Cooperative Coarse Timing Synchronization for OFDM-Based Distributed Antenna Systems

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Abstract. In this paper, a cooperative coarse timing synchronization method for OFDM-based distributed antenna systems is proposed. Without increasing the false alarm probability at each remote antenna, we exploit the cooperation of the multiple remote antennas, and a new detection threshold is formulated to avoid the missed detection that occurs according to the independent timing synchronization. The analytical and simulation results confirm the effectiveness of the proposed method.

Keywords: coarse timing synchronization, cooperative processing, distributed antenna systems, OFDM.

1 Introduction

Coarse timing synchronization for orthogonal frequency-division multiplexing (OFDM) systems is needed to indicate the beginning of the fast Fourier transform (FFT) window. Many proposed approaches, which estimate timing offset by using the autocorrelation of the training sequence consisting of two or more identical parts, have been summarized in [1]. However, these autocorrelation methods are not robust in wideband fading scenarios [2], [3]. Therefore, the cross-correlation method with threshold-based detection for timing synchronization are proposed in [2] and [3].

Timing synchronization for OFDM-based distributed antenna systems (DAS) has been investigated in [4]–[6]. These synchronization methods estimate the timing offset at each remote antenna (RA) independently, without any cooperation among the RAs. To exploit the advantages of cooperation, a cooperative coarse timing synchronization (CCTS) method is proposed in this paper. With the helping from two or more RAs that have achieved coarse timing synchronization according to the pre-defined detection threshold, a new detection threshold can be formulated for some missed RAs to avoid a miss without increasing the false alarm probability at each RA. The analytical and simulation results show that the failure of coarse timing synchronization can be improved by employing the CCTS method.

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The rest of this paper is organized as follows. In the next section, we describe the system model. In Section 3, we present the coarse timing synchronization method. Some numerical results are given in Section 4. Finally, Section 5 concludes this paper.

2 System Model

In this paper, we assume $M_r (M_r > 2)$ RAs are connected to the central processor of the receiver for receiving the signal transmitted from the transmitter with a single antenna. The OFDM baseband signal at the transmitter is generated by the IFFT transform

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s_k e^{j2\pi kn/N}, \quad -G \le n \le N-1, \tag{1}$$

where N is the FFT size, s_k represents the data sequence modulated on the kth subcarrier, which is independently and identically distributed with zero mean and variance $E\left\{|s_k|^2\right\} = \sigma_s^2$. G is the length of cyclic prefix (guard time). The received signal samples at RA$_i$, $i = 1, \cdots, M_r$ can be expressed as

$$r_i(n) = \sum_{m=0}^{L_i-1} \sqrt{\xi_i} h_i(m) x(n - m - \tau_i) e^{j2\pi\varepsilon_i n/N} + w_i(n), \tag{2}$$

where L_i $(L_i \le G)$ is the memory length of the multipath fading channel, $\sqrt{\xi_i}$ denotes the large-scale fading that captures the effects of mean path loss and log-normal shadow fading, $h_i(m)$ represents the channel impulse response of mth path for small-scale fading, τ_i stands for the timing offset, ε_i is the normalized carrier frequency offset, and w_i denotes the samples of a zero-mean complex white Gaussian noise random process with variance $E\left\{|w_i(n)|^2\right\} = \sigma_w^2$ and is assumed independent with respect to $x(n)$.

3 Coarse Timing Synchronization

In this section, we recall the cross-correlation based synchronization method with pre-defined detection threshold, and we will base on this scheme to describe our proposed algorithm. Note that the proposed method can also apply to the autocorrelation method to obtain similar conclusion. However, for a pre-defined false alarm probability, the closed-form expression of the detection threshold in autocorrelation method cannot be obtained [7] (resorted to numerical calculations, see subsection A of section IV in [7]). For convenience, the cross-correlation method for coarse timing synchronization is considered in this paper.

Similar to [8], the constant envelop preamble is considered in this paper. We describe the preamble structure as

$$\mathbf{S} = \tilde{\mathbf{S}} \odot \mathbf{S}_{PN}, \tag{3}$$

where $\mathbf{S} = [s(0), \cdots, s(N-1)]$ is $1 \times N$ preamble sequence, $\tilde{\mathbf{S}}$ is the repetitive sequences of the form $\tilde{\mathbf{S}} = [\mathbf{A}_{N/2}\ \mathbf{A}_{N/2}]$, $\mathbf{A}_{N/2}$ is a random complex vector of length $N/2$ [1], the operator "$\odot$" indicates the Hadamard product, and the pseudo-noise (PN) sequence weighted factors are introduced by the $1 \times N$ vector $\mathbf{S}_{PN}$ [8]. In (3), we reserve the repetitive form $\tilde{\mathbf{S}}$ in [1] for the fine synchronization and fractional frequency offset estimation after coarse timing sychronization, and the PN sequence is adopted to avoid the multiple peaks appear in [2] and [3].

