Frequency-domain One-Tap Weight Control for Single-carrier Multiple Access with Multiple Antennas

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***Abstract*- In this paper, frequency-domain one-tap weight control for single-carrier multiple access with multiple antennas is considered. Adaptive antenna array (AAA) weight control, diversity combining (DC) weight control and least square (LS) weight control are studied. These three weight control algorithms belong to multiple-input multiple-output (MIMO) beam forming, MIMO diversity and MIMO multiplexing, respectively. The weight control algorithms will be evaluated and compared in terms of computational complexity as well as bit error rate (BER) performance in a frequency-selective Rayleigh fading channel.**

Keywords*：*frequency domain, one-tap weight control, single carrier multiple access, computational complexity

I. INTRODUCTION

In broadband data communication, wireless channel is characterized by frequency-selective fading [1]. The transmission performance is severely degraded due to inter-symbol interference (ISI). ISI can be suppressed by time-domain equalization techniques, such as coherent rake combing in direct-sequence code division multiple access [2]. However, as the data rate increases, the number of resolvable paths increases and the performance will degrade greatly due to the residue ISI after rake combining. In this case, frequency-domain equalization (FDE) is more effective to combat the ISI problem.

Recently, the combination of FDE and single-carrier (SC) multiple access [4] is considered as a suitable solution for the uplink (from user to BS) transmission for its low peak-to-average power ratio (PAPR). In uplink transmission, BSs are usually equipped with multiple antennas. When FDE is employed at a BS with multiple antennas, several one-tap weight control algorithms can be used. In our previous study [5], we proposed a frequency-domain adaptive antenna array (FDAAA) which uses AAA weight control on each frequency of SC signal. It has been shown that the FDAAA can achieve good performance in SC transmission.

In this paper, we will evaluate frequency domain one-tap weight control algorithms in terms of computational complexity and bit error rate (BER) performance. Three one-tap weight control algorithms, namely, AAA weight control, diversity combining (DC) weight control and least square (LS) weight control will be considered. These three weight control algorithms belong to multiple-input multiple-output (MIMO) beam forming, MIMO diversity and MIMO multiplexing, respectively.

The rest of the paper is organized as follows. The system model of uplink transmission will be given in Section II. The three frequency-domain one-tap weight control algorithms will be described in Section III. The computational complexity analysis will be given in Section IV. And simulation results are shown in Section V. Finally, the paper will be concluded by Section VI.

II. SYSTEM MODEL

In this study, single cell is considered and the system model of uplink transmission is shown in Fig. 1. The BS is equipped with N_r antennas, and the space between each antenna is $\lambda/2$ where λ is the wavelength so that the antennas are uncorrelated. 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 of a block. 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 l-th path time delay is a multiple integer of the symbol duration and $\tau_l=l$. The cyclic-prefixed (CP) block signal transmission is used to avoid inter block interference (IBI). It is assumed that the CP is longer than the maximum path delay of the signal to make the received signal to be a circular convolution of the channel impulse response and the transmit block. In the following, we omit the insertion and removal of the CP for the simplicity purpose.

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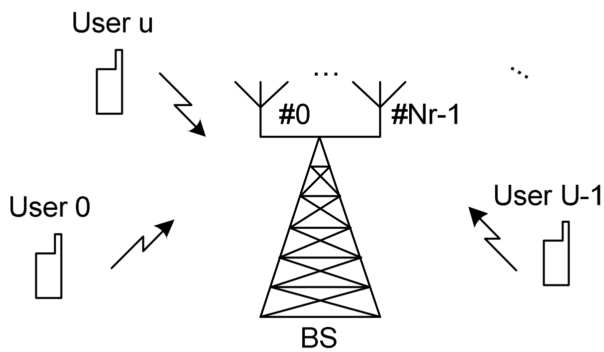

Fig. 1 Uplink transmission.

