

SPECIAL ISSUE PAPER

Capacity of distributed antenna network by using single-carrier frequency domain adaptive antenna array

Wei Peng^{1, 2*} and Fumiyuki Adachi²¹ School of Electronic Information, Wuhan University, Wuhan, China² Department of Electrical and Communication, Tohoku University, Sendai, Japan

ABSTRACT

Single-carrier frequency domain adaptive antenna array (SC-FDAAA) has been proposed and proved in our previous study to be effective in suppressing multiple access interference in a severely frequency selective fading channel. In this paper, we studied the performance of SC-FDAAA in a distributed antenna network (DAN). To make it clear whether the performance of SC-FDAAA can benefit from the distributed nature of DAN or not, we made a comparison between DAN and the traditional cellular network, that is, central antenna network. The bit error rate distribution and the system capacity (both link capacity and cellular link capacity) are presented. It is shown that by using the SC-FDAAA, cellular link capacity is maximized by using single frequency reuse. In addition, the capacity of SC-FDAAA can also benefit from the distributed nature of DAN. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS

distributed antenna network; uplink detection; frequency domain adaptive antenna array; cellular link capacity

*Correspondence

Wei Peng, Department of Electrical and Communication, Tohoku University, Sendai, Japan.

E-mail: peng@mobile.ecei.tohoku.ac.jp

1. INTRODUCTION

The target data rate for the next generation wireless communication network will be around 1 Gbps. To realize such a high data rate transmission, broadband transmission has been used in the current wireless communication network, and it is also going to be employed by the next generation network. Because of the multi-path fading with large delay spread, broadband 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 the maximum likelihood sequence estimation [2]. However, when the data rate increases, the number of resolvable propagation paths increases as well, and hence, the complexity of the maximum likelihood sequence estimation grows exponentially to the number of paths. Fortunately, the ISI problem can be solved by introducing frequency domain equalization (FDE) [3] at the receiver. It is well known that the frequency selectivity problem can be solved by the use of multi-carrier transmission technique such as the orthogonal frequency division multiple access (OFDMA) [4] for the

downlink (from base station (BS) to mobile users) transmission. However, the multi-carrier transceivers are suffering from high peak-to-average power ratio (PAPR) problem that can lead to severe performance degradation. To solve the high PAPR problem, conventional single-carrier (SC) transmission, again, attracted much interest. Recently, the combination of SC-FDE and frequency division multiple access (called SC-FDMA) [5] has been considered as a more suitable solution for the uplink (from mobile users to BS) transmission. On the other hand, to save the bandwidth usage, the same carrier frequency/frequencies may be reused by neighboring cells to increase the bandwidth efficiency. As a result, co-channel interference (CCI) [6] becomes the dominant performance limitation instead of the thermal noise. In addition, multi-user interference (MUI) occurs when multiple users transmit simultaneously within the same cell (the MUI and CCI together is called multiple access interference). Therefore, interference cancellation is necessary in uplink transmissions.

Recently, distributed antenna network (DAN) [7] has been proposed to solve the transmit power problem in broadband signal transmissions. As the data rate increases,

impractically large transmit power will be required to realize the high data rate if cell coverage is kept unchanged. Otherwise, the cell coverage has to be reduced if the transmit power is kept unchanged. DAN 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 those antennas are connected with the DAN central processor (which is similar to the BS in conventional cellular system) through optical cables. A mobile user can communicate with its nearby located antennas even when it is at the cell edge. Therefore, the transmit power in DAN can be kept low while the coverage of the cell can be greatly increased.

In our previous studies [8,9], we have proposed an SC frequency domain adaptive antenna array (SC-FDAAA) for the uplink transmission. It has been shown that the SC-FDAAA can effectively suppress multiple access interference in a severely frequency selective fading channel. In this paper, we will study the performance of DAN SC-FDAAA. To find out how the distributed nature of the DAN may affect the performance of SC-FDAAA, we will compare SC-FDAAA in DAN and in conventional cellular system with centralized antennas at the BS (referred to as central antenna network (CAN) system hereafter).

