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Study on the Capacity of Distributed Antenna Network System by using Single Carrier Frequency Domain Adaptive Antenna Array

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Abstract—**In our previous study, we proposed a single-carrier frequency domain adaptive antenna array (SC-FDAAA) for the distributed antenna network (DAN). 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 studied the capacity performance of DAN SC-FDAAA. Both the ergodic capacity and outage capacity given by the maximum number of users are evaluated.**

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

1. INTRODUCTION

The target data rate for the next generation wireless communication system is up to 1Gbps. To realize such a high data rate transmission, there are two major problems. On one hand, due to many propagation paths having different time delays, the wireless channel is subjected to severely frequency-selective fading [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 propagation 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) for the uplink transmission. And in [5], we proposed SC-FDAAA for distributed antenna network (DAN). 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. In this paper, we will study the uplink capacity of DAN SC-FDAAA. The maximum number of supportable users is considered.

The rest of the paper is organized as follows. The system model is given in Section 2. DAN SC-FDAAA will be described in Section 3. The uplink capacity of DAN FDAAA will be shown in Section 4. Finally, the paper will be concluded by Section 5.

2. SYSTEM MODEL

The same carrier frequency is reused in different 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. 1. To study the capacity of the SC-FDAAA given as the normalized maximum number of users, we will use FRF=1, 3, 4, 7, 9 and 12. 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. There are N_r distributed antennas and they are connected to the DAN central processor by optical fibers. To lower the cost, the signal processing will be carried out by the DAN central processor.

It is assumed that 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 antenna 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 can be expressed as

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

where $h_{u,m,l}$ and τ_l are the path gain and time delay of the l^{th} path, respectively. $h_{u,m,l}$ follows the complex Gaussian distribution and satisfies $\sum_{l=0}^{L-1}E\left\{\left|h_{u,m,l}\right|^2\right\}=1$, 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.

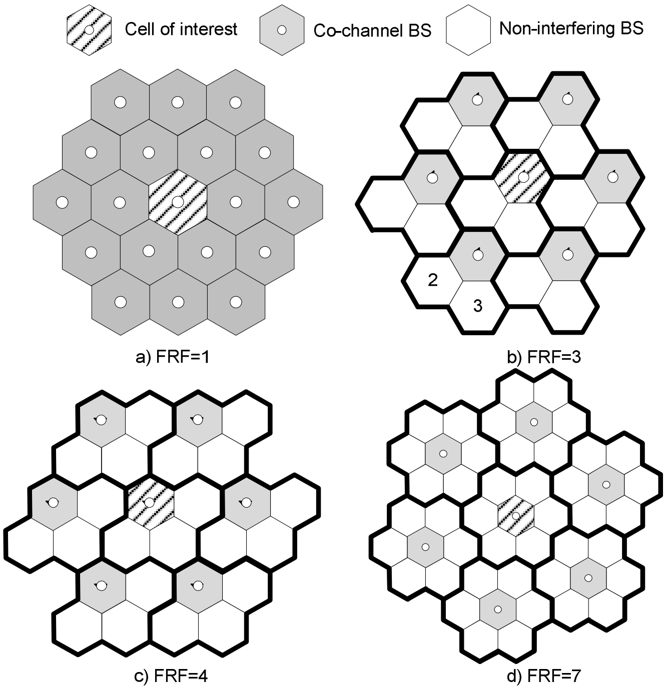

Figure 1 Cellular system.

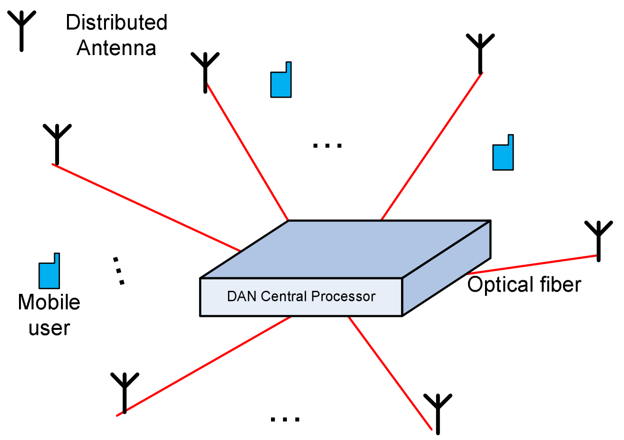

Figure 2 DAN structure.

