Impact of Antenna Placement on the Radiation Pattern of Frequency Domain Adaptive Antenna Array

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***Abstract*–Frequency domain adaptive antenna array (FDAAA) was proposed in our previous study and was proved to be an effective method to suppress interference caused by frequency selective fading and multiple access interference (MAI) in single-carrier (SC) transmission. The performance of FDAAA receiver will be affected by the antenna placement parameters such as antenna separation and spread of angle-of-arrival (AOA) of resolvable paths. In this paper, we analyze the impact of antenna separation and AOA spread on the radiation pattern of FDAAA receiver and shows the effects of two important parameters: antenna separation and AOA spread.**

***Index-terms*-Single-carrier; Frequency domain adaptive antenna array; Antenna separation; Angle-of-arrival spread**

I. Introduction

In high speed wireless communication, the wireless channel becomes severely frequency selective as the data rate increases due to the multiple paths with different time delays [1]. In such a frequency-selective channel, inter block interference (IBI) and inter symbol interference (ISI) degrade the transmission significantly. To deal with this problem, cyclic prefix (CP) is inserted to each block at the transmitter side and then be removed at the receiver side to avoid IBI. Frequency domain equalization (FDE) technique has been proposed to suppress ISI in single-carrier (SC) transmission [2]. In our previous study [3], frequency domain adaptive antenna array (FDAAA) has been proposed and proved to be effective to suppress the interference in severe frequency selective fading channel. Independent fading between antennas has been assumed. However, the performance of antenna array will be affected by the antenna placement, which determines the radiation pattern of the array [4].

The impact of antenna placement on the radiation pattern of FDAAA receiver is studied in this paper. Both antenna separation and the AOA spread will be considered. The remaining of the paper is organized as follows. Uplink FDAAA receiver for cellular system is introduced in Section II; In Section III, the impact of antenna placement, i.e., antenna separation and AOA spread will be analyzed; Numerical results on the radiation pattern of FDAAA receiver will then be shown in Section IV and finally the paper will be concluded in section V.

II. Uplink FDAAA Receiver in Cellular System

A. System model

It is assumed that the base station (BS) locating at the center of each cell is equipped with N_r antennas, and there are U mobile stations (MSs, i.e., users) in each cell and each user is equipped with a single transmit antenna, as shown in Fig. 1.The *0*-th user is taken as the desired user and the other users are taken as the interfering users. It is assumed that the channel remains unchanged during one block transmission.

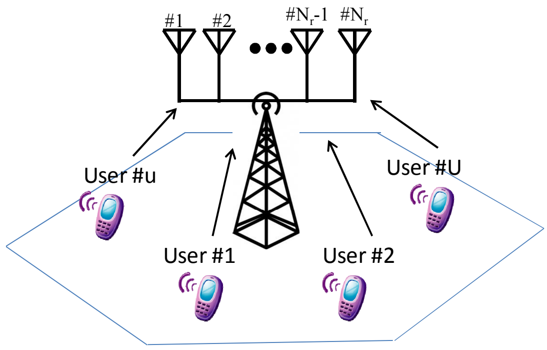


Fig. 1 Uplink transmission in a single cell.

The impulse channel response between the *u*-th user and the BS can be expressed as

$$\mathbf{h}_u(\tau)=\sum_{l=0}^{L-1}\mathbf{h}_{u,l}\delta(\tau-\tau_l), \tag{1}$$

where $\mathbf{h}_{u,l}$ and τ_l are the channel gain vector and time delay of the *l*-th path respectively, $\sum_{l=0}^{L-1}E\left\{\left|h_{u,m,l}\right|^2\right\}=1$ where $h_{u,m,l}$ is the *m*-th element of $\mathbf{h}_{u,l}$ and $E\{\cdot\}$ denotes the statistical expectation. The path delay is assumed to be an integer multiples of the symbol duration and $\tau_l=l$. CP is used and its length is assumed to be longer than the maximum channel length so that IBI can be avoided.