The baseband equivalent received signal block $\{r_m(i); i = 0 \sim N_c - 1\}$ of N_c symbols at the m^{th} antenna of BS is given by

$$r_m(i) = \sum_{l=0}^{L-1} \sqrt{\frac{2E_0}{T}} d_0^{-\alpha} 10^{-\xi/10} h_{0,m,l} s_0(i-l) + \sum_{u=1}^{U-1} \sum_{l=0}^{L-1} \sqrt{\frac{2E_u}{T}} d_u^{-\alpha} 10^{-\xi/10} h_{u,m,l} s_u(i-l) + n_m(i), \quad (2)$$

where $s_u(i)$ and $E_u(u = 0, \cdots, U-1)$ are the transmitted signal and transmit power from user u, respectively. d_0 represents the distance between the desired user and the BS; d_u represents the distance between the u^{th} interfering user and the BS. α and ξ represent the path loss exponent and shadowing loss in dB, respectively. To simplify the analysis, $\xi = 0$ (no shadowing loss) is assumed. In addition, slow transmit power control (TPC) is assumed so that different user will have unit receive signal power at the BS. T is the signal period and $n_m(i)$ is the additive white Gaussian noise (AWGN). Let the transmitted signal from the $u = 0^{th}$ user be the desired signal, and the transmitted 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

$$\begin{cases} S_u(k) = \dfrac{1}{\sqrt{N_c}} \sum_{i=0}^{N_c-1} s_u(i) \exp\left(-j2\pi k \dfrac{i}{N_c}\right) \\ H_{u,m}(k) = \sum_{l=0}^{L-1} \sum_{i=0}^{N_c-1} h_{u,m,l} \exp\left(-j2\pi k \dfrac{i}{N_c}\right) \\ N_m(k) = \sum_{i=0}^{N_c-1} n_m(i) \exp\left(-j2\pi k \dfrac{i}{N_c}\right) \end{cases}. \quad (4)$$

The first item in (3) corresponds to the desired signal, the second item corresponds to the multi-user interference (MUI) and the last item is the noise component. The received signal vector $\mathbf{R}(k)$ is then expressed as

$$\mathbf{R}(k) = \mathbf{H}_0(k) S_0(k) + \sum_{u=1}^{U-1} \mathbf{H}_u(k) S_u(k) + \mathbf{N}(k), \quad (5)$$

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 symbol $[\cdot]^T$ representing transpose operation.

III. Frequency Domain One-Tap Weight Control Algorithms

The transceiver structure of SC uplink transmission is shown in Fig. 2. Here we use the block of one-tap weight control to generally represent the frequency domain weight control using different algorithms. After N_c-point FFT, the received signal will be transformed into frequency domain and the frequency domain signal expression is given in (3). It has been shown in our previous work [5] that the FDAAA receiver can deal with up to $N_r - 1$ interferences. The LS receiver also requires that the number of receive antennas be larger than or equal to the number of parallel data streams [6]. Therefore, it is supposed that $N_r \geq U$. In the next, the three one-tap weight control algorithms will be described respectively.

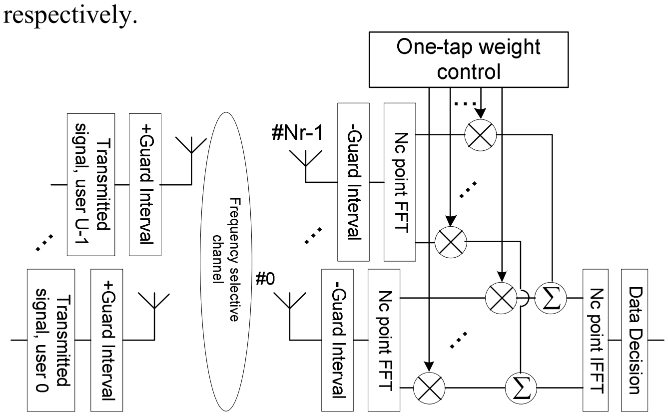

Fig. 2 FD-AAA uplink transmission.

A. AAA weight control

AAA weight control is performed on each frequency as

$$\tilde{R}_{FD-AAA}(k) = \mathbf{W}_{FD-AAA}^T(k) \mathbf{R}(k), \quad (6)$$

where $\mathbf{W}_{FD-AAA}(k) = \left[W_{FD-AAA,0}(k), \cdots, W_{FD-AAA,N_r-1}(k)\right]^T$ is the AAA weight. The AAA weight that minimize the mean squared error (MSE) between $\tilde{R}_{FD-AAA}(k)$ and the transmitted signal $S_0(k)$ is given by [7]

