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다중 입출력 직교 주파수 분할 다중화 시스템에서의 반송파 주파수 오프셋 추정을 위한 새로운 기법

A New Techniques for Estimation of Carrier Frequency Offset in MIMO OFDM Systems

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Abstract - Multiple input, multiple output orthogonal frequency division multiplexing (MIMO OFDM) systems are the candidate for the future wireless communications. However, the main drawback of MIMO OFDM systems is their sensitivity to carrier frequency offset (CFO) similar to the single input, single output OFDM (SISO OFDM) systems. The demodulation of a signal with CFO causes large bit error rate and degrade the performance of a symbol synchronizer. It is important to estimate the frequency offset and minimize or eliminate its impact. In this paper, we propose a technique based on observation training symbols for estimating CFO by employing block-by-block estimation for SISO OFDM systems. The technique of SISO OFDM is extended to the MIMO OFDM systems. Simulation results show that the proposed techniques have a superior performance and better accuracy compared to the conventional techniques in the sense of mean square error.

Key Words : Multiple input, Multiple output orthogonal frequency division multiplexing (MIMO OFDM), Single input, Single output OFDM (SISO OFDM), Carrier frequency offset (CFO)

1. Introduction

One of the principal advantages of orthogonal frequency division multiplexing(OFDM) system is its robust against multi-path channel which can cause inter-symbol interference (ISI) and inter-carrier interference(ICI). The main disadvantages of OFDM systems is sensitivity against carrier frequency offset (CFO), which causes inter-carrier interference. The sensitivity of the OFDM to the CFO in single carrier systems is a critical issue[1]. The CFO is defined as the difference between the nominal frequency and actual output frequency. In OFDM, the uncertainty in carrier frequency due to a difference in the frequencies of the local oscillators in the transmitter and receiver gives rise to a shift in the frequency domain.

This shift is also referred as frequency offset. It can also be caused due to Doppler shift in the channel. The demodulation of a signal with offset in the carrier frequency can cause large bit error rate and may degrade the performance of a symbol synchronizer. Therefore, it is important to estimate the frequency offset and minimize or eliminate its impact[2].

Several techniques were proposed to estimate the carrier frequency offset in time domain and frequency domain. Moose[3] proposed a technique for maximum likelihood estimate of frequency offset using the discrete Fourier transform(DFT) values of a repeated data symbol. In this technique, the accuracy required of frequency offset correction depends on how much residual offset can be tolerated. The acquisition range of the technique is the intercarrier spacing of the repeated symbol. Schmidl and Cox[4] proposed the frequency and timing synchronization algorithm by using repeated data symbols. The range of CFO estimation is ±1. Beek, Sandell and Borjesson [5] proposed the joint maximum likelihood estimator of time and frequency offset in OFDM systems. The estimation uses the redundant information contained within the cyclic prefix. Zhou et al.[6] presented two maximum likelihood CFO estimation schemes, one in frequency domain and another in time domain, both under Doppler fading. Classen and Meyr [7] introduced a technique to find both the symbol timing and carrier frequency offset. Pilot tones can be inserted in the frequency domain and transmitted

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in every OFDM symbol for the carrier frequency offset tracking. After estimating carrier frequency offset from pilot tones in the frequency domain, the signal is compensated with the estimated carrier frequency offset in the time domain.

The increase in data rates comes with the increase in the capacity of the systems. In the very general, the mobile or wireless communication systems transmit information bits information in the radio space to the receiver[8]. The multiple input, multiple output(MIMO) system is an attractive technique to achieve this goal compared to the single input, single output(SISO) system, especially in the rich scattering environment .The MIMO system uses multiple antennas at the transmitter and receiver, and the spatial diversity is obtained by spatially separated antennas.

The combination of these two powerful techniques, MIMO and OFDM, is the candidate for the future wireless communications, which can provide higher transmission data rate and better transmission quality for wireless communications, However, similar to the SISO OFDM, the main disadvantages of MIMO OFDM is its sensitivity to carrier frequency offset. The presence of CFO introduces severe ICI, which, if not properly compensated, would result in loss of orthogonality and significantly degrade the system performance.

In this paper, we propose a technique based on observation training symbols to estimate the CFO in OFDM system. The training symbols are grouped into two consecutive blocks, where each block has a length of $S/2$ and block-by-block estimation is used. The technique of SISO OFDM is extended to the MIMO OFDM systems. To demonstrate the efficiency of the proposed technique, we compare it with other existing techniques in terms of the mean square error(MSE) and estimation range.