The baseband receive signal vector $\mathbf{r}(n)=[r_0(n),r_1(n),...,$

$r_{N_r-1}(n)\big]^T, (n=1,\cdots,N_c)$ is given by Eq. (2)

$$\begin{aligned}\mathbf{r}(n) &= \sqrt{P_0 d_0^{-\alpha} 10^{-\xi_0/10}} \sum_{l=0}^{L-1} \mathbf{h}_0 s_0(n-\tau_l) \\ &+ \sum_{u=1}^{U-1} \sqrt{P_u d_u^{-\alpha} 10^{-\xi_u/10}} \sum_{l=0}^{L-1} \mathbf{h}_u s_u(n-\tau_l) \\ &+ \sum_{i=0}^{I-1}\sum_{u=0}^{U-1} \sqrt{P_{u,i} d_{u,i}^{-\alpha} 10^{-\xi_{u,i}/10}} \sum_{l=0}^{L-1} \mathbf{h}_{u,i} s_{u,i}(n-\tau_l) + z(n)\end{aligned} \quad (2)$$

where I is the number of co-channel cells; Subscripts u and (u,i) represent the index of the u-th user at the desired cell and the u-th user at the i-th co-channel cell respectively; P represents the transmit power; s is the transmit signal; d represents the normalized distance between the user and the BS of the desired cell; α and ξ represent the path loss exponent and shadowing loss, respectively. $\mathbf{z}(n)=\big[z_0(n) \quad z_1(n) \quad \ldots \quad z_{N_r-1}(n)\big]^T$ is the vector of complex additive white Gaussian noise (AWGN) and superscript ^{T} represents the transpose operation. In this study, slow transmit power control (TPC) in each cell is assumed so that each user will have the same target receive-signal power in average at the corresponding BS. Therefore, the transmit power is given by

$$P_u = \left(\frac{P_{\text{target}}}{d_u^{-\alpha} 10^{-\xi_u/10}} \right) d_{u,0}^{-\alpha} 10^{-\xi_{u,0}/10}, \quad (3)$$

where P_{target} is the target receive-signal power; The frequency domain received signal on the k-th frequency is then expressed as

$$\begin{aligned}\mathbf{R}(k) &= \mathbf{H}_0(k) S_0(k) + \sum_{u=1}^{U-1} \mathbf{H}_u(k) S_u(k) \\ &+ \sum_{i=0}^{I-1}\sum_{u=0}^{U-1} \mathbf{H}_{u,i}(k) S_{u,i}(k) + \mathbf{Z}(k)\end{aligned}, \quad (4)$$

where $\mathbf{H}_u = \big[H_{u,0}(k) \quad H_{u,1}(k) \quad \cdots \quad H_{u,N_r-1}(k)\big]^T$, $S_u(k)$, and $\mathbf{Z}(k) = \big[Z_0(k) \quad Z_1(k) \quad \ldots \quad Z_{N_r-1}(k)\big]^T$ are respectively the frequency domain channel response, transmit signal and noise component, given by Eq. (5). In the right hand side of Eq. (4), the first term comes from the desired user, the second term comes from MUI, the third term comes from CCI and the last term is the noise component.

$$\begin{cases} S_u(k) = \sqrt{P_u d_u^{-\alpha} 10^{-\xi_u/10}} \\ \cdot \sum_{n=0}^{N_c-1} s_u(n) \exp\left(-j2\pi n \frac{k}{N_c}\right) \\ H_{u,m}(k) = \sum_{n=0}^{N_c-1} h_{u,m} \exp\left(-j2\pi n \frac{k}{N_c}\right) \\ Z_m(k) = \sum_{n=0}^{N_c-1} z_m(n) \exp\left(-j2\pi n \frac{k}{N_c}\right) \end{cases}. \quad (5)$$

B. Propagation Model of Adaptive Antenna Array

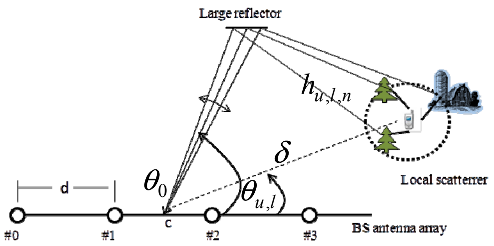


Fig. 2. Propagation model of linear antenna array.

Linear antenna array is assumed and the propagation model is shown in Fig. 2. The geometric center of the array is denoted by c and the antenna separation is denoted by d. θ_0 represents the angle between the line of sight (LOS) direction of MS and the plane of BS array; The plane waveform of the l-th path from the u-th user is consisted of a number of un-resolvable paths and the angle spread of the un-resolvable paths is denoted by δ; In this study, δ is assumed to be zero for simplicity and $h_{u,l}$ represents the plane waveform of the l-th path from the u-th user. The nominal AOA of $h_{u,l}$ observed at array center c is denoted by $\theta_{u,l}$ and the AOA spread of $\theta_{u,l}$ is uniformly distributed within a range of Δ. Therefore, the l-th path gain of the u-th user which is observed at the m-th antenna element can be given by

$$h_{u,l,m} = h_{u,l} \exp\left(-j2\pi \frac{(0.5M - m + 0.5)}{\lambda} d \cos\theta_{u,l}\right), \quad (6)$$

where m = 1, 2, 3, .. , N_r and λ is the carrier wavelength.

