FPGA Implementation of Carrier Frequency Offset Estimation in B3G MIMO OFDM System

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ABSTRACT
Frequency offset estimation algorithms based on time domain training sequence in MIMO-OFDM system were demonstrated. With a view to hardware implementation of frequency offset estimation algorithms in MIMO-OFDM system, the complexity of the algorithm implementation was analyzed. In order to make the frequency offset estimation algorithm in MIMO-OFDM system less complicated during FPGA implementation, a simplified implementation scheme was brought forth, and statistics on resource occupation of such a scheme in VirtexII-Pro series FPGA of Xilinx Company was given, while the scheme was verified on B3G TDD system hardware platform. Study shows the simplified implementation scheme is applicable in hardware implementation of B3G MIMO-OFDM system frequency offset estimation algorithm.

Categories and Subject Descriptors
B.5.1[HARDWARE]
REGISTER-TRANSFER-LEVEL
IMPLEMENTATION, Design

General Terms
Algorithms, Verification.

Keywords
frequency offset estimation, multi-input multi-output, orthogonal frequency division multiplexing, field programmable gate array

1. INTRODUCTION
Wireless communications systems are developing from 3G toward Beyond 3G[1] or 4G systems aiming to support high data rate services with higher spectrum efficiency and higher power efficiency than previous systems. A lot of technical innovations in physical layer are initiated to satisfy the challenging requirements. Being critical physical layer techniques in current wireless communications field, Orthogonal Frequency Division Multiplexing (OFDM) and Multi-Input Multi-Output (MIMO) have become important alternatives for B3G mobile communications system.

OFDM is a special multi-carrier modulation technique, in which is an effective transmission scheme to cope with many channel impairments, such as cochannel interference, severe multipath fading, and impulsive parasitic noise [2]. OFDM systems however are extremely sensitive to Carrier Frequency Offsets (CFO) and they can only tolerate offsets just to within a small fraction of the subcarrier spacing. Synchronization of frequency at the receiver must be performed very accurately, or there will be loss of orthogonality between the subsymbols, which will lead to inter carrier interference (ICI) and eventually a large degradation in system performance [3].

Frequency synchronization involves in estimating Carrier Frequency Offsets (CFO) and correcting it. The CFO may results from the differences in oscillator frequencies at the transmitter and the receiver or Doppler Effect. The algorithm of frequency synchronization is a critical one in MIMO-OFDM system and its accuracy will directly affect performance of the whole system. There have been several papers on the subject of frequency synchronization in recent years. Nogami and Nagashima[4] present algorithms to find the CFO using a null symbol where nothing is transmitted for one symbol period ,the CFO is found in the frequency domain after applying a Hannig window and taking the FFT. But this algorithm is only applicable to a continuous mode, since there would be no difference between the null symbol and the idle period between bursts in a burst mode. Classen introduces a method which jointly finds both the symbol timing and carrier frequency offset [5]. It is, however, very computationally complex because it uses a trial and error method where the carrier frequency is incremented in small steps over the entire acquisition range until the correct carrier frequency is found. JIANG Yan-xiang[6] proposed a ratio-adjustable time-frequency training sequence, and he obtains the course CFO estimation with the aid of the training sequence in frequency domain and the fine one
in the time domain, which is relatively more complex and difficult for hardware implementation. In general, there are three kinds of algorithms of CFO estimation in OFDM systems. One is based on CP, another one is based on time domain or frequency domain training sequences, and the third one is based on PN sequences.

Though many frequency synchronization algorithms have been proposed for OFDM systems, few are proposed for MIMO-OFDM system. In this paper, we introduced MIMO-OFDM system model in part II and analyzed a simple training sequence based CFO estimation algorithm that meets system requirements in part III, then we studied FPGA implementation of the given algorithm and give a useful or simplified implementation scheme of frequency synchronization in MIMO OFDM system.

2. \textbf{SYSTEM MODEL}

Assumed the number of transmit antennas is Q and the number of receive antennas is L, taking into consideration the effect of various transmission delay from different transmit antennas to different receive antennas, the MIMO-OFDM system model is shown in Figure 1.

![Fig. 1 MIMO-OFDM System Model](image)

Given length of IFFT N, CP is added before symbols through N points IFFT while the CP length G should be longer than the maximum time delay spread of channel to avoid Inter Symbol Interference (ISI); then the digital signal is transformed to analog signal via D/A device, to RF signal via up-converter and sent out; received samples are transformed to digital baseband signal via down converter and A/D device. Time synchronization and frequency synchronization is done on each transmit/receive antenna pairs in digital domain, and then CP is removed from synchronized signal before N points FFT[7].