$$\mathbf{W}_{FD-AAA}(k) = \mathbf{C}_{rr}^{-1}(k)\mathbf{C}_{rd}(k), \tag{7}$$

where

$$\mathbf{C}_{rr}(k) = E\{\mathbf{R}^*(k)\mathbf{R}(k)\} \tag{8}$$

is the auto-correlation matrix of the received signal and

$$\mathbf{C}_{rd}(k) = E\{\mathbf{R}^*(k)S_0(k)\} \tag{9}$$

is the cross-correlation matrix between the received signal and the reference signal, * denotes complex conjugate operation. By substituting (5) into (8) we will have

$$\mathbf{C}_{rr}(k) = E\{\mathbf{R}^*(k)\mathbf{R}(k)\} = E\left\{\begin{bmatrix} R_0^*(k)R_0(k) & R_1^*(k)R_0(k) & \cdots & R_{N_r-1}^*(k)R_0(k) \\ R_0^*(k)R_1(k) & R_1^*(k)R_1(k) & \cdots & R_{N_r-1}^*(k)R_1(k) \\ \vdots & \vdots & \ddots & \vdots \\ R_0^*(k)R_{N_r-1}(k) & R_1^*(k)R_{N_r-1}(k) & \cdots & R_{N_r-1}^*(k)R_{N_r-1}(k) \end{bmatrix}\right\}. \tag{10}$$

It is supposed that the interfering transmit signals and noise components are uncorrelated to the desired transmit signal. Therefore, the off-diagonal elements in the right hand side of (10) will reduce to zero after the expectation operation. Then the m^{th} diagonal element of matrix $\mathbf{C}_{rr}(k)$ can be obtained by

$$\begin{aligned}\mathbf{C}_{rr,m}(k) &= E\{R_m^*(k)R_m(k)\} \\ &= E\{S_0^*(k)H_{0,m}^*(k)H_{0,m}(k)S_0(k)\} \\ &+\sum_{u=1}^{U-1}E\{S_u^*(k)H_{u,m}^*(k)H_{u,m}(k)S_u(k)\} \\ &+E\{N_m^*(k)N_m(k)\}\end{aligned}. \tag{11}$$

Similarly, the m^{th} element of matrix $\mathbf{C}_{rd}(k)$ can be given by

$$\begin{aligned}\mathbf{C}_{rd,m}(k) &= E\{R_m^*(k)S_0(k)\} \\ &= E\{S_0^*(k)H_{0,m}^*(k)S_0(k)\} \\ &+\sum_{u=1}^{U-1}E\{S_u^*(k)H_{u,m}^*(k)S_u(k)\}\end{aligned}. \tag{12}$$

B. DC weight control

For the DC algorithm, the signal on the k^{th} frequency after diversity combing is expressed by

$$\tilde{R}_{FD\_DC}(k) = \mathbf{W}_{FD\_DC}^T(k)\mathbf{R}(k), \tag{13}$$

where $\mathbf{W}_{FD\_DC}(k) = \left[W_{FD\_DC,0}(k),\cdots,W_{FD\_DC,N_r-1}(k)\right]^T$ is the DC weight. In DC algorithm, unlike AAA algorithm, the MUI is treated as noise so that the DC technique can be used. There are various DC criterions as [8]

$$\mathbf{W}_{FD\_DC}(k) = \begin{cases} \dfrac{\left[H_{0,0}^*(k),\cdots,H_{0,N_r-1}^*(k)\right]^T}{\sum_{m=0}^{N_r-1}\left|H_{0,m}(k)\right|^2} & ZF \\ \left[\dfrac{H_{0,0}^*(k)}{\left|H_{0,0}^*(k)\right|},\cdots,\dfrac{H_{0,N_r-1}^*(k)}{\left|H_{0,N_r-1}^*(k)\right|}\right]^T & EGC \\ \left[H_{0,0}^*(k),\cdots,H_{0,N_r-1}^*(k)\right]^T & MRC \\ \dfrac{\left[H_{0,0}^*(k),\cdots,H_{0,N_r-1}^*(k)\right]^T}{\sum_{m=0}^{N_r-1}\left|H_{0,m}(k)\right|^2+\left(\sigma^2+P_I\right)/P_0} & MMSE \end{cases}. \tag{14}$$

where ZF, EGC, MRC and MMSE represent the corresponding DC techniques, P_I is the interference power. It is shown in [8] that when $N_r \geq 2$, ZF DC weight and MMSE DC weight have almost the same BER performance. Therefore, ZF DC weight will be used in the following for its simplicity.