C. FDAAA Receiver

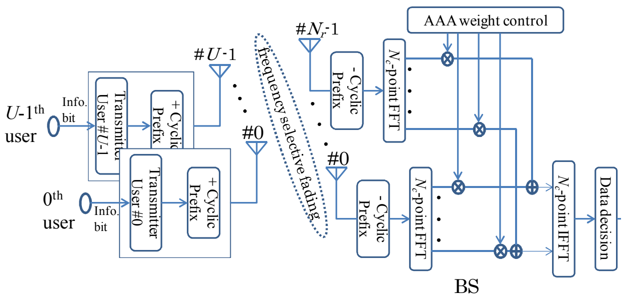


Fig. 3. FDAAA uplink transmission.

In our previous study, FDAAA receiver has been investigated in [3]. The transceiver structure of SC transmission using FDAAA is shown in Fig. 3. At the receiver side, CP is removed and the receive signal at each antenna is transformed to frequency domain signal by using fast Fourier transform (FFT), AAA weight control is then performed on each frequency and the output after AAA weight control is given by

$$\hat{R}(k) = \mathbf{W}_{FDAAA}^H(k)\mathbf{R}(k), \quad (7)$$

where $\mathbf{W}_{FDAAA}(k) = \big[W_{FDAAA,0}(k), W_{FDAAA,1}(k), \ldots, W_{FDAAA,N_r-1}(k)\big]^T$ minimizes the mean square error (MMSE) between $\hat{R}(k)$ and the frequency domain desired signal $S_0(k)$, given by [5]

$$\mathbf{W}_{FDAAA}(k) = \mathbf{X}(k)^{-1}\mathbf{p}(k) , \tag{8}$$

where $\mathbf{X}(k) = E\{\mathbf{R}(k)\mathbf{R}(k)^H\}$ is the auto-correlation matrix of the received signal vector, $\mathbf{p}(k) = E\{\mathbf{R}(k)S_0^*(k)\}$ is the cross correlation vector between the receive signal and the reference signal, superscript ^{H} denotes Hermitan transposition and * denotes the complex conjugate operation. Data decision is then made based on the time domain signal estimate which is obtained by applying inverse FFT (IFFT) to the frequency domain signal component in (7), given by

$$\hat{r}(n) = \frac{1}{N_c}\sum_{k=0}^{Nc-1}\hat{R}(k)\exp\left(j2\pi k\frac{n}{N_c}\right). \tag{9}$$

III. Impact of Antenna Placement

FDAAA receiver was proposed as a solution to combat multiple access interference (MAI) in frequency selective fading environment. In has been proved that when the antennas are considered to be uncorrelated with each other, FDAAA receiver has the ability to accommodate up to N_r users in a single cell and even in cellular environment when the frequency reuse factor (FRF) is big enough. However, the non-antenna-correlation assumption is impractical and correlation often occurs depending on the antenna placement in an array. To understand the impact of antenna placement, antenna separation d and AOA spread Δ are considered in this study. Equation (6) can be re-written by

$$\mathbf{h}_{u,l} = h_{u,l}\mathbf{w}(\theta_{u,l}), \tag{10}$$

where $\mathbf{w}(\theta_{u,l})$ is the steering vector of the linear array, given by

$$\mathbf{w}(\theta_{u,l}) = \left[w_0(\theta_{u,l}), w_1(\theta_{u,l}), \cdots, w_{Nr-1}(\theta_{u,l})\right]^T = \begin{bmatrix} \exp\left(-j2\pi\frac{(0.5N_r-0.5)}{\lambda}d\cos\theta_{u,l}\right) \\ \exp\left(-j2\pi\frac{(0.5N_r-1.5)}{\lambda}d\cos\theta_{u,l}\right) \\ \vdots \\ \exp\left(j2\pi\frac{(0.5N_r-0.5)}{\lambda}d\cos\theta_{u,l}\right) \end{bmatrix}. \tag{11}$$

where $\theta_{u,l}$ is uniformly distributed within a range of Δ and the probability density function of $\theta_{u,l}$ is given by

$$f(\theta_{u,l}) = \begin{cases} \frac{1}{\Delta}; & -\frac{\Delta}{2}+\theta_0 \le \theta_{u,l} \le \frac{\Delta}{2}+\theta_0 \\ 0; & \text{otherwise} \end{cases}. \tag{12}$$

