ON TIMING SYNCHRONIZATION APPROACHES FOR OFDM SYSTEMS WITH RECEIVE ANTENNA DIVERSITY

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***Abstract* — This paper applies two timing estimators, the Schmidl-Cox and Minn's timing estimation methods, to a SIMO-OFDM system to find the starting point of the FFT (fast Fourier transform) window. Two different combination methods, maximal ratio combining (MRC) and selection combining (SC) are used for the timing synchronization processing with each of the two timing estimators. It is shown that, when we adopt the Schmidl-Cox method, MRC achieves a better performance than SC; however, if we choose the Minn's approach, SC is the better one.**

1. INTRODUCTION

In rich multipath environments, multi-antenna systems and orthogonal frequency division multiplexing (OFDM) technology can improve the transmission performance significantly [1]. Many digital communication systems are OFDM based. At the receiver, transmitted date is recovered by performing a discrete Fourier transform (DFT) on the received baseband signals. Timing synchronization is required to determine the correct symbol start position before DFT processing.

Timing synchronization techniques for single antenna OFDM systems have been widely discussed in the existing technical literature both for additive white Gaussian noise (AWGN) and multipath fading channels [2]-[7]. Timing synchronization issues and algorithms for multi-antenna OFDM systems have also begun to appear in recent publications. In [1] it was stressed that the availability of spatial diversity can improve the performance of the timing estimation outcome. At the receiver end, multiple transmission streams due to different transmit/receive paths can be combined to improve performance. In [6] an analogy between possible timing metric combining options, available for SIMO systems such as maximal ratio combining (MRC) and equal gain combining (EGC), was illustrated. However such techniques also add to the receiver complexity because several streams must be processed.

In this paper we compare two timing estimators with different spatial processing techniques in a SIMO-OFDM system. The estimators proposed by Schmidl and Cox [5] and Minn *et al.* [3] are used in combination with both MRC and selection combining (SC) [6] and their performances explored. The results indicate that the best combining method depends on which timing estimator is used.

The rest of the paper is organized as follows. In Section II we describe the SIMO-OFDM system. Section III describes the two timing estimators and combination methods. Analysis and simulation results comparing the performance of the estimators with different combining options appear in Section IV. Finally we draw some concluding remarks in Section V.

2. SIMO-OFDM SYSTEM MODEL

Let us consider an OFDM communication systems consisting of a single transmit and n receive antennas denoted as a $1\times n_R$ system. Fig. 1 illustrates such a system, where Tx is the transmit antenna, Rx_i $(1\le i\le n)$ is the i-th receive antenna, $r_i(d)$ is the i-th receive signal, $P_i(d)$ is the i-th autocorrelation function and w_i is the weight of each receive antenna which will be discussed in section 3.3.

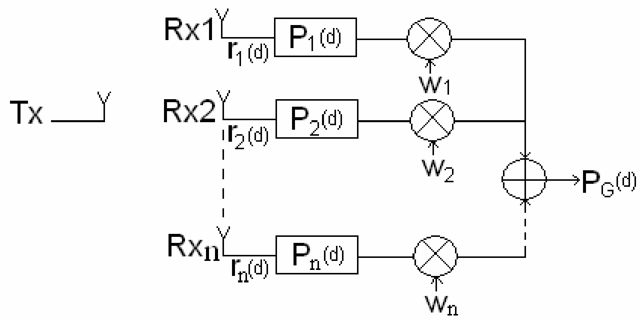

Fig. 1 Block diagram of the SIMO system

The discrete time domain samples of the m-th transmitted OFDM symbol is given by

$$x_m(n)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}X_{m,k}\exp(\frac{j2\pi nk}{N}) \qquad (1)$$

We assume that the cyclic prefix length is greater than the maximum delay of the channel. This guarantees an intersymbol interference (ISI) free condition. Next the signal is up-converted into a radio frequency f_c and transmitted to the quasi-static multipath fading SIMO channel.

