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Uplink Capacity of Cellular System Using Frequency Domain Adaptive Antenna Array

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Abstract— In this paper, uplink capacity of cellular system using frequency domain adaptive antenna array (FDAAA) is studied by taking hybrid frequency reuse factor (FRF) into consideration. The system capacity for fixed FRF cellular system and hybrid FRF cellular system is analyzed and compared. The effectiveness of hybrid FRF in improving the system capacity is proven by simulation results.

Keywords: *Uplink, FDAAA, single user, Hybrid FRF*

1. Introduction

High speed data rate (1Gbps) is demanded for mobile communication system. As a result, wireless channel becomes severely frequency selective due to multi-path fading [1] and inter symbol interference (ISI) effect will degrade system performance. It is presented in [2] that single-carrier (SC) transmission gives low peak-to-average-power-ratio (PAPR) and can deal with frequency selectivity by applying frequency domain adaptive antenna array (FDAAA) at receiver side. FDAAA receiver is implemented by adjusting AAA weight for each frequency [2] to maximize the signal to interference plus noise ratio (SINR).

In cellular system, the same carrier frequency is reused by neighboring cells due to bandwidth limitation. As a result, interference due to co-channel users limits the system performance instead of noise [3]. AAA is one of the powerful methods to suppress interference by changing the beam pattern of antenna adaptively. AAA weight control will give the biggest array gain to the direction of the desired signal and the lowest array gain to the direction of the interference signal. It has been reported in [5-6] that for a system using multiple receive antennas, the system capacity can be increased by using hybrid/fractional frequency reuse factor (FRF) when compared to the fixed FRF scheme. This paper uses hybrid FRF to improve the uplink capacity by using FDAAA receiver and single user/cell is considered.

The rest of paper is organized as follows. Section 2 describes the system model. Cellular FDAAA algorithm and hybrid FRF will be introduced in section 3. Capacity analysis and simulation results are then presented in section 4 and 5. Finally, the paper will be concluded in section 6.

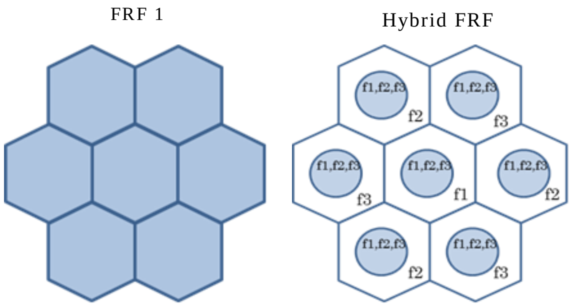


Fig. 1 Structure of Fixed FRF and Hybrid FRF

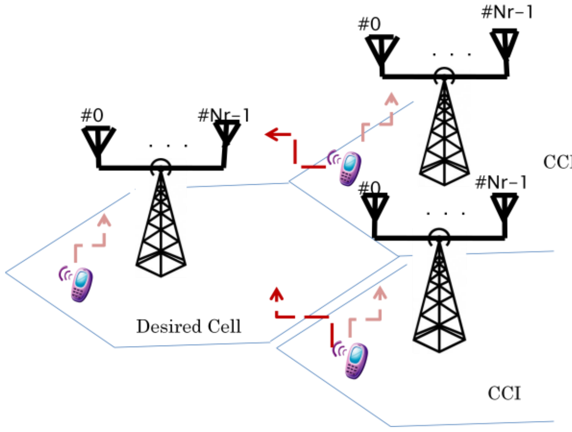


Fig. 2 Uplink Communication for single user case

2. System Model

A. Uplink Transmission Model

Two cellular structures are shown in Fig. 1. On the left is the conventional cellular structure using fixed single FRF (FRF 1), on the right is the cellular structure using hybrid FRF. FRF 1 scheme uses the same carrier frequency (frequencies) for every cell and everywhere in each cell. While hybrid FRF scheme uses the same carrier frequencies (frequencies) in the near-center area of each cell and uses one third of the carrier frequency bandwidth in the cell edge area adaptively so that the FRF for near-center area is equivalent to 1 and the FRF for cell edge area is equivalent to 3.