3. \textbf{ALGORITHMS ANALYSIS}

Synchronization technique of MIMO-OFDM system consists of timing synchronization and carrier frequency synchronization. There also have been several algorithms about time synchronization in recent years, as in reference [6] and [8]. In the following frequency synchronization algorithm in MIMO-OFDM system, receiver first needs to know the starting moment of the received OFDM symbols, then estimate the carrier frequency offset between the transmitter and the receiver, compensate carrier frequency offset and finally conduct FFT. The error introduced by time synchronization to OFDM symbol may result in FFT window displacement and ISI. The error introduced by frequency offset may result in the carrier waveform distorting and ICI, hence prevent receiver from correct data processing.

Both time synchronization and frequency synchronization of MIMO-OFDM system can be complemented by using training sequences, which can be transmitted in the synchronization time slot of the OFDM frame. We only introduce a simple frequency synchronization algorithm and focus on its hardware implementation. The CFO estimation is made out in the downlink, the training sequences of the downlink can be simultaneously used for time and frequency synchronization, which are economical in data transmission. Frequency synchronization involves in estimating the CFO value and using the CFO value to adjust the frequency of the oscillator of the receiver. Frequency offset estimation includes coarse frequency offset estimation and fine frequency offset estimation. The downlink synchronization time slot includes three OFDM symbols, as shown in Figure 2, the first one, consists of two identical N/2 points GOLD code after IFFT is used to do the coarse frequency offset estimation. The last two are used to do fine frequency offset estimation which consists of two identical N points GOLD code after IFFT. On the assumption that the timing synchronization has already been done, the position of the training sequences was known, and then the frequency offset can be estimated using the phase of the complex correlation between the two consecutive received training symbols.
Fig. 2 training sequences for CFO estimation in OFDM frame structure

Assumed the received consecutive training sequences is \( r(n) \) and \( r(n + N_d) \), the estimated frequency offset is given by

\[
\Delta f = f - f = \frac{\text{arg}(R_i) NA_f}{2\pi N_d}
\]

(1)

\[
R_i = \sum_{n=0}^{L} r(n) r^*(n + N_d)
\]

(2)

Where \( N \) is the number of subcarriers, \( \Delta F = \frac{1}{(NT_s)} \) is the subcarrier spacing, \( T_s \) is the sampling interval, \( L \) is the number of points participating in the correlation, \( N_d \) is the distance between the two repeat training sequence which is \( \frac{N}{2} \) in the coarse frequency offset and \( N \) in the fine frequency offset. The estimation range is given by

\[
|\Delta f| \leq \frac{N \Delta F}{N_d} \frac{2}{2}
\]

(3)

Therefore the range of the coarse estimation is the subcarrier spacing and the range of the fine estimation is half the subcarrier spacing but more accurate, since the longer the correlation sequences is, the more accurate the estimation will be, according to Schmidl. \(^6\) So this simple frequency synchronization algorithm is applicable to systems whose frequency offset is within the subcarrier spacing. For systems whose frequency offset is larger than subcarrier spacing, we can refer to Hsieh\(^7\), who introduced a larger range frequency estimation algorithm and his estimation range is as large as ± 200 times of the subcarrier spacing however much more complex.

Refer to Figure 3 for curve of frequency synchronization mean square error (MSE) probability in 4-transmitting and 8-receiving MIMO system of the above frequency synchronization algorithm based on time domain training sequence. Here \( N = 1024, T_s = 50\text{ns}, N_d = 512 \) in coarse frequency synchronization and \( N_d = 1024 \) in fine frequency synchronization. There are 3 curves in Figure 3, the square one represents MSE of the system without any frequency offset, the round one represents MSE of the system with frequency offset but without frequency offset estimation and correction, and the triangle one represents MSE of the system with the given frequency offset estimation algorithm, which shows when the frequency offset has not been estimated and corrected, the system performance descend distinctly, Floor Effect appears when MSE probability reach \( 5 \times 10^{-4} \), the given CFO estimation algorithm can effectively reduce the CFO’s influence to the system performance, and can make the MSE probability curve very near to that of system without any frequency offset, the \( E_b / N_0 \) loss is less than \( 1\text{dB} \) when the error probability is \( 10^{-6} \).

4. IMPLEMENTATION

4.1 Implementation of Single CFO Estimation Module

Structure diagram in Figure 4 shows implementing the above frequency offset estimation algorithm with FPGA. Design of the correlating process and the calculating of
the angle of the correlation result process are the most critical parts in hardware implementation, which will greatly affect implementation complexity and synchronization performance.

Suppose the timing synchronization has been done and the start moment of the OFDM frame has been obtained, in which some timing errors can be tolerant due to the existence of CP, then the training sequences were extracted from the received data which has been through buffers and then to the multiple to do correlation. Once the correlation result was obtained, the angle of the complex correlation result can be calculated. Then it was multiplied by some already known coefficients, according to equation (1). Finally, the multiple results were transmitted to the receiver to adjust the oscillator.

