Frequency Domain Adaptive Antenna Array for Single-Carrier Uplink Transmission

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Abstract—**In this study, we present a single-carrier frequency domain adaptive antenna array (SC-FDAAA) scheme for the uplink transmission and apply the SC-FDAAA scheme to single cell and cellular distributed antenna network (DAN) as well. It is shown by simulation results that the SC-FDAAA scheme can effectively suppress the interfering signals in a severely frequency selective fading channel both in the single cell as well as in the cellular DAN.**

Keywords- uplink transmission; frequency domain adaptive antenna array, cellular system, distributed antenna network

I. INTRODUCTION

The target data rate for the next generation wireless communication system is 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]. Both frequency domain equalization (FDE) and time domain equalization can be used to deal with the frequency selectivity. However, FDE has much less complexity than the time domain equalization [2, 3]. 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) [4, 5] (the in-cell interference and CCI together is called multi-access interference (MAI)).

In order to design an uplink receiver to suppress the MAI in the frequency selective fading channel, we have recently proposed a single-carrier frequency domain adaptive antenna array (SC-FDAAA) scheme for the uplink transmission. The SC-FDAAA scheme can be applied to both the conventional cellular network (CN) and the distributed antenna network (DAN) as well. This paper is a comprehensive study of the SC-FDAAA .

The rest of the paper is organized as follows. The system model of single cell and cellular DAN will be described in Section II. The SC-FDAAA scheme 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 uplink transmission in a single cell 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

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

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 and $\tau_l=l$. 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 simplicity.

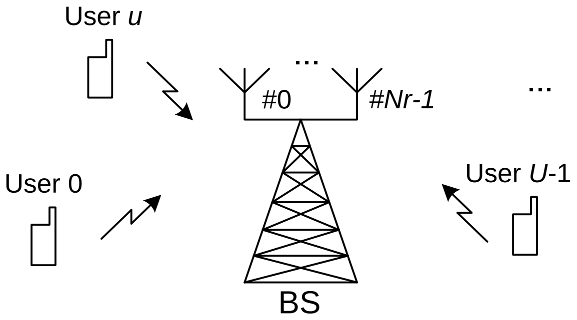


Figure 1 Uplink transmission in single cell.

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

$$\begin{aligned}r_m(t)=&\sqrt{P_0}\sum_{l=0}^{L-1}h_{0,m,l}s_0(t-l)\\&+\sqrt{P_u}\sum_{u=1}^{U-1}\sum_{l=0}^{L-1}h_{u,m,l}s_u(t-l)+n_m(t)\end{aligned}\,, \qquad (2)$$

where $s_u(t)$ and P_u, $u = 0 \sim U-1$, are the transmit signal and transmit signal 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

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

where

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

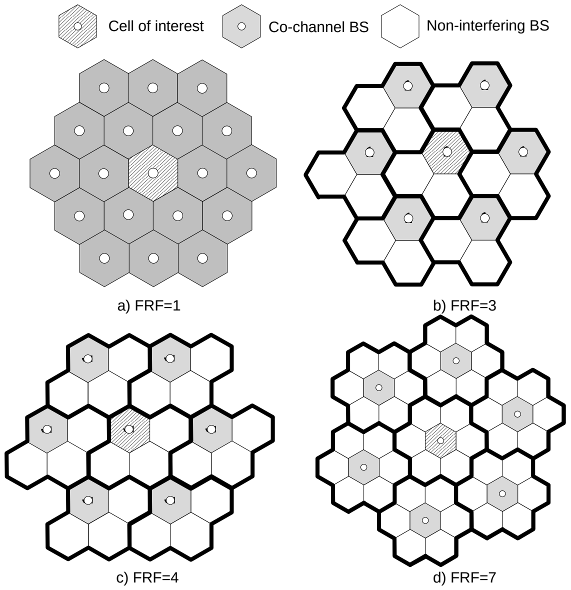
The received signal vector $\mathbf{R}(k) = \left[R_0(k), \cdots, R_{N_r-1}(k)\right]^T$ is then expressed as

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

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.

When the cellular DAN is considered, the same carrier frequency is reused in different DAN cells to utilize the limited spectrum efficiently [6]. The cellular systems with frequency reuse factors (FRFs) of 1, 3, 4 and 7 are shown in Fig. 2. 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. 3. The distributed clusters of antennas are connected to the DAN central processor by optical fibers.