C. LS weight control

The LS weight control is performed by

$$\tilde{\mathbf{R}}_{FD\_LS}(k) = \mathbf{W}_{FD\_LS}\mathbf{R}(k), \tag{15}$$

where $\tilde{\mathbf{R}}_{FD\_LS}(k)$ is the vector of frequency signal estimates of U users. $\mathbf{W}_{FD\_LS} = \mathbf{H}^H(k)\left(\mathbf{H}(k)\mathbf{H}^H(k)\right)^{-1}$ and

$$\mathbf{H}(k) = \begin{bmatrix} H_{0,0}(k) & H_{1,0}(k) & \cdots & H_{U-1,0}(k) \\ H_{0,1}(k) & H_{1,1}(k) & \cdots & H_{U-1,1}(k) \\ \vdots & \vdots & \ddots & \vdots \\ H_{0,N_r-1}(k) & H_{1,N_r-1}(k) & \cdots & H_{U-1,N_r-1}(k) \end{bmatrix}.$$

After performing weight control, time domain signal block estimate is obtained by N_c-point inverse FFT (IFFT) for data decision, given by

$$\hat{d}(t) = \frac{1}{\sqrt{N_c}}\sum_{k=0}^{N_c-1}\tilde{R}(k)\exp\left(-j2\pi k\frac{t}{N_c}\right), \tag{16}$$

where $\tilde{R}(k)$ generally represents the frequency domain signal after weight control.

IV. COMPLEXITY ANALYSIS

In this section, we will discuss the computational complexity of the three weight control algorithms in terms of the number of complex-valued multiply operations. The computational complexity of the three frequency domain one-tap weight control algorithms is listed in Tab. I. Note that in real system, channel estimation is necessary for DC algorithm and LS algorithm and simple least square channel estimation is assumed which costs one complex-valued multiply operation on each frequency.

Table I Computational complexity

Weight control	Number of complex-valued multiplications on each frequency		Total computational complexity
AAA	$\mathbf{C}_{rr}$	$O(N_r^2)$	$N_c O(N_r^3 + 2N_r^2 + 2N_r)$
	$\mathbf{C}_{rd}$	$O(N_r)$	
	$\mathbf{C}_{rr}^{-1}$	$O(N_r^3)$	
	$\mathbf{C}_{rr}^{-1}\mathbf{C}_{rd}$	$O(N_r^2)$	
	$\mathbf{W}_{FD\_AAA}^T(k)\mathbf{R}(k)$	$O(N_r)$	
LS	Channel estimation	1	$N_c O(N_r^3 + N_r + 1)$
	$\mathbf{H}^H(k)\left(\mathbf{H}(k)\mathbf{H}^H(k)\right)^{-1}$	$O(N_r^3)$	
	$\mathbf{H}^H(k)\left(\mathbf{H}(k)\mathbf{H}^H(k)\right)^{-1}\mathbf{R}(k)$	$O(N_r)$	
DC	Channel estimation	1	$N_c O(2N_r + 1)$
	$\dfrac{\left[H_{0,0}^*(k),\cdots,H_{0,N_r-1}^*(k)\right]^T}{\sum_{m=0}^{N_r-1}\left\|H_{0,m}(k)\right\|^2}$	$O(N_r)$	
	$\mathbf{W}_{FDDC}^T(k)\mathbf{R}(k)$	$O(N_r)$	

The computational complexity of the three algorithms is then calculated according to Tab. I and compared as shown in Fig. 3. It is shown that DC algorithm has the lowest complexity among the three algorithms. On the other hands, AAA weight control and LS weight control has almost the same complexity, especially when the number of antennas increases.

