Antenna Location Design for Distributed Antenna Systems Based on Timing Acquisition

Tian Xia[1], Chaojin Qing[1,2], Shihai Shao[1], Mintao Zhang[2], and Youxi Tang[1]

[1] National Key Lab of Communications,
University of Electronic Science and Technology of China, Chengdu 610054, China
qingchj@uestc.edu.cn
[2] School of Electrical and Information Engineering,
Xihua University, Chengdu, 610039, China

Abstract. We address the antenna location problem for distributed antenna systems based on timing acquisition in frequency selective channel. Coarse timing estimation is performed for the orthogonal frequency division multiplexing system. The probability of worst case is introduced in terms of the probability of correct detection of each distributed receive antenna. A minimax criterion is proposed to provide the optimal antenna locations in a sense that it offers the best system performance that the probability of worst case is minimized. Simulation results illustrate that the distributed receive antennas should be located symmetrically about the linear cell when the mobile station distribution is uniform. The optimal antenna locations also show robustness to carrier frequency offset.

Keywords: antenna location design, distributed antenna systems, OFDM, minimax criterion.

1 Introduction

Distributed antenna system (DAS) is increasingly gaining interest from academic researchers for its attractive merits such as increased system capacity, lowered transmit power, and enhanced cell coverage [1], [2]. Whether these advantages can be realized is directly affected by antenna locations. In order to achieve the optimal system performance under certain criterion, we need carefully design distributed antennas locations.

In [3], the antenna location design problem was investigated for two transmit antennas in a linear cell to minimize the area averaged bit error probability (AABEP). This work is then extended to a more general scenario called generalized DAS (GDAS) in [4], where the authors proposed a squared distance criterion (SDC) to maximize the cell averaged ergodic capacity. The method proposed in [5] is similar to [3] whereas a circular cell and more than 2 antennas are considered. However, they all assume the timing and frequency synchronization is perfectly accomplished, which is not a trivial task in distributed antenna systems. In synchronization process, timing acquisition is the first and crucial step the receive antenna takes and directly determines the performance of following procedures [6].

P. Ren et al. (Eds.): WICON 2011, LNICST 98, pp. 73–81, 2012.

This paper deals with distributed antenna location design problem based on timing acquisition for the orthogonal frequency division multiplexing (OFDM) system. The probability of worst case, denoted as P_{WC}, is derived in term of the probability of correct detection of each antenna. Optimal antenna locations can then be obtained by minimizing the probability of worst case P_{WC} for every possible combination of antenna locations. Simulation results show that the optimal antenna locations ought to be located symmetrically about the linear cell center, when the mobile station (MS) distribution is uniform. The optimal antenna locations are also robust for several trial values of carrier frequency offset.

The rest of the paper is organized as follows. Section 2 describes the system model. Section 3 develops the process of timing acquisition. In section 4, the minimax criterion is proposed. Section 5 provides the simulation results. Section 6 concludes this paper.

2 System Model

We consider a linear cell as shown in Fig. 1. The length of the linear cell is R. The distributed receive antenna, denoted as RX_i, is placed at a_i. A MS is at position x.

The OFDM symbol at the output of the inverse fast fourier transform (IFFT) transmitted from the MS is given by

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

where N is the total number of subcarriers, X_n represents the data symbol transmitted on the nth subcarrier, and N_g is the length of guard interval, which is designed longer than the maximum channel delay spread to avoid intersymbol interference (ISI). The transmit power is $E\{|x(k)|^2\} = \sigma_s^2$.

We consider a composite channel model, which comprises path loss, shadow fading, and multipath fading. The channel fading coefficient between the MS and RX_i can then be expressed as [4]

$$g_i = \sqrt{\frac{cs_i}{D_i^{\alpha}}} H_i, \quad i = 1, 2, \tag{2}$$

where c is a constant, s_i is a log-normal random variable representing shadow fading, i.e., $10 \log_{10} s_i$ is a zero-mean Gaussian random variable with standard deviation σ_{sh}, α is the path loss exponent, D_i is the effective distance from the MS to RX_i, which is given by [4]

$$D_i = \max\{d_0, d_i\}, \tag{3}$$

where d_i is the distance between the MS and RX_i, d_0 is the minimum allowable value of d_i. Multipath fading H_i can be written as

$$H_i = [h_i(0), h_i(1), \cdots, h_i(l_i), \cdots, h_i(L_i - 1)], \tag{4}$$

where $h_i(l_i)$ is the channel tap and L_i is the duration of channel impulse response.

