Single-Carrier Frequency Domain Adaptive Antenna Array for Distributed Antenna Network

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

Fumiyuki Adachi
Department of Electrical and Communication
Tohoku University
Sendai, Japan
adachi@ecei.tohoku.ac.jp

Abstract—**In our previous study, we proposed a single-carrier frequency domain adaptive antenna array (SC-FDAAA) for the conventional cellular network. It has been proved that the SC-FDAAA can effectively suppress the interfering signals from other users in a severely frequency selective fading channel. In this paper, we study the SC-FDAAA for distributed antenna network (DAN) and two DAN SC-FDAAA schemes are proposed. They are, namely, distributed SC-FDAAA and unified SC-FDAAA. The performances of the two DAN SC-FDAAA schemes are compared by computer simulations and the results show that the unified SC-FDAAA has better bit error rate (BER) performance.**

Keywords-distributed antenna network; uplink detection; frequency domain adaptive antenna array

I. INTRODUCTION

The target data rate for the next generation wireless communication system is up to 1Gbps. To realize such a high data rate, there are two major problems. On one hand, due to the multi-path fading, the wireless channel is characterized by severe 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 maximum likelihood sequence estimation (MLSE) [2]. However, when the data rate increases, the number of resolvable paths increases as well and hence, the complexity of MLSE grows exponentially. Compared to the time domain equalization techniques, the frequency domain equalization (FDE) has much less complexity which is not a function of the channel frequency selectivity. On the other hand, the data transmission between the mobile user and the base station (BS) suffers from the interference from the in-cell users as well as the co-channel interference (CCI) [3] (the in-cell interference and CCI together is called multi-access interference (MAI)). In our previous study [4], we have proposed a single-carrier frequency domain adaptive antenna array (SC-FDAAA) algorithm for the uplink transmission for conventional cellular systems. It has been shown that the SC-FDAAA algorithm can achieve good performance in the presence of MAI in a severely frequency selective fading channel.

On the one hand, huge transmit power will be required to realize the high data rate if the cell coverage is kept unchanged. On the other hand, if the transmit power is kept unchanged, then the cell coverage has to be reduced greatly. Distributed antenna network (DAN) [4] was proposed as a solution to increase the cell coverage while maintaining the low transmit power. In the DAN, a number of antennas are distributed in each cell and distributed antennas are connected with the DAN central processor (which is similar to the BS in the conventional cellular system). The mobile user can communicate with the nearby located antennas even when it is at the cell edge. Therefore, the transmit power in the DAN can be kept low while the coverage of the cell can be greatly increased.

In this paper, we will study the SC-FDAAA for DAN. Two DAN SC-FDAAA schemes will be proposed. By using distributed SC-FDAAA, the SC-FDAAA weight for each active cluster of antennas will be generated respectively and then the post SC-FDAAA signals will be combined; while by using the unified SC-FDAAA, the AAA weight for all active clusters of antennas will be uniformly generated. The performance of the proposed DAN SC-FDAAA schemes will be confirmed and compared by computer simulations.

The rest of the paper is organized as follows. The system model of DAN will be described in Section II. The two DAN SC-FDAAA schemes will be proposed in Section III. And simulation results for the achievable bit error rates (BER) are shown in Section IV. Finally, the paper will be concluded by Section V.

II. SYSTEM MODEL

The same carrier frequency is reused in different cells to utilize the limited spectrum efficiently [5]. The cellular systems with frequency reuse factors (FRFs) of 1, 3, 4 and 7 are shown in Fig. 1. 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 $B=6$. In addition, DAN is assumed in each cell and the DAN structure is shown in Fig. 2. The distributed clusters of antennas are connected to the DAN central processor by optical fibers. To lower the cost, each cluster is simply composed of multiple