3. TIMING SYNCHRONIZATION

So far a large number of timing synchronization techniques for OFDM systems has been proposed including time domain correlation based method and maximum likelihood estimation using the cyclic prefix of the OFDM symbols [8] and [9]. In this paper we use two popular time domain correlation methods proposed by Schmidl and Cox [5] and Minn *et al.* [3] and investigate their synchronization performance with different combination techniques in the SIMO-OFDM system.

3.1 Schmidl-Cox Timing Metric

The training symbol (excluding cyclic prefix, CP) of Schmidl-Cox estimator consists of two identical halves in time domain and is followed by OFDM data symbol. At the receiver, an autocorrelation is performed by correlating the received signal $r(d)$ with the complex conjugate version $r^*(d+L)$, where $L = N/2$, N is the number of subcarriers. Hence the timing metric is given by [5]

$$M(d) = \frac{|P(d)|^2}{(R(d))^2} \qquad (2)$$

where

$$P_{cox}(d) = \sum_{m=0}^{L-1} (r_{d+m}^* \cdot r_{d+m+L}) \qquad (3)$$

and

$$R_{cox}(d) = \sum_{m=0}^{L-1} |r_{d+m+L}|^2 \qquad (4)$$

and *d* is a time index and the size of the correlation window is *L*.

A disadvantage of the Schmidl-Cox metric is that it has a flat region in the timing metric which is due to the CP. This has the same length as that of CP in AWGN channel, and a length equal to the difference between the length of the CP and the length of the channel impulse response in multipath channels [5]. Fig. 2 shows the Schmidl-Cox timing metric, when the number of subcarriers and cyclic prefix are 1024 and 64 (samples) respectively, and the length of the channel impulse response is 30 (samples). The actual optimum point (index 0) is the start position of the receiver FFT window for the following OFDM data symbols (excluding CP) [3]. Many papers use the Schmidl-Cox estimator to bench-mark the performance of other estimators. In [1] Schellman *et a.l* introduce a preamble-based synchronization scheme into MIMO system. This is similar to the Schmidl-Cox estimator, but only utilizes $P(d)$ in (2) and then multiplies by weights (w_i), shown in Fig.1, calculated according to MRC and EGC criteria. Whereas, in this paper, we multiply $M(d)$ by weights (w_i) and, in addition, we adopt the average 90% of maximum points method [5] to get the fine timing estimation.

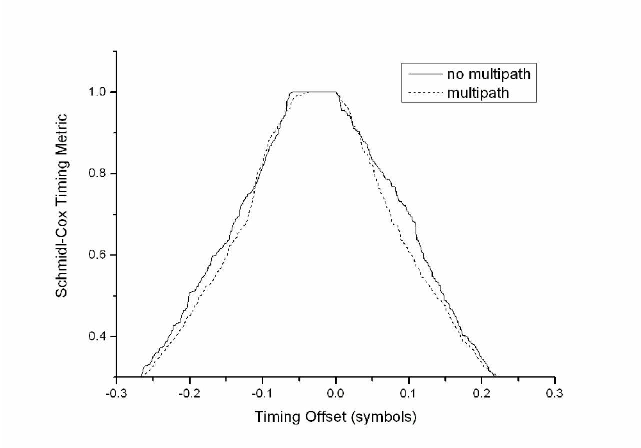

Fig. 2 Schmidl-Cox Timing Metric

3.2 Minn-Zeng-Bhargava Timing Metric

In [3], the Minn-Zeng-Bhargava method (we call Minn's method in this paper) is proposed. The samples of the training symbol (excluding CP) are designed to be of the form

$$s = [A \quad A \quad -A \quad -A] \qquad (5)$$

where A represents a sequence of samples with length $L = N/4$. The sequence is generated by an $N/4$ point FFT modulated by a PN sequence. The timing metric is the same as (2), and

$$P_{minn}(d) = \sum_{k=0}^{1} \sum_{m=0}^{L-1} r_{d+2Lk+m}^* \cdot r_{d+2Lk+m+L} \qquad (6)$$

and

$$R_{minn}(d) = \sum_{k=0}^{1} \sum_{m=0}^{L-1} |r_{d+2Lk+m+L}|^2 \qquad (7)$$

Fig.3 shows Minn's metric. The systems and multipath channel conditions are the same as those of Fig.2.