It is assumed that the base station (BS) in the center of each cell is equipped with Nr antennas. There is a single user in each cell and the user is equipped with one transmit antenna. Block fading is assumed. The channel impulse response between the user and the BS can be expressed as

$$\mathbf{h}(\tau)=\sum_{l=0}^{L-1}\mathbf{h}_l\delta(\tau-\tau_l) \quad (1)$$

where $\mathbf{h}_l$ and τ_l are the l^{th} path gain vector and time delay respectively, $\sum_{l=0}^{L-1}E\left\{\left|h_{l,i}\right|^2\right\}=1$ where $h_{l,i}$ is the i^{th} element of the gain vector $\mathbf{h}_l$. The path delay is assumed to be integer multiples of symbol duration and $\tau_l=l$. Cyclic prefix (CP) is assumed to be used and the length of CP is assumed to be longer than the maximum path delay so that inter block interference (IBI) can be avoided.

The baseband received signal vector $\mathbf{r}(n)=\left[r_0(n),r_1(n),...,r_{N_r-1}(n)\right]^T,(n=1,\cdots,N_c)$ is given by

$$\begin{aligned}\mathbf{r}(t)=&\sqrt{2P_0d_0^{-\alpha}10^{-\xi_0/10}}\sum_{l=0}^{L-1}\mathbf{h}_0s_0(t-\tau_l)\\&+\sum_{i=0}^{I-1}\sqrt{2P_id_i^{-\alpha}10^{-\xi_i/10}}\sum_{l=0}^{L-1}\mathbf{h}_is_i(t-\tau_l)\\&+\mathbf{n}(t)\end{aligned} \quad (2)$$

For the i^{th} user, P_i represents the transmit power, $s_i(n)$ is the transmit signal; d_i represents the distance between the user and the BS; α and ξ represent path loss exponent and shadowing loss parameter, respectively. $\mathbf{z}(n)=\left[z_0(n),\ z_1(n),\ ...,\ z_{N_r-1}(n)\right]^T$ is the additive white Gaussian noise (AWGN) vector.

The frequency domain received signal on the k^{th} frequency is then expressed as

$$\mathbf{R}(k)=\mathbf{H}_0(k)S_0(k)+\sum_{u=1}^{U-1}\mathbf{H}_i(k)S_i(k)+\mathbf{Z}(k) \quad (3)$$

where $\mathbf{H}_u(k)=\left[H_{u,0}(k),H_{u,1}(k),...,H_{u,N_r-1}(k)\right]^T$, $S_0(k)$ and $\mathbf{N}(k)=\left[N_0(k)N_1(k)...N_{N_r-1}(k)\right]^T$ are respectively the frequency domain channel response, transmit data and noise component, given by

$$\begin{cases}H_{u,m}(k)=\sum_{l=0}^{L-1}\sum_{n=0}^{N_c-1}h_{u,l,m}\exp\left(-j2\pi n\frac{k}{Nc}\right)\\S_u(k)=\sqrt{2P_u}\sum_{n=0}^{N_c-1}s_u(n)\exp\left(-j2\pi n\frac{k}{Nc}\right)\\Z_m(k)=\sum_{t=0}^{N_c-1}z_m(t)\exp\left(-j2\pi n\frac{k}{Nc}\right)\end{cases} \quad (4)$$

