Frequency Domain Adaptive Antenna Array Algorithm for Single-carrier Uplink Transmission

Wei Peng and Fumiyuki Adachi
Department of Electrical and Communication Engineering, Tohoku University
Sendai, Japan
peng@mobile.ecei.tohoku.ac.jp

Abstract— **In this paper, a frequency domain adaptive antenna array (FD-AAA) algorithm is proposed for the uplink detection in the broadband single-carrier multiple access system. By employing AAA in the frequency domain, the detector is able to suppress both the inter-chip interference (ICI) and the multi-user interference (MUI). Comparison between the proposed FD-AAA algorithm and the frequency domain receive diversity combining (FD-RDC) algorithm is made through simulation. It is shown that when there is no MUI, the bit error rate (BER) performances of the two algorithms are close to each other, i.e., the proposed algorithm can achieve the same frequency diversity gain and receive diversity gain as the FD-RDC algorithm does. However, with the existence of MUI, the proposed algorithm shows a great superiority over the FD-RDC algorithm.**

Keywords-Adaptive antenna array, Single-carrier frequency domain equalization, Receive diversity combining

I. INTRODUCTION

Due to the multi-path fading, the wireless channel is usually characterized by frequency selectivity [1]. As a result, it is necessary to suppress the inter-chip interference (ICI) at the receiver. The ICI can be suppressed by time domain equalization techniques such as coherent rake combing [2]. However, when the data rate increases, the number of resolvable paths increases as well and it becomes difficult for the rake receiver to separate all the paths and the performance will degrade greatly due to the residue ICI. In this case, the frequency domain ICI cancellation will yield better performance. The combination of frequency domain equalization (FDE) and multi-carrier code division multiple access (MC-CDMA) [3] is a good solution for the downlink (from base station (BS) to user) transmission. Recently, the combination of FDE and single-carrier (SC) multiple access [4] is considered as a more suitable solution for the uplink (from user to BS) transmission for its low peak to average power ratio (PAPR). This paper studies the uplink detection for SC transmission by assuming multiple antennas at the BS.

When there are multiple users in the uplink transmission, multi-user interference (MUI) occurs. It is reported [5] that adaptive antenna array (AAA) can effectively reduce the interference in frequency non-selective fading channel when the number of interferers is less than or equal to $(N_r - 1)$ where N_r is the number of receive antennas. However, its application to frequency selective fading channel has been rarely studied. A joint FDE and AAA algorithm was proposed in [6] for frequency selective fading channel. It is assumed in [6] that for each user, its angle of arrival (AOA) for all frequencies is the same and AAA and FDE are performed separately. In other words, the same AAA weight will be used for all frequencies. Limited by this assumption, the algorithm in [6] can not be used when the AOAs of each user spread, which is usually the case in real systems.

In this paper, a frequency domain adaptive antenna array (FD-AAA) algorithm will be proposed for the uplink detection. In the proposed algorithm, the AAA will be carried out in frequency domain and the AAA weight will be derived for each frequency respectively. Note that the proposed algorithm does not have limitations on the AOA distribution of users. Therefore, it is generally applicable. Its performance will be testified by simulation and will be compared with the frequency domain receive diversity combining (FD-RDC) algorithm [7].

The rest of the paper is organized as follows. The system model will be described in Section II. The FD-AAA algorithm will be proposed in Section III followed by a description of the FD-RDC algorithm in Section IV. The performances of the two algorithms are compared by simulation results in Section V. Finally, the paper will be concluded by Section VI.