The rest of the paper is organized as follows. The system model is given in Section 2. SC-FDAAA for DAN and CAN will be described in Section 3. The post SC-FDAAA signal to interference plus noise (SINR) will be analyzed in Section 4. The performance of SC-FDAAA will be shown in Section 5, both bit error rate (BER) distribution and the system capacity will be presented. Finally, the paper will be concluded in Section 6.

2. SYSTEM MODEL

In cellular system, the same carrier frequency/frequencies will be reused in neighboring cells to effectively utilize the limited spectrum. Cellular structures with frequency reuse factors (FRFs) of 1, 3, 4, and 7 are shown in Figure 1 as examples of frequency reuse. And FRF = 1, 3, 4, 7, 9, and 12 will be considered in this study. The commonly used first layer CCI model is used here, that is, only the CCI from the first layer neighboring cells will be considered and the number of CCI cells will be $B = 6$. As stated in the Introduction, we are going to use both CAN and DAN in each cell. CAN and DAN structures are shown in Figure 2. There are totally N_r centralized / distributed antennas. In the DAN system,

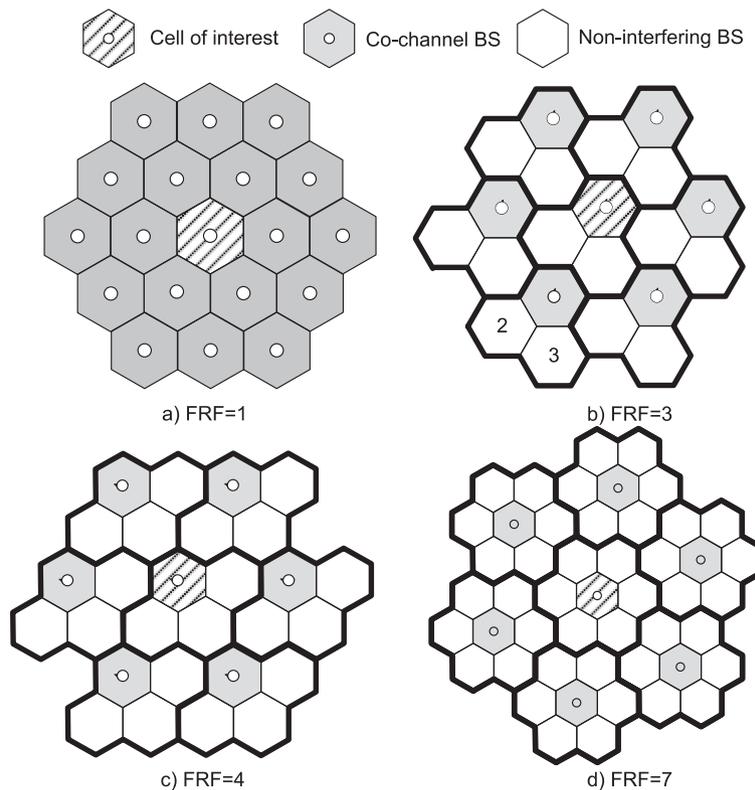


Figure 1. Frequency reuse in cellular system.

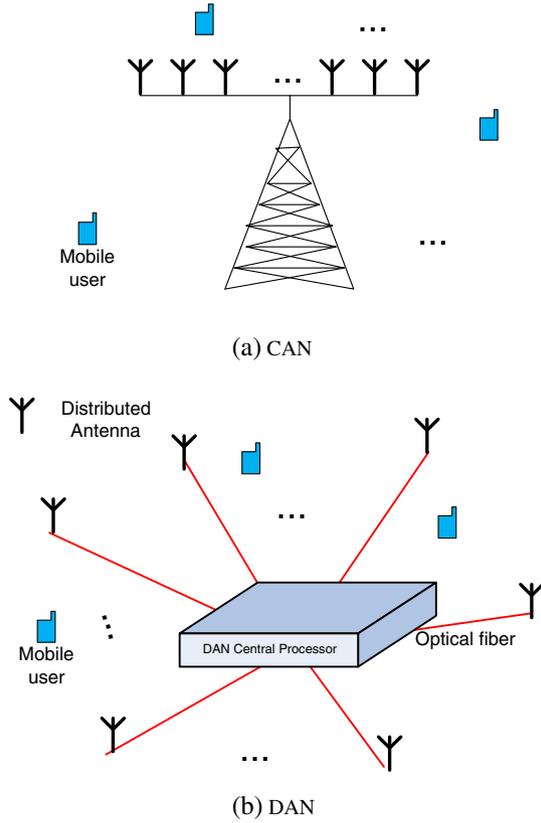


Figure 2. (a) Central antenna network (CAN) system and (b) distributed antenna network (DAN) system.

