Efficient Arctangent Processor Design for the Frequency Offset Estimation of IEEE 802.11 Wireless LAN System

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Abstract : - This paper presents a hardware design of an arctangent processor for the OFDM-based wireless LAN system. The arctangent processor is required in most OFDM-based communication system to estimate the frequency offset. The proposed arctangent processor does not require the division value of imaginary/real for the input argument, and uses these two values, respectively, to look up the tangent ROM table. We reduce the tangent look-up table size to one eighth of 2π rad using the imaginary and real component exchange method for memory size and operation speed. Consequently, the designed arctangent process for wireless LAN system takes seven clocks to evaluate an arctangent value and has the resolution of 2π/512 rad. The maximum absolute error of this arctangent hardware is 5.75e-3 rad (0.33°) comparing to mathematical result.

Key words: - arctangent, WLAN, OFDM, frequency offset

1 Introduction

Orthogonal frequency-division multiplexing (OFDM) is an effective modulation technique to mitigate the inter-symbol interference (ISI) caused by multi-path propagation[1]. It has been adopted for high-bit rate wireless local area networks (WLANs) standards such as IEEE802.11a [2] due to its high data rate transmission and its robustness to multi-path propagation channels.

However, there are also few disadvantages in OFDM system such as large Peak to Average Power Ratio (PAPR) and its serious degradation of performance caused by imperfect synchronization. Time synchronization is to find the best sampling time instant for the start of receive OFDM frame. Frequency synchronization is performed with finding an estimate of the difference in the frequencies between the transmitter and receiver local oscillators.

The frequency offset estimate, especially, is critical since any frequency offset causes a loss of inter-subcarrier orthogonality which results in inter-carrier interference (ICI) [3]. The frequency offset compensation is performed by adjusting the local oscillator's frequency with the information of the frequency offset estimated. The receiver, therefore, is required to estimate frequency offset accurately within a permissible range described in a standard of wireless LAN system, and needs an arctangent calculation which convert the vector of a two-dimensional space to the amount of rotated phase value.

Numerous algorithms are available to implement the arctangent function, such as Taylor series expansion based algorithm, iterative method using coordinated rotation digital computer (CORDIC), look-up table method, and interpolation approximation method. This paper contains our propose design of arctangent processor which can be applied to the IEEE 802.11 OFDM-base wireless LAN system [4].

We used the tangent look-up table (not arctangent) method which is convince for implementing and does not need a divided value of imaginary and real input argument. This modified look-up table operation is to search the index of table, which means the phase value, or resultant of arctangent. This tangent table size is one eighth of 2π full phase range so that the required memory and searching cycles can be reduced

In Section II we introduce the way of frequency offset measurement and compensation for OFDM symbol structure in the wireless LAN system. Section III covers the design of arctangent processor for this system and performance of the arctangent function. In Section IV, the results of implementation are described in terms of simulation waveforms and usage of resources of FPGA. Finally, conclusion is drawn in Section V.

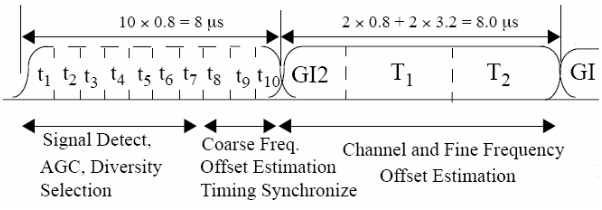

Fig. 1. PLCP preamble structure

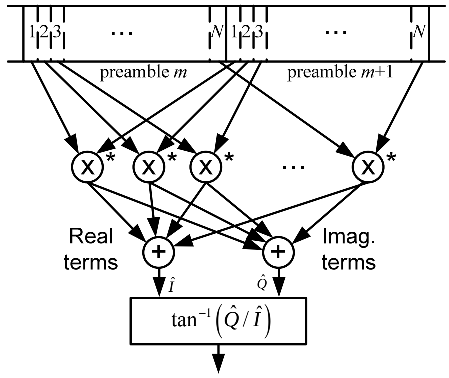

Fig. 2. Frequency offset estimation.

2 OFDM-WLAN Frequency Offset Correction

The 802.11a standard defines the preamble as shown in Fig. 1. Every frame has the preamble. The preamble consists of ten identical short training symbols (t1,t2,…,t10) and two identical long training symbols (T1, T2). Each short and long training symbol consists of 16 and 64 samples, respectively [1]. In addition, the GI field represents a guard interval for the long symbol. It is a replicated filed consisting of the last 32 samples of the long symbol. The frequency offset compensation is accomplished sequentially by coarse and fine frequency compensation. Coarse frequency compensation is performed in the short preamble period, and fine frequency compensation is accomplished in the long preamble period of PLCP preamble field as showed in Fig.1.