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.



a) FRF=1

b) FRF=3

c) FRF=4

d) FRF=7

Figure 2 Frequency reuse in cellular DAN.

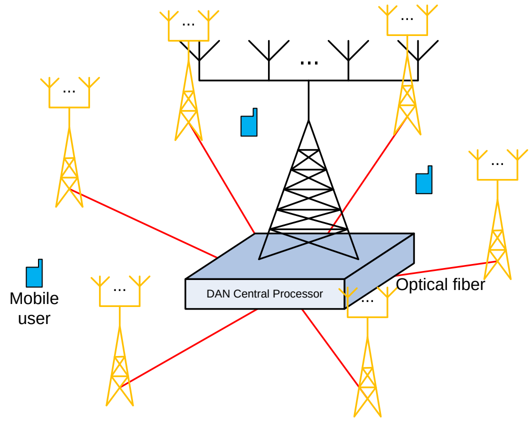


Figure 3 DAN structure.

The baseband equivalent received signal block at the m^{th} antenna of the d^{th} antenna cluster is given by

$$\begin{aligned} r_{m,d}(t) &= \sqrt{P_0 \delta_{0,d}^{-\alpha}} \sum_{l=0}^{L-1} h_{0,m,d,l} s_0(t-l) \\ &+ \sum_{u=1}^{U-1} \sqrt{P_u \delta_{u,d}^{-\alpha}} \sum_{l=0}^{L-1} h_{u,m,d,l} s_u(t-l) \\ &+ \sum_{i=1}^{B} \sum_{u_i=0}^{U_i-1} \sqrt{P_{i,u_i} \delta_{i,u_i,d}^{-\alpha}} \sum_{l=0}^{L-1} h_{u_i,m,d,l} s_{u_i}(t-l) + n_{m,d}(t-l) \end{aligned}, \qquad (5)$$

where 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).

The frequency domain representation of (5) is given by

$$\begin{aligned}R_{m,d}(k)&=H_{0,m,d}(k)S_0(k)+\sum_{u=1}^{U-1}H_{u,m,d}(k)S_u(k)\\&+\sum_{i=1}^{B}\sum_{u_i=0}^{U_i-1}H_{u_i,m,d}(k)S_{i,u_i}(k)+N_{m,d}(k)\end{aligned}, \qquad (6)$$

where

$$\begin{cases}S_{i,u_i}(k)=\dfrac{1}{\sqrt{N_c}}\sqrt{P_{u_i}\delta_{i,u_i}^{-\alpha}}\displaystyle\sum_{t=0}^{N_c-1}s_{i,u_i}(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ H_{u,m,d}(k)=\displaystyle\sum_{l=0}^{L-1}\sum_{t=0}^{N_c-1}h_{u,m,d,l}\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ H_{u_i,m,d}(k)=\displaystyle\sum_{l=0}^{L-1}\sum_{t=0}^{N_c-1}h_{u_i,m,d,l}\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ N_{m,d}(k)=\dfrac{1}{\sqrt{N_c}}\displaystyle\sum_{t=0}^{N_c-1}n_{m,d}(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\end{cases}. \qquad (7)$$

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 matrix form as

$$\begin{aligned}\mathbf{R}_d(k)&=\mathbf{H}_{0,d}(k)S_0(k)+\sum_{u=1}^{U-1}\mathbf{H}_{u,d}(k)S_u(k)\\&+\sum_{i=1}^{B}\sum_{u_i=0}^{U_i-1}\mathbf{H}_{i,u_i,d}(k)S_{i,u_i}(k)+\mathbf{N}_d(k)\end{aligned} \qquad (8)$$

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 $\mathbf{N}_d(k)=\left[N_{0,d}(k)\quad N_{1,d}(k)\quad\cdots\quad N_{N_r-1,d}(k)\right]^T$.

III. SC-FDAAA

In this section, the SC-FDAAA scheme for single cell is presented first; then the SC-FDAAA scheme for cellular DAN will be described.

A. SC-FDAAA for single cell

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. 4. 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.