The correlation process is relative simple since it can be completed by using 4 multiple cores which are already designed in FPGA.

It is a difficult and complex step to calculate the angle of the correlation result directly since there is no core or function calculating a complex’s angle in FPGA. Here we bring forth a simple method of using a typical lookuptable to calculate the angle of the complex correlation result. It equals to implementing a contrary tangential function in FPGA. Firstly, the function output is stored in a block ram, whose range is \([-\pi, \pi]\), then the input address of this block ram is obtained by dividing the correlation result value’s image part Q by the real part I, and finally the output angle will be got uniquely according to the input address. The above step is not only save time and also save resource since it only costs one clock period and just needs one block ram. Finally, the estimated angle is transformed to frequency offset which is then transmitted to adjust the oscillator of the receiver.

The above method can also be used to calculate the quotient of Q/I since the divide core of FPGA is time consuming. Firstly, the reciprocals of some real numbers are stored in another block ram which can also be thought as a lookuptable, the range of these real numbers is fixed which relates to the range of the real part of the correlation result \(I\), the input address of the block ram is the real number \(I\), every input address \(I\) was mapped to one output number uniquely, then through looking up in the table the reciprocal of \(I\) is obtained. Finally, \(Q*(1/I)\) is got by multiple Q with the reciprocal of I. This step needs one block ram and one multiple core and costs just several time periods. So the above lookuptable scheme can save time and resources fatherly.

### 4.2 Complexity analysis

In single CFO estimation module, for the course frequency offset estimation, we need to do complex correlation between two N/2 points training sequences, so every frame there are N/2 times complex multiplication and (N/2)-1 times complex addition, and last 1 time calculating of the angle of the correlation result; For the fine frequency offset estimation, we need to do complex correlation between two N points training sequences, so every frame there are N times complex multiplication and N-1 times complex addition, and last 1 time calculating of the angle of the correlation result.

By using the above lookuptable scheme, the time of once calculating of the angle occupy only several time periods, and hence much time can be saved, so the CFO estimation can be made out faster and eventually the system performance can be improved.

In MIMO system, if synchronization module is required for each transmit/receive antenna pair and take into consideration effect on Y users in the system, \(Q \times L \times Y\) modules is a minimum at base station receiving part, which is difficult to achieve. Therefore simplified implementation of time synchronization should be considered in MIMO system.

### 4.3 Simplified Implementation Scheme for Frequency Synchronization of MIMO-OFDM System

In most MIMO-OFDM systems, the distances between different transmit antennas or different receive antennas are relatively small and the difference of frequency offset between different transmit/receive antenna pairs is small or the difference is only in the fine estimation, so the L receive antennas can share one course estimation module. Therefore the implementation of frequency synchronization in MIMO-OFDM system can be much
simpler. As shown in Figure 5, only receive antenna 1 calculates the Y users’ coarse frequency offsets estimation and the other antennas share the result and only need to do their different fine estimation, so Y coarse frequency offset estimation modules and L fine frequency offset estimation modules are sufficient to implement frequency synchronization of MIMO-OFDM system.

![Fig. 5 Simplified Scheme for Implementation of Frequency Synchronization in MIMO System](image)

5. RESOURCES UTILIZATION AND EXPERIMENTAL VERIFICATION

Xilinx Company, inventor of FPGA, is among the largest programmable devices suppliers in the world. Its Virtex-II Pro series FPGA is large-capacity and high-performance FPGA chip based on SRAM with capacities ranging from 100,000 gates to 10,000,000 gates.

Tests prove that frequency synchronization of 2-user, 4×8 MIMO-OFDM system can be achieved in Virtex-II Pro series FPGA chip XC2VP50 adopting the abovementioned simplified scheme. The design uses 5704 Slice, accounting for 24.16% of the total and 80 Block RAM, 34.48% of the total and the clock frequency can reach 100MHz.

Refer to the function simulation result using ISE modsim in figure 6, given the actual frequency offset is 500Hz, the estimation result of the above mentioned implementation scheme is 496Hz. It means that the estimation error is within 1% which is tolerant in the real system. The error must exist since the lookuptable is not absolutely accurate which depends on the width of the block ram, and there also must be some hardware errors in hardware implementation.

![Fig. 6 FPGA Implementation Result of CFO Estimation](image)

I. CONCLUSION

Being the alternatives for B3G mobile communications system, MIMO-OFDM technique has gained more and more attention. As numbers of antennas and users gradually increase, frequency synchronization becomes more and more important and implementing of frequency synchronization becomes more and more complex. This paper brings forward a simplified algorithm and implementation scheme to frequency synchronization in MIMO-OFDM system with small inter-antenna distances, which are realizable and applicable to most MIMO-OFDM systems.

REFERENCES