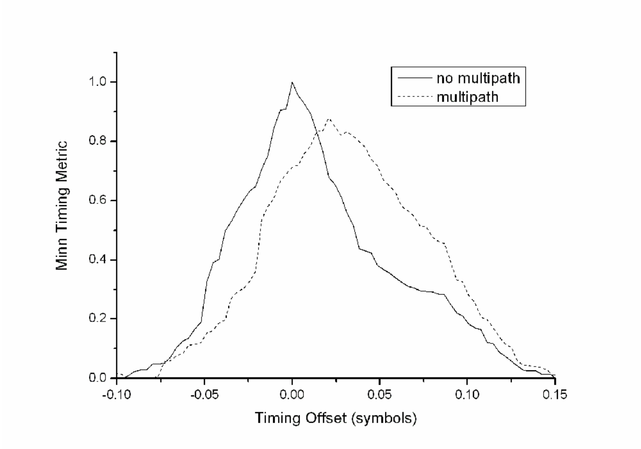

Fig.3 Minn's Timing metric.

3.3 Receive Diversity Aided Synchronization

In [1] it was shown that the spatial diversity of a SIMO system can be exploited to enhance the reliability of the timing synchronization estimator.

When outputs of the single signals are summed, one may apply weights (w_i) as illustrated in Fig. 1. In [1] these weights have been chosen according to the signal energy collected at each receive antenna. Therefore the authors suggest choosing the height of the peaks in the single autocorrelation function to get w_i as

$$w_i = \max(|P_i(d)|) \quad (8)$$

This technique is referred to as MRC in [1]. An alternative to summing is to simply select the branch with the highest $w_i = \max(|P_i(d)|)$ of all receive antennas and use this as the correct timing metric, we refer to this method as selection combining (SC).

4. SIMULATION RESULTS AND ANALYSIS

The mean and variance of Schmidl-Cox and Minn's timing offset estimation and the failure probability of Schmidl-Cox method have been evaluated using Matlab computer simulations. The number of subcarriers and cyclic prefix are 256 and 32 (samples) respectively. The COST-207 multipath channel model is considered. Each transmitter/receiver path consists of six Rayleigh taps of power delay profile as specified in the COST-207 model, where the path delay is [0, 2, 4, 6, 8, 10] samples and path gain is [0, -6, -12, -18, -24, -30] dB. The channel taps are uncorrelated for different transmit/receive paths. Hence this scenario is a rich scattering environment. Note that, in practice, the first taps of different paths between the transmitter and receivers will not experience the same propagation delay characteristics. This can influence the timing offset estimation process significantly. In the context of this paper, our aim is to utilize the spatial diversity for various timing estimators and to investigate various combination performances. Therefore, we assume that the first taps of different paths experience the same propagation delay.

Fig. 4 shows that, when we utilise Schmidl-Cox estimator in SIMO system, the mean of timing offset is about the middle of the CP area (index -16) of the following OFDM data symbol (i.e. within CP) and postponed some amount due to the multipath channel. The mean of timing offset derived from MRC is closer to the optimum point (index 0) than that of SC.