II. SYSTEM MODEL

The uplink transmission model is shown in Fig. 1. The BS is equipped with N_r antennas. There are U users and each user has one transmit antenna. A block fading channel between each user and the BS is assumed, i.e., the channel remains unchanged during the transmission period. In this paper, the symbol-spaced discrete time representation of the signal is used. Assuming $L-$path channel, the impulse response of the channel between user k and the m^{th} antenna of the BS can be expressed as

$$h_{k,m}(\tau) = \sum_{l=0}^{L-1} h_{k,m,l}\delta(\tau - \tau_l), \tag{1}$$

where $h_{k,m,l}$ and τ_l are the path gain and time delay of the l^{th} path, respectively. $h_{k,m,l}$ follows the complex Gaussian distribution and satisfies $\sum_{l=0}^{L-1} E\left\{\left|h_{k,m,l}\right|^2\right\} = 1$ where $E\{\cdot\}$ represents the expectation. It is assumed that the time delay is an integer multiple of the symbol duration T and $\tau_l = lT$. We assume that block signal transmission with cyclic prefix (CP) insertion is used. It is also assumed that the length of the CP is longer than the maximum path delay of the signal. In the following, the insertion and removal of the CP is omitted for the purpose of simplicity.

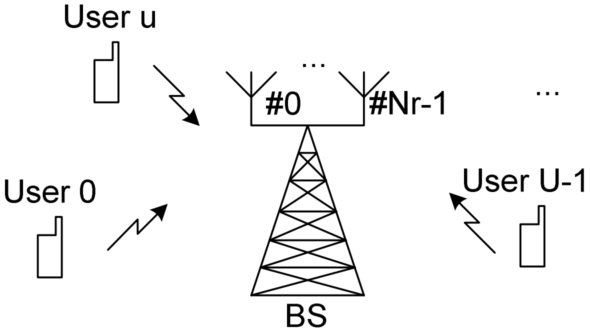

Figure 1 The uplink transmission.

The baseband equivalent received signal block $\{r_m(t); t = 0 \sim N_c\}$ of N_c symbols at the m^{th} antenna is given by

$$r_m(t) = \sqrt{\frac{2E_0}{T}} \sum_{l=0}^{L-1} h_{0,m,l} s_0(t-l) + \sqrt{\frac{2E_u}{T}} \sum_{u=1}^{U-1} \sum_{l=0}^{L-1} h_{u,m,l} s_u(t-l) + n_m(t), \quad (2)$$

where $s_u(t)$ and E_u, $u = 0 \sim U-1$, are the transmit signal and transmit power from user u, respectively; $n_m(t)$ is the additive white Gaussian noise (AWGN). Let the transmit signal from the $u = 0^{th}$ user be the desired signal, and the transmit signals from the other users be the interfering signals.

The frequency domain representation of (2) is given by

$$R_m(k) = H_{0,m}(k) S_0(k) + \sum_{u=1}^{U-1} H_{u,m}(k) S_u(k) + N_m(k), \quad (3)$$

where

$$\begin{cases} S_u(k) = \sqrt{\frac{2E_u}{T}} \sum_{t=0}^{N_c-1} s_u(t) \exp\left(-j2\pi k \frac{t}{N_c}\right) \\ H_{u,m}(k) = \sum_{l=0}^{L-1} \sum_{t=0}^{N_c-1} h_{u,m,l} \exp\left(-j2\pi k \frac{t}{N_c}\right) \\ N_m(k) = \sum_{t=0}^{N_c-1} n_m(t) \exp\left(-j2\pi k \frac{t}{N_c}\right) \end{cases}.$$

The received signal vector $\mathbf{R}(k) = \left[R_0(k), \cdots, R_{N_r-1}(k)\right]^T$ is then expressed as

$$\mathbf{R}(k) = \mathbf{H}_0(k) S_0(k) + \sum_{u=1}^{U-1} \mathbf{H}_u(k) S_u(k) + \mathbf{N}(k), \quad (4)$$

where $\mathbf{H}_u(k) = \left[H_{u,0}(k) \quad H_{u,1}(k) \quad \cdots \quad H_{u,N_r-1}(k)\right]^T$ and $\mathbf{N}(k) = \left[N_0(k) \quad N_1(k) \quad \cdots \quad N_{N_r-1}(k)\right]^T$ with $[\cdot]^T$ representing transpose operation.

