Single-carrier Frequency Domain Adaptive Antenna Array for Cellular Systems

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Abstract- **In this paper, a single-carrier frequency domain adaptive antenna array (FDAAA) is proposed for the uplink transmission in cellular systems. The FDAAA algorithm will deal with co-channel interference and exploit the frequency selectivity of the channel fading jointly by using adaptive antenna array in the frequency domain. The receiver of the base station (BS) needs to adjust the AAA weight to optimize the system performance. The conventional cellular structures using frequency reuse factors 1, 3, 4 and 7 are considered. The performance of the proposed algorithm is confirmed by simulations.**

I. INTRODUCTION

Due to the multi-path fading, the wireless channel is characterized by frequency selectivity [1]. As a result, it is necessary to suppress the inter-symbol interference (ISI) at the receiver. The ISI 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 ISI. In this case, the frequency domain ISI 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).

In our previous study [5], we have proposed a frequency domain adaptive antenna algorithm (FDAAA) for the uplink transmission and single cell environment was assumed. It has been shown that the single-cell FDAAA algorithm can achieve good performance and it is not sensitive to the spread of direction of arrivals (DOA) of the received signals [6]. However, in the practical cellular systems, the same carrier frequency will be reused to save the bandwidth resource and co-channel interference (CCI) exists. The channel is no longer noise limited but interference limited instead.

In this paper, we will continue our work on single cell FDAAA and propose a FDAAA algorithm for cellular systems. It will be shown that this is not a simple extension of previous work. Instead, there exists a tradeoff between the interference suppression and diversity gain on the system performance and the optimal cellular FDAAA algorithm depends on the cellular structure and system requirement. The conventional cellular structures using frequency reuse factor (FRF) 1, 3, 4 and 7 will be considered.

The rest of the paper is organized as follows. The system model of uplink transmission in cellular system will be described in Section II. The cellular FDAAA algorithm will be proposed in Section III. And simulation results are shown in Section IV. Finally, the paper will be concluded by Section V.

II. SYSTEM MODEL

The system model of uplink transmission is shown in Fig. 1. At first, the single cell model is described and then extended to multi-cell model. 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 of a block. In this paper, the symbol-spaced discrete time representation of the signal is used. Assuming an $L-$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 $\sum_{l=0}^{L-1}E\{|h_{k,m,l}|^2\}=1$ where $E\{\cdot\}$ represents the expectation. It is assumed that the time delay is a multiple integer of the symbol duration and $\tau_l=l$. The cyclic-prefixed block signal transmission is used to avoid inter block interference (IBI) and it is assumed that the cyclic prefix (CP) is longer than the maximum path delay of the signal. In the following, we omit the insertion and removal of the CP for the simplicity purpose.

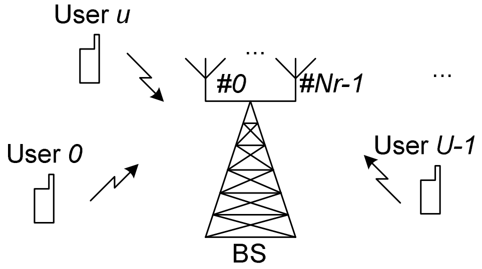

Fig. 1 The uplink transmission.

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

$$\begin{aligned} r_m(t)=&\sqrt{\frac{2E_0}{T}d_0^{-\alpha}10^{-\xi_0/10}}\sum_{l=0}^{L-1}h_{0,m,l}s_0(t-l)\\ &+\sum_{u=1}^{U-1}\sqrt{\frac{2E_u}{T}d_u^{-\alpha}10^{-\xi_u/10}}\sum_{l=0}^{L-1}h_{u,m,l}s_u(t-l)+n_m(t) \end{aligned}, \tag{2}$$

where $s_u(t)$ and E_u are the transmit signal and transmit signal energy of user u $(u=0\sim U-1)$, respectively. d_0

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represents the distance between the desired user and the BS; d_i represents the distance between the i^{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. T is the symbol duration and $n_m(t)$ 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