those antennas are connected to the DAN central processor by optical fibers. The received signals will be transmitted to the DAN central processor, and to lower the cost, 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. A block fading channel between each user and each antenna is assumed, that is, 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

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

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 complex Gaussian

distribution and satisfies $\sum_{l=0}^{L-1} E \{ |h_{u,m,l}|^2 \} = 1$, where $E\{\cdot\}$ represents the expectation. It is assumed that the time delay is a multiple integer of the symbol duration, and $\tau_l = l$ is used. 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. It is also 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.

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

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

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 $h_{u_i,m,l}$ are, respectively, the distance and channel gain between the CCI user and the m th antenna, α represents the path loss exponent in decibels, and $n_m(t)$ is the additive white Gaussian noise. 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

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

The first term in (3) is the desired signal, the second term is the MUI, 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 a matrix form as

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

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

3. SINGLE-CARRIER FREQUENCY DOMAIN ADAPTIVE ANTENNA ARRAY

The structure of the SC-FDAAA transceiver in both CAN system and DAN system can be generalized and shown in Figure 3. Binary data sequence is modulated and divided into a sequence of blocks of N_c data symbols. The last N_g symbols in each block are copied and inserted as CP into the guard interval and placed at the beginning of each block. The received signal is transformed by an N_c -point fast Fourier transform (FFT) into the frequency domain signal, and SC-FDAAA weight control is then performed on each frequency as

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

where $\mathbf{W}(k) = [W_0(k), \dots, W_{N_r-1}(k)]^T$. It should be noted that the SC-FDAAA is different from the multi-carrier transmission case. The major difference between

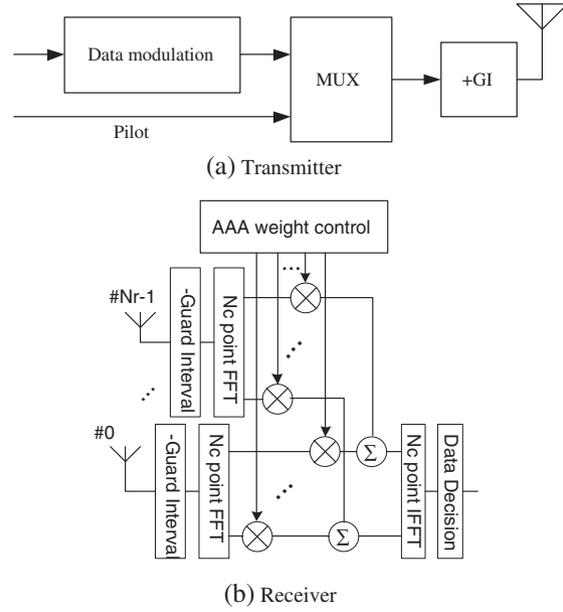


Figure 3. Single-carrier frequency domain adaptive antenna array (SC-FDAAA) transceiver structure. (a) Transmitter and (b) receiver. GI, guard interval; MUX, multiplexing.

the SC-FDAAA and the multi-carrier case is that in SC case, each transmitted symbol will be transmitted over the whole bandwidth. Therefore, even if the channel is frequency selective, the signal spectrum will be only partially affected at frequencies experiencing deep fading. Furthermore, in the SC case, the frequency diversity can be gained by the use of FDE. On the other hand, in the multi-carrier case like OFDMA, different symbols will be transmitted in parallel over different orthogonal subcarriers (frequencies); no frequency diversity can be gained, and furthermore, high PAPR will occur.