The signal received by RX_i can be represented as

$$r_i(k) = e^{j2\pi\varepsilon_i k/N} y_i(k) + w_i(k), \tag{5}$$

where

$$y_i(k) = \sum_{l_i=0}^{L_i-1} \sqrt{\frac{cs_i}{D_i^{\alpha}}} h_i(l_i) x(k - l_i - \tau_i), \tag{6}$$

where ε_i is the frequency offset normalized to the subcarrier spacing, τ_i is the symbol timing offset between the MS and RX_i, and $w_i(k)$ is complex additive white Gaussian noise (AWGN) with zero mean and variance σ_{iw}^2.

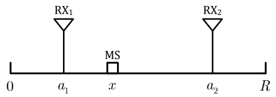

Fig. 1. Linear cell layout

3 Timing Acquisition

3.1 Training Symbols

In [7], training symbol is specifically designed for OFDM timing acquisition, which comprise L identical part and have a specific pattern (signs). The identical structure is desirable as it is robust to possible large carrier frequency offset when auto-correlation method is applied. Since training symbol structure is not the major point of this paper and it matters little when cross-correlation approach is employed, we simply select the polyphase codes introduced by CHU [8] as the training symbol for its perfect auto-correlation property.

3.2 Cross-Correlation

The cross-correlation method in [9] is employed. The cross-correlation between the received signal and the training symbol is given by

$$\begin{aligned} C_i(m) &= \sum_{k=0}^{N-1} r_i(k+m) s^*(k) \\ &= P_i(m) + W_i(m), \quad m \in [0, U-N], \end{aligned} \tag{7}$$

where

$$P_i(m) = \sum_{k=0}^{N-1} e^{j2\pi\varepsilon_i k/N} y_i(k+m) s^*(k), \tag{8}$$

$$W_i(m) = \sum_{k=0}^{N-1} w_i(k+m) s^*(k), \tag{9}$$

where U represents the the observation window which is sufficiently long to accommodate at least two symbols with CP, $W_i(m)$ is AWGN with zero mean and variance $N\sigma_{iw}^2$ as $w_i(k+m)s^*(k)$ has the same statistic with $w_i(k+m)$.

3.3 Timing Acquisition

The timing offset estimate can be found by searching the maximum of absolute value $|C_i(m)|$, which is given by

$$\hat{\tau}_i = \arg\max_m |C_i(m)| . \tag{10}$$

Since we consider the ISI channel, the mean of timing estimate might be delayed due to the channel dispersion. Fortunately the cyclic prefix (CP) exists, and the coarse timing estimate can therefore be shifted earlier within the CP range by some samples λ as [7]

$$\hat{\tau}_{ic} = \hat{\tau}_i - \lambda, \tag{11}$$

where λ need be carefully chosen so that the start point of the DFT window will not be distorted by the dispersive channel.

4 Minimax Criterion

The minimax approach [10] is applied to design distributed antenna locations for an unknown MS position. For given distributed antenna locations, there exists a least favorable MS position which lead to the worst system performance. The minimax approach offers the optimal upper bound of the worst system performance by searching for every possible combination of antenna locations. In this section, we first derive the probability of correct detection, then introduce the probability of worst case, and finally obtain the optimal antenna locations.