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

where

$$\begin{cases} S_u(k) = \sqrt{\dfrac{2E_u}{T}} \displaystyle\sum_{t=0}^{N_c-1} s_u(t) \exp\left(-j2\pi k \frac{t}{N_c}\right) \\ H_{u,m}(k) = \displaystyle\sum_{l=0}^{L-1} \sum_{t=0}^{N_c-1} h_{u,m,l} \exp\left(-j2\pi k \frac{t}{N_c}\right) \\ N_m(k) = \displaystyle\sum_{t=0}^{N_c-1} n_m(t) \exp\left(-j2\pi k \frac{t}{N_c}\right) \end{cases}. \tag{4}$$

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

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

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

In the multi-cell environment, there exists CCI from the neighboring cells due to the frequency reuse. The frequency reuse in cellular systems is shown in Fig. 2, where the FRF are 1, 3, 4 and 7, respectively. The commonly used first layer CCI model is used here, i.e., only the CCI from the first layer neighboring cells will be considered and the number of CCI will be B =6.

The received signal at the m^{th} antenna in (2) should be modified to include the CCI, and it can be written as

$$\begin{aligned} r_m(t) = & \sqrt{\frac{2E_0}{T} d_0^{-\alpha}} \sum_{l=0}^{L-1} h_{0,m,l} s_0(t-l) \\ & + \sum_{u=1}^{U-1} \sqrt{\frac{2E_u}{T} d_u^{-\alpha}} \sum_{l=0}^{L-1} h_{u,m,l} s_u(t-l) \\ & + \sum_{i=1}^{B} \sum_{u_i=0}^{U_i-1} \sqrt{\frac{2I_{i,u_i}}{T} d_{i,u_i}^{-\alpha}} \sum_{l=0}^{L-1} c_{u_i,m,l} s_{u_i}(t-l) + n_m(t-l) \end{aligned} \tag{6}$$

where s_{u_i} and I_{i,u_i} is transmit signal and transmit signal energy of the u_i^{th} user in the i^{th} co-channel cell; d_{i,u_i} and $c_{u_i,m,l}$ is the distance and channel gain between the CCI user and the BS.

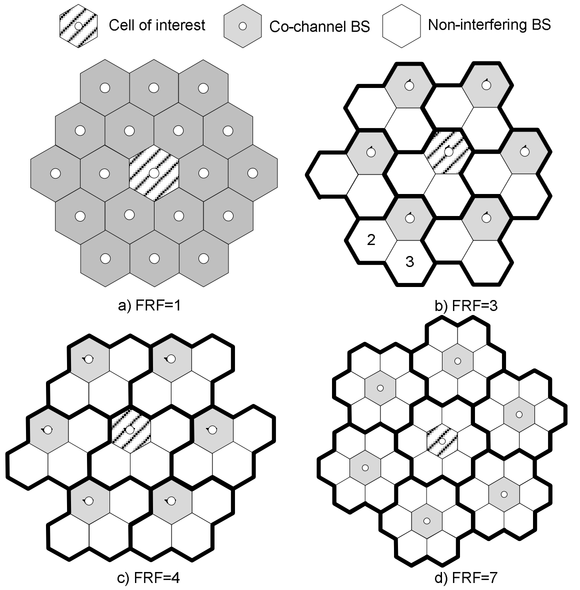
The frequency domain received signal on the k^{th} subcarrier in (3) should be modified as

$$\begin{aligned} R_m(k) = & H_{0,m}(k) S_0(k) + \sum_{u=1}^{U-1} H_{u,m}(k) S_u(k) \\ & + \sum_{i=1}^{B} \sum_{u_i=0}^{U_i-1} H_{u_i,m}(k) S_{u_i}(k) + N_m(k) \end{aligned}, \tag{7}$$

where

$$\begin{cases} S_{u_i}(k) = \sqrt{\dfrac{2I_{u_i}}{T} d_{i,u_i}^{-\alpha}} \displaystyle\sum_{t=0}^{N_c-1} s_{u_i}(t) \exp\left(-j2\pi k \frac{t}{N_c}\right) \\ H_{u_i,m}(k) = \displaystyle\sum_{l=0}^{L-1} \sum_{t=0}^{N_c-1} c_{u_i,m,l} \exp\left(-j2\pi k \frac{t}{N_c}\right) \end{cases}. \tag{8}$$

The third term in (7) is the CCI component.



a) FRF=1 b) FRF=3 c) FRF=4 d) FRF=7

Fig. 2 Frequency reuse in cellular systems.