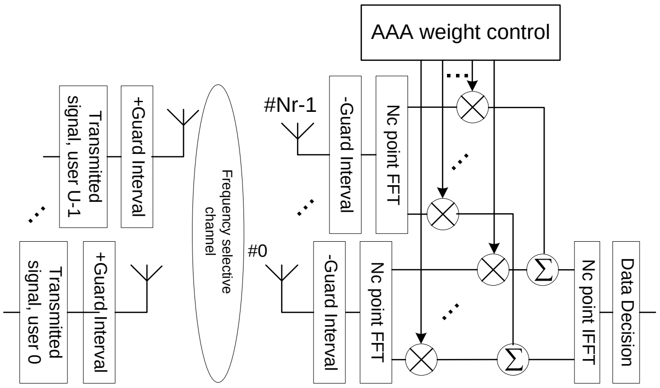


Fig. 4 SC-FDAAA for single cell.

AAA is performed on each frequency as

$$\tilde{R}(k)=\mathbf{W}_{FD-AAA}^{T}(k)\mathbf{R}(k), \qquad (9)$$

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 [7]

$$\mathbf{W}_{FD-AAA}(k)=\mathbf{C}_{rr}^{-1}(k)\mathbf{C}_{rd}(k), \qquad (10)$$

where

$$\begin{aligned}\mathbf{C}_{rr}(k)&=E\left\{\mathbf{R}^*(k)\mathbf{R}(k)\right\}\\&=\mathbf{A}_0^*(k)\mathbf{A}_0(k)+\sum_{u=1}^{U-1}\mathbf{A}_u^*(k)\mathbf{A}_u(k)+N_0\mathbf{I}\end{aligned}, \qquad (11)$$

and

$$\mathbf{C}_{rd}(k)=E\left\{\mathbf{R}^*(k)S_0(k)\right\}=\mathbf{A}_0^*(k). \qquad (12)$$

In (11) and (12), * denotes complex conjugate operation; $\mathbf{A}_u(k)$ represents the signal propagation vector 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

$$\hat{d}(t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{R}(k)\exp\left(-j2\pi k\frac{t}{N_c}\right) \qquad (13)$$

for data decision.

B. SC-FDAAA for cellular DAN

The SC-FDAAA receiver for cellular DAN is shown in Fig. 5. 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.

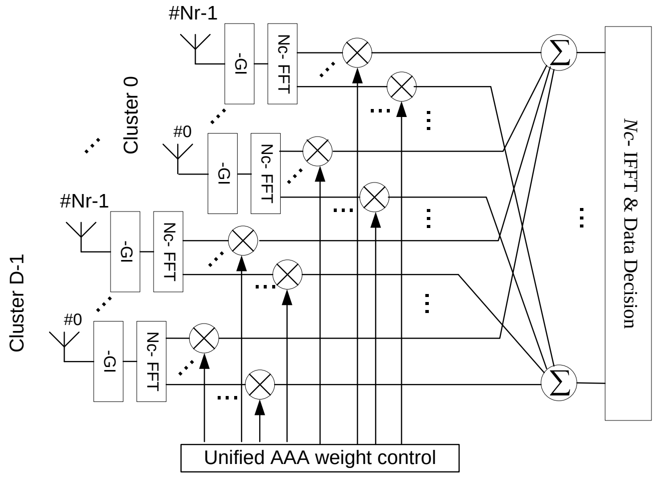


Figure 5 SC-FDAAA for cellular DAN.

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

$$\tilde{R}'(k)=\left[\mathbf{W}'(k)\right]^T\mathbf{R}'(k), \qquad (14)$$

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 (6) 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

$$\mathbf{W}'(k)=\left[\mathbf{C}_{rr}'(k)\right]^{-1}\mathbf{C}_{rd}'(k), \qquad (15)$$

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 weighted signals in (15) is then fed to the N_c-point IFFT and the time domain signal block estimate is then obtained for data decision.

IV. SIMULATION RESULTS

In this section, the performance of the SC-FDAAA scheme will be investigated by simulation results. Both single cell and cellular DAN will be considered. The cellular structures using FRF =1, 3, 4 and 7 shown in Fig. 2 will be used.

First, the single cell is considered and the parameters used in the simulation are listed in Tab. I.

TABLE I. SIMULATION PARAMETERS FORSINGLE CELL

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

Simulation is carried out to testify the performance of SC-FDAAA versus the number U of users. N_r is set to 4 and U varies from 1 to 5. The performance is shown in Fig. 6. It is shown that given N_r, the performance of SC-FDAAA scheme becomes worse when U increases. This is because that as U increases, the degrees of freedom of the receiver is used to cancel the MAI instead of to achieve diversity gain. 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 SC-FDAAA scheme is applied.