978-1-4244-7006-8/10/$26.00 ©2010 IEEE

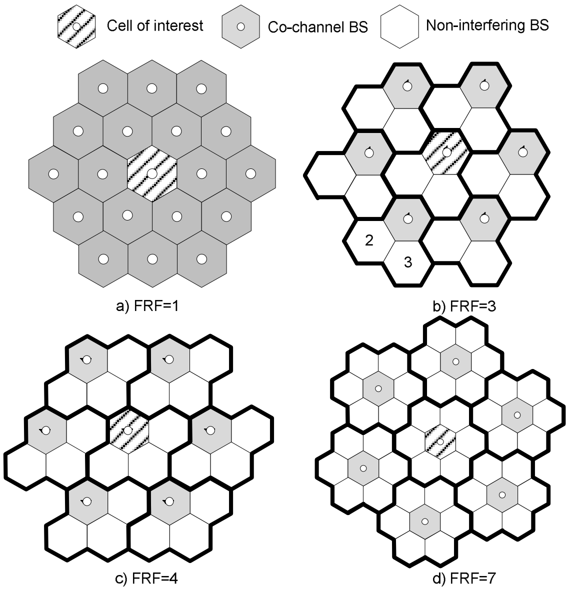
antennas and the signal processing will be carried out by the DAN central processor.

It is assumed that there are D active clusters of antennas and each antenna cluster is equipped with N_r antennas; there are U users within each cell and each user is equipped with one omni antenna. SC-FDAAA transmission is a block transmission. A block fading channel between each user and each cluster of antennas 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 the u^{th} user and the m^{th} antenna of the d^{th} cluster can be expressed as

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

where $h_{u,m,d,l}$ and τ_l are the path gain and time delay of the l^{th} path, respectively. $h_{u,m,d,l}$ follows the complex Gaussian distribution and satisfies $\sum_{l=0}^{L-1}E\left\{\left|h_{u,m,d,l}\right|^2\right\}=1$, 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 (CP) block signal transmission is used to make the received symbol block to be a circular convolution of the transmitted symbol block and the channel impulse response as well as to avoid inter block interference (IBI).

It is assumed that the 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.



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

Figure 1 Cellular system.

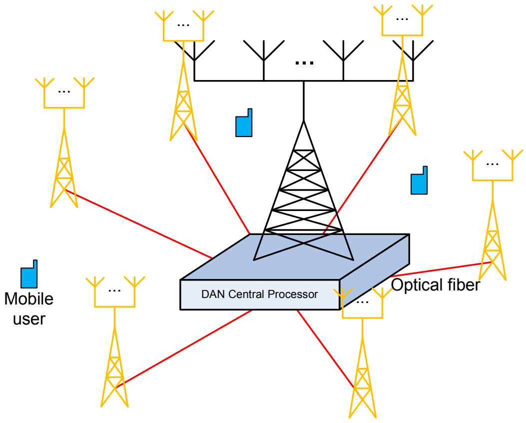


Figure 2 DAN structure.

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

$$\begin{aligned}r_{m,d}(t)&=\sqrt{P_0\delta_{0,d}^{-\alpha}}\sum_{l=0}^{L-1}h_{0,m,d,l}s_0(t-l)\\&+\sum_{u=1}^{U-1}\sqrt{P_u\delta_{u,d}^{-\alpha}}\sum_{l=0}^{L-1}h_{u,m,d,l}s_u(t-l)\\&+\sum_{i=1}^{B}\sum_{u_i=0}^{U_i-1}\sqrt{P_{i,u_i}\delta_{i,u_i,d}^{-\alpha}}\sum_{l=0}^{L-1}h_{u_i,m,d,l}s_{u_i}(t-l)+n_{m,d}(t-l)\end{aligned}, \qquad (2)$$

where $s_u(t)$ and P_u are the transmit signal and transmit signal power of the u^{th} user $(u=0\sim U-1)$, respectively; s_{u_i} and P_{i,u_i} is the transmit signal and transmit signal power of the u_i^{th} user in the i^{th} co-channel cell; $\delta_{0,d}$ represents the distance between the desired user and the d^{th} antenna cluster; $\delta_{i,d}$ represents the distance between the i^{th} interfering user and the d^{th} cluster; $\delta_{i,u_i,d}$ and $h_{u_i,m,l,d}$ is the distance and channel gain between the CCI user and the d^{th} cluster. α represents the path loss exponent in dB. To simplify the analysis, no shadowing loss is assumed. $n_{m,d}(t)$ 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