Fast transmit power control (TPC) in each cell is assumed. The users in each cell will adjust their transmit power so that the signal to noise ratio (SNR) received at the corresponding BS will satisfy the system requirement on receive SNR, i.e.,

$$10\log\left(\frac{E_i}{T} \cdot d_i^{-\alpha} \Big/ \sigma^2\right) = 10\log\left(\frac{I_{i,u_i}}{T} \cdot d_{i,u_i}^{-\alpha} \Big/ \sigma^2\right) = Q \cdot \tag{9}$$

where σ^2 is the noise power and Q is the required receive SNR.

III. CELLULAR FDAAA ALGORITHM

The transceiver structure of the FDAAA algorithm is shown in Fig. 3. After the N_c-point FFT, the received signal will be transformed into frequency domain and the signal has been given in (7). It has been shown in our previous work [5] that the FDAAA receiver can deal with up to $N_r - 1$ interferences. It is supposed that $N_r \geq U + B$ so that the FDAAA receiver will have enough degree of freedom to deal with the MUI and the CCI at the same time. It is also supposed that the BS has the perfect knowledge of channel state information (CSI) between itself and all the users (including the co-channel users). For simplicity, 1 active user in each cell is assumed and in the future we will extend our analysis to the case of multiple users in each cell.

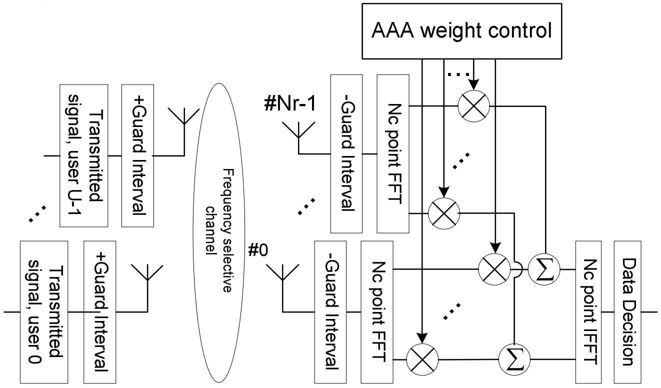


Fig. 3 FD-AAA uplink transmission.

As shown in Fig. 3, AAA weight control is performed on each frequency as

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

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 $\tilde{R}(k)$ and the reference signal $S_0(k)$ (the pilot signal will be used as the reference signal) is given by [7]

$$\mathbf{W}_{FD-AAA}(k) = \mathbf{C}_{rr}^{-1}(k)\mathbf{C}_{rd}(k), \tag{11}$$

where $\mathbf{C}_{rr}(k) = E\left\{\mathbf{R}^*(k)\mathbf{R}(k)\right\}$ is the auto-correlation of the received signal and $\mathbf{C}_{rd}(k) = E\left\{\mathbf{R}^*(k)S_0(k)\right\}$ is the cross-correlation between the received signal and the reference signal, and * denotes complex conjugate operation. After performing AAA, the time domain signal block estimate is obtained by N_c point inverse FFT (IFFT) for data decision, given by

$$\hat{d}(t) = \frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{R}(k)\exp\left(-j2\pi k\frac{t}{N_c}\right). \tag{12}$$

By substituting (7) into (11), $\mathbf{C}_{rr}(k)$ can be obtained as

$$\begin{aligned}\mathbf{C}_{rr}(k) &= E\left\{\mathbf{R}^*(k)\mathbf{R}(k)\right\}\\ &= E\left\{\left[R_0^*(k)R_0(k)\quad\cdots\quad R_{N_r-1}^*(k)R_{N_r-1}(k)\right]^T\right\}\end{aligned}. \tag{13}$$

The m^{th} element of vector $\mathbf{C}_{rr}(k)$ is given by

$$\begin{aligned}\mathbf{C}_{rr,m}(k) &= E\left\{R_m^*(k)R_m(k)\right\}\\ &= E\left\{S_0^*(k)H_{0,m}^*(k)H_{0,m}(k)S_0(k)\right\}\\ &+\sum_{i=1}^{B}E\left\{S_i^*(k)H_{i,m}^*(k)H_{i,m}(k)S_i(k)\right\}\\ &+E\left\{N_m^*(k)N_m(k)\right\}\end{aligned}. \tag{14}$$