2. The Conventional Techniques

In the OFDM transmission scheme, the data stream is split into N subcarriers and transformed to an OFDM signal by inverse discrete Fourier transform(IDFT). Then, the received signal detected on the kth subcarrier of the lth transmitted OFDM symbol in the frequency domain, with a small CFO, the output of DFT is equal to

$$R_l(k) = X_l(k) H_l(k) e^{j2\pi \epsilon l N_p / N} + L_l(k) + W_l(k) \tag{1}$$

where $X_l(k)$ are the OFDM symbols during the lth period, and N_p denotes the length of the observation training symbol. $W_l(k)$ is the additive white Gaussian noise(AWGN) and ϵ is the normalize carrier frequency offset. N is the number of the subcarriers, $H_l(k)$ is the channel frequency response, and $L_l(k)$ is the ICI generated by frequency error. For simplicity, in the following derivations we neglect the ICI term since its power is very small compared with the additive noise power.

It is known that when the CFO is relatively small or the noise is very large, the differences of the rotated phases between two adjacent symbols are very small. This may result in poor estimations or in some cases give estimations of the opposite sign. If we compare the phase rotation of the current symbol with the next$S$ symbol that delays S, the effects of noise can be reduced to some extent. It is a simple way to increase the accuracy of the S symbol estimation, which can be done with a differential estimator by comparing two OFDM received symbols, $R_l(k)$and $R_{l+s-1}(k)$ [9].

$$\Psi(k) = R_l^*(k) R_{l+s-1}(k) \tag{2}$$

For 2×2 MIMO OFDM system employing N_t transmit and N_r receive antennas, data symbols are distributed to N_t data streams with N subcarriers. At the receiver side, rth receive antenna detected on the kth subcarriers on the lth transmitted OFDM symbol in the frequency domain. The received signal with the effect of the CFO is given below [9],[10], where r = 1, 2.

$$R_{l,m}(k) = \sum_{m=1}^{2} X_{l,m}(k) H_{l,r,m}(k) e^{j2\pi \epsilon l N_p / N} + L_{l,r}(k) + W_{l,r}(k) \tag{3}$$

N_p is the number of guard interval, ϵ is normalized CFO, m is the number of transmit antenna, r is the number of receive antenna, $H_{l,r,m}(k)$ is channel frequency response from transmit antenna to receive antenna, $L_{l,r}(k)$ is ICI generated by frequency error and $W_{l,r}(k)$ is zero-mean complex Gaussian noise. The frequency synchronization has to correct for the frequency offset, which is caused by the difference in oscillator frequencies at the transmitter and the receiver.

A simple extension of the Moose's algorithm for MIMO was proposed in [9]. Here, it is assumed that all transmit and receive branches of one MIMO transmitter and receiver use the same oscillator, which is a valid assumption if the different transmit and receive branches are co-located. The estimation of frequency offset becomes the phase of the summation of the complex correlations of the training symbols originating from the different transmitters. The maximum estimated frequency offset is limited, since the angle that can be estimated without phase ambiguity is limited to $\theta_{\max} = \pm\pi$. This relates to a maximum frequency offset of $|\Delta f_{\max}| = \frac{|\theta_{\max}| f_s}{2\pi N_c} = f_s/2N_C$, which equals half the subcarrier spacing. A larger range can be achieved by using training symbols that are repetitive with some shorter period[11].

3. The Proposed Techniques

3.1 SISO OFDM Systems

In our proposed technique, instead of comparing the current symbol with the next symbol [10], we use a block of observation symbols. These are grouped into two consecutive blocks, where each block has a length of $S/2$. The observation training symbols are added sequentially so that the summed results are correlated as represented in the following expression.

$$\Psi(k) = \sum_{n=1}^{S/2} R_n^*(k) \sum_{m=S/2}^{S} R_m(k) \tag{4}$$

When we assumed the channel is to be idle over several symbols, the $\Psi(k)$ is then derived as in Eq. (5).

$$\Psi(k) = |X_l(k)|^2 \sum_{m=S/2}^{S} \sum_{n=1}^{S/2} e^{j(n-m)2\pi\epsilon N_p/N} + \widehat{W}(k) \tag{5}$$

Therefore,

$$\Psi(k) = |X_l(k)|^2 \frac{\sin\left(\frac{2\pi N_p(S-S/2)}{2N}\right)\sin\left(-\frac{2\pi N_p S}{2\times 2N}\right)}{\sin\left(\frac{2\pi\epsilon N_p}{2N}\right)\sin\left(-\frac{2\pi N_p}{2N}\right)} e^{j2\pi S\epsilon N_p/2N} + \widehat{W}(k) \tag{6}$$