2.1 Frequency Offset Estimation

The frequency offset estimation is performed by the measuring the phase rotation in the Euclidian two dimensional space between two complex vectors which are separated in specific time interval. The frequency offset $\Delta\theta$, therefore, is expressed in equation (1).

$$\Delta\theta = \frac{1}{N}\tan^{-1}\left(\frac{\sum_{n=0}^{N}\mathrm{Im}\left\{r_n \cdot r_{n+N}^*\right\}}{\sum_{n=0}^{N}\mathrm{Re}\left\{r_n \cdot r_{n+N}^*\right\}}\right) \qquad (1)$$

where r_n is the received signal and n is the sample index. Im{} and Re{} represent imaginary and real component, respectively. Fig. 2 gives a pictorial view of the operation of (1). N is 16 in the case of coarse frequency estimation and 64 in the case of fine frequency estimation.

Since the short preamble symbol time duration is 0.8μs, it allows frequency estimation up to 1/(0.8μsx2) = ±625kHz. Similarly, long preamble symbol duration of 3.2μs allows estimation up to ±156.25 kHz. Assuming RF frequency is 5.8GHz, the tolerable frequency offset Coarse frequency offset is 0.5x625k/5.8GHz = ±53.8ppm which is larger than ±20ppm specified in IEEE 802.11a standard.

2.2 Frequency Offset Compensation

Frequency offset compensation is to correct the frequency error by adjusting the receiver's local oscillator using the resultant value of frequency offset estimation. Fig. 3 shows an example of frequency compensation system which has VTCXO (voltage controlled oscillator) as local oscillator. Accumulator performs not only low pass filtering of the offset through the average but also conversion this offset value to proper level for input of PDM(pulse density modulation) signal generator. This offset level is converted to the PDM signal by PDM generator, and then PDM signal becomes the voltage level by low pass filter such as analog RC filter. Finally, generated frequency of the local oscillator is tuned in to proper frequency by the voltage level.

3 Arctangent Processor Design

We know that arctangent calculation is required to perform frequency synchronization from previous chapter. It is matter of course that the more accurate arctangent evaluation is better, but we need an efficient arctangent processor which holds the accuracy required by the system considering the hardware resources.

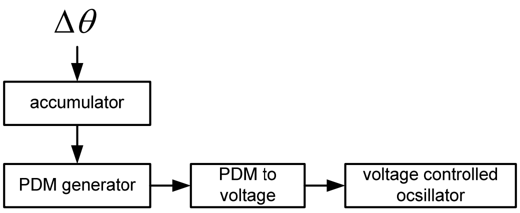

Fig. 3. Frequency offset compensation.

The look-up table based arctangent processor has parameters which should be considered. These parameters affect the complexity and accuracy of the processor.

1. Resolution for the phase from 0 to 2π. This is the depth of the look-up table.
2. Bit-width of the look-up table entry

In order to decide these two parameters related to the arctangent resolution, the accuracy required by the wireless LAN system should be considered. Most OFDM communication system including the wireless LAN request 1% of subcarrier spacing as the tolerable frequency error [5]. Constellation EVM is 2.5% if the frequency offset is 1% of the subcarrier spacing in wireless LAN system for reference.

The subcarrier spacing Δf of wireless LAN system is 312.5 kHz and it's 1% is about 3 kHz. The arctangent processor, therefore, is required to recognize the phase rotation caused by 3 kHz minimum frequency offset. Then, what is the depth of the tangent look-up table for the resolution of phase rotation caused by 3kHz frequency offset? It depends on the measurable maximum frequency offset by the frequency offset estimator. The possible estimated maximum frequency error is ±625 kHz (= 1.25 MHz) which is the range of coarse frequency offset estimator's output. 1.25 MHz divided by 3 kHz makes 417. Hence we can decide that the depth of the tangent look-up table should be larger than 417. Finally, we select the smallest number of the power of two larger than 417, that is, 512. Considering the only octant phase, the actual depth of tangent look-up table is 64, which contains the tangent value of 0 to π/4.

Second parameter is the problem of selecting bit-width of this tangent table. The bit-width should be the smallest number of bits for bit-vector which can represent the values of tan(0) to tan(π/4) without overlapping. This means that all binary vectors, tangent value, should be different from each other. The resultant bit-width is the seven. Consequently, we have the 7x64 tangent look-up table covering from 0 to π/4 radian for frequency estimator of wireless LAN system. For example, 50th entry's value of this table is the nearest integer of 2^7x tan(π/4x50/64). The value of *n*th entry of the table *LUT*(*n*) can be express as follows:

$$LUT(n) = Round\left(2^7 \cdot \tan\left(\frac{\pi}{4}\frac{n}{64}\right)\right),\quad n = 0,\ldots,63 \tag{2}$$

where *Round*( ) is the rounding off operator.