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

$$\begin{aligned}\mathbf{C}_{rd,m}(k) &= E\left\{R_m^*(k)S_0(k)\right\}\\ &= E\left\{S_0^*(k)H_{0,m}^*(k)S_0(k)\right\}\\ &+\sum_{i=1}^{B}E\left\{S_i^*(k)H_{i,m}^*(k)S_0(k)\right\}\end{aligned}. \tag{15}$$

It has been mentioned in the previous section that the BS is assumed to have the perfect knowledge of CSI from both the desired user and the co-channel users. Therefore, the BS can realize CCI suppression and/or receive diversity by AAA weight control. If all the interfering signals are treated as equivalent noise, the FD-AAA detector will have full diversity order. However, the signal to interference plus noise ratio (SINR) will be minimized. On the other hand, if the AAA weight is adjusted so that all the interference will be suppressed, then the diversity order will be minimized, but the SINR will be maximized. Therefore, there exists a tradeoff between the SINR level and the diversity order. It is interesting to find out how to perform interference cancellation so that the system performance can be optimized.

IV. SIMULATION RESULTS

In this section, the performance of the cellular FDAAA algorithm will be investigated by simulations. The cellular structure shown in Fig. 2 will be used. To find out the best way to perform interference suppression and to increase the diversity order, 7 modes are defined for the FDAAA receiver. They are listed in Tab. I.

Table I Working modes of FDAAA receiver

Mode #	Diversity order	CCI level
0	N_r	6
1	N_r-1	5
2	N_r-2	4
3	N_r-3	3
4	N_r-4	2
5	N_r-5	1
6	N_r-6	0(No CCI)

The CCI level is the number of remaining CCI signals. For example, mode 0 has a diversity order of N_r which means that all the CCI signals are treated as equivalent noise. Therefore, the corresponding CCI level is 6. In the simulations, if CCI suppression is performed, it will be performed on the CCI users with the most significant receive power at the BS.

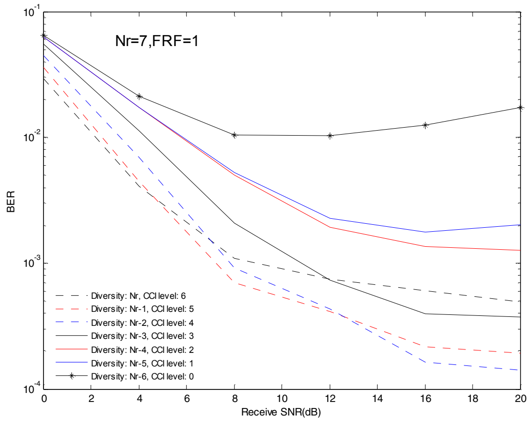
The parameters used in the simulations are listed in Tab. II.

Table II Parameters

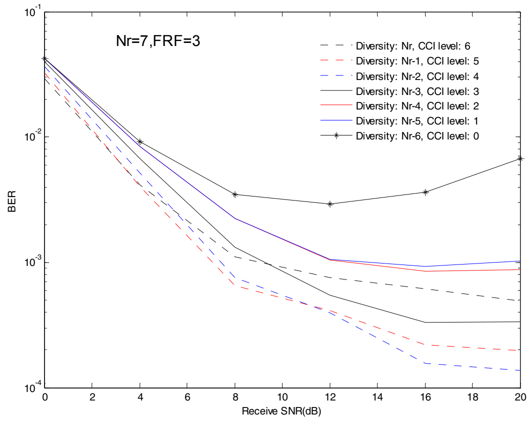
Data modulation		QPSK
Number of antennas N_r		7,8
FRF		1,3,4,7
Number of CCI cells B		6
Number of users U in each cell		1
Channel	Number of paths L	16
	Power delay profile	Uniform
	Estimation	Ideal
N_c		256
Required receive SNR(dB)		0~20
FDAAA working mode		0~6

At first, the bit error rate (BER) performance of FDAAA receiver with 7 receive antennas (N_r =7) is studied. The simulation results are shown in Fig. 4 (a) ~ (d) as a function of required receive SNR. It is very interesting to observe that (1) from Fig. 4 (a) (FRF=1), when the working mode is changed from mode 0 to mode 1, and also from mode 1 to mode 2, the BER performance will be improved. (2) However, when the working mode is changed from mode 2 to mode 3, the BER performance becomes worse in the region of lower receive SNR, but better in the region of higher receive SNR. (3) When we keep changing the working mode from 3 to mode 4, the performance will be degraded, and it does so also from mode 4 to mode 5. The performance becomes worst when mode 6 is employed. (4) The BER performance shown in Fig. 4 (b) (FRF=3) also tells the same story. (5)When the FRF=4 is used (shown in Fig. 4 (c)), the performance becomes better when the working mode is changed from mode 0 to mode 2, it becomes worse from mode 2 to mode 6. (6) When FRF=7 is used, the best BER performance is achieved by working mode 4 in the region of lower receive SNR and by working mode 3 in the region of higher receive SNR.

