Measurement Results of Frequency Offset in DVB-C2 Receiver

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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.

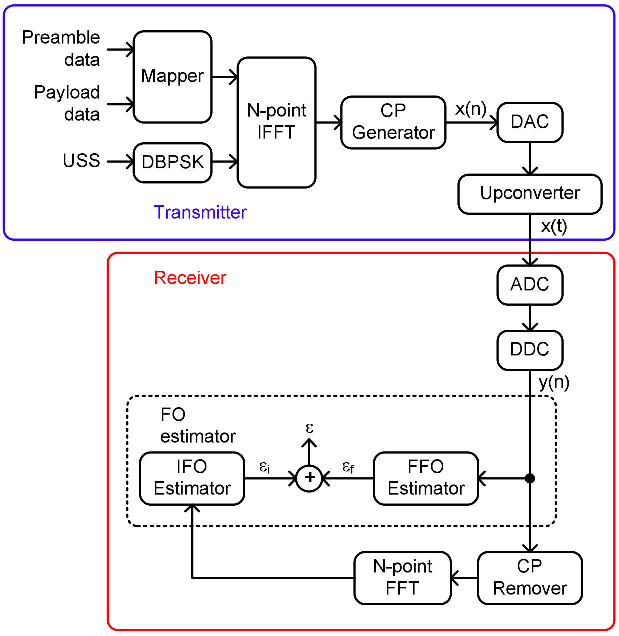


Figure 1. The block diagram of the implemented OFDM tranceiver

As shown in Figure 1, the transmitter in OFDM system consists of mapper, IFFT, CP generator, digital-to-analog converter (DAC) and upconverter. Mapper converts preamble and payload data into various QAM symbols by. USS is generated by two pseudo random binary sequences (PRBS) and is mapped by differential binary phase shift keying (DPBSK) for preamble pilot symbols. Preamble pilot symbols can be used for channel compensation and inserted for every 6 subcarriers [2], [3].

CP generator copies the last L samples of IFFT output and appends them to it. Upconverter modulates a baseband signal to 44 MHz intermediate frequency (IF).

The receiver shown in Figure 1 consists of analog-to-digital converter (ADC), DDC, FOC, CP remover and FFT. DDC demodulates IF signal to baseband signal digitally. FOC is made of FFO estimator and IFO estimator. ϵ is normalized FO, ϵ_f is FFO and ϵ_i is IFO

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

TABLE 1. SYSTEM PARAMETERS OF OFDM TRANSMITTER

Number of total subcarriers per OFDM symbol, N	4096
Number of used subcarriers per OFDM symbol, N_{USED}	3409
Number of CP, L	64 samples
Number of pilot subcarriers per OFDM symbol in preamble, N_{PRP}	569
Subcarrier spacing, Δf	1.674 kHz
DAC and ADC bit resolution	16 bits
IFFT/FFT period, T_{FFT}	593.7 µs
Sampling frequency, f_s	6.85 MHz
Tx IF frequency, f_{c_tx}	44 MHz
DDC IF frequency, f_c	10.85 MHz

B. DDC

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

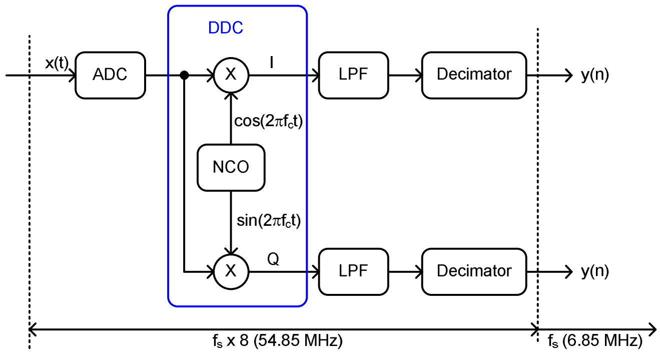


Figure 2. The block diagram of DDC

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.