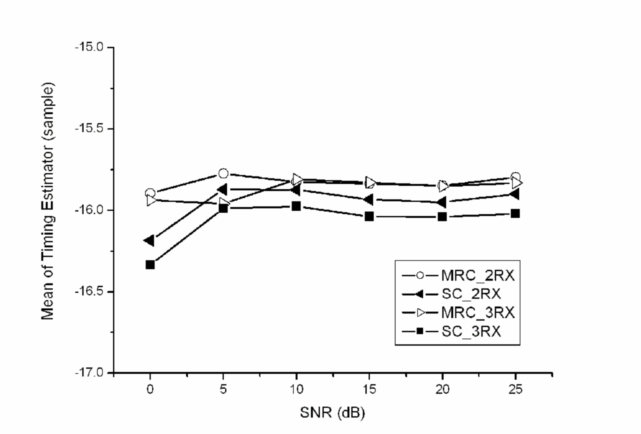

Fig. 4 Mean of Schmidl-Cox timing offset estimation in multipath channel

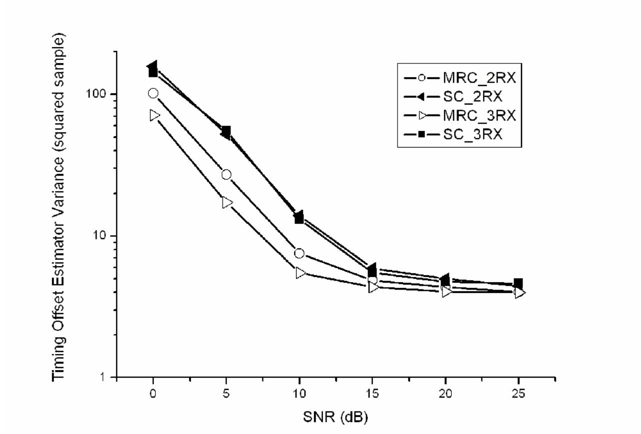

Fig.5 Variance of Schmidl-Cox timing offset estimation in multipath channel

Similarly, shown in Fig. 5, the variance of MRC is smaller than that of SC. Therefore, the MRC outperforms SC when Schmidl-Cox estimator is used in SIMO system.

In [8] and [10], the lock-in probability is measured, which is defined as the probability of the timing estimation offset falling in the ISI free region (within the CP and not contaminated by the preceding symbol owing to the multipath channel). Shown in Fig. 2 and 4, with Schmidl-Cox estimator, the mean of timing offset falls in the CP area of the following OFDM data symbol, and the uncontaminated CP area is from -22 to -1 samples (the lengths of CP and channel impulse response are 32 and 10 samples respectively).

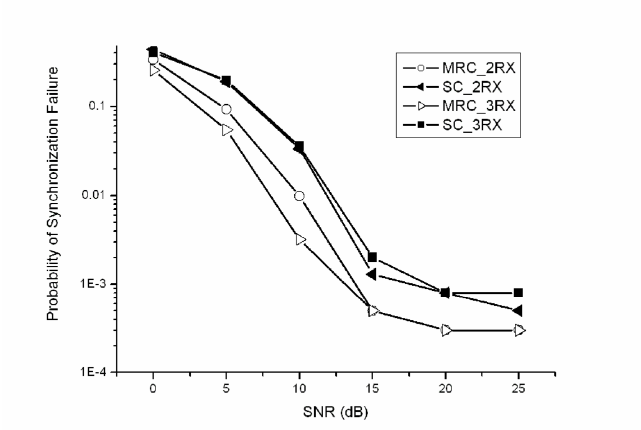

Fig. 6 Probability of synchronization failure

Fig. 6 shows the probability of synchronization failure, which is defined as the probability of the timing estimation offset falling out of the ISI free region. Again, we can see that, MRC combination with Schmidl and Cox estimator is much better than SC combination. In addition, systems with two and three receive antennas (MRC_2RX and 3RX) have almost the same performance, when the SNR is higher than 10dB, which means that, when Schmidl-Cox method is combined with MRC, simply adding receive antennas, namely system complexity, will not increase system performance significantly.