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

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

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

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

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

where

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

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 signals $\{R_m(k);\ m=0 \sim N_r\}$ are then expressed in the matrix form as

$$\mathbf{R}(k)=\mathbf{H}_0(k)S_0(k)+\sum_{u=1}^{U-1}\mathbf{H}_u(k)S_u(k)+\sum_{i=1}^{B}\sum_{u_i=0}^{U_i-1}\mathbf{H}_{i,u_i}(k)S_{i,u_i}(k)+\mathbf{N}_d(k) \quad (5)$$

where $\mathbf{R}(k)=\left[R_0(k),R_1(k)\cdots R_{N_r-1}(k)\right]^T$, $\mathbf{H}_u(k)=\left[H_{u,0}(k)\ \ H_{u,1}(k)\ \ \cdots\ \ H_{u,N_r-1}(k)\right]^T$, and $\mathbf{N}(k)=\left[N_0(k)\ \ N_1(k)\ \ \cdots\ \ N_{N_r-1}(k)\right]^T$ with $[\cdot]^T$ representing the transpose operation.

3. DAN SC-FDAAA

The uplink transceiver structure of the DAN SC-FDAAA is shown in Fig. 3.

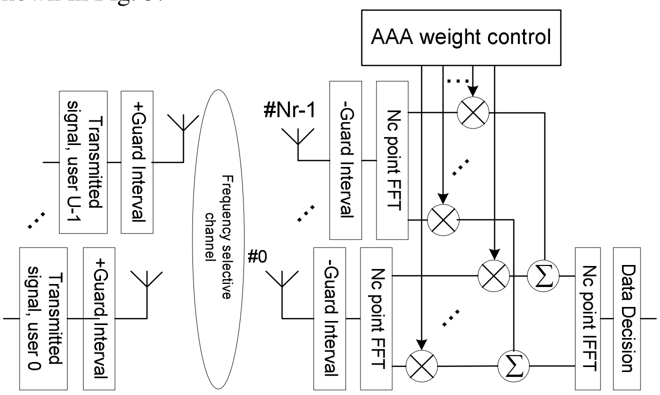

Fig. 3 DAN SC-FDAAA.

The received signal is transformed by an N_c-point fast Fourier transform (FFT) into the frequency domain signal and AAA weight control is then performed on each frequency. SC-FDAAA weight control is performed on each frequency as

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

where $\mathbf{W}(k)=\left[W_0(k),\cdots,W_{N_r-1}(k)\right]^T$.

The AAA weight that minimizes 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]

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

where $\mathbf{C}_{rr}(k)=E\left\{\mathbf{R}^*(k)\mathbf{R}(k)\right\}$ is the correlation matrix of the received signal and $\mathbf{C}_{rd}(k)=E\left\{\mathbf{R}^*(k)S_0(k)\right\}$ 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 an N_c- point IFFT for data decision as

$$\hat{d}(t)=\frac{1}{\sqrt{N_c}}\sum_{k=0}^{N_c-1}\tilde{R}(k)\exp\left(j2\pi k\frac{t}{N_c}\right). \quad (8)$$

4. SIMULATION RESULTS

In this section, the performance of the DAN SC-FDAAA will be investigated by simulations. The cellular structures using FRF =1, 3, 4, 7, 9 and 12 will be considered. The parameters used in the simulations are listed in Tab. I. For simplicity, no channel coding is used. And a slow transmit power control (TPC) is assumed to achieve the required received signal-to-noise ratio (SNR) in each cell. In addition, we assume that the required received SNR is infinitely large, i.e., the noise can be ignored and the link is interference limited. In this study, the scheduling among the distributed antennas is not considered. The distributed antennas are located in a cell randomly. The scheduling algorithm and more complicated situation remain 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	$\alpha=3.5$
TPC		slow
Required receive SNR		∞
Number of co-channel cells		$B=6$
Number of antennas of mobile user		1
Number of users per cell		U = 2~6
User location distribution		Random
Number of antennas		$N_r=6$
FFT (IFFT) points		$N_c=256$

At first, the average bit error rate (BER) performance is investigated as a function of FRF and the result is shown in Fig. 4. It is shown that the DAN SC-FDAAA can successfully cancel the MAI, and the average BER performance improves as the FRF increases, as already been proved in [5]. Since we are considering an un-coded system, a target average BER of 10^{-2} is used, which is marked by the dotted red line in Fig. 4. By using the target average BER, we can see that 6 users can be accommodated in each cell by the DAN system using SC-FDAAA when the FRF is larger than 4.