III. FD-AAA Algorithm

The transmission structure by using the proposed algorithm is shown in Fig. 2.

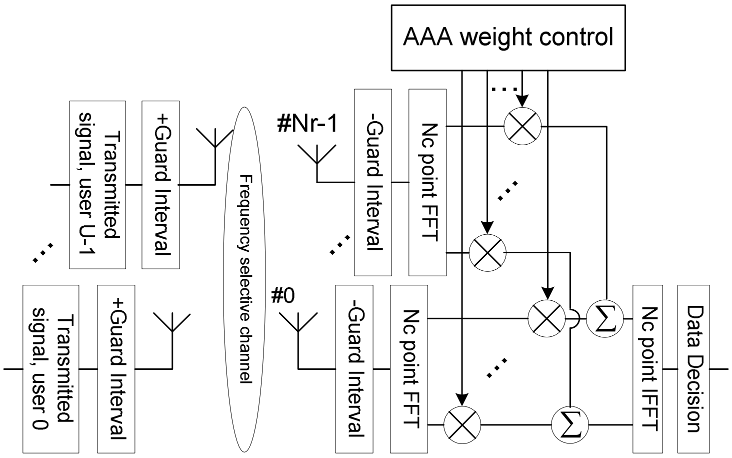

Figure 2 The FD-AAA uplink transmission.

AAA is performed on each frequency as

$$\tilde{R}(k) = \mathbf{W}_{FD-AAA}^T(k) \mathbf{R}(k), \quad (5)$$

where $\mathbf{W}_{FD-AAA}(k) = \left[W_{FD-AAA,0}(k), \cdots, W_{FD-AAA,N_r-1}(k)\right]^T$. The AAA weight that minimize the mean squared error (MSE) between $\tilde{R}(f)$ and the transmitted signal $S_0(k)$ is given by [8]

$$\mathbf{W}_{FD-AAA}(k) = \mathbf{C}_{rr}^{-1}(k) \mathbf{C}_{rd}(k), \quad (6)$$

where

$$\begin{aligned} \mathbf{C}_{rr}(k) &= E\left\{\mathbf{R}^*(k) \mathbf{R}(k)\right\} \\ &= \mathbf{A}_0^*(k) \mathbf{A}_0(k) + \sum_{u=1}^{U-1} \mathbf{A}_u^*(k) \mathbf{A}_u(k) + N_0 \mathbf{I} \end{aligned}, \quad (7)$$

and

$$\mathbf{C}_{rd}(k) = E\left\{\mathbf{R}^*(k) S_0(k)\right\} = \mathbf{A}_0^*(k). \quad (8)$$

In (6) and (7), * denotes complex conjugate operation; $\mathbf{A}_u(k)$ represents the signal propagation vector [9] of user u; N_0 represents the noise power and $\mathbf{I}$ is an $N_r \times N_r$ standard matrix.

After performing AAA, the time domain signal block estimate is obtained by N_c point inverse FFT (IFFT) as

$$\hat{d}(t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{R}(k)\exp\left(-j2\pi k\frac{t}{N_c}\right) \quad (9)$$

for data decision.

IV. FD-RDC Algorithm

The FD-RDC algorithm [7] has similar transmission structure as the FD-AAA algorithm. The difference is that the AAA weight control should be replaced by the RDC weight control to perform RDC instead of AAA. The after-RDC signal is expressed by

$$\tilde{R}_{FD-RDC}(k)=\mathbf{W}_{FD-RDC}^{T}(k)\mathbf{R}(k), \quad (10)$$

where $\mathbf{W}_{FD-RDC}(k)=\left[W_{FD-RDC,0}(k),\cdots,W_{FD-RDC,N_r-1}(k)\right]^T$. In the FD-RDC algorithm, the MUI is treated as noise so that the diversity combining technique can be used to calculate the RDC weight. The RDC weights by various diversity combining criterions can be calculated by [7]