The SC-FDAAA weight that minimizes the mean squared error between $\tilde{R}(k)$ and the reference signal $S_0(k)$ (the pilot signal will be used as the reference signal) is given by [10,11]

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

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

$$\begin{aligned} \mathbf{C}_{rr}(k) &= E\{\mathbf{R}^*(k)\mathbf{R}(k)\} \\ &= \mathbf{A}_0^*(k)\mathbf{A}_0(k) + \sum_{u=1}^{U-1} \mathbf{A}_u^*(k)\mathbf{A}_u(k) \\ &+ \sum_{i=1}^B \sum_{u_i=0}^{U_i-1} \mathbf{A}_{i,u_i}^*(k)\mathbf{A}_{i,u_i}(k) + N_0\mathbf{I} \\ &= \mathbf{A}_0^*(k)\mathbf{A}_0(k) + \mathbf{N}'(k) \end{aligned} \quad (8)$$

and

$$\mathbf{C}_{rd}(k) = E \{ \mathbf{R}^*(k) S_0(k) \} = \mathbf{A}_0(k) S_0(k) \quad (9)$$

where $\mathbf{A}_0(k) = \mathbf{H}_0(k) S_0(k)$ [12], $\mathbf{N}' = \sum_{u=1}^{U-1} \mathbf{A}_u^*(k) \mathbf{A}_u(k) + \sum_{i=1}^B \sum_{u_i=0}^{U_i-1} \mathbf{A}_{i,u_i}^*(k) \mathbf{A}_{i,u_i}(k) + N_0 \mathbf{I}$ is used to represent the interference plus noise.

In the next, time domain signal block estimate is then obtained by an N_c -point IFFT for data decision as

$$\hat{d}(t) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{N_c-1} \tilde{R}(k) \exp\left(j 2\pi k \frac{t}{N_c}\right) \quad (10)$$

4. POST SC-FDAAA SINR ANALYSIS

The post SC-FDAAA SINR on the k th frequency can be evaluated by [13]

$$\Gamma(k) = \frac{\mathbf{W}^H(k) \mathbf{R}_S(k) \mathbf{W}(k)}{\mathbf{W}^H(k) \mathbf{R}_{N'}(k) \mathbf{W}(k)} \quad (11)$$

where $\mathbf{R}_S(k)$ and $\mathbf{R}_{N'}(k)$ are the auto-correlation matrix of the received desired signal and the interference plus noise, respectively.

Property: if a matrix \mathbf{Z} can be written as $\mathbf{Z} = \mathbf{T}^{-1} + \mathbf{P}\mathbf{Q}^{-1}\mathbf{P}^$, then the inverse matrix of \mathbf{Z} can be obtained by [14]*

$$\mathbf{Z}^{-1} = \mathbf{T} - \mathbf{T}\mathbf{P}(\mathbf{Q} + \mathbf{P}^*\mathbf{T}\mathbf{P})^{-1}\mathbf{P}^*\mathbf{T} \quad (12)$$

Let $\mathbf{Z} = \mathbf{C}_{rr}(k)$, $\mathbf{T} = \mathbf{R}_{N'}^{-1}(k)$, $\mathbf{P} = \mathbf{A}_0^*(k)$ where $\mathbf{A}_0(k) = \mathbf{H}_0(k) S_0(k)$ and $\mathbf{Q} = \mathbf{I}$, then the inverse matrix $\mathbf{C}_{rr}^{-1}(k)$ can be calculated by submitting \mathbf{Z} , \mathbf{T} , \mathbf{P} , and \mathbf{I} into (12)

$$\begin{aligned} \mathbf{C}_{rr}^{-1} &= \mathbf{R}_{N'}^{-1}(k) - \mathbf{R}_{N'}^{-1}(k) \mathbf{A}_0^*(k) \\ &\quad \times [\mathbf{I} + \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1} \mathbf{A}_0^*(k)]^{-1} \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1}(k) \\ &= \mathbf{R}_{N'}^{-1}(k) \left[\mathbf{I} - \frac{\mathbf{A}_0^*(k) \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1}(k)}{\mathbf{I} + \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1} \mathbf{A}_0^*(k)} \right] \\ &= \left[\frac{1}{1 + \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1} \mathbf{A}_0^*(k)} \right] \mathbf{R}_{N'}^{-1}(k) \end{aligned} \quad (13)$$