Using the cross-correlation detection method [2], [3], we compute the cross-correlation between the received signal and the known preamble sequence, i.e.,

$$P_i(d_i) = \sum_{k=0}^{N-1} r_i(d_i + k) s^*(k), \quad i = 1, 2, \cdots, M_r, \tag{4}$$

where "$*$" denotes the complex conjugate. From [2] and [3], $|P_i(d_i)|$ at all other timing instants apart from those corresponding to the channel paths, denoted as $|P_i(\beta_{NC,i})|$, can be regarded as a Rayleigh distributed random variable. Hence, the detection threshold for each RA can be given by [3]

$$T_{c,i} = \sqrt{-2\sigma_i^2 \ln(P_{FA})},\ i = 1, \cdots, M_r, \tag{5}$$

where P_{FA} is the pre-defined false alarm probability for each RA. According to [3], the σ_i in equation (5) can be estimated by $\hat{\sigma}_i = \sqrt{2/\pi} \cdot E\{|P_i(\beta_{NC,i})|\}$.

3.1 Independent Coarse Timing Synchronization

For DAS, the M_r RAs are deployed at different locations, and the transmitted signal is experienced different paths to reach the M_r RAs. Thus, τ_i, $i = 1, \cdots, M_r$ are generally different. If the coarse timing synchronization is done at each RA independently, we call it as *independent coarse timing synchronization* (**ICTS**) in this paper. Thus, the timing offset for each RA$_i$ ($i = 1, \cdots, M_r$) can be estimated as

$$\hat{d}_i = \arg\max_{d_i} \{|P_i(d_i)| \geq T_{c,i}\},\ d_i \in [0, U-N], \tag{6}$$

where U is the observation vector length, which is assumed to be long enough to incorporate the whole preamble sequence.

In multi-path channels, the trajectory peak of $|P_i(d_i)|$ would be delayed due to the channel dispersion [9]. Hence, the coarse-timing estimate should be pre-advanced by some samples to guarantee that the estimate of τ_i, i.e., $\hat{\tau}_i$, satisfies $|\hat{\tau}_i - \tau_i| \leq G/2$ (i.e., pre-advanced towards the middle of the cyclic prefix zone [3], [9]). We express $\hat{\tau}_i$ as

$$\hat{\tau}_i = \hat{d}_i - \frac{G}{2},\ i = 1, 2, \cdots, M_r. \tag{7}$$

Since the ICTS method do not need the cooperation among the receive antennas, the existing coarse timing synchronization methods, e.g., [1]–[9], can also be adopted by ICTS method. In DAS, the signal-to-noise ratios (SNR) at different RAs are imbalance. Hence, the ICTS method performs very bad at some RAs with relatively low received SNRs. To improve the ICTS method, we propose a *cooperative coarse timing synchronization* (**CCTS**) in the following subsection.

3.2 Cooperative Coarse Timing Synchronization

When the transmitted signal experiences deep fading and cannot be synchronized by RA_k according to the detection threshold $T_{c,k}$ (see Equation (5)), a missed detection happens at RA_k in ICTS method. In fact, as two or more RAs have reached the detection threshold given in (5), the false alarm probability at the central processor is generally more lower than the given P_{FA} according to the "data fusion rule" in [10]. Thus, the false alarm probability at the central processor can guarantee that the false alarm probability at RA_k is not higher than the pre-defined P_{FA}. Then, a lower detection threshold $\tilde{T}_{c,k}$, i.e., $\tilde{T}_{c,k} < T_{c,k}$ can be exploited for RA_k without increasing the false alarm probability at RA_k.