According to [9], at timing instants other than those having path channels, denoted as m_{NC}, $P_i(m_{NC})$ can be negligible due to the sharp auto-correlation property of $s^*(k)$, then $C_i(m_{NC}) \approx P_i(m_{NC})$ thus $|C_i(m_{NC})|$ a Rayleigh variable. Consider the constant false alarm detection, i.e., the probability of false alarm, denoted as P_{FA}, is assumed a constant, the threshold of RX$_i$ can then be set by [11]

$$\gamma_i = \sqrt{-2N\sigma_{iw}^2 \ln P_{FA}}. \tag{12}$$

With the threshold derived above and the coarse timing estimate obtained in (11), the probability of correct detection P_{Di} can be obtained, which means the maximum of $|C_i(m)|$ must exceed the threshold indicating the signal is coming and the timing offset estimate must also be dropped in the ISI free area. Thus, P_{Di} can be presented as

$$\begin{aligned} P_{Di} &= P\left\{|C_i(\hat{\tau}_i)| > \gamma_i,\ -N_g + L_i \le \hat{\tau}_{ic} \le 0\right\} \\ &= P\left\{|C_i(\hat{\tau}_i)| > \gamma_i\right\} P\left\{-N_g + L_i \le \hat{\tau}_{ic} \le 0\right\}, \end{aligned} \tag{13}$$

and the probability that neither receive antenna correctly detects the signal from the MS, denoted by P_N, can be given by

$$P_N = \prod_{i=1}^{I} \left(1 - P_{Di}(|x - a_i|)\right), \tag{14}$$

which means a miss or error detection occurs. The probability of correct detection P_{Di} here is represented as a function of $|x - a_i|$ which is the distance between the MS and RX_i as illustrated in Fig. 1.

The worst case happens when the probability P_N reaches its maximum in terms of a specific MS position (usually at the cell edge); its probability can be expressed as

$$P_{WC} = \max_x \{p(x)P_N\}, \quad x \in [0, R], \tag{15}$$

where $p(x)$ is the probability density function (PDF) of MS distribution.

Apparently the worst case probability P_{WC} should be made as small as possible to provide the best system performance overall. Then, the antenna location design problem becomes an minimax estimation problem [10] and the optimal antenna location solution can be obtained by

$$\hat{a}_i = \arg\min_{a_i} P_{WC}. \tag{16}$$

Substituting (15) into (16), we obtain

$$\hat{a}_i = \arg\min_{a_i} \left\{\max_x \{p(x)P_N\}\right\}. \tag{17}$$

Assuming the MS distribution is uniform, hence $p(x)$ is a constant and can be dropped without affecting the optimal solution, then (17) becomes

$$\hat{a}_i = \arg\min_{a_i} \left\{\max_x P_N\right\}, \quad x, a_i \in [0, R]. \tag{18}$$

5 Simulation Results

The proposed method is investigated by computer simulations. The parameters are depicted in Table. I. The system operates in the ITU-R M.1225 Vehicular test Channel A model [12] with the maximum Doppler shift of 222 Hz which is induced by the MS motion of 120 km/h. The receiver input signal-to-noise ratio (SNR), averaged over multipath fading, is denoted as $\overline{\text{SNR}}$, which is a random variable over the shadow fading at a given distance D. The median of $\overline{\text{SNR}}$, denoted as ρ, is given by [13]

$$\rho = \frac{c\sigma_s^2}{D^\alpha \sigma_w^2}, \tag{19}$$

where the transmit power σ_s^2 can be adjust according to ρ. D is set to $R/2$.

As long as we find out the probability of worst case for every possible set of antenna locations, the optimal antenna locations can immediately be obtained by searching for its minimum. Fig. 2 shows the probability of worst case P_{WC} versus two receive antenna locations with $\rho = 5$ dB assuming no carrier frequency offset. The curve has exactly two minimum points indicating the optimal antenna locations. It is obtained that two distributed receive antennas ought to be located at 170 m and 830 m, respectively, when the search step is set to 5

Table 1. Simulation Parameters

Parameters	**Description**
FFT size	128
CP length	16
Carrier Frequency (GHz)	2
Sampling Frequency (MHz)	1.5
Linear cell length (m)	1000
Constant c [4]	$c \cdot 100^{-3.7} = -78$dB
Minimum distance (m)	20
Noise power (dBm)	-100
Shadowing standard deviation (dB)	8
Path loss exponent	3.7
Probability of false alarm	1×10^{-6}