The SC-FDAAA weight is then obtained by substituting (9) and (13) into (7), given by

$$\mathbf{W}(k) = \left[\frac{1}{1 + \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1} \mathbf{A}_0^*(k)} \right] \mathbf{R}_{N'}^{-1}(k) \mathbf{A}_0(k) S_0(k) \quad (14)$$

Finally, the SINR after the weight control can be expressed by substituting (14) into (9) as

$$\Gamma(k) = \mathbf{A}_0(k) \mathbf{R}_{N'}^{-1}(k) \mathbf{A}_0^*(k) \quad (15)$$

5. SIMULATION RESULTS

Performance of DAN SC-FDAAA system will be investigated in this section as a reference for comparison; the performance of CAN SC-FDAAA will also be evaluated. Cellular structures using FRF = 1, 3, 4, 7, 9, and 12 will be considered. The parameters used to generate the results are listed in Table I. No channel coding is used for simplicity, and we assume that the transmit signal-to-noise ratio is 10 dB. The distributed antennas are located in a cell as shown in Figure 4. In this study, scheduling among the distributed antennas is not considered. The scheduling algorithm and more complicated situation remain as the topics of our future work.

Bit error rate performance is investigated at first. To find out behaviors of both average BER and outage BER, the cumulative distribution functions (CDFs) of BER performance are calculated and shown in Figures 5–7 where the FRF equals to 1, 3, and 4, respectively. For the cases of FRF 7, 9, and 12, the results are not shown for brevity. Figure 5 shows a comparison between the CDFs of BER

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	$\alpha = 3.5$
SNR		10 dB
Number of co-channel cells		$B = 6$
Number of antennas of mobile user		1
Number of users per cell		$U = 2 \sim 6$
User location distribution		Random
Number of antennas		$N_r = 6$
FFT (IFFT) points		$N_c = 256$

SNR, signal-to-noise ratio; FFT, fast Fourier transform; IFFT, inverse fast Fourier transform; QPSK, Quadrature phase shift keying.

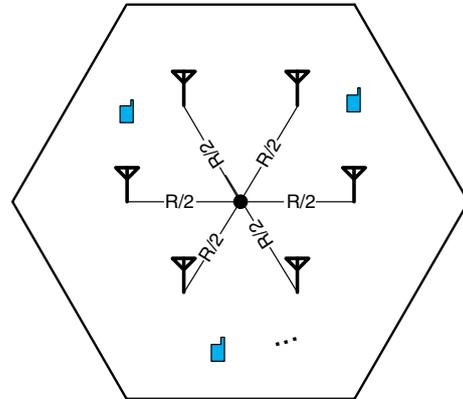


Figure 4. Antenna distribution in distributed antenna network system.

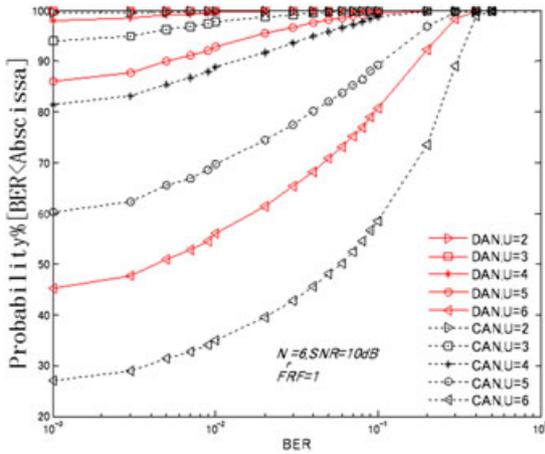


Figure 5. Cumulative distribution function (CDF) of bit error rate (BER) performance, frequency reuse factor (FRF) = 1.