Since ϵ is small, and $E[\widehat{W}(k)] = 0$, then

$$\arg\{E[\Psi(k)]\} = \frac{2\pi\epsilon S N_p}{2N} \tag{7}$$

where $E[\widehat{W}(k)]$ is the mean of $\Psi(k)$. However, in our work $N_p = N$,

$$\arg\{E[\Psi(k)]\} = \pi\epsilon S \tag{8}$$

Therefore, $\hat{\epsilon}$ which is an estimate of ϵ is derived by finding the argument of the summation of $\Psi(k)$ over all possible training symbols in the OFDM system.

$$\hat{\epsilon} = \frac{1}{\pi S}\arg\left\{\sum_{k=0}^{N-1}\Psi(k)\right\} \tag{9}$$

We compared the simulation results of the proposed estimation technique to the conventional techniques. In the simulation tests, the MSE is selected to be the performance metric. The AWGN is also considered when evaluating the simulation. The MSE refers to the average error within an OFDM block. The block size OFDM system parameters are chosen based on the IEEE 802.11a standard as follows: $N = 64$, $N_g = 16$, where N_g is the number of guard interval samples. The simulation tests are carried out at a different signal to noise ratio (SNR). The plots of Fig. 1 represent the first series of simulation signals with CFO that was sent over a communication channel with an AWGN. From simulation results, it could be seen that at the small CFO ($\epsilon = 0.02$), the MSE of our proposed technique estimator has superior performance compared to the conventional techniques. Between the proposed technique estimator and the conventional

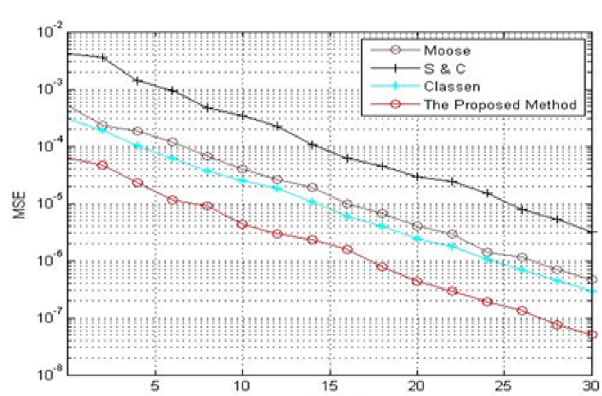

Fig. 1 MSE of CFO estimation in AWGN ($S=4$, CFO=0.02).

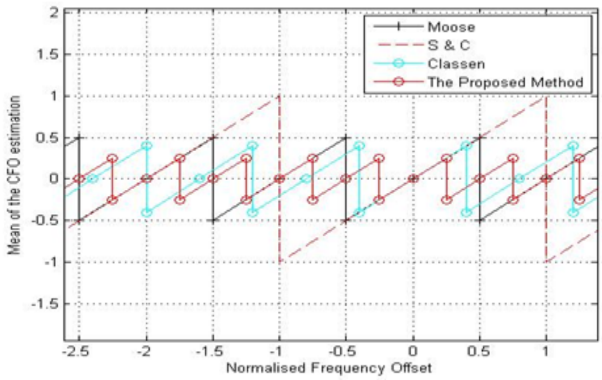

Fig. 2 Comparison for the mean values of CFO offset estimation techniques.

techniques' estimators, the proposed technique shows the best results; therefore, confirming the excellence of this technique under $\epsilon = 0.02$.

Fig. 2 shows a comparison of the estimation ranges of our proposed technique to the conventional techniques of Schmidl, Moose and Classen. From the simulation results, it is found that the proposed technique gives better accuracy but the estimation range is slightly decreased compare to other techniques.

3.2 MIMO OFDM Systems

To distinguish the antennas and estimate the CFO, each transmit antenna should be assigned the same training sequence. The training sequences are composed of repeated PN sequences which have good cross-correlation function, thus the interference of inter-transmit antennas is eliminated. A simple MIMO extension of the proposed technique for SISO OFDM is to use a block of S observation symbols. These are grouped into two consecutive blocks, where each block has a length of $S/2$. The observation training symbols are added sequentially and block-by-block estimation as shown in the following expression

$$\Psi_r(k) = \sum_{n=1}^{S/2} R_{n,r}^*(k) \sum_{m=S/2}^{S} R_{m,r}(k) \tag{10}$$