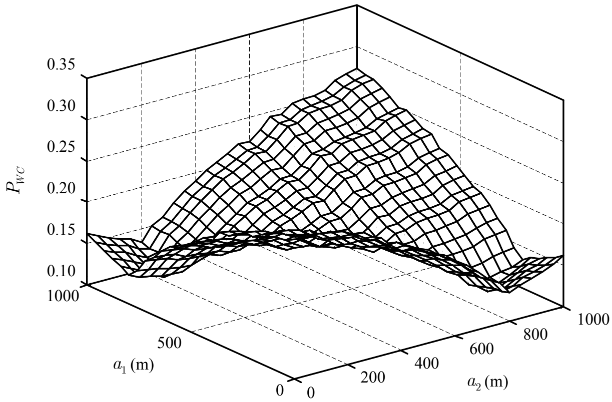

Fig. 2. Probability of worst case versus two receive antenna locations. $\rho = 5$ dB, the search step is 40 m, and carrier frequency offset $\varepsilon = 0$.

m. The curve is also symmetrical about the line $a_1 + a_2 = 1000$, which crosses the two minimum points. Therefore, the distributed antennas should be placed symmetrically about the linear cell center.

Since we employ the cross-correlation method to implement timing acquisition, the effect of carrier frequency offset is concerned. Here we assume that each RX_i has same carrier frequency offset for simplicity. The carrier frequency offset trial values [0, 0.5, 5.6] are evaluated in Fig. 3. The distributed antennas are located at optimal place obtained in Fig. 2. It shows that the carrier frequency offset has little affect on the probability P_N. Thus optimal antenna locations obtained for these carrier frequency offset values are much the same. This result demonstrates robustness to carrier frequency offset as long as which is not very

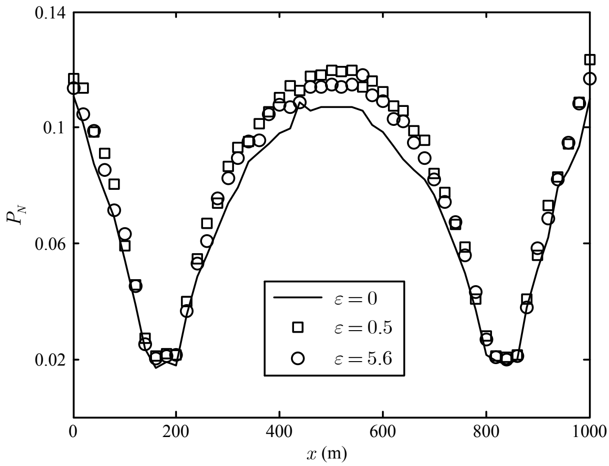

Fig. 3. Probability that neither receive antenna correctly detects the signal versus the MS position. Carrier frequency offset $\varepsilon = 0, 0.5, 5.6$.

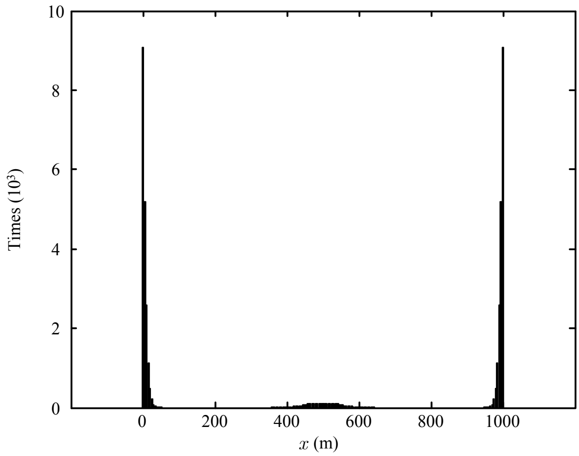

Fig. 4. The times that worst case happens versus the MS position for all combination of antenna locations. Carrier frequency offset $\varepsilon = 0$.

large. It is also observed that the probability P_N has a floor effect when the MS is near the antenna location. This is because the effective distance D_i defined in (3) has a minimum value of 20 m.