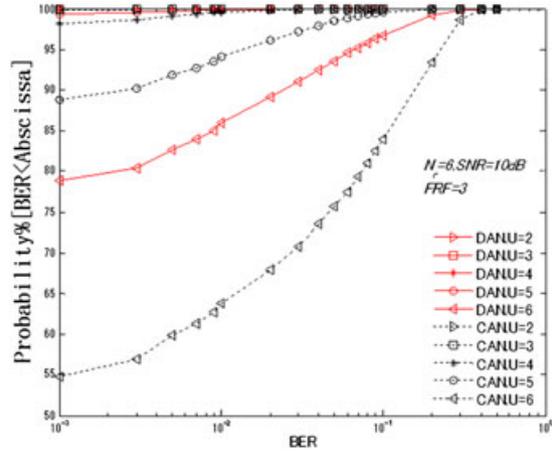


Figure 6. Cumulative distribution function (CDF) of bit error rate (BER) performance, frequency reuse factor (FRF) = 3.

in DAN system and CAN system when $FRF = 1$. The x -axis is the BER abscissa, and the y -axis is the probability that $BER < abscissa$. It can be observed that DAN SC-FDAAA outperforms CAN SC-FDAAA by having better BER performance. It can also be observed that when the number of users increases, the BER performance of SC-FDAAA will degrade in both DAN and CAN systems, which can be intuitively expected because of the reduction of the degree of freedom. From the results shown in Figures 6 and 7, it can be further observed that when FRF increases, the CDF curves of BER performance 'shift' to the right side, which means that the BER performance improves because of the reduction of CCI power. In addition, DAN SC-FDAAA always achieves better BER performance than CAN SC-FDAAA no matter how FRF varies. The results of BER performance have shown that the distributed nature of DAN system can significantly improve the BER performance of SC-FDAAA over CAN system.

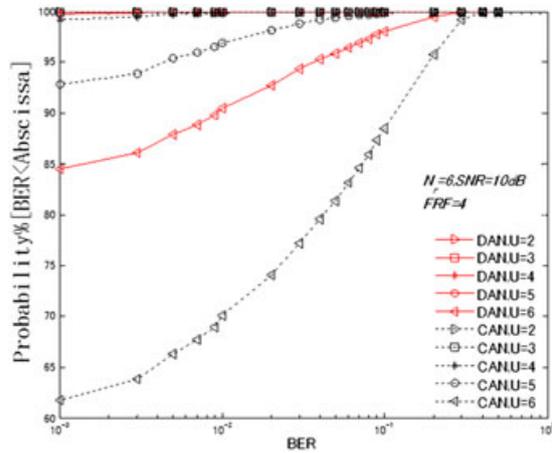


Figure 7. Cumulative distribution function (CDF) of bit error rate (BER) performance, frequency reuse factor (FRF) = 4.

System capacity given by bits/s/Hz can be calculated by Shannon capacity definition [15,16] by using the SINR given in (15). However, the number of users that can be accommodated is a practical criterion to be considered as system capacity. Therefore, the following results will focus on the number of simultaneous users instead of the value given by bits/s/Hz. The average BER performance of DAN SC-FDAAA as a function of FRF is shown in Figure 8. Because uncoded system is assumed, average $BER = 10^{-2}$ is used as a criterion to see how many users can be accommodated using DAN SC-FDAAA. In the next, link capacity (maximum number of users/cell) and cellular link capacity (link capacity/FRF) of DAN SC-FDAAA are evaluated, and the results are shown in Figures 9 and 10.

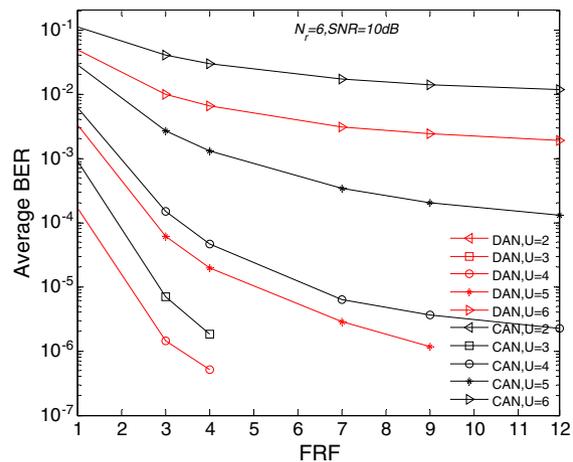


Figure 8. Average bit error rate (BER).