Because the two input values of imaginary and real component, however, is not always positive and located in the first octant phase, the processor should force the input complex value, real and imageinary component, into the first octant phase by sign inversion and exchanging two components, e.g. the complex value -20+j100 in a third octant phase becoms 100+j20. Since arctangent value we want is the address of tangent look-up table, tangent LUT block search the best address which holds tan(*address*)x100 = 20 using the binary searching algorithm. In this case, the address θ_0 is 16 which stands for 11.25°(=16/512*360), and the phase recovery block (refer Fig. 4) makes output through the mapping

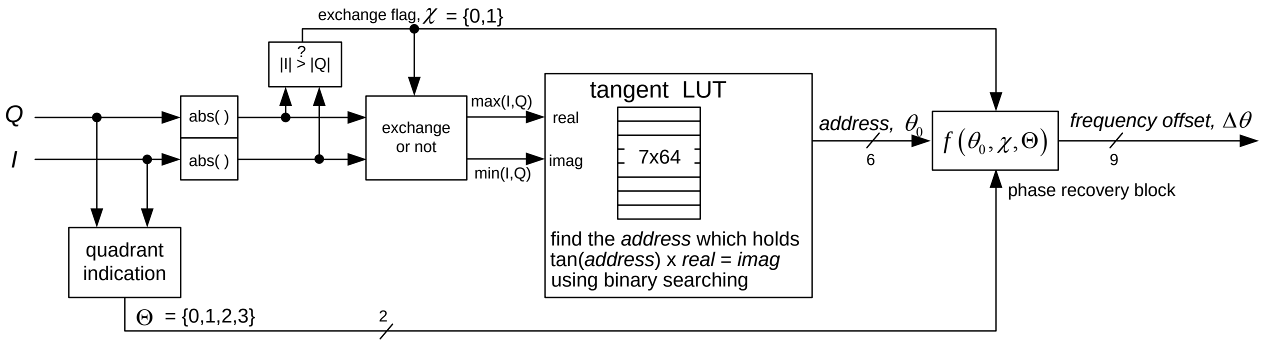

Fig. 4. Arctangne processor block diagram

function of $f(\theta_0, \chi, \Theta)$ which can be summarize as Table 1.

The last output, frequency offset, $\Delta\theta$ is 144, or 101.25° (=144/512 *360) which is differ from the mathematical result of arctan(-20/100) by 0.05°. Fig. 5 shows the absolute errors between the proposed arctangent processor output and mathematical calculation through the range from 0 to 1 of input argument. The maximum absolute error magnitude is 5.75e-3 rad or 0.33°, and RMSE (root mean square error) is 2.15e-3.

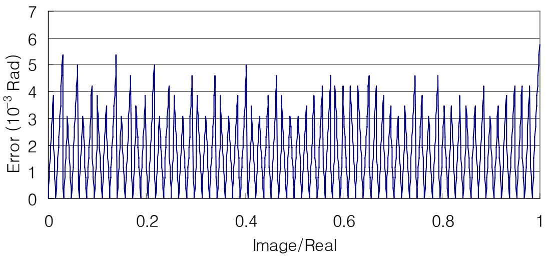

Fig. 5. Error of arctangent evaluation for WLAN system.

Table 1

The phase recover block mapping function, $f(\theta_0, \chi, \Theta)$

χ	Θ	$\Delta\theta$	Octant phase
0	0	θ_0	1st
1		128-θ_0	2nd
0	1	256-θ_0	4th
1		128+θ_0	3rd
0	2	-256+θ_0	5th
1		-128-θ_0	6th
0	3	-θ_0	8th
1		-128+θ_0	7th

4 Implementation on FPGA

Fig. 6 shows the waveform for evaluation of arctangent if the real component is 100 and imaginary component is -20. The exchange flag, signal 'chi', becomes high at the pulse of trigger signal 'ex_pulse', which means |real| is not larger than |imaginary|. The signal "quad_ind" becomes "1" at the same time, since the (-20,100) is located in the second quadrant phase. You can see that frequency offset, $\Delta\theta$, signal "atan_out" is the 144 as stated above.

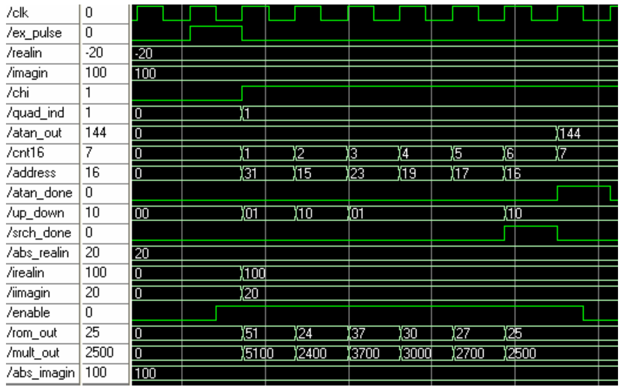

Fig. 6. Simulation wave form of the arctangent.

The design of register transfer level (RTL) model is described in VHDL. The RTL design is synthesis using the XST™ of and simulated using ModelSim™. The implementation of the synchronizer utilizes 150 slices, one block RAM(18kbits) for LUT ROM and one 18x18 multiplier of Xilinx Virtex2 (XC2V1000).

5 Conlcusion

We proposed the one of the arctangent design for wireless LAN system. It does not require the ratio of imaginary and real value as input argument because it uses the binary searching look-up table method. The size of look-up table is reduced by using the only octant phase. And a few parameters for the resolution and accuracy are determined by considering the specification required from the standard. This design method can be used for any other system which needs to evaluate the arctangent value.

Acknowledgements

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