$$\begin{aligned}R_{m,d}(k)&=H_{0,m,d}(k)S_0(k)+\sum_{u=1}^{U-1}H_{u,m,d}(k)S_u(k)\\&+\sum_{i=1}^{B}\sum_{u_i=0}^{U_i-1}H_{u_i,m,d}(k)S_{i,u_i}(k)+N_{m,d}(k)\end{aligned}, \qquad (3)$$

where

$$\begin{cases} S_u(k) = \dfrac{1}{\sqrt{N_c}}\sqrt{P_u\delta_{u,d}^{-\alpha}}\sum\limits_{t=0}^{N_c-1} s_u(t)\exp\left(-j2\pi k\dfrac{t}{N_c}\right) \\ S_{i,u_i}(k) = \dfrac{1}{\sqrt{N_c}}\sqrt{P_{u_i}\delta_{i,u_i}^{-\alpha}}\sum\limits_{t=0}^{N_c-1} s_{i,u_i}(t)\exp\left(-j2\pi k\dfrac{t}{N_c}\right) \\ H_{u,m,d}(k) = \sum\limits_{l=0}^{L-1}\sum\limits_{t=0}^{N_c-1} h_{u,m,d,l}\exp\left(-j2\pi k\dfrac{t}{N_c}\right) \\ H_{u_i,m,d}(k) = \sum\limits_{l=0}^{L-1}\sum\limits_{t=0}^{N_c-1} h_{u_i,m,d,l}\exp\left(-j2\pi k\dfrac{t}{N_c}\right) \\ N_{m,d}(k) = \dfrac{1}{\sqrt{N_c}}\sum\limits_{t=0}^{N_c-1} n_{m,d}(t)\exp\left(-j2\pi k\dfrac{t}{N_c}\right) \end{cases} . \tag{4}$$

The first term in (3) is the desired signal, the second term is the MAI, the third term is the CCI and the last term is the noise component.

The received signal vector at the d^{th} cluster $\mathbf{R}_d(k) = \left[R_{0,d}(k), R_{1,d}(k)\cdots R_{N_r-1,d}(k)\right]^T$ is then expressed in the vector form as

$$\begin{aligned}\mathbf{R}_d(k) &= \mathbf{H}_{0,d}(k)S_0(k) + \sum_{u=1}^{U-1}\mathbf{H}_{u,d}(k)S_u(k) \\ &+ \sum_{i=1}^{B}\sum_{u_i=0}^{U_i-1}\mathbf{H}_{i,u_i,d}(k)S_{i,u_i}(k) + \mathbf{N}_d(k)\end{aligned} \tag{5}$$

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

III. DAN SC-FDAAA

In this section, the SC-FDAAA algorithm for conventional cellular system will be described at first; then the distributed SC-FDAAA and unified SC-FDAAA for the DAN will be proposed.

A. SC-FDAAA

The transceiver structure of the SC-FDAAA for the uplink transmission in conventional cellular system with N_r antennas at the receiver is shown in Fig. 3. After the N_c-point fast Fourier transform (FFT), the received signal is transformed into the frequency domain signal and AAA weight control is then performed on each frequency. The objective of the AAA weight control is to suppress the MAI as well as the ISI so that the signal to interference plus noise ratio (SINR) can be maximized [4]. N_c-point inverse FFT (IFFT) is then used to obtain the time domain signal estimate for data decision.

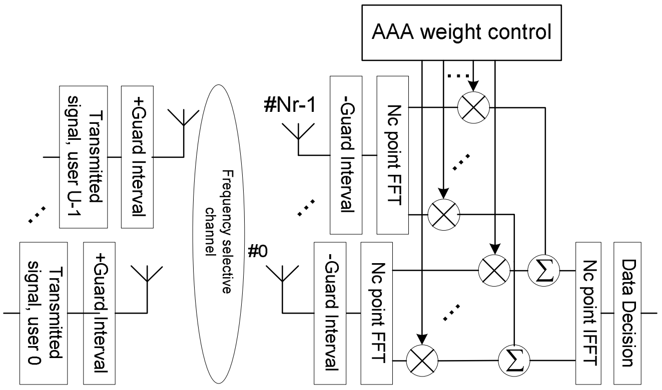


Fig. 3 SC-FDAAA uplink transmission

B. Distributed SC-FDAAA for DAN

The distributed SC-FDAAA receiver is shown in Fig. 4. At first, FDAAA weight control is performed on each cluster of antennas. Take the d^{th} antenna cluster as an example, the received signal is first transformed to the frequency domain signal as given in (3) ~ (5). SC-FDAAA weight control is then performed on each frequency as