3.2.1 Initial Estimation

The CCTS method searches the number of RAs that $|P_i(d_i)|$ can reach $T_{c,i}$ according to (6) firstly. We denote the indexes of the M_u RAs that $|P_i(d_i)|$ can reach $T_{c,i}$ as set $\mathbf{M}_u$, and the indexes of the $M_r - M_u$ RAs that $|P_i(d_i)|$ cannot reach $T_{c,i}$ are denoted as $\mathbf{M}_n$, i.e.,

$$\begin{cases} \mathbf{M}_u = \left\{ i \left| \max_{d_i} \{|P_i(d_i)|\} \geq T_{c,i} \right. \right\}, \\ \mathbf{M}_n = \left\{ i \left| \max_{d_i} \{|P_i(d_i)|\} < T_{c,i} \right. \right\}. \end{cases} \tag{8}$$

In (8), $\mathbf{M}_n$ can be viewed as the complement of $\mathbf{M}_u$. Then, at least M_u RAs can detect the signal from transmitter with the detection threshold $T_{c,i}$. The estimate for timing offset τ_i, $i \in \mathbf{M}_u$ can be obtained according to (6) and (7).

3.2.2 Detection Threshold $T_{c,i}^{(1)}$

When $1 < M_u < M_r$, a detection threshold $T_{c,i}^{(1)}$ based on the false alarm probability $\tilde{P}_{FA}$ for RA_i is considered. Since there are M_u RAs can reach the detection threshold $T_{c,i}$, then at least M_u RAs can reach the $T_{c,k}^{(1)}$ as $T_{c,k}^{(1)} < T_{c,k}$ is considered.

Denoting B_j as the event that there are M_u RAs have synchronized the signal from the transmitter according to the detection threshold $T_{c,i}^{(1)}$, then we have

$$N_{combi} = \frac{M_r!}{M_u!\,(M_r - M_u)!}, \tag{9}$$

where N_{combi} is the combinations from M_r RAs for the event B_j. According to the "data fusion rule" in [10], the false alarm probability that M_u RAs have detected the signal from the transmitter at the central processor according to the detection threshold $T_{c,i}^{(1)}$ is

$$P_{false}\{B_j\} = \left(\tilde{P}_{FA}\right)^{M_u}, \tag{10}$$

where $P_{false}\{B_j\}$ is the false alarm probability that event B_j occurs, and $\tilde{P}_{FA}$ is the false alarm probability that each RA independently detects the signal according to detection threshold $T_{c,i}^{(1)}$.

Considering any M_u RAs among the M_r RAs have detected the signal, then the false alarm probability at central processor can be expressed as

$$\begin{aligned} \tilde{P}_{FA}^{C} &= Pr_{false}\{B_1 \cup B_2 \cup \cdots \cup B_{N_{combi}}\} \\ &\le Pr_{false}\{B_1\} + \cdots + Pr_{false}\{B_{C_{combi}}\} \\ &= N_{combi} \cdot \left(\tilde{P}_{FA}\right)^{M_u}. \end{aligned} \tag{11}$$

To guarantee the false alarm probability will be not higher than pre-defined false alarm probability P_{FA} for each RA, we can choose $\tilde{P}_{FA}^{C} \le N_{combi} \cdot \left(\tilde{P}_{FA}\right)^{M_u} \le P_{FA}$. Then we have

$$\tilde{P}_{FA} \le \left(\frac{P_{FA}}{N_{combi}}\right)^{1/M_u}. \tag{12}$$

Replacing P_{FA} in (5) by the maximum of $\tilde{P}_{FA}$, the new detection threshold $T_{c,i}^{(1)}$ for RA_i, $i \in \mathbf{M}_n$ is given by

$$T_{c,i}^{(1)} = \sqrt{\frac{-2\sigma_i^2}{M_u} \cdot \ln\left(\frac{P_{FA}}{N_{combi}}\right)}. \tag{13}$$

To achieve $T_{c,i}^{(1)} < T_{c,i}$, a constraint can be formulated according to (5) and (13), i.e.,

$$N_{combi} < (P_{FA})^{-M_u+1}. \tag{14}$$

As $N_{combi} = M_r$, $M_u = 1$ and (14) cannot be satisfied. Meanwhile, all RAs have detected the signal with the detection threshold $T_{c,i}$ when $M_u = M_r$. Therefore, the detection threshold $T_{c,i}^{(1)}$ in (13) can be employed for the scenarios that $1 < M_u < M_r$.

3.2.3 Detection Threshold $T_{c,i}^{(2)}$

Although the detection threshold $T_{c,i}^{(1)} < T_{c,i}$ can be obtained without increasing the false alarm probability for each RA when $1 < M_u < M_r$, too low detection threshold cannot ensure the effectiveness of the synchronized RAs. Hence, a desired correct detection probability $\bar{P}_D$ should be considered.