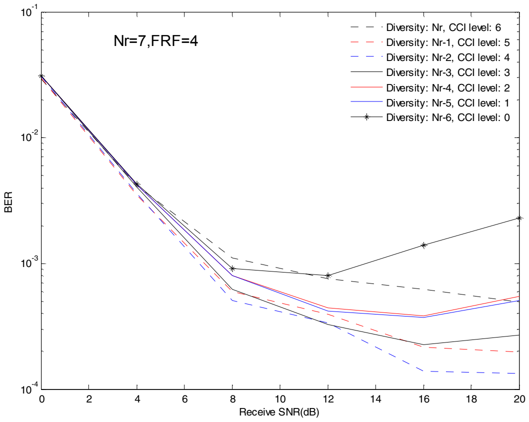
The observations (1) ~ (6) make it clear that (a) the there exist a tradeoff between the CCI suppression and the diversity order, as we have expected. (b) In addition, the best BER performance cannot be achieved by using one working mode. Instead, the working mode that achieves the best performance vary when FRF changes or when the receive SNR changes.



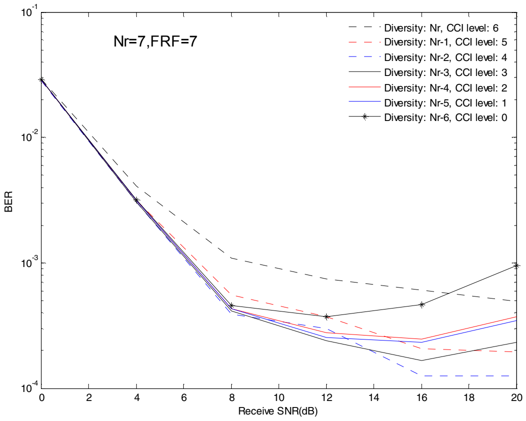
(a) FRF=1



(b) FRF=3



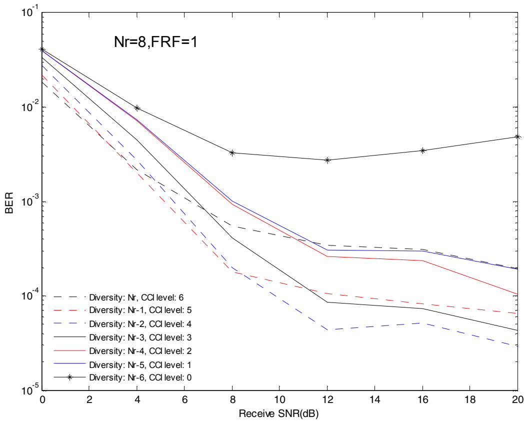
(c) FRF=4



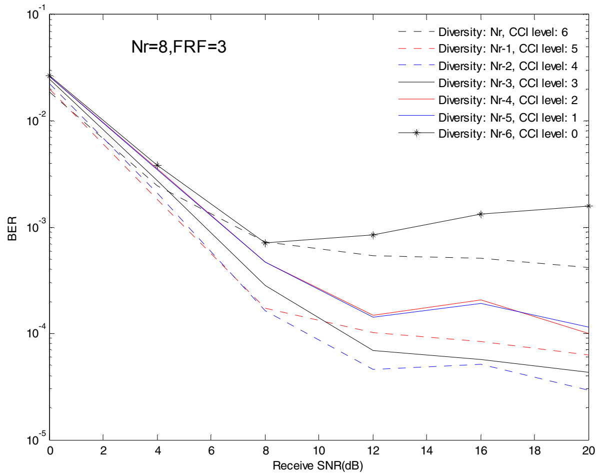
(d) FRF=7

Fig. 4 Performance of FDAAA receiver with N_r =7.