$$\tilde{R}_d(k) = \mathbf{W}_d^T(k)\mathbf{R}_d(k) \tag{6}$$

where $\mathbf{W}_d(k) = \left[W_{d,0}(k), \cdots, W_{d,N_r-1}(k)\right]^T$. The AAA weighted signals $\left\{\tilde{R}_d(k); d = 0, \cdots, D-1\right\}$ are combined as

$$\hat{R}(k) = \mathbf{G}(k)\tilde{\mathbf{R}}_d(k). \tag{7}$$

where $\mathbf{G}(k) = \left[G_0(k), \cdots, G_{D-1}(k)\right]$ and $\tilde{\mathbf{R}}_d(k) = \left[\tilde{R}_0(k), \cdots, \tilde{R}_{D-1}(k)\right]$.

The AAA weight that minimize the mean squared error (MSE) between $\tilde{R}_d(k)$ and the reference signal $S_0(k)$ (the pilot signal will be used as the reference signal) is given by [6]

$$\mathbf{W}_d(k) = \mathbf{C}_{rr,d}^{-1}(k)\mathbf{C}_{rd,d}(k), \tag{8}$$

where $\mathbf{C}_{rr,d}(k) = E\left\{\mathbf{R}_d^*(k)\mathbf{R}_d(k)\right\}$ is the correlation matrix of the received signal and $\mathbf{C}_{rd,d}(k) = E\left\{\mathbf{R}_d^*(k)S_0(k)\right\}$ is the cross-correlation vector between the received signal and the reference signal, and * denotes complex conjugate operation.

The time domain signal block estimate is then obtained by N_c- point IFFT for data decision, given by

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

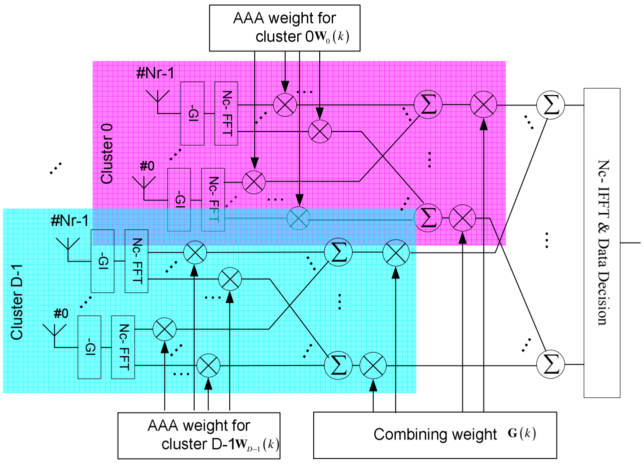


Figure 4 Distributed DAN SC-FDAAA.

C. *Unified SC-FDAAA for DAN*

The unified SC-FDAAA receiver is shown in Fig. 5. In stead of performing SC-FDAAA on each active cluster of antennas, the received signals from all the active clusters of antennas are processed uniformly. The unified FDAAA weight is generated by the DAN central processor. In this study, perfect synchronization among the clusters of antennas is assumed for simplicity. In our future work, the de-synchronization problem will be addressed.