Setting $X = \max|P_i(\beta_{NC,i})|$ for $|\beta_{NC,i} - \tau_i| > G/2$, then $|P_i(\beta_{NC,i})|$ is a Rayleigh distributed random variable, the cumulative distribution function (CDF) of X is

$$F_X(x) = \left(1 - \exp\left(-\frac{x^2}{2\sigma_i^2}\right)\right)^{\bar{U}}, \tag{15}$$

where $\bar{U} = U - N - G$. Considering a detection threshold $T_{c,i}^{(2)}$, then we have

$$\Pr\left(X < T_{c,i}^{(2)}\right) = \left(1 - \exp\left(-\frac{\left(T_{c,i}^{(2)}\right)^2}{2\sigma_i^2}\right)\right)^{\bar{U}}. \tag{16}$$

According to the desired correct detection probability $\bar{P}_D$, we choose

$\Pr\left(X < T_{c,i}^{(2)}\right) \geq \bar{P}_D$. Then $T_{c,i}^{(2)}$ should satisfy $T_{c,i}^{(2)} \geq \sqrt{-2\sigma_i^2 \ln\left(1 - \left(\bar{P}_D\right)^{1/\bar{U}}\right)}$. That is, the $T_{c,i}^{(2)}$ can be set as

$$T_{c,i}^{(2)} = \sqrt{-2\sigma_i^2 \ln\left(1 - \left(\bar{P}_D\right)^{1/\bar{U}}\right)}. \tag{17}$$

In (17), the $\bar{P}_D$ should be chosen according to $T_{c,i}^{(2)} < T_{c,i}$. From (5) and (17), we have

$$\bar{P}_D < (1 - P_{FA})^{\bar{U}}. \tag{18}$$

3.2.4 Additional Remote Antennas

To guarantee the effectiveness of the synchronized RAs, a new detection threshold $\tilde{T}_{c,i}$ should be chosen according to (13) and (17) for each RA, i.e.,

$$\tilde{T}_{c,i} = \max\left\{T_{c,i}^{(1)}, T_{c,i}^{(2)}\right\}. \tag{19}$$

For $1 < M_u < M_r$, we employ the new detection threshold $\tilde{T}_{c,i}$ (given in (19)) to estimate the timing offset τ_i, $i \in \mathbf{M}_n$, i.e.,

$$\hat{\tau}_i = \arg\max_{d_i}\left\{|P_i(d_i)| \geq \tilde{T}_{c,i}\right\} - \frac{G}{2}, \tag{20}$$

where $d_i \in [0, U - N]$, the missed detection at RA_i, $i \in \mathbf{M}_n$ can be avoided as the $P_i(d_i)$ reaches to the new detection threshold $\tilde{T}_{c,i}$.

From (13) and (17), $T_{c,i}^{(1)} = T_{c,i}^{(2)}$ is equivalent to $(P_{FA}/N_{cb})^{1/M_u} = 1 - \left(\bar{P}_W\right)^{1/\bar{U}}$. If the parameters P_{FA}, M_r, $\bar{P}_W$, and $\bar{U}$ are given, the $\tilde{T}_{c,i}$ is decided by M_u. For example, given $P_{FA} = 10^{-6}$, $M_r = 6$, $\bar{P}_W = 90\%$, and $\bar{U} = 112$ (assuming $N = 128$, $U = 2N$, $G = N/8$, and $\bar{U} = U - N - G$), $\tilde{T}_{c,i}$ is equal to $T_{c,i}^{(1)}$ for $M_u = 2$ and $T_{c,i}^{(2)}$ for M_u is 3, 4, and 5. In general, P_{FA}, M_r, $\bar{P}_W$, and $\bar{U}$ are known before the starting of a synchronization process. Thus, according to M_u, we select $T_{c,i}^{(1)}$ or $T_{c,i}^{(2)}$ to compute $\tilde{T}_{c,i}$, rather than to compute both $T_{c,i}^{(1)}$ and $T_{c,i}^{(2)}$ to formulate $\tilde{T}_{c,i}$. Then, the operation of CCTS method is simplified.

3.2.5 Summary for CCTS Method

We briefly summarize the proposed coarse timing synchronization method as follows.