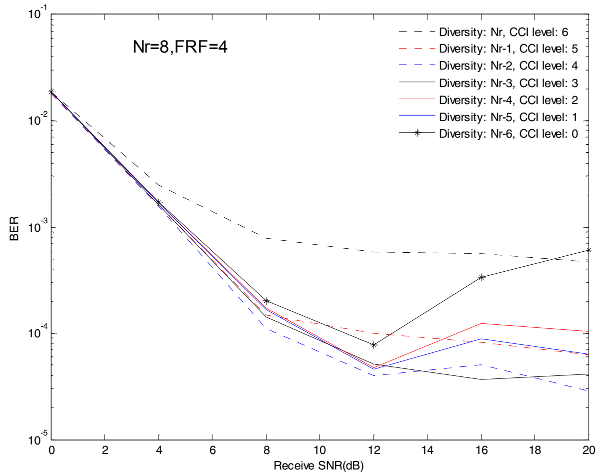
If we increase the number of receive antennas N_r , the receiver will have larger degree of freedom. The simulation results for N_r =8 are shown in Fig. 5 (a) ~ (d). It is shown that the conclusions (a) and (b) are also true with N_r =8 case.



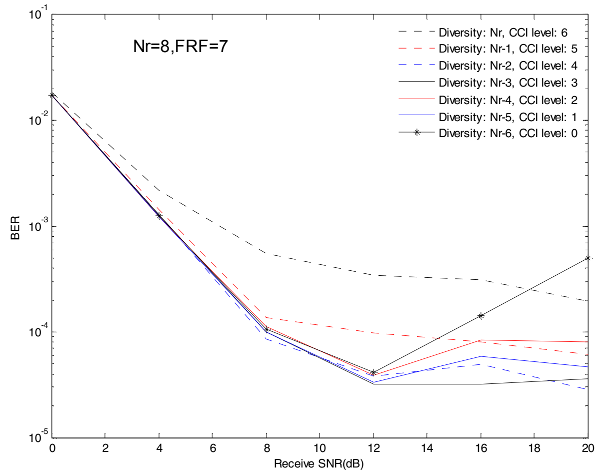
(a) FRF=1



(b) FRF=3



(c) FRF=3



(d) FRF=7

Fig. 5 Performance of FDAAA receiver with N_r =8.

The interested readers may find out that for the working modes which have lower diversity order, the BER performance of the FDAAA receiver becomes worse when the received SNR increases. The reason for this is that by simply using the AAA weight control, the CCI cannot be cancelled out completely and residual CCI exists. When the receive SNR increases, the CCI users will increase their transmit power to meet the receive SNR requirement. As a result, the residual CCI increases. Therefore, the BER performance will be seriously degraded by the residual CCI when the FDAAA receiver woks with less diversity order. In our future study, we will use iterative interference cancellation together with AAA weight control to further cancel out the residual CCI and to improve the system performance.

V. CONCLUSIONS

In this paper, a single-carrier frequency domain adaptive antenna array (FDAAA) algorithm has been proposed for the uplink transmission in cellular systems. Starting from our previous work on the single-cell FDAAA algorithm, the cellular systems have been assumed and the CCI has been taken into consideration. The proposed FDAAA receiver can deal with the CCI suppression and also provide diversity gain. There exists a tradeoff between these two advantages. To find out the best way to use the degree of freedom of the FDAAA receiver, 7 working modes have been defined and their performance have been investigated by simulations. The simulation results show that the working mode to optimize the system performance depends on the frequency reuse factor and the required receive SNR as well. The results also indicate that the system performance could be improved by using iterative CCI cancellation and AAA weigh control. This remains as a topic of our future work.

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

[6] W. Peng and F. Adachi, “A Comparative Study on Pre-FFT and Post-FFT Frequency Domain Adaptive Antenna Array,” Technical Report, IEICE Radio Communication System (RCS), pp. 1-5, Dec. 2009.

[5] J. H. Winters, “Signal Acquisition and Tracking with Adaptive Arrays in the Digital Mobile Radio System IS-36 with Flat Fading,” IEEE Trans. Vehicular 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 VTC 2007- Fall, pp. 491-495, Sept. 2007.

[7] F. Adachi, H. Tomeba, and K. Takeda, “Frequency-Domain Equalization for Broadband Single-Carrier Multiple Access,” IEICE Trans. Communications, vol. E92-B, no. 5, pp. 1441-1456, May 2009.