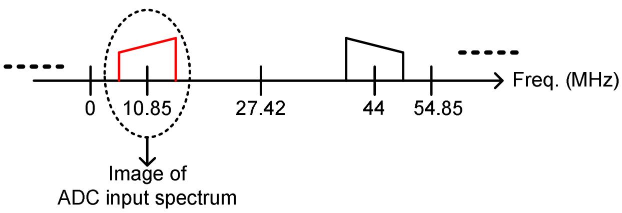


Figure 3. The spectrum after ADC

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 Δf and is expressed as equation (1).

$$\frac{FO}{\Delta f} = \varepsilon = \epsilon_f + \epsilon_i \quad (1)$$

where ϵ is normalized FO, ϵ_f is FFO and ϵ_i is IFO.

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

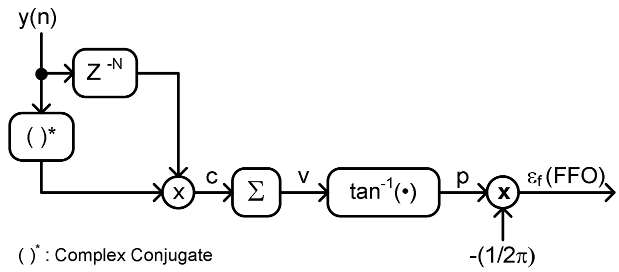


Figure 4. FFO estiamtor

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

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

$$\begin{aligned} c(n) &= y^*(n)y(n-N) \\ &= x^*(n)x(n-N)e^{\frac{-j2\pi\epsilon n}{N}}e^{\frac{j2\pi\epsilon(n-N)}{N}} + z'(n) \\ &= |x(n)|^2 e^{-j2\pi\epsilon} + z'(n) \end{aligned}$$

$$\begin{aligned} v(n) &= e^{-j2\pi\epsilon}\left(\frac{1}{L}\right)\sum_{n=0}^{L-1}|x(n)|^2 + z'(n) \quad (2) \\ &= Ae^{-j2\pi\epsilon} + noise \end{aligned}$$

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

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 (ϵ_f) of FO (ϵ) and is affected with CP length.

The function of $\tan^{-1}(\ )$ is implemented by CORDIC algorithm shown in Figure 5.

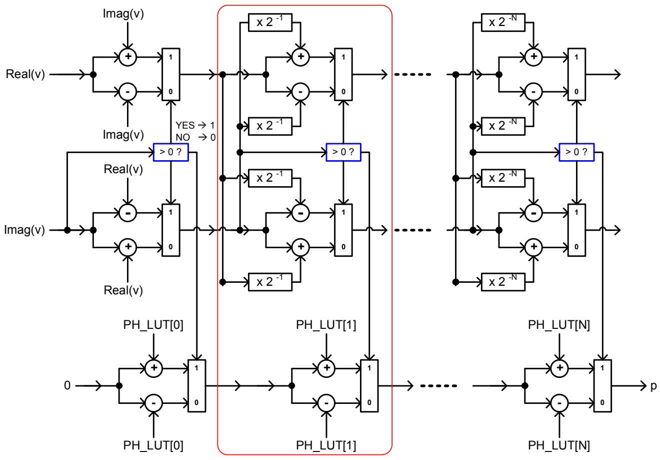


Figure 5. Implemented $\tan^{-1}(\,)$ function

As shown in Figure 5, PH_LUT is a phase lookup table and generated in as equation (3).

$$PH\_LUT[X] = \tan^{-1}(2^{-X})\,radian \quad X = 0, 1, \dots, \mathrm{N} \qquad (3)$$

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.

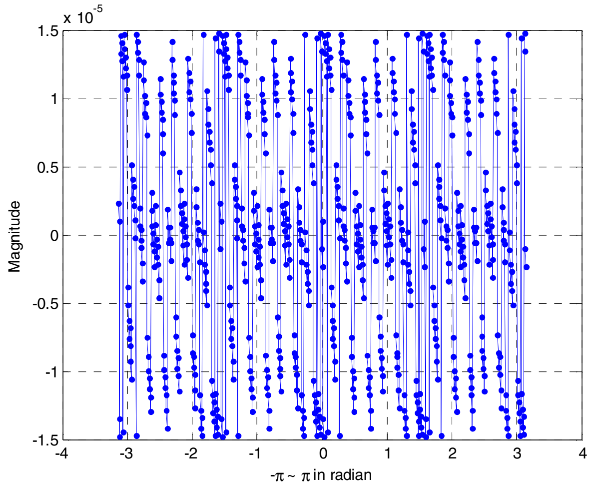


Figure 6. Estimated phase error when N is 16

As shown in Figure 6, the estimated phase error is very small.