1) Take an initial estimation, including computing $P_i(d_i)$ according to (4), detecting the presence of the transmitted signal according to (6), and returning M_u, $\mathbf{M}_u$, and $\mathbf{M}_n$.
2) If $\mathbf{M}_u$ is not null, we estimate $\tau_i, i \in \mathbf{M}_u$, according to (7). Else, we return to step 1), i.e., we wait for the timing synchronization of the next time.
3) If $2 \leq M_u < M_r$ is not satisfied, jump to step 8). Else, we do the next step.
4) If equation (14) is not satisfied, jump to step 8). Else, we compute $T_{c,i}^{(1)}$ according to (13).
5) If equation (18) is not satisfied, jump to step 8). Else, we compute $T_{c,i}^{(2)}$ according to (17).
6) Compute $\tilde{T}_{c,i}$ according to (19) and estimate the timing offset $\tau_i, i \in \mathbf{M}_n$ with the detection threshold $\tilde{T}_{c,i}$ according to (20).
7) Add the index of the detected DRXs according to (20) into the set $\mathbf{M}_u$.
8) Go to the fine synchronization for DRX_i, $i \in \mathbf{M}_u$.

4 Numerical and Simulation Results

Computer simulation results are presented in this section. We set $N = 128$, $G = 16$, $M_r = 6$, $P_{FA} = 10^{-6}$, $U = 256$, the sample period is $1/1.5\mu$s. Two cases for $\bar{P}_D$ are considered, i.e., $\bar{P}_D = 90\%$ and $\bar{P}_D = 99\%$.

The channel model for computer simulation follows the power delay profile of the Vehicular-A channel in [11]. From the transmitter to the M_r RAs, the channels are independent of each other (the different paths from the transmitter to a given RA are also mutually independent). The carrier frequency and the speed of relative movement between the RAs and the transmitter are set to 2GHz and 120km/h, respectively, then the maximum Doppler frequency is given by

$$\frac{120\text{km/h} \times 2 \times 10^9\text{Hz}}{3 \times 10^8\text{m/s}} \approx 222.2\text{Hz}. \tag{21}$$

To confirm the effectiveness of the proposed CCTS method, the ***failure probability*** of coarse timing synchronization is plotted in Fig. 1 and Fig. 2, where the ***failure of coarse timing synchronization*** is an event either a missed detection or $|\hat{\tau}_i - \tau_i| > G/2$ (without a miss) occurs. The $T_{c,i}^{(1)}$ (see (13)) is employed to improve the missed detection probability, and $T_{c,i}^{(2)}$ (see (17)) is employed to guarantee the desired probability $\bar{P}_D$. Thus, the *failure probability* is reasonable consideration to measure the improvement of the coarse timing synchronization, rather than making a single evaluation on missed detection.

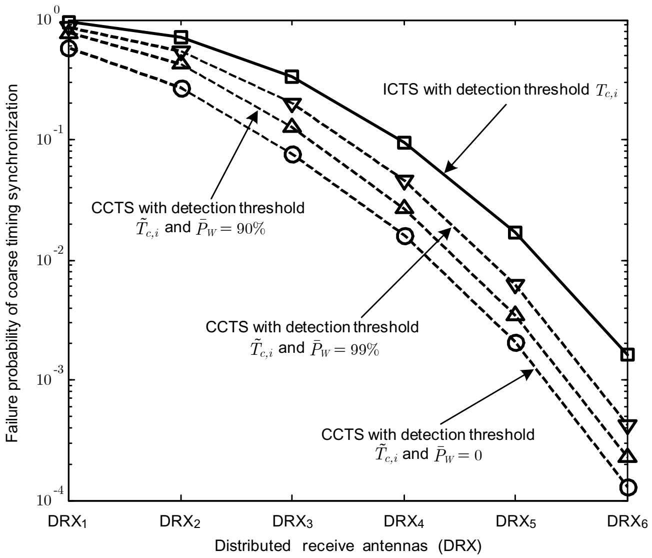

Fig. 1. Failure probability of coarse timing synchronization, where the SNRs from DRX_1 to DRX_6 are respectively set to be $\{-10\text{dB}\ -6\text{dB}\ -2\text{dB}\ 2\text{dB}\ 6\text{dB}\ 10\text{dB}\}$