Fig. 4 investigate the least favorable MS positions where the worst case happens for all combinations of antenna locations. It shows that the worst case happens either at the cell edges or in the middle of antennas. Both sides of cell edge account for an overwhelming proportion. This is because when the MS is at cell edge, the distance between the MS and the antenna nearest to it, is almost always larger than the distance corresponding to other MS positions.

6 Conclusion

We design distributed antenna locations based on timing acquisition for OFDM systems. With the objective to minimize the probability of worse case among all the possible combinations of antenna position, which is a minimax estimation problem, the optimal antenna locations can be obtained in a sense that the system performs best in the allowed worst case. Simulation results show that the distributed receive antennas should be located symmetrically about the linear cell center when the MS distribution is assumed uniform. The optimal locations are also robust to several trial values of carrier frequency offset. The method can straightforwardly be applied to certain MS distribution and the circular cell scenario as well. However, the search time grows exponentially with the antenna number and some efficient searching algorithms may be required to reduce the computational complexity.

Acknowledgment. This work is supported in part by the National Natural Science Foundation under Grant number 60832007, 60901018, 60902027, U1035002/L05, 61001087, 863 Project under Grant number 2009AA01Z236, the National major projects under Grant number 2010ZX03003–002, 2011ZX03001–006–01, and the Fundamental Research Funds for the Central Universities under Grant number ZYGX2009J008, ZYGX2009J010 of China.

References

1. Zhang, J., Andrews, J.: Distributed antenna systems with randomness. IEEE Trans. Wireless Commun. 7, 3636–3646 (2008)
2. You, X.-H., Wang, D.-M., Sheng, B., Gao, X.-Q., Zhao, X.-S., Chen, M.: Cooperative distributed antenna systems for mobile communications. IEEE Wireless Commun. Mag. 17(3), 35–43 (2010)
3. Shen, Y., Tang, Y., Kong, T., Shao, S.: Optimal antenna location for STBC-OFDM downlink with distributed transmit antennas in linear cells. IEEE Commun. Lett. 11, 387–389 (2007)
4. Wang, X., Zhu, P., Chen, M.: Antenna location design for generalized distributed antenna systems. IEEE Commun. Lett. 13, 315–317 (2009)
5. Han, L., Tang, Y., Shao, S., Wu, T.: On the design of antenna location for OSTBC with distributed transmit antennas in a circular cell. In: Proc. IEEE International Conference on Communications (ICC), Cape Town, South Africa, pp. 1–5 (2010)
6. Morelli, M., Kuo, C.-C., Pun, M.-O.: Synchronization techniques for orthogonal frequency division multiple access (OFDMA): a tutorial review. Proc. IEEE 95, 1394–1427 (2007)
7. Minn, H., Bhargava, V., Letaief, K.: A robust timing and frequency synchronization for OFDM systems. IEEE Trans. Wireless Commun. 2(4), 822–839 (2003)
8. Chu, D.: Polyphase codes with good periodic correlation properties. IEEE Trans. Inform. Theory 18(4), 531–532 (1972)
9. Awoseyila, A., Kasparis, C., Evans, B.: Robust time-domain timing and frequency synchronization for OFDM systems. IEEE Trans. Consumer Electron. 55(2), 391–399 (2009)

10. Verdu, S., Poor, H.: On minimax robustness: a general approach and applications. IEEE Trans. Inform. Theory 30(2), 328–340 (1984)
11. Kay, S.M.: Fundamentals of Statistical Signal Processing: Detection Theory. Prentice-Hall, Upper Saddle River (1998)
12. Guidelines for evaluation of radio transmission technologies for IMT-2000, Recommendation ITU-R M.1225 (1997)
13. Catreux, S., Driessen, P., Greenstein, L.: Data throughputs using multiple-input multiple-output (MIMO) techniques in a noise-limited cellular environment. IEEE Trans. Wireless Commun. 1(2), 226–235 (2002)