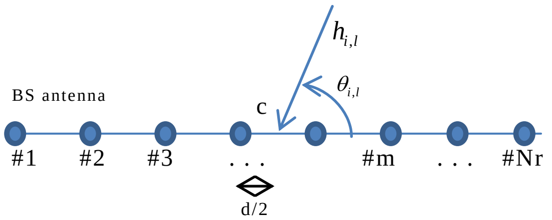


Fig. 3 Linear antenna array with Nr antennas

The first term in equation (3) comes from desired user, the second term comes from the interfering users, and the last term is the AWGN component. Slow transmit power control (TPC) in each cell is assumed. Therefore, each user will have the same target receive signal power at the corresponding BS. And the received signal power at desired BS from the i^{th} user is given by

$$P_i=\left(\frac{P}{\bar{d}_i^{-\alpha}10^{-\xi_i/10}}\right)\bar{d}_{i,0}^{-\alpha}10^{-\xi_{i,0}/10} \quad (5)$$

where P is the target receive signal power; α is path loss exponent, $\bar{d}_i$ and ξ_i are normalized distance (when radius of cell is 1) and log-normally distributed shadowing loss between the i^{th} user and the corresponding BS respectively; $\bar{d}_{i,0}$ are normalized distance between i^{th} user and desired BS; $\xi_{i,0}$ is the log-normally distributed shadowing loss parameter.

B. Propagation Model of Adaptive Antenna Array

The propagation model of a linear AAA is shown in Fig. 3. $h_{i,l}$ represents the l^{th} delay-path gain from the i^{th} user at the center of the array and no spread between the un-resolvable paths is used. Nominal angle of arrival (AOA) of $h_{i,l}$ is denoted by $\theta_{i,l}$, and the AOA spread of $\theta_{i,l}$ is uniformly distributed within a range of Δ (in this study, all direction AOA is used so that $\Delta=2\pi$). The l^{th} path gain observed at the m^{th} antenna element is then expressed as

$$h_{i,l,m} = h_{i,l} \exp\left(-j2\pi \frac{(0.5N_r - m + 0.5)}{\lambda} d \cos\theta_{i,l} \right) \qquad (6)$$

where m = 1,2,3,..,Nr and λ is the carrier wavelength. In the following, antenna separation d is expressed in terms of λ. The beam pattern of AAA is formed by multiplying AAA weight and array factor (AF), given by

$$AF(\theta) = \sum_{m=0}^{N_r-1} \mathbf{W}_{FDAAA}^{H}(k)\mathbf{a}(\theta) \qquad (7)$$

where superscript H represents Hermitan transpose and vector $\mathbf{a}(\theta)$ is the AF in direction θ. $\mathbf{a}(\theta) = \left[a_0(\theta) \quad a_1(\theta) \quad \dots \quad a_{N_r-1}(\theta) \right]^T$, where $a_m(\theta) = \exp\left(j2\pi \frac{(0.5N_r - m + 0.5)}{\lambda} d \cos\theta \right)$. The AAA weight calculation will be presented later in the following section.

Assuming perfect AAA weight control, the beam patterns of an 8-element antenna array are drawn in fig.4. Fig. 4 shows how beam pattern behaves in cases with/without co-channel interference (CCI). A 16-path delay is used to get the results while no AOA spread between multiple paths was assumed.

C. Hybrid FRF

Hybrid FRF [5] is designed as a combination of FRF 1 and FRF 3 within a cell, as shown in Fig. 6. FRF 1 is used for area near cell center and the else area of a cell uses FRF 3. The coverage of FRF 1 area depends on path loss exponent, shadowing loss parameter, and the target receive signal power as well.