We assumed the channel is to be idle same in SISO OFDM system. The $\Psi(k)$ is then derived follow as

$$\Psi(k) = \sum_{m=S/2}^{S} \sum_{n=1}^{S/2} \sum_{q=1}^{N_r} |X_{l,q}|^2 e^{j2\pi(n-m)\epsilon N_p/N} + \widehat{W}(k) \tag{11}$$

Therefore,

$$\Psi(k) = \left| \sum_{q=1}^{N_r} X_{l,q}(k) \right|^2 \frac{\sin\left(\frac{2\pi\epsilon N_p(S-S/2)}{2N}\right)\sin\left(-\frac{2\pi\epsilon N_p S}{2\times 2N}\right)}{\sin\left(\frac{2\pi\epsilon N_p}{2N}\right)\sin\left(-\frac{2\pi\epsilon N_p}{2N}\right)} e^{j2\pi S\epsilon N_p/2N} + \widehat{W}(k) \tag{12}$$

Since ϵ is small and $E[\widehat{W}(k)] = 0$, then

$$\arg\{E[\Psi(k)]\} = \frac{2\pi\epsilon S N_p}{2N} \tag{13}$$

where $E[\widehat{W}(k)]$ is the mean of $\widehat{W}(k)$. However, in our work we proposed $N_p = N$.

$$\arg\{E[\Psi(k\} = \pi\epsilon S \tag{14}$$

Therefore, $\hat{\epsilon}$ which is an estimate of ϵ is derived by finding the argument of the summation of $\Psi(k)$ over all possible training symbols and receiver antennas in the MIMO OFDM system.

$$\hat{\epsilon}(k) = \frac{1}{\pi S} \arg \sum_{k=0}^{N-1} \sum_{r=1}^{N_r} \Psi_r(k) \tag{15}$$

The simulation results of the technique were then compared those of the conventional techniques for MIMO [9]. In the simulation tests, the channel effect is neglected, whereas AWGN is considered. The block size of the OFDM symbol has selected to kept at $N = 64$, The simulation tests are carried out at a different signal to noise ratio and the number of antennas is $N_t = 2$, $N_r = 2$, and the length of the guard interval is chosen

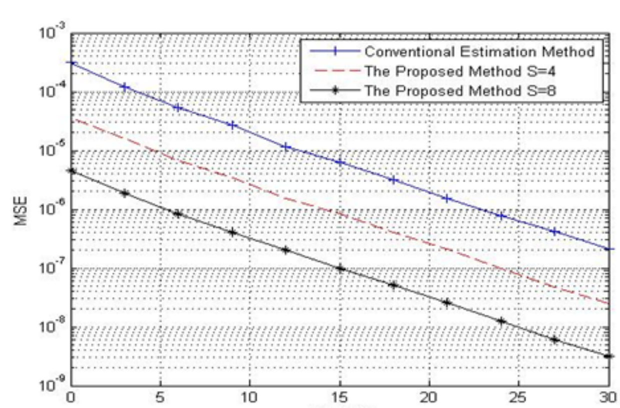

Fig. 3 MSE of CFO estimation in AWGN with $N_t = 2$, $N_r = 2$ (CFO = 0.02)

to be $N/4=16$. The simulation results are shown in Fig. 3. The relative CFO ϵ is 0.02.

As we can see the proposed technique has better accuracy than the conventional technique, and increase the number of the observation can lead to increase of the estimation performance However, increasing the accuracy will occur at the cost of decreasing frequency acquisition range.

4. Conclusions

This paper proposed a technique based on S symbol observation for estimating CFO using training symbols which have a good autocorrelation function during the preamble period for SISO OFDM. An analytical expression for the MSE of the frequency synchronization scheme is achieved. CFO estimation error has been considered under an AWGN channel. The proposed technique has a more accurate result than the conventional techniques. The accuracy of our proposed technique estimator can be improved by increasing the number of observations. However, increasing the accuracy will occur at the cost of decreasing frequency acquisition range.

The MIMO OFDM system is also very sensitive to CFO. Moreover, for MIMO OFDM, there is multi-antenna interference (MAI) in the receiving antennas between the received signals. The MAI makes CFO estimation more difficult when compared to SISO OFDM systems. The technique for SISO OFDM systems was extended to 2 MIMO OFDM system and the proposed technique has better accuracy than the conventional technique.

Further intensive research is needed in MIMO OFDM system considering the generalized system model which the CFO and propagation delay between each transmit antenna and receive antenna are possibly different for high Doppler shift in an indoor and outdoor.

감사의 글

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