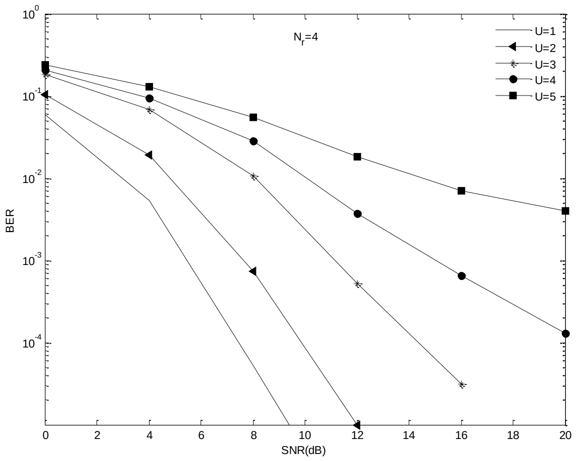


Figure 6 Performance of SC-FDAAA in single cell.

Next, the cellular DAN is considered. The parameters used in this simulation which are different from Tab. I are shown in Tab. II. 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 II. SIMULATION PARAMETERS FOR CELLULAR DAN

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 receive antennas	$N_r=4$
Number of antennas in each cluster	$D=1,2$

At first, one active cluster of antennas is used and the BER performance is shown in Fig. 7. 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 FRF = 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.

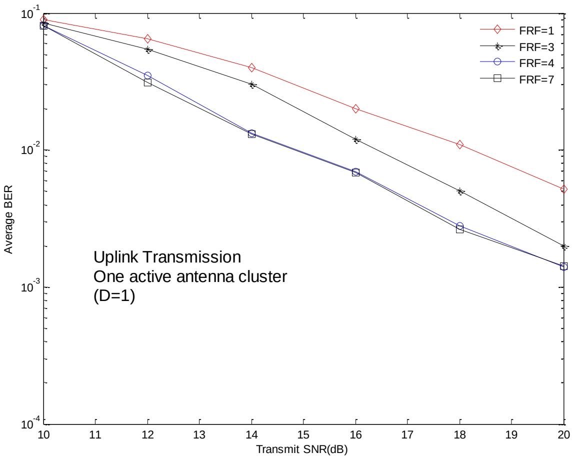


Figure 7 Performance with one active cluster of antennas (D =1) for cellular DAN.

Next, two active clusters of antennas are used and the performance of the SC-FDAAA scheme is shown in Fig. 8. In this simulation, we also give the performance of distributed SC-FDAAA scheme to make a comparison. Instead of performing unified AAA weight control on all the distributed antenna, the distributed SC-FDAAA performs the weight control on each antenna cluster at first and then combined the weighted signals. Hear after, the SC-FDAAA scheme proposed in Section III for cellular DAN is referred to as unified SC-FDAAA. The 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.

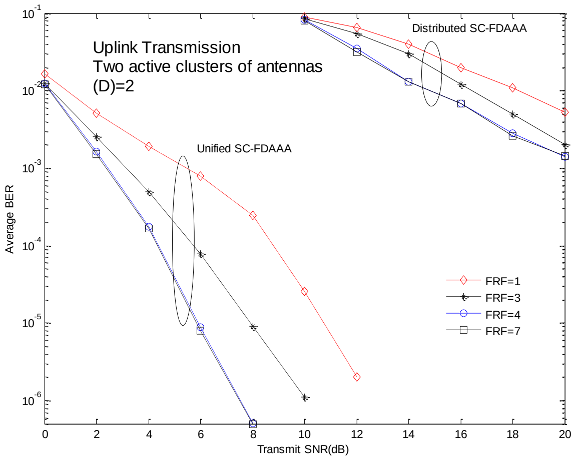


Figure 8 Performance comparison between distributed SC-FDAAA and unified SC-FDAAA with two active clusters of antennas (D =2) for cellular DAN.

V. CONCLUSIONS

In this paper, we have studied SC-FDAAA for single cell and cellular DAN. The BER performance of the SC-FDAAA schemes for both single cell and cellular DAN has been studied by computer simulations. It has been shown that 1) the SC-FDAAA scheme can suppress the MAI in single cell efficiently as long as $U \le N_r$; 2) in cellular DAN, the BER performance will be improved by using larger FRF. However, the performance can not be further improved when FRF is larger than 4; 3) both the distributed SC-FDAAA and unified SC-FDAAA achieve better performance than the one active cluster of antennas case; and 4) 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.

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