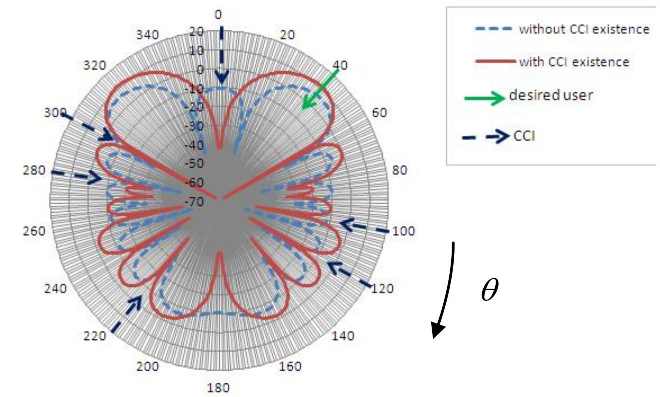


Fig. 4 Beam Pattern of AAA

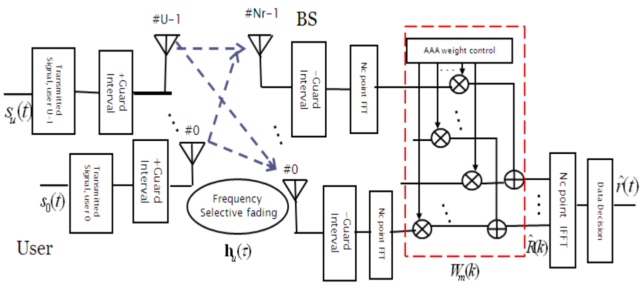


Fig. 5 FDAAA Receiver Scheme

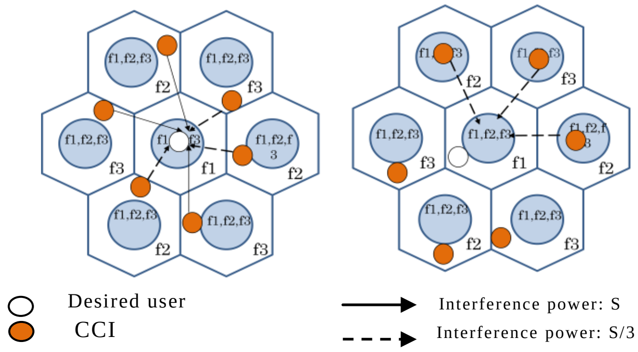


Fig. 6 **Hybrid FRF**

3. CELLULAR FDAAA ALGORITHM

FDAAA receiver has been investigated in [2] and [4]. The transceiver structure of FDAAA receiver is shown in Fig.5. The output of received signal after applying AAA weight is expressed as

$$\hat{R}(k) = \mathbf{W}_{FDAAA}^{H}(k)\mathbf{R}(k) \qquad (8)$$

where $\mathbf{W}_{FDAAA}(k) = \left[W_{FDAAA,0}(k), W_{FDAAA,1}(k), \dots, W_{FDAAA,N_r-1}(k) \right]^T$. AAA weight is the optimum weights which minimize the mean square error between $\hat{R}(k)$ and the desired signal $S_0(k)$. AAA weight is calculated following MMSE criterion as follows [8]

$$\mathbf{W}_{FDAAA}(k) = \mathbf{X}(k)^{-1}\mathbf{p}(k) \qquad (9)$$

where $\mathbf{X}(k) = E\{\mathbf{R}(k)\mathbf{R}(k)^H\}$ is auto-correlation matrix of the received signal vector, $\mathbf{p}(k) = E\{\mathbf{R}(k)S_0^{\ *}(k)\}$ is cross correlation between the received signal and the reference signal, and symbol * denotes complex conjugate operation. $\mathbf{X}(k)$ is square matrix with Nr x Nr dimension and the $(m,n)^{th}$ element of $\mathbf{X}(k)$ is given by

$$\begin{aligned} X_{m,n}(k) &= E\{R_m(k)R_n^{\ *}(k)\} \\ &= E\{S_0(k)H_{0,m}(k)H_{0,n}^{*}(k)S_0^{*}(k)\} \\ &+ \sum_{i=0}^{I-1} E\{S_i(k)H_{i,m}(k)H_{i,n}^{*}(k)S_i^{*}(k)\} \\ &+ E\{N_m(k)N_n^{*}(k)\} \end{aligned} \qquad (10)$$

Assuming that the transmit signals from different users are independent and the noise component is also independent as well.