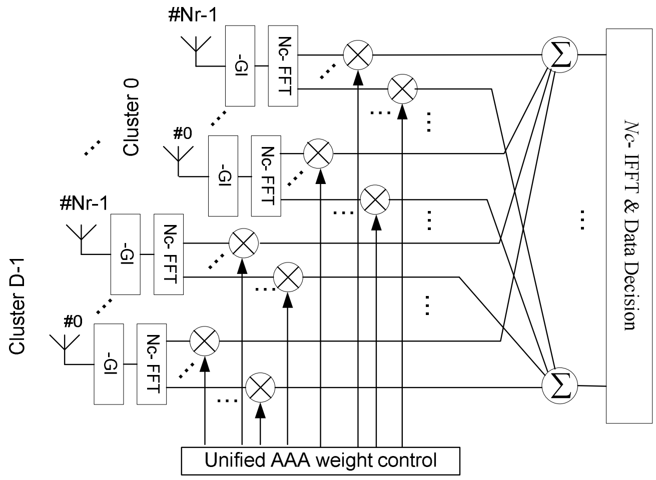


Figure 5 Unified SC-FDAAA for DAN.

The frequency domain signal on the k^{th} frequency after the unified SC-FDAAA weight control is given by

$$\tilde{R}'(k)=\left[\mathbf{W}'(k)\right]^T\mathbf{R}'(k), \tag{10}$$

where $\mathbf{W}'(k)=\left[W_0'(k),\cdots,W_{DN_r-1}'(k)\right]^T$ is the $DN_r\times 1$ weight control vector and $\mathbf{R}'(k)=\left[R_{0,0}\cdots R_{N_r-1,0},R_{0,1}\cdots R_{N_r-1,1},\cdots,R_{0,D-1}\cdots R_{N_r-1,D-1}\right]^T$ is the frequency domain received signal vector which composes of (3) from all the active clusters of antennas. The AAA weight that minimizes the MSE between $\tilde{R}'(k)$ and the reference signal $S_0(k)$ is given by

$$\mathbf{W}'(k)=\left[\mathbf{C}_{rr}'(k)\right]^{-1}\mathbf{C}_{rd}'(k), \tag{11}$$

where $\mathbf{C}_{rr}'(k)=E\left\{\left[\mathbf{R}'(k)\right]^*\mathbf{R}'(k)\right\}$ and $\mathbf{C}_{rd}'(k)=E\left\{\left[\mathbf{R}'(k)\right]^*S_0(k)\right\}$.

The unified SC-FDAAA weighted signals in (11) is then fed to the N_c -point IFFT and the time domain signal block estimate is then obtained for data decision, given by

$$\hat{d}'(t)=\frac{1}{\sqrt{N_c}}\sum_{k=0}^{N_c-1}\hat{R}'(k)\exp\left(j2\pi k\frac{t}{N_c}\right). \tag{12}$$

IV. SIMULATION RESULTS

In this section, the performance of the distributed SC-FDAAA and unified SC-FDAAA schemes for DAN will be investigated by simulations. The cellular structures using FRF =1, 3, 4 and 7 shown in Fig. 1 will be considered. The parameters used in the simulations are listed in Tab. I. In this study, the scheduling among all clusters of antennas is not considered and up to two ($D=1,2$) active clusters of antennas, which are randomly located in a cell, are assumed for simplicity. The scheduling algorithm and more complicated situation remains as the topics of our future work.

TABLE I. SIMULATION PARAMETER

Modulation		QPSK
Channel	Channel Model	Frequency selective block Rayleigh fading
	Number of paths	$L=16$
	Power delay profile	Uniform
	Path loss	$\alpha=3.5$
Number of co-channel cells		$B=6$
Number of antennas of mobile user		1
Number of users per cell		$U=2$
User location distribution		Random
Number of antennas in each cluster		$N_r=4$
Number of active clusters		$D=1,2$
Distribution of clusters		Random
FFT (IFFT) points		$N_c=256$

At first, one active cluster of antennas is used and the BER performance of the uplink transmission as a function of transmit signal to noise ratio (SNR) is shown in Fig. 6. It is shown that better BER performance is achieved when larger

FRF is used. The reason is that when FRF increases, the CCI power reduces due to the increased distance between the CCI user and the receive antennas. However, only a slight BER performance improvement can be seen by increasing the FRF from 4 to 7 and the two curves of FRT=7 and 4 is very close to each other. This is because when the FRF become larger and larger, the CCI power becomes too weak to affect the BER performance. Therefore, the BER performance can not be further improved by increasing the FRF.