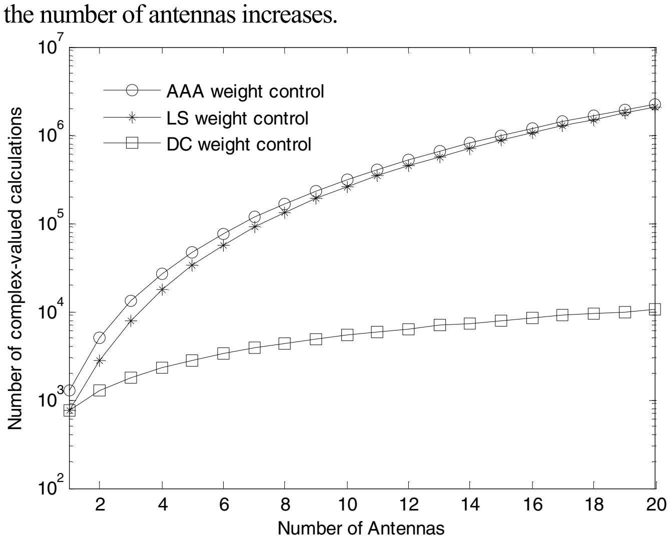

Fig. 3 Computational complexity of the three weight control algorithms.

V. Simulation Results

In this section, the BER performance of the three one-tap weight control algorithms will be compared by simulations. The parameters used in the simulations are listed in Tab. II.

Table II Parameters

Number of antennas, N_r		4
Number of users, U		1~4
Channel	Fading	Block Rayleigh fading
	Number of paths, L	16
	Arriving angles	Random
	Power delay profile	Uniform
	Estimation	Ideal
Number of subcarriers, N_c		256
Signal to noise ratio (SNR)		0dB~20dB
Data modulation		QPSK

At first, $U = 1$ is used so that no MUI exists. The average bit error rate (BER) performance is shown in Fig. 4. It is observed that the three weight control algorithms have almost the same performance when no MUI exists.

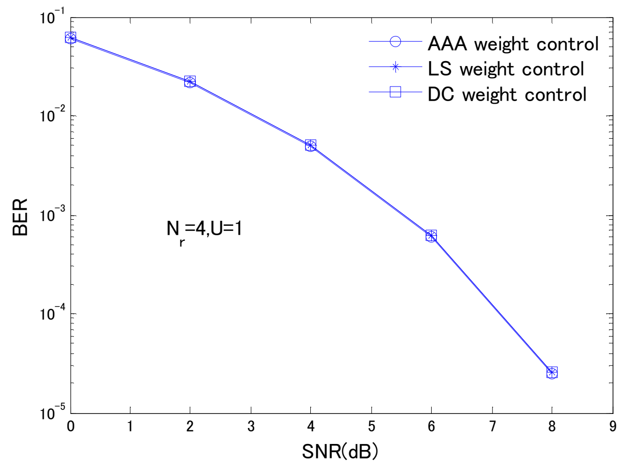

Fig. 4 BER performance comparison, $U = 1$.

In the next, the number of users U is increased from 2 to 4, and the BER performance of the weight control algorithms are shown in Figures 5~7, respectively.

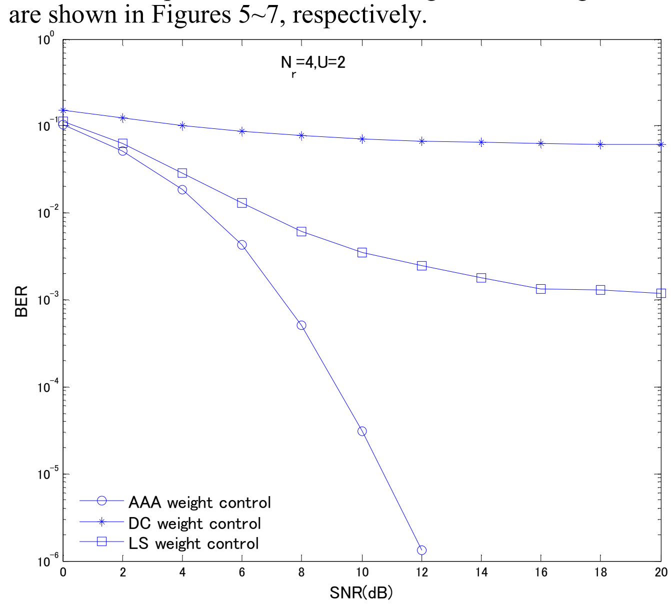

Fig. 5 BER performance comparison, $U = 2$.