4. System Capacity Analysis

According to the definition of Shannon capacity, system capacity is calculated by

$$c = \left(1 + \log_2 SINR\right)\ (bps/Hz) \tag{11}$$

Practically, the channel capacity varies according to the distance-dependent path loss, shadowing loss, and multi-path fading. In the following, system capacity is calculated for each cell and normalized by FRF, given by

$$c = \frac{1}{FRF}\left(1 + \log_2 SINR\right)\ (bps/Hz/cell) \tag{12}$$

where SINR is the signal to interference plus noise ratio, given by

$$SINR = \frac{\sum_{k=0}^{Nc-1} \mathbf{W}_{FDAAA}^{H}(k)\mathbf{R}_{s}(k)\mathbf{W}_{FDAAA}(k)}{\sum_{k=0}^{Nc-1} \mathbf{W}_{FDAAA}^{H}(k)\mathbf{R}_{NI}(k)\mathbf{W}_{FDAAA}(k)} \tag{13}$$

$\mathbf{R}_s(k)$ is the auto-correlation matrix of the received desired user's signal and $\mathbf{R}_{NI}(k)$ is auto-correlation matrix of the received signal from interfering users together with noise.

Here, capacity calculation for fixed FRF and hybrid FRF are investigated. For fixed FRF case, system capacity can be easily calculated by using equation (12). While the capacity calculation for hybrid FRF depends on the actual FRF.

5. Simulation Results

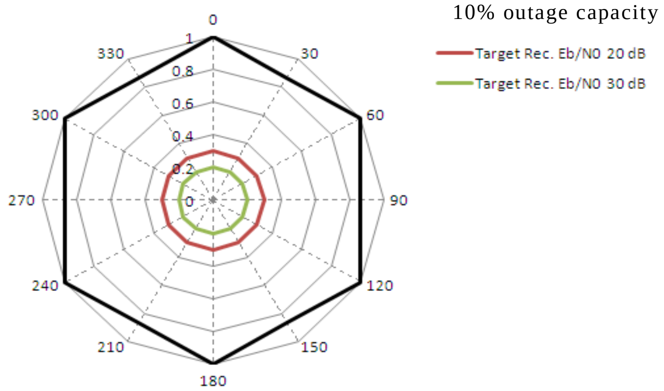
In this section, capacity performance of hybrid FRF is investigated and it will be compared with capacity performance of fixed FRF system. The parameters used for the simulation are listed in Table 1.

A. FRF allocation of hybrid FRF

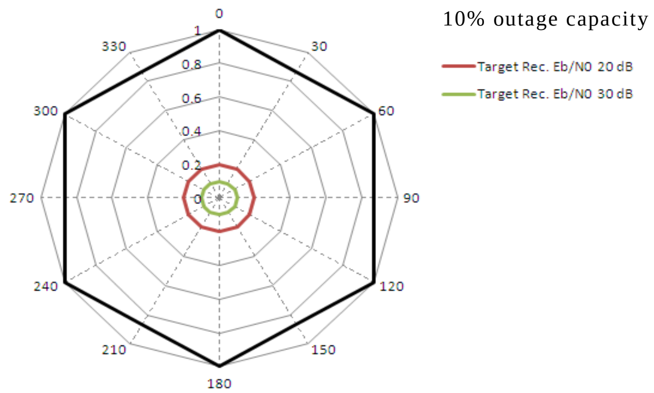
At first, the FRF 1 area for hybrid FRF scheme with and without the effect of shadowing loss is calculated and drawn in Fig. 7 and Fig. 8, respectively. The area within the circle uses FRF 1 while the area outside the circle uses FRF 3. The inner-circle user uses FRF 1 while the outside-circle user uses FRF 3.