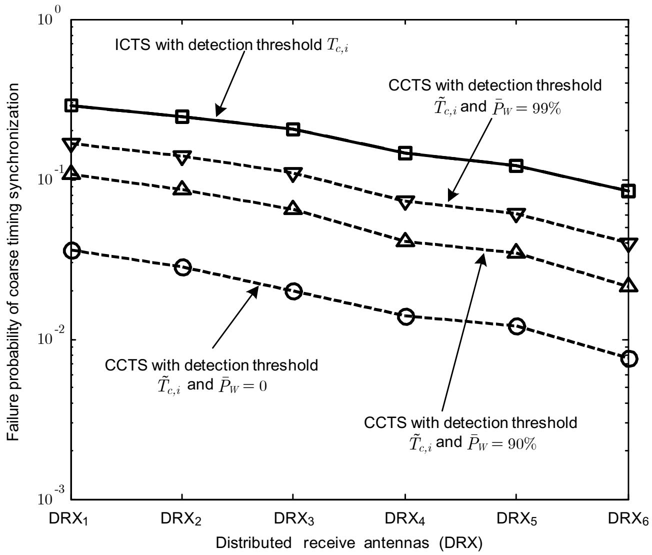

Fig. 2. Failure probability of coarse timing synchronization, where the SNRs form DRX_1 to DRX_6 are set to be $\{0\text{dB}\ 0.5\text{dB}\ 1\text{dB}\ 2\text{dB}\ 3\text{dB}\ 4\text{dB}\}$, respectively

In Fig. 1, the SNRs from DRX_1 to DRX_6 are set to be $\{-10\text{dB}\ -6\text{dB}\ -2\text{dB}\ 2\text{dB}\ 6\text{dB}\ 10\text{dB}\}$, respectively. This scenario can be viewed as the attenuation of the transmitted signal for one of the DRXs (i.e., DRX_6) is evidently less than the other DRXs, the transmitter may be close to the DRX_6 while it is relatively far from the other DRXs. In Fig. 2, the SNRs form DRX_1 to DRX_6 are set to be {0dB 0.5dB 1dB 2dB 3dB 4dB}, respectively. The attenuation differences of the transmitted signal among the 6 DRXs are not significant, e.g., similar distances from the transmitter to each DRX are considered.

From Fig. 1 and Fig. 2, the failure probability of each DRX in CCTS method is lower than ICTS method when the detection threshold $T_{c,i}^{(1)}$ (see (13), i.e., $\tilde{T}_{c,i} = T_{c,i}^{(1)}$ without considering $T_{c,i}^{(2)}$ in (17)) or $\tilde{T}_{c,i}$ (see (19)) is employed.

In Fig. 1 and Fig. 2, with detection threshold $\tilde{T}_{c,i} = T_{c,i}^{(1)}$, the failure probability of each DRX in the CCTS method is much lower than the others, i.e., the CCTS method with detection threshold $\tilde{T}_{c,i}$ (including $\bar{P}_W = 90\%$ and $\bar{P}_W = 99\%$) and the ICTS method with threshold $T_{c,i}$. We discard some DRXs to guarantee the desired correct detection probability $\bar{P}_D$. Thus, the detection threshold $\tilde{T}_{c,i}$ in (19) is a tradeoff between the presence of a new frame, i.e., keeping the pre-defined false alarm probability not be exceeded, and the desired probability $\bar{P}_D$ can be obtained.

Both in Fig. 1 and Fig. 2, $\bar{P}_W = 90\%$ and $\bar{P}_W = 99\%$ are considered. As can be seen in the two figures, the failure probability for $\bar{P}_W = 90\%$ is lower than the case of $\bar{P}_W = 99\%$. From the discussion for $\tilde{T}_{c,i}$ in subsection (3.2.4), $\tilde{T}_{c,i} = T_{c,i}^{(1)}$ for $M_u = 2$ and $\tilde{T}_{c,i} = T_{c,i}^{(2)}$ for M_u is 3, 4, and 5. In general, $M_u \geq 3$ is obtained for the SNRs configuration in Fig. 1 and Fig. 2 (note that $M_u = 2$ is also occurred). Thus, $\bar{P}_W$ is main reason to effect the failure probability according to (17), and the lower desired probability $\bar{P}_W$ yields lower failure probability can be obtained. The lowest failure probability is obtained as $\bar{P}_W = 0$, i.e., $\tilde{T}_{c,i} = T_{c,i}^{(1)}$ in (19), and can also be derived from (17) and (19).

5 Conclusion

In this paper, the CCTS for OFDM-based DAS has been investigated. By cooperating among the RAs, the detection threshold can be reduced without increasing the false alarm probability at each RA. Relative to the ICTS method, the analytical and simulation results have been shown that the failure of coarse timing synchronization can be improved by employing the CCTS method.

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