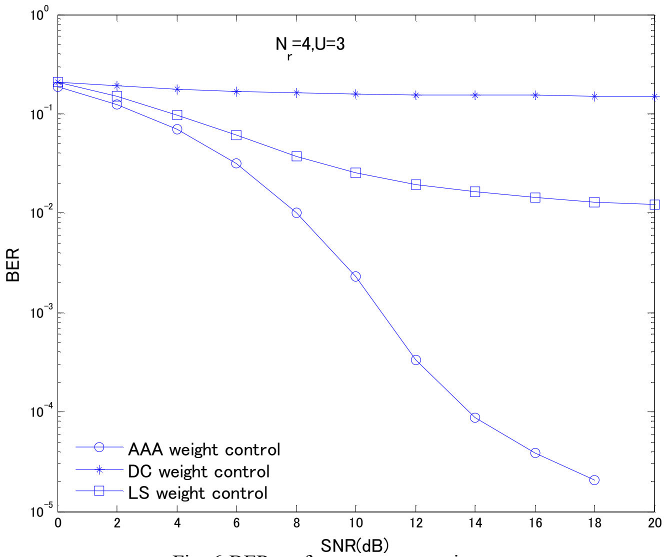

Fig. 6 BER performance comparison, $U = 3$

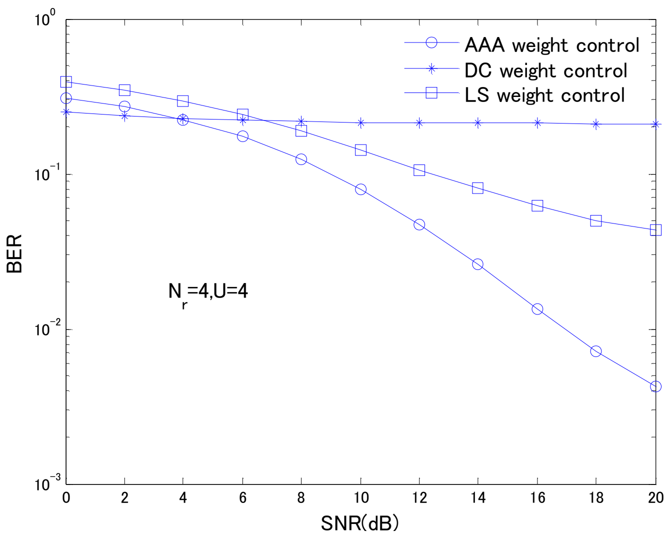

Fig. 7 BER performance comparison, $U = 4$.

It is observed that 1) the performance of the three algorithms all degrades when the number of users increases. This result is straightforward and the performance degradation is caused by the increased amount of MUI. 2) the performance of DC algorithm suffers from significant error floor when $U \geq 2$. The reason is, as already mentioned in Section III-B, the MUI is treated as noise in DC algorithm. When $U \geq 2$, MUI will dominate the BER performance instead of the noise. Therefore, significant error floor occurs in the BER curves of DC algorithm. 3) AAA weight control achieves better performance than that of LS algorithm. This is because that the objective of AAA weight control is to minimize the mean square error between the signal estimate and the transmitted signal of the desired user, while the objective of the LS algorithm is to minimize the square error of the signal estimate vector and the transmitted signal vector. As a result, the LS algorithm will increase the noise power on the desired user while the AAA algorithm will not. Therefore, AAA algorithm can achieve better performance than the LS algorithm. 4) DC algorithm achieves the best performance in low SNR region in the case when $U = 4$. The reason is that when $U = 4$, all the degree of freedom of the receive antennas will be used to suppress the MUI for AAA algorithm as well as the LS algorithm. Since the performance of AAA and LS algorithms are dominated by noise, the diversity gain achieved by DC algorithm can yield better performance in the low SNR region.

VI. CONCLUSIONS

In this paper, three frequency one-tap weight control algorithms have been considered and compared. AAA weight control, DC weight control and LS weight control are chosen as representive of MIMO beam forming, MIMO diversity and MIMO multiplexing respectively. The complexity of the three algorithms have been analyzed, it has been shown that DC algorithm has the lowest complexity among the three algorithms, while the AAA algorithm and LS algorithm have almost the same complexity especially when the number of antennas increases. The BER performance of the three algorithms has been compared through simulation results. It has been observed that the three algorithms will achieve almost the same performance when no MUI exists. And when the number of users increases, DC algorithm will achieve the best performance in low SNR region, however, it suffers from severe error floor when SNR increases. On the other hand, the performance of LS algorithm will be outperformed by the AAA algorithm.

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