Figure 9 shows the link capacity of DAN SC-FDAAA and CAN SC-FDAAA. It is shown that four users can be accommodated by DAN SC-FDAAA when FRF 1 is used, whereas two users can be accommodated by CAN

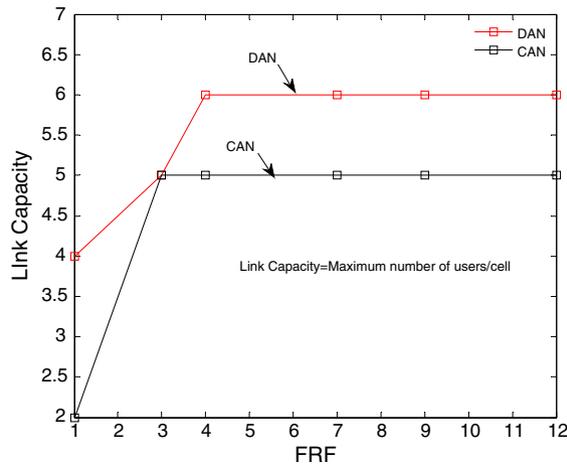


Figure 9. Link capacity.

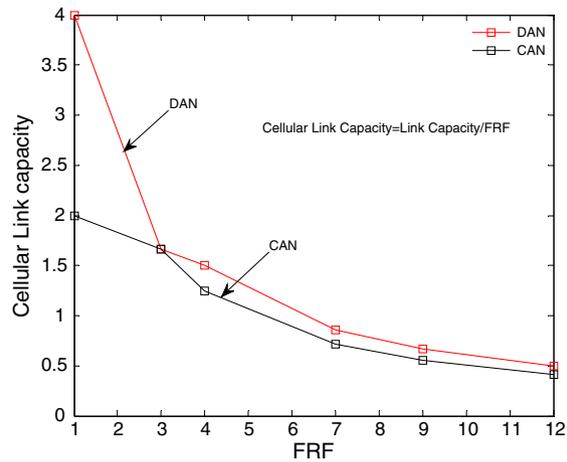


Figure 10. Cellular link capacity.

SC-FDAAA; therefore, the link capacity can be doubled by using DAN SC-FDAAA. As the FRF increases, link capacities increase as the CCI power decreases. And when FRF is larger than 4, six users can be accommodated. Because $N_r = 6$ and the AAA receiver can deal with up to $N_r - 1$ interference, it can be concluded that the maximum number of users/cell of the DAN SC-FDAAA can approach its maximum value when FRF is larger than 4.

Larger FRF means more bandwidth will be consumed. To measure the spectrum efficiency, cellular link capacity is calculated, and the results are shown in Figure 10. It is shown that cellular link capacity of DAN SC-FDAAA can achieve its maximum value when $FRF = 1$ and decreases when FRF increases. Note that in our previous work on the cellular link capacity for conventional cellular system [17], it has been pointed out that the cellular link capacity can be maximized using $FRF = 1$ in the area near the cell center and $FRF = 3$ in the area near the cell edge. Therefore, by using the DAN SC-FDAAA, a smaller FRF can be used and the spectrum efficiency can be greatly improved as a

result. In addition, taking $FRF = 1$ as an example, DAN SC-FDAAA achieves twice of the cellular link capacity as CAN SC-FDAAA does.

6. CONCLUSIONS

In this paper, we have studied the performance of DAN SC-FDAAA and also the performance of CAN SC-FDAAA as a reference. Both the BER distribution and capacity (link capacity and cellular link capacity) have been evaluated. It has been shown that by using the DAN SC-FDAAA, 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. In addition, the performance of DAN SC-FDAAA can benefit from the distributed nature of DAN, and it can double the cellular link capacity by using the single frequency reuse when compared with CAN SC-FDAAA.

ACKNOWLEDGEMENT

This work was supported in part by 2011 KDDI Research Grant Program (J110000208).