The spatial correlation between the m-th and n-th antenna elements can be calculated by [6]

$$\begin{aligned} D_s(m,n) &= \int_{\theta_{u,l}} w_m(\theta_{u,l})w_n^*(\theta_{u,l})f(\theta_{u,l})d\theta_{u,l} \\ &= \frac{1}{\Delta}\int_{-\frac{\Delta}{2}+\theta_0}^{\frac{\Delta}{2}+\theta_0}\exp\left(j2\pi\frac{m-n}{\lambda}d\cos\theta_{u,l}\right)d\theta_{u,l} \end{aligned} . \tag{13}$$

According to (13), the correlation between antenna elements is a function of AOA spread Δ as well as the antenna separation d. The antenna correlation for $\theta_0 = 60^o$ is shown in Fig. 4. It is shown that when d increases, the antenna correlation decreases with vibration and finally converges to zero as d becomes infinite. In the extreme case when d=0, all the antenna elements in the array become completely correlated. On the other hand, to increase the AOA spread Δ will speed up the decrease of antenna correlation to zero. Therefore, in order to have less correlation between antennas, two possible ways are to increase d by occupying more space or to increase Δ by introducing more reflectors around the antenna array.

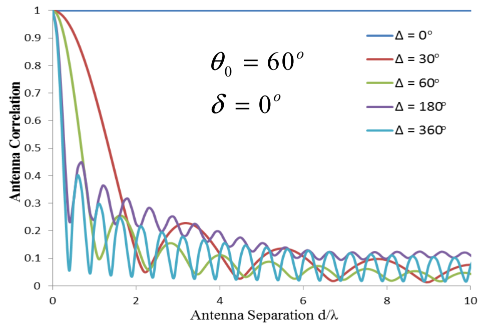


Fig. 4 Antenna correlation for $\theta_0 = 60^o$.

In addition, the antenna correlation will also be affected by angle θ_0 and the relation between antenna correlation, AOA spread, and θ_0 is shown in Fig. 5 where d=λ/2 is used. It is shown that the antenna correlation has the smallest value when $\theta_0 = 90^o$ or $\theta_0 = 270^o$. In other words, in order to reduce the antenna correlation, the third way is to adjust the array plane to be vertical to the incoming waveform.

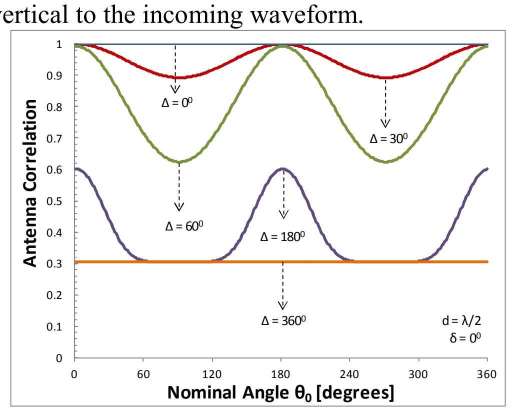


Fig. 5 Antenna correlation and AOA spread.

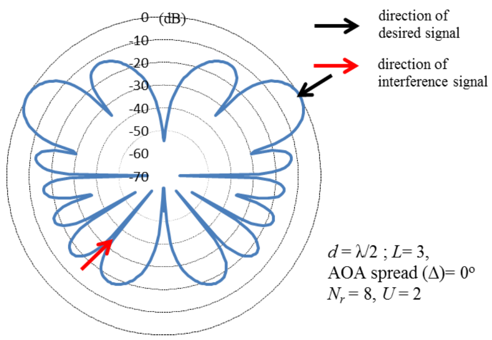
IV. NUMERICAL RESULT

In the next, we are going to study the impact of antenna placement on the radiation pattern of FDAAA receiver by Monte Carlo simulations. The parameters to be used are listed in Tab. 1.

Tab. 1 Simulation Parameters

Transmitter	Data Modulation	QPSK
	FFT size	N_c =256
	TPC	Slow TPC
	Number of user per cell	U = 1~8
	No. of CCI cells	I = 18
	Target receive E_s/N_0 per antenna	10 dB
Channel	Channel model	Frequency-selective block Rayleigh fading
	Power delay profile	L = 16 uniform power delay
	Angle spread of resolvable paths (AOA)	Δ= 30º, 60º, 180º, 360º
	Path loss exponent	α= 3.5
	Standard deviation of shadowing losses	ξ= 6 dB
	Channel State Information	Available only for user within the desired cell
	Nominal angle	Random
Receiver	No. of antennas	N_r = 8
	Antenna separation	λ/2, λ, 5λ, 10λ
	Channel estimation	Ideal

The impact of AOA spread is considered at first. When AOA spread changes from $\Delta = 0^\circ$ to $\Delta = 180^\circ$, the antenna correlation decreases and the radiation pattern of the array is shown in Fig. 6. The arrow in black represents the incoming direction of the desired signal and the arrow in red represents the incoming direction of the interference signal. It is observed that, when the AOA spread increases, the antenna correlation decreases. When $\Delta = 0^\circ$, it is clear that a "beam" is formed towards the direction of the desired signal and a "null" is formed towards the interference signal. However, when $\Delta = 180^\circ$, non-zero array gains appear at the direction of interference signal. It is concluded that the capability of the FDAAA receiver to form "beams" decreases as the AOA spread increases.



