</td>
<td></td>
</tr>
<tr>
<td>$f_c$ + ($\Delta f$ x 3) + ($\Delta f$ x 0.286875) = 10.85 MHz + 5.5022 kHz</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12 shows the measurement results for three IF center frequency.

![Figure 12. The measured FO (a) when IF center frequency is 10.85 MHz + 2.1568 kHz (b) Estimated FO when IF center frequency is 10.85 MHz + 3.8308 kHz (c) when IF center frequency is 10.85 MHz + 5.5022 kHz](image)

As shown in Figure 12, Table 3 summarizes the measured FO with respect to various IF center frequency.

<table>
<thead>
<tr>
<th>IF center frequency</th>
<th>FO polarity</th>
<th>Measured FO</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.85 MHz + 2.1568 kHz</td>
<td>positive</td>
<td>2.1586 kHz</td>
</tr>
<tr>
<td>10.85 MHz + 3.8308 kHz</td>
<td>negative</td>
<td>1.1539x10^-3 kHz</td>
</tr>
<tr>
<td>10.85 MHz + 5.5022 kHz</td>
<td>negative</td>
<td>(3.348+1.0385x10^-3) kHz</td>
</tr>
</tbody>
</table>

As shown in Table 3, the implemented FO estimator has 1 Hz frequency resolution approximately.

### IV. Conclusion
We implement FO estimator which consists of FFO and IFO estimator. The FFO estimator uses CP in time domain and the CORDIC algorithm is used. The IFO estimator uses the correlation with USS in frequency domain. The implemented FO estimator has 1 Hz resolution approximately from measurement results.

ACKNOWLEDGMENT
This work was supported by the Broadcast and Telecommunications R&D program. [10-921-02-001, Development of Next-Generation Digital Cable Transmission Technology].

REFERENCES

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