$$\mathbf{W}_{FD-RDC}(k) = \begin{cases} \dfrac{\left[H_{0,0}^{*}(k),\cdots,H_{0,N_r-1}^{*}(k)\right]^T}{\sum_{m=0}^{N_r-1}\left|H_{0,m}(k)\right|^2} & ZF \\ \left[\dfrac{H_{0,0}^{*}(k)}{\left|H_{0,0}^{*}(k)\right|},\cdots,\dfrac{H_{0,N_r-1}^{*}(k)}{\left|H_{0,N_r-1}^{*}(k)\right|}\right]^T & EGC \\ \left[H_{0,0}^{*}(k),\cdots,H_{0,N_r-1}^{*}(k)\right]^T & MRC \\ \dfrac{\left[H_{0,0}^{*}(k),\cdots,H_{0,N_r-1}^{*}(k)\right]^T}{\sum_{m=0}^{N_r-1}\left|H_{0,m}(k)\right|^2+(N_0+E_I)/E_0} & MMSE \end{cases} . \quad (11)$$

where E_I represents the interference power; ZF, EGC, MRC and MMSE represents the corresponding diversity combing technique, respectively. It is shown in [7] that when $N_r \geq 2$, the zero forcing (ZF) RDC and minimum mean squared error (MMSE) RDC have almost the same performance. Therefore, we use the ZF RDC in this study for simplicity.

V. Simulation Results

In this section, the performance of the proposed FD-AAA algorithm is compared with that of the FD-RDC algorithm by simulations. The parameters used in the simulation are listed in the following table.

TABLE I. SIMULATION PARAMETERS

Number of antennas N_r		2, 3, 4
Number of Users U		$1, N_r-1, N_r, N_r+1$
Channel	***Number of paths*** L	16
	Power delay profile	Uniform
N_c		256
E_0/N_0		0dB ~ 20dB
Data modulation		QPSK
AOA distribution		Uniform on $[-\pi,\pi]$

Firstly, no MUI is assumed. The performances of the two algorithms are shown in Fig. 3. It is shown that when no MUI exists, the performance of the FD-AAA algorithm is almost the same as that of the FD-RDC. As the number N_r of antennas increases, both algorithms benefit from the diversity gain and the BER performance improves. In this case, the FD-AAA algorithm can achieve the same receive diversity gain and the frequency diversity gain as the FD-RDC algorithm does.

Next, we consider the situation when $U=N_r-1$. In this simulation, the number of interferers for $N_r=2,3,4$ is 0, 1 and 2, respectively. The performances of the two algorithms are shown in Fig.4. It is shown that with the existence of MUI, the performances of both algorithms degrade. The performance of FD-RDC algorithm degrades because that the MUI is treated as noise and such MUI will not decrease as the signal to noise ratio (SNR) increases. Therefore, error floor occurs. The performance of FD-AAA algorithm degrades because of the residue MUI. However, the residue MUI becomes less significant when SNR increases. As a result, the degraded performance of FD-AAA algorithm is much better than the degraded performance of FD-RDC algorithm which suffers a significant error floor even if there is only one interferer.

It is reported in [5] that an AAA receiver can "tolerate" N_r-1 interferers in a frequency non-selective fading channel. Here, we consider the situation when $U=N_r$ to testify the FD-AAA algorithm's ability to tolerate interference in a frequency selective fading channel. The performances of the two algorithms are shown in Fig. 5. It is shown that when $U=N_r$, the FD-RDC algorithm suffers so deeply from the MUI that its performance is poor even with high SNR= 20dB. On the contrary, the proposed FD-AAA algorithm still achieves satisfactory performance. Due to the diversity gain, its performance improves N_r increases. Therefore, the proposed FD-AAA algorithm can "tolerate" N_r-1 interferers in a frequency selective fading channel, as AAA does in a frequency non-selective fading channel.