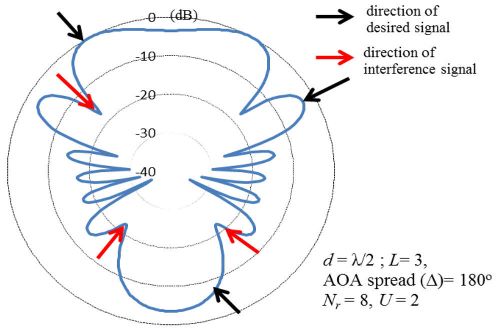


Fig. 6 FDAAA radiation pattern vs. AOA spread.

The impact of antenna separation d is considered in the next. Assuming AOA spread Δ = 30º, the FDAAA radiation pattern is calculated for d=λ/2 and 10λ, respectively, as shown in Fig. 7.

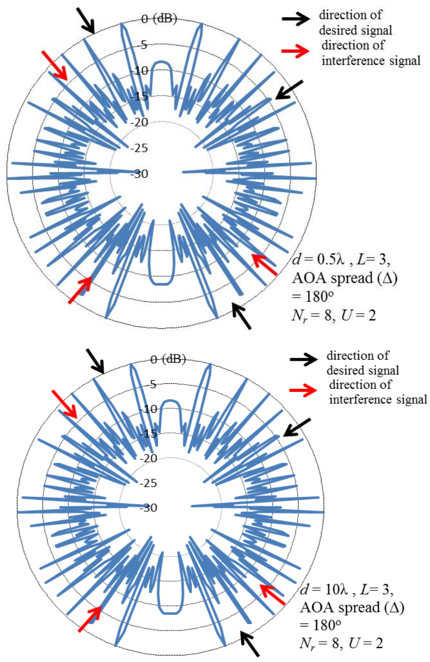


Fig. 7 FDAAA radiation pattern vs. antenna separation d.

When antenna serration increases, the antenna correlation decreases. When $d = 0.5\lambda$, "beams" are formed towards the direction of desired signals while "nulls" are formed towards the direction of interference signals. However, when $d = 10\lambda$, no "beams" nor "nulls" are formed due to the low correlation between antennas. Therefore, when the antenna separation is small, the FDAAA receiver uses beam forming gain to suppress the interference. While when the antenna separation is large, the FDAAA receive uses the diversity gain to suppress the interference.

V.Conclusions

In this paper, the impact of antenna placement on the radiation pattern of FDAAA receiver has been studied. Two parameters, antenna separation and AOA spread, have been considered. It has been shown that, similar to the time domain adaptive antenna array, when the AOA spread increases, the capability of the FDAAA receiver to form "beams" towards the direction of desired user decreases. On the other hand, FDAAA receiver can use the beam forming gain to suppress the interference when the antenna separation is small. Therefore, in the frequency domain array processing, there still exist a tradeoff between the diversity gain and beamforming gain.

Acknowledgement

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References

[1] J. G. Proakis, Digital Communications, New York: McGraw Hill, 2001.

[2] F. Adachi, H. Tomeba, K. Takeda, "Frequency domain Equalization for Broadband Single-Carrier Multiple Access," *IEICE Trans. Commun., vol. 92-B, No. 5, pp1441-1456,* May 2009.

[3] W. Peng and F. Adachi, "Frequency Domain Adaptive Antenna Array Algorithm for Single-carrier Uplink Transmission," *IEEE PIMRC conference*, pp.1-5, Sept. 2009.

[4] J. H. Winters, "Signal Acquisition and Tracking with Adaptive Arrays in the Digital Mobile Radio System IS-36 with Flat Fading," *IEEE Trans. Veh. Tech., vol. 42, pp. 377–384*, Nov. 1993.

[5] J. C. Liberti and J. S. Rappaport, *Smart Antenna for Wireless Communication: IS-95 and Third Generation CDMA Applications*, New Jersey: Prentice Hall, 1995.

[6] B. Friedlander and S. Scherzer, "Beamforming Versus Transmit Diversity in the Downlink of Cellular Communication System," *IEEE Trans. on Veh. Tech.*, vol. 53, No. 4, July 2004.