IFO (ϵ_i) of FO (ϵ) is estimated in frequency domain after FFT and IFO estimator is shown in Figure 7 [3].

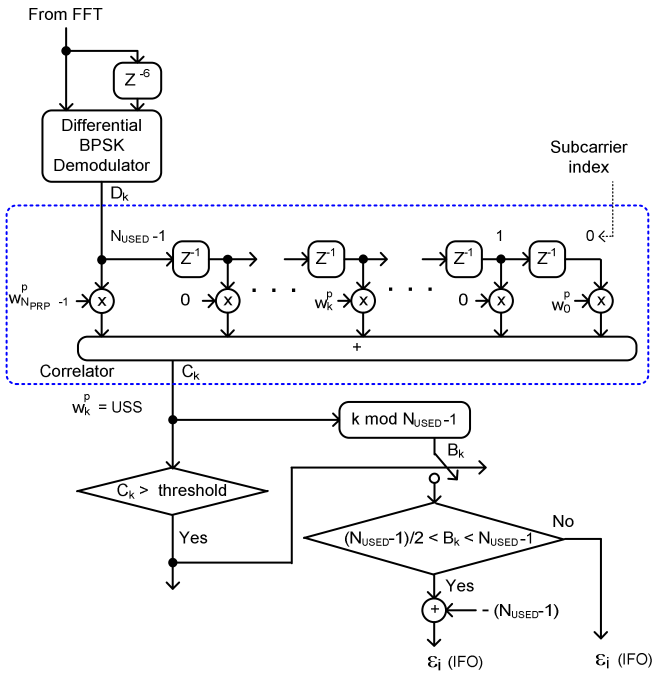


Figure 7. IFO estimator

As shown in Figure 7, k is the subcarrier index and IFO (ϵ_i) is estimated using USS and a correlator.

We simulate to evaluate the MSE of FO estimation under AWGN which can be expressed as equation (5).

$$MSE = \frac{\sum_M \left|\epsilon_{given} - \epsilon_{estimated}\right|^2}{M} \qquad (5)$$

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

Figure 10 shows the MSEs under AWGN.

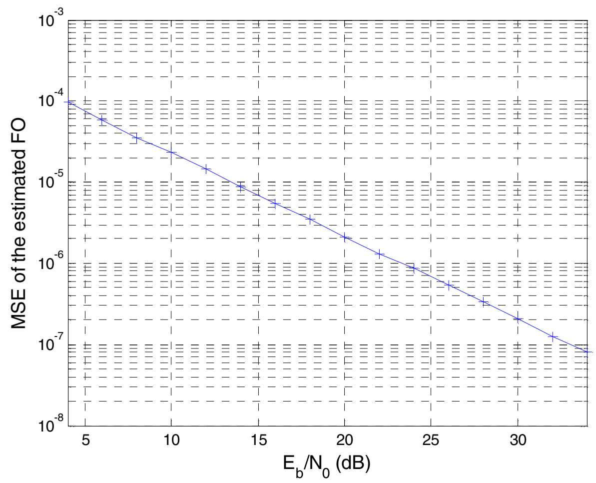


Figure 8. MSE of the estimated FO under AWGN when FO is 2.0925 kHz

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/6MHz.

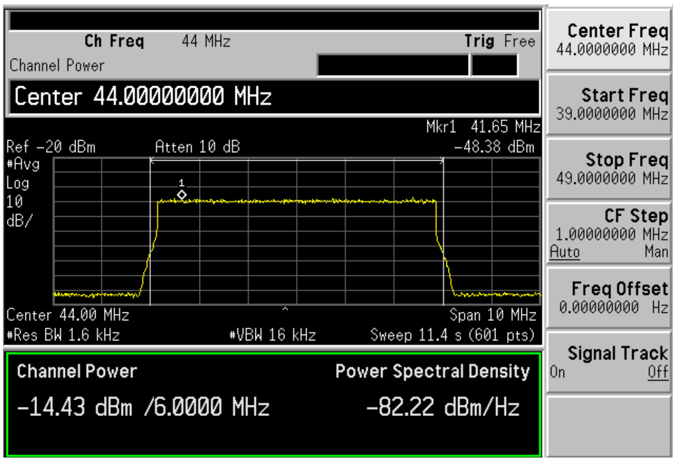


Figure 9. The spectrum of ADC input

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.