Finally, simulation is carried out to testify the performance of FD-AAA versus the number U of users. N_r is set to 4 and U varies from 2 to 5. The performance is shown in Fig. 6. It is shown that given a fixed N_r, the performance of FD-AAA algorithm becomes worse when U increases. This is due to the increase of residue MUI, as we have discussed already. It is also shown that an error floor occurs when U exceeds N_r.

This obvious performance degradation is limited by the fact that AAA can and can only tolerate $N_r - 1$ interferers. Therefore, the number of simultaneous users in the uplink transmission should be limited to $U \le N_r$ when the FD-AAA algorithm is applied.

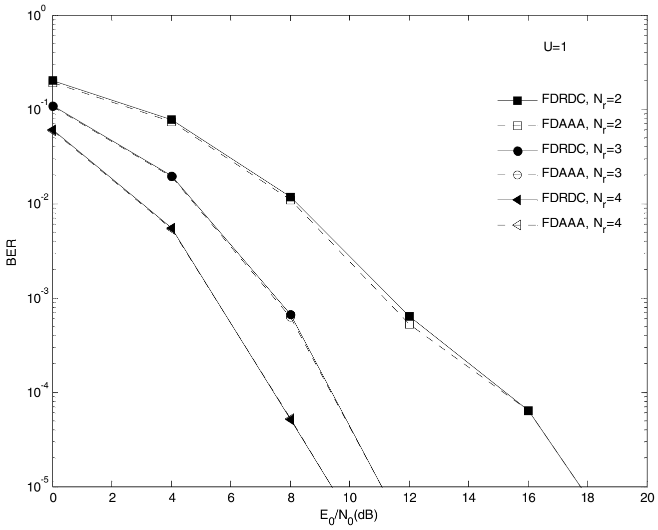

Figure 3 Performance comparison without MUI.

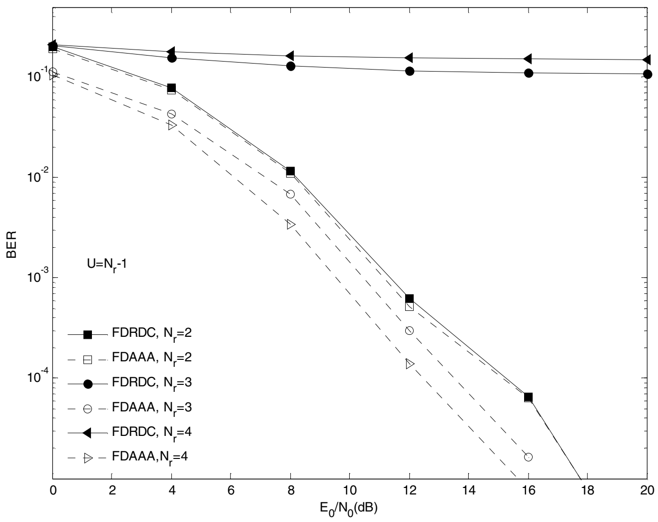

Figure 4 Performance comparison when $U = N_r - 1$.

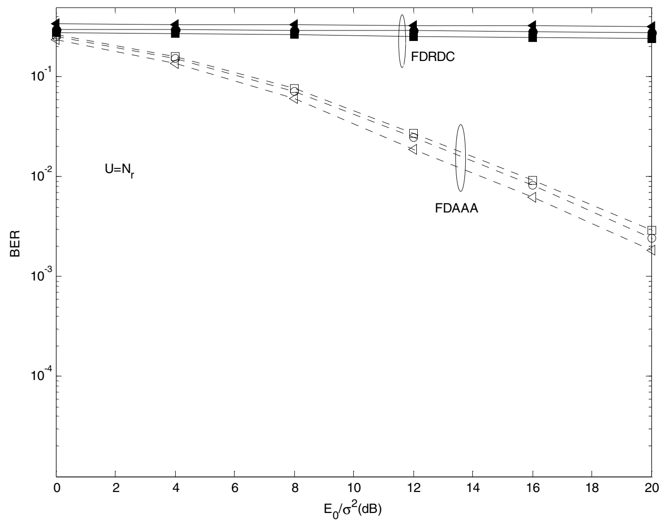

Figure 5 Performance comparison when $U = N_r$.