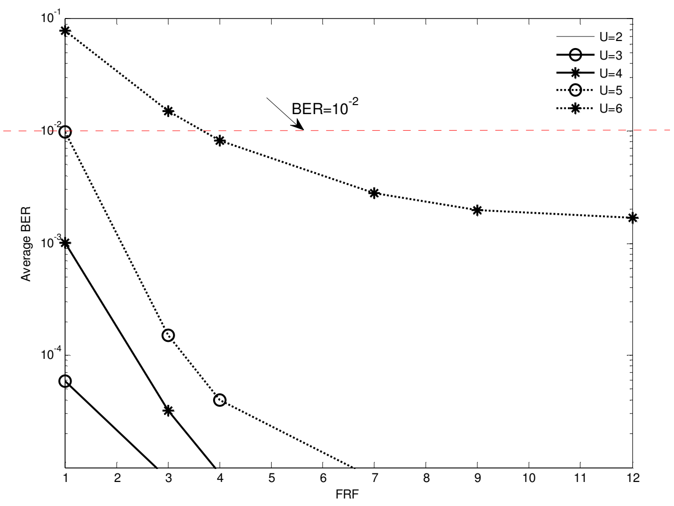

Fig. 4 Average BER of DAN FDAAA

In the next, the link capacity (maximum number of users/cell) and cellular link capacity (maximum number of users/cell/FRF) of DAN SC-FDAAA is evaluated. We studied the average capacity as well as the 10% outage capacity (the instantaneous capacity falls below outage capacity with the probability of 10%). The results are shown in Fig. 5 and Fig. 6.

Fig. 5 shows the link capacity as a function of FRF. It is shown that 4 users can be accommodated when FRF 1 is used. As the FRF increases, both the average and outage capacities increase. And when FRF is larger than 7, 6 users can be accommodated. Since the AAA receiver can deal with up to $N_r - 1$ interference and $N_r = 6$ is used, it can be concluded that the maximum number of users/cell of the DAN SC-FDAAA can approach its maximum when FRF is larger than 7. In addition, it is also shown that the average and outage capacities are close to each other. This is different from the results in the conventional cellular structure where the outage capacity is much smaller than the average capacity. The benefit comes from the DAN system where the users can access the distributed nearby antennas instead of the BS which can be out of the range of effective communication when the user is near the cell edge.

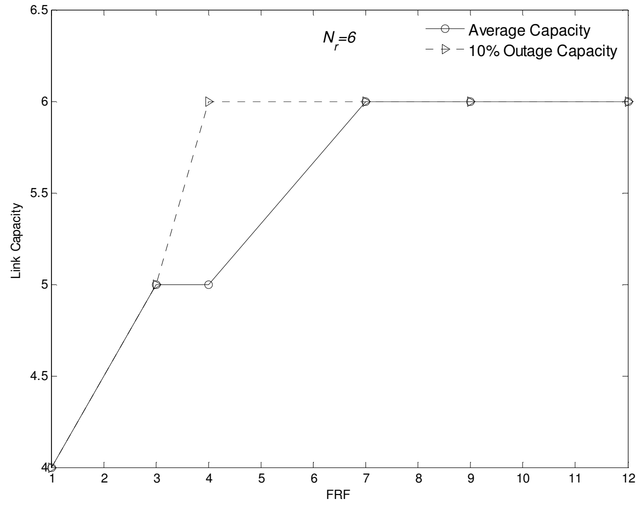

Fig. 5 Link Capacity of DAN SC-FDAAA.

The cellular link capacity is then considered and the results are shown in Fig. 6. It is shown that both the cellular average link capacity and cellular outage link capacity achieve their maximum values when FRF =1 and decrease when FRF increases. In our previous work on the cellular link capacity for conventional cellular system [8], it has been shown that the cellular link capacity can be maximized by using FRF=1 in the area near cell center and FRF = 3 in the area near the cell edge. The result shown in Fig. 6 is different from the results for conventional cellular system. This is because by using DAN SC-FDAAA, the MAI can be successfully cancelled out in everywhere of the cell. Therefore, by using the DAN SC-FDAAA, a smaller FRF can be used and the spectrum efficiency can be greatly improved as a result.

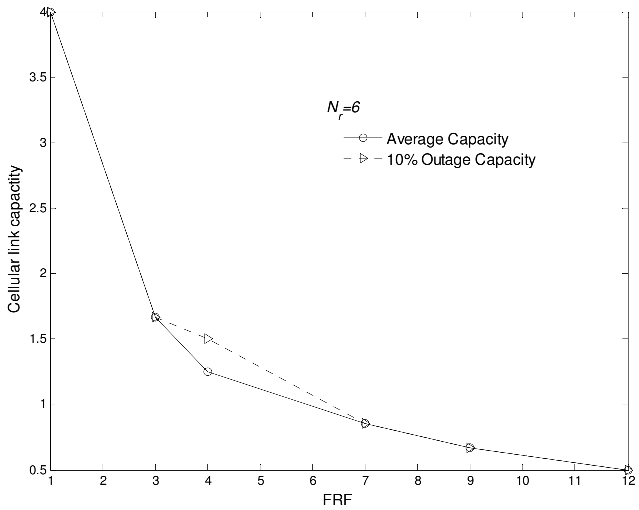

Fig. 6 Cellular link capacity.

5. CONCLUSIONS

In this paper, we have studied the capacity performance of DAN SC-FDAAA. Both the ergodic and outage cellular link capacities were evaluated. It was shown that by using the DAN SC-FDAAA, the cellular link capacity is maximized when FRF=1. Therefore, the DAN SC-FDAAA can use the single frequency reuse (i.e., FRF=1) and improve the spectrum efficiency greatly.

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