REFERENCES

1. Proakis JG. *Digital Communications*, (4th edn). McGraw Hill: New York, 2001.
2. Price R, Green PE. A communication technique for multipath channels. *Proceedings of the Institute of Radio Engineers* 1958; **46**(3): 555–570.
3. Falconer D, Ariyavistakul SL, Benyamin-Seeyar A, Edison B. Frequency domain equalization for single-carrier broadband wireless systems. *IEEE Communication Magazine* 2002; **40**: 58–66.
4. Van Nee R, Prasad R. *OFDM for Wireless Multimedia Communications*. Arctech House Publishers: UK, 1999.
5. Adachi F, Takeda K, Obara T, Yamamoto T, Matsuda H. Recent advances in single-carrier frequency-domain equalization and distributed antenna network. In *IEEE ICICS*, Singapore, March 2009; 1–5.
6. Sivanesan K, Beaulieu NC. Outage and BER of MRC diversity in band-limited micro-cellular systems with CCI. *IEEE Communications Letters* 2005; **9**(3): 207–209.
7. Zhang J, Andrews J. Distributed antenna systems with randomness. *IEEE Transactions on Wireless Communications* 2008; **7**(9): 3636–3646.
8. Peng W, Adachi F. Frequency domain adaptive antenna array for broadband single-carrier uplink transmission. *IEICE Transactions on Communications* 2011; **E94-B**(7): 2003–2012.

9. Peng W, Adachi F. Single-Carrier Frequency Domain Adaptive Antenna Array for Distributed Antenna Network, In *IEEE ICCS*, Singapore, Dec. 2010; 1–5.
10. Zooghy AEI. *Smart Antenn Engineering*. Artech House Publisher: London, 2005.
11. Haykin S. *Adaptive Filter Theory*. Prentice Hall: New York, 2002.
12. Winters JH. Signal acquisition and tracking with adaptive arrays in the digital mobile radio system IS-36 with flat fading. *IEEE Transactions on Vehicular Technology* 1993; **42**: 377–384.
13. Hamdi K. On the statistics of signal-to-interference plus noise ratio in wireless communications. *IEEE Transactions on Communications* 2009; **57**(11): 3199–3204.
14. Woodbury MA. *Inverting Modified Matrices*. Princeton: New Jersey, 1950.
15. Shannon CE. A mathematical theory of communication I. *Bell System Technical Journal* 1948; **27**: 379–423.
16. Shannon CE. A mathematical theory of communication II. *Bell System Technical Journal* 1948; **27**: 623–656.
17. Peng W, Adachi F. Hybrid frequency reuse scheme for cellular MIMO systems. *IEICE (the Institute of Electronics, Information and Communication Engineers) Transactions on Communications* 2009; **E92-B**: 1641–1648.

she joined Tohoku University, and currently, she is with the Department of Electrical and Communication Engineering as an assistant professor. Her research interests are in multiple antenna technology, cellular system, and distributed antenna network.



Fumiyuki Adachi received the BS and Dr. Eng degrees in electrical engineering from Tohoku University, Sendai, Japan, in 1973 and 1984, respectively. In April 1973, he joined the Electrical Communications Laboratories of Nippon Telegraph and Telephone Corporation (now NTT) and conducted various types of research related to digital cellular mobile communications. From July 1992 to December 1999, he was with NTT Mobile Communications Network, Inc. (now NTT DoCoMo, Inc.), where he lead a research group on wide-band/broadband code division multiple access (CDMA) wireless access for IMT-2000 and beyond. Since January 2000, he has been with Tohoku University, Sendai, Japan, where he is a Professor of Electrical and Communication Engineering at the Graduate School of Engineering. His research interests are in CDMA wireless access techniques, equalization, transmit/receive antenna diversity, multiple-input multiple-output, adaptive transmission, and channel coding, with particular application to broadband wireless communications systems.

AUTHORS' BIOGRAPHIES



Wei Peng received her BS and MS degrees in electrical engineering from Wuhan University, Wuhan, China, in 2000 and 2003, respectively. She received the Dr. Eng degree in electrical and electronic engineering from the University of Hong Kong, Hong Kong, in 2007. Since December 2007,