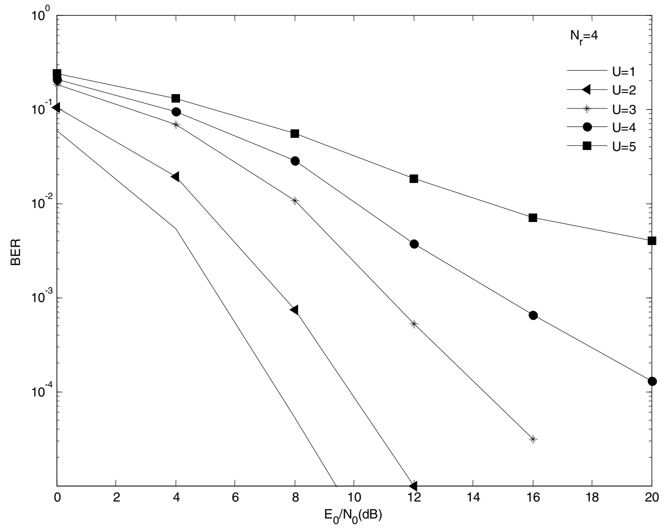

Figure 6 The impact of U on the performance of FD-AAA.

VI. CONCLUSION

In this paper, we proposed a FD-AAA algorithm for the single carrier uplink transmission. This algorithm is effective in both ICI suppression and MUI suppression. Comparisons between the proposed FD-AAA algorithm and the FD-RDC algorithm have been made. It has been shown that when no MUI exists, the FD-AAA algorithm can achieve the same receive diversity order and frequency diversity order as FD-RDC algorithm does. When MUI exists, the performance of FD-RDC algorithm suffers an error floor while the FD-AAA algorithm can still benefit from the receive diversity and achieve good performance. It has also been shown that the FD-AAA algorithm can deal with up to $N_r - 1$ interferers in a frequency selective fading channel.

REFERENCES

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

[2] R. Price and P. E. Green, "A Communication Technique for Multipath Channels," IEEE Proceeding of the IRE, vol. 46, pp. 555-570, March 1958.

[3] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Communication Magazine, vol. 35, pp. 126-133, Dec. 1998.

[4] D. Falconer, S. L. Ariyavistakul, A. Benyamin-Seeyar and B. Edison, "Frequency Domain Equalization for Single-carrier Broadband Wireless Systems," IEEE Communication Magazine, vol. 40, pp. 58-66, April 2002.

[5] J. H. Winters, "Signal Acquisition and Tracking with Adaptive Arrays in the Digital Mobile Radio System IS-36 with Flat Fading," IEEE Transactions on Vehicle Technology, vol. 42, pp. 377–384, Nov. 1993.

[6] B. W. Kang, K. Takeda and F. Adachi, "Performance of Single-Carrier Frequency-Domain Adaptive Antenna Array," IEEE conference VTC Fall 2007, pp. 491-495, Sept. 2007.

[7] F. Adachi, H. Tomeba and K. Takeda, "Frequency-Domain Equalization for Broadband Single-Carrier Multiple Access," IEICE Transactions on Communications, col. E92-B, No. 5, pp. 1441-1456, May 2009.

[8] J. H. Winters, "Signal Acquisition and Tracking with Adaptive Arrays in Wireless Systems," IEEE Conference VTC 1993, pp. 85-88, May 1993.

[9] J. H. Winters, "Optimum Combining for Indoor Radio Systems with Multiple Users," IEEE Transactions on Communications, vol. COM-35, pp. 1222-1230, Nov. 1987.