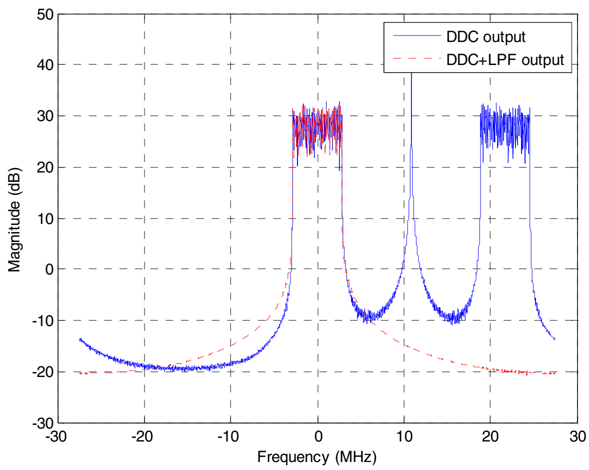


Figure 10. The spectrum of DDC and DDC+LPF output

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.

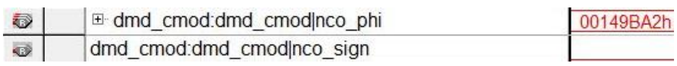


Figure 11. The measurement of the estimated FO when IF center frequency is 10.85 MHz

If the nco_sign is 0, it means positive FO. Otherwise, it represents negative FO. The nco_phi is eight-digit hexadecimal and the first three digit of it is the normalized IFO and the other 5 digit of it is the normalized FFO.

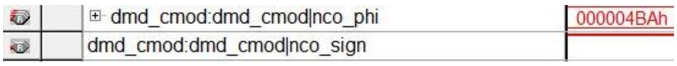
IFO has the bit resolution of [12,12,u] and the first 12 means the number of the total bits, and the second 12 expresses the number of the integer bits, and u represents unsigned number. Because the IFO is 001, the floating value of it is 1. FFO has the bit resolution of [20,0,u]. Because the FFO is 49BA2, the floating value of it is 0.286875. Therefore, the un-normalized FO is 2.1568 kHz (Δf x 1 + Δf x 0.286875).

To test FO estimation, we change the IF center frequency intentionally listed in Table 2.

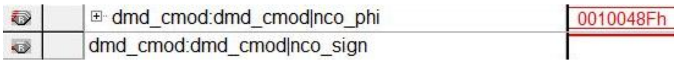
TABLE 2. Several IF center freqeuncy

IF center frequency	Value
f_c	10.85 MHz + (Δf x 1) + (Δf x 0.286875) = 10.85 MHz + 2.1568 kHz
f_c	10.85 MHz + (Δf x 2) + (Δf x 0.286875) = 10.85 MHz + 3.8308 kHz
f_c	10.85 MHz + (Δf x 3) + (Δf x 0.286875) = 10.85 MHz + 5.5022 kHz

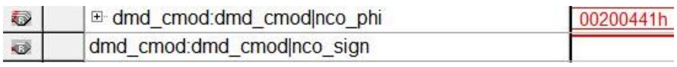
Figure 12 shows the measurement results for three IF center frequency.



(a)



(b)



(c)

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

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

TABLE 3. IF freqeuncy

IF center frequency	FO polarity	Measured FO
10.85MHz	positive	2.1586 kHz
10.85MHz+2.1568kHz	negative	$1.1539\text{x}10^{-3}$ kHz
10.85MHz+3.8308kHz	negative	$(1.674+1.1129\text{x}10^{-3})$ kHz
10.85MHz+5.5022kHz	negative	$(3.348+1.0385\text{x}10^{-3})$ kHz

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 correlaiton with USS in frequency domain. The implemented FO estimator has 1 Hz resolution approximately from measurement results.

ACKNOWLEDGMENT

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