In contrast, Fig. 7 shows that, with Minn's timing estimator, the SC combination attains a better mean timing offset, which is closer to the optimum point. When the SNR is higher than 10dB, MRC with three receiver antennas (MRC_3RX) has the same level as SC with two receiver antennas (SC_2RX), and SC_3RX has the best performance. As to the variance, shown in Fig. 8, when the SNR is higher than 15 dB, the difference between the two combinations with the same number of receive antennas is very small.

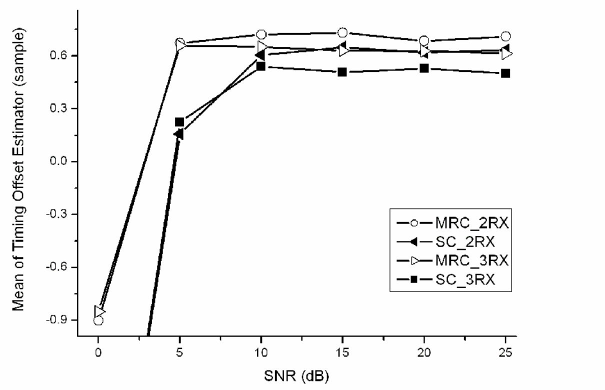

Fig. 7 Mean of Minn's timing offset estimation in multipath channel.

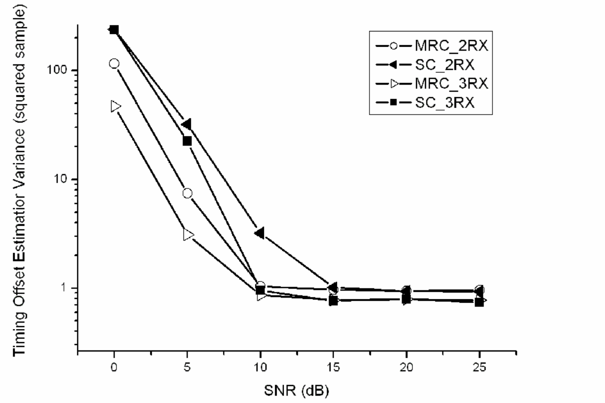

Fig. 8 Variance of Minn's timing offset estimation in multipath channel.

Here, we consider an ideal condition, assuming there is only AWGN channel. Seen from Fig. 2 and 3, the Minn's method can exactly detect the start time of the following OFDM signal when the SNR is high enough. Therefore, in MIMO systems, the combination coefficients w_i have to be chosen to acquire the maximum SNR. In [6], the SNR is given by:

$$\frac{S}{N}=\frac{S_s\cdot\left|H_1(\omega)\right|^2\cdot k_1^2+S_s\cdot\left|H_2(\omega)\right|^2\cdot k_2^2}{S_n\cdot k_1^2+S_n\cdot k_2^2} \tag{9}$$

Where S_s and S_n is the transmitted signal and received noise power respectively, and $H(\omega)$ is channel impulse response and, in this paper, it has been assumed uncorrelated with each other. So, no matter what w_i is, only the SC combination can get the highest SNR as long as r_1 and r_2 (shown in Fig. 1) are uncorrelated. That is why SC outperforms in a MIMO system with Minn's method. We should clarify that, here, we just discuss the timing offset performance for SIMO-OFDM system with different combination.

As for the Schmidl-Cox estimator, even if there is no noise, there is still a plateau (shown in Fig.2) which disturbs the decision of timing offset severely, thus, it should take more equivalent averaging calculations, such as MRC, just like what averaging 90% maximum points dose. As a result, choosing the highest SNR, i.e. SC is much worse than MRC.

5. CONCLUSIONS

We have investigated timing estimators for SIMO-OFDM systems. In a SIMO system estimates based on the signals from different receive antennas can be combined to improve performance. In this paper simulation results are presented for the cases where MRC and SC combining are used with two different timing estimators: the Schmidl-Cox estimator and the Minn's estimator. We have shown that MRC is more suitable for Schmidl-Cox method and SC is better for Minn's approach.

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