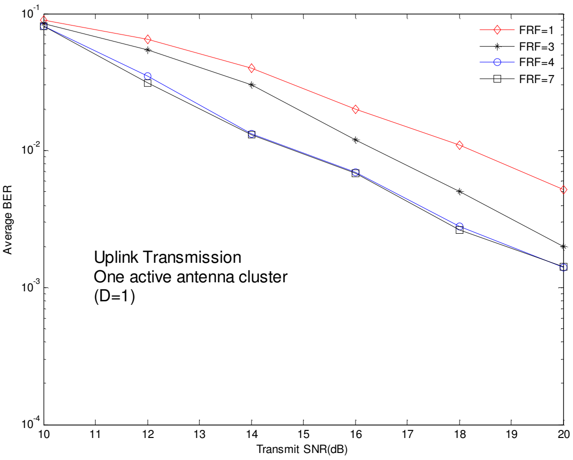


Figure 6 Uplink BER performance when one active cluster of antennas (D =1) is used.

Next, two active clusters of antennas are used and the distributed SC-FDAAA scheme and unified SC-FDAAA scheme are studied and compared as shown in Fig. 7. The uplink average BER performance by using the distributed SC-FDAAA scheme is represented by solid curves. It is observed that: 1) the average BER performance of two active clusters of antennas case has been improved over the case of one active antenna cluster; this improvement comes from the diversity gain obtained from the additional cluster of antennas. The uplink average BER performance by using the unified SC-FDAAA scheme is represented by the dotted curves. It is observed that: 2) the unified SC-FDAAA scheme achieves much better performance than the distributed SC-FDAAA scheme. However, to realize the unified SC-FDAAA scheme, the unified weight control is more computationally complicated.

In addition, good synchronization among different antenna clusters is required for both schemes. In this study, perfect synchronization has been assumed and how to synchronize the active antenna clusters remains as our future work.

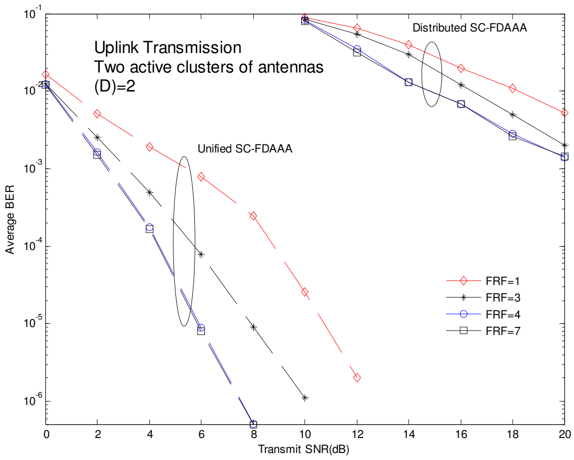


Figure 7 Performance comparison between distributed SC-FDAAA and unified SC-FDAAA when two active clusters of antennas (D =2) are used.

V. CONCLUSIONS

In this paper, we have studied SC-FDAAA for DAN and proposed two DAN SC-FDAAA schemes. The distributed SC-FDAAA scheme performs the weight control on each active cluster of antennas and then combines the weighted signals; while the unified SC-FDAAA scheme performs the weight control on the received signals from all the active clusters of antennas. The BER performance of the two proposed schemes has been studied by computer simulations. It has been shown that 1) the BER performance will be improved by using larger FRF, however, the performance can not be further improved when FRF is larger than 4, 2) both the distributed SC-FDAAA and unified SC-FDAAA achieve better performance than the one active cluster of antennas case, and 3) the unified SC-FDAAA scheme achieves better performance than the distributed SC-FDAAA scheme. In addition, the spectrum efficiency may degrade as FRF increases and therefore, how SC-FDAAA can improve the spectrum efficiency is an important future study.

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] F. Adachi, K. Takeda, T. Obara, T. Yamamoto and H. Matsuda, “Recent advances in single-carrier frequency-domain equalization and distributed antenna network,” IEEE ICICS 2009, pp.1-5, March 2009.

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

[5] W. Peng and F. Adachi, “Multi-user hybrid FRF algorithm for downlink cellular MIMO systems,” IEEE PIMRC, pp.968 - 972, Sept. 2009.

[6] 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.