Table 1 Simulation Condition

Transmitter	Data Modulation	QPSK
	FFT size	256
	TPC	Slow TPC
	No. of user per cell	1
	No. of CCI	I = 6
	Target receive Eb/N0	20 dB, 30 dB
Channel	Channel model	Frequency-selective block Rayleigh fading
	Power delay profile	L = 16 uniform power delay profile
	Angle spread of irresolvable paths	δ=0 degrees
	Angle spread of resolvable paths (AOA)	△ = 360 degrees
	Path loss exponent	α= 3.5
	Standard deviation of shadowing losses	ξ= 6 dB
Receiver	No. of antennas	Nr = 8
	Antenna separation	d = 0.5λ
	Channel estimation	Ideal

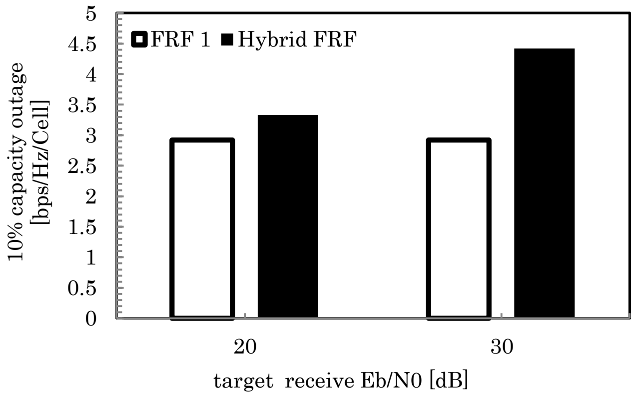


(a) Without shadowing loss

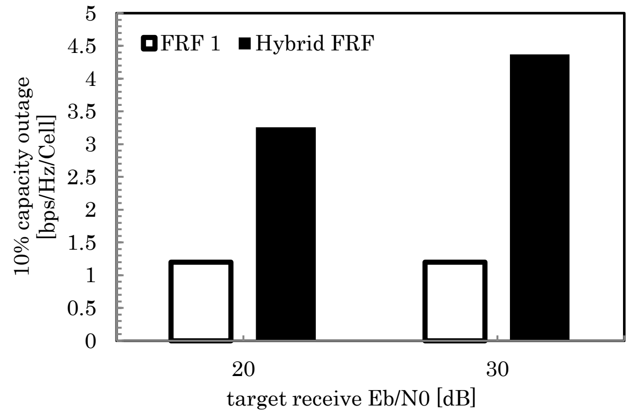


(b) With shadowing loss ξ= 6 dB

Fig. 7 FRF allocation within a cell



(a) No shadowing loss



(b) Shadowing loss

Fig. 8 10% outage capacity performance of uplink cellular system using FRF 1 and hybrid FRF

Table 2 Capacity Gain

Target Receive E_b/N_0	20 dB	30 dB
No shadowing	14.0 %	51.4 %
With shadowing	171 %	264 %

B. Capacity performance

System capacity of uplink communication system can be calculated following equation (12). The capacity performance without shadowing loss effect is shown in Fig. 8(a) and the same result is also presented in Tab. 2. A 14% increase in capacity can be observed for target receive Eb/N_0 of 20dB and a 51% increase in capacity can be observed for target receive Eb/N_0 of 30dB.

In the next, the impact of shadowing loss is considered. It is observed that with the existence of shadowing loss, the capacity of fixed FRF will be decreased when compared to the no shadowing loss case. This is understandable since slow TPC is applied to the system and as a result, when shadowing loss is considered, the interference power increases. However, when hybrid FRF is applied, the capacity performance is the same as the no-shadowing loss case due to the interference power minimization. Therefore, the capacity improvement gained by hybrid FRF becomes more significant when shadowing loss is considered.

6. Conclusion

In this paper, FDAAA receiver is used to for uplink transmission in cellular system and hybrid FRF has been considered for single user case. The hybrid FRF range is adaptively determined to maximize the system capacity according to the theoretical calculation. It has been observed that hybrid FRF for uplink cellular system can greatly improve the system capacity especially when shadowing loss is considered.

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