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논문 18-43-04-03 The Journal of Korean Institute of Communications and Information Sciences '18-04 Vol.43 No.04
https://doi.org/10.7840/kics.2018.43.4.637

채널의 클러스터링 특성을 고려한 이종 빔포밍 시스템의 용량 분석

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Capacity Analysis of a Hybrid Beamforming System with the Characteristics of Channel Clustering

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요 약

공간분할다중접속을 위한 이종 빔포밍 시스템은 하향링크 다중 사용자 multiple-input multiple-output (MIMO) 채널 환경에서 스마트 안테나 기술을 사용하여 시스템 용량을 증가시킬 것으로 기대되는 기술이다. 본 논문에서는 N개의 안테나로 구성된 M개의 송신기가 원형 등간격 어레이 안테나를 구성하는 이종 빔포밍 구조를 고려하였다. 이종 빔포밍 시스템에서 공간 다이버시티와 다중 사용자 다이버시티를 달성하기 위해서는 사용자 선택 기법이 중요하다. 따라서 이종 빔포밍 시스템에서 기지국은 채널 클러스터링 특성을 고려하여서 높은 채널 이득을 가지는 다수의 사용자를 선택함으로써 공간 다이버시티와 다중 사용자 다이버시티를 달성한다. 이를 위해 사용자는 angle-of-departure (AOD)를 고려한 채널 상태 정보를 기지국에게 보고하며, 기지국은 사용자로부터 수신한 채널 상태 정보를 바탕으로 서비스하기 위한 사용자를 선택한다. 본 논문은 채널의 클러스터링 특성을 고려한 이종 빔포밍 시스템의 용량을 수학적으로 계산하고, AOD 전송을 위한 비트의 크기, 송신기의 개수 및 송신기당 안테나의 개수에 따른 이종 빔포밍 시스템의 성능을 평가한다.

Key Words : Hybrid beamforming, space division multiple access, clustering nature, angle-of-departure

ABSTRACT

Hybrid beamforming (HBF) for space division multiple access is a promising technique to improve the capacity of the downlink multiuser multiple-input multiple-output system by exploiting the advantages of smart antenna technologies. This paper considers an M (the number of transceivers) by N (the number of antennas per transceiver) HBF structure, where the total $M \cdot N$ antennas are implemented as a uniform circular array antenna. A user selection algorithm in the HBF system is important to achieve spatial and multiuser diversity. To achieve spatial and multiuser diversity, a base station in the HBF system selects multiple users who have high channel gain, taking the channel clustering nature into consideration. Users report the channel state information that was calculated taking the angle-of-departure (AOD) into consideration and the base station selects multiple users to be served on the basis of the received channel state information from users. This paper mathematically derives the capacity of the HBF system and evaluates the performance of the HBF system in terms of the number of AOD representation bits, the number of transceivers, and the number of antennas per transceiver.

※ 이 논문은 2016년도 정부(교육부)의 재원으로 한국연구재단의 지원을 받아 수행된 기초연구사업임 (2016R1D1A1B03934150). 또한 2017년도 서강대학교 교내연구비 지원에 의한 연구임 (201710129.02).

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논문번호 : KICS2018-01-015, Received January 11, 2018; Revised March 26, 2018; Accepted March 26, 2018

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Ⅰ. Introduction

A hybrid beamforming (HBF) technique proposed for space division multiple access (SDMA) increases the capacity of the downlink multiuser multiple-input multiple-output (MIMO) system by using smart antenna technologies. In a practical massive MIMO deployment, hybrid digital and analog beamforming structures with massive antennas are an alternative choice. In the HBF system, massive antennas of a base station (BS) are divided into a number of transceivers, each of which is a subset of the massive antennas[1]. If the BS knows the channel state information (CSI) of all the users, it can achieve high system capacity by selecting the users having a high channel state[2]. The BS broadcasts the pilot signal and users report their CSI to the BS on the basis of the received pilot signal. On the basis of the CSI fed back by users, the BS selects users to be served in the downlink, where the number of users that can be served at the same time is dependent on the number of transceivers at the BS. However, in a practical system, because the number of feedback bits is limited, a BS knows the partial CSI fed back by users. If the BS wants to know the accurate CSI, the number of feedback bits should be very large. However, as the number of feedback bits increases, the signaling overhead also increases. Therefore, it is essential to reduce the number of feedback bits while providing a high system capacity[3,4].

To the best of our knowledge, few studies related to the user selection algorithm that take the effect of feedback representation bits into consideration in the HBF system have been reported. However, for SDMA systems, many researchers have proposed various user selection algorithms on the basis of the pilot signal to increase the system capacity with the limited feedback[5,6]. In [7], a BS broadcasts a pilot signal to all the users and users report their signal-to-noise ratio (SNR) information to the BS. The BS selects the user who has the highest SNR for each frame. However, in the user selection algorithm of [7], the increase of the system capacity is limited because the number of users to be served in a frame is fixed to one regardless of the number of the BS antennas. In [8], a BS transmits different pilot signals to users during multiple slots and the BS selects multiple users on the basis of the CSI fed back by users. However, because the BS broadcasts multiple pilot signals, the signaling overhead increases. The authors of [9-11] theoretically analyzed the capacity of the SDMA systems with and without limited feedback bits taking various user selection algorithms into consideration.

In practical SDMA systems, the signal propagated from the BS is concentrated on the group of scatterers and reflected to the designated user. That is, in an SDMA system, the scatterers are not uniformly distributed but concentrated in some clusters. This phenomenon is called the channel clustering nature[12]. If a BS takes the channel clustering nature into consideration when it transmits data to users, users can increase the received signal power by combining the multiple signals from the multi-path, and the system capacity thereby increases. The authors of [13] showed that, even if the number of users is small, the BS can achieve a high system capacity if the BS selects users to be served taking the channel clustering nature between the BS and users into consideration. However, the authors of [13] did not take the structure of an HBF system into consideration and moreover they failed to derive a mathematical form of the system capacity. In [14] and [15], the authors proposed a user selection algorithm and analyzed the capacity in the HBF systems, respectively. However, the authors of [14] and [15] did not take the clustering nature into consideration.

This paper analyzes the capacity of an HBF system taking the channel clustering nature into consideration, where a BS broadcasts multiple pilot signals and selects multiple users to be served on the basis of the CSI fed back by users. This paper theoretically derives the capacity of the HBF system with a uniform circular array (UCA) antenna, under the assumption that there is no interference between users that are served by the BS. Moreover, this paper evaluates the performance of the HBF system in terms of the number of feedback bits, the number

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of transceivers, and the number of antennas per transceiver.

The remainder of this paper is organized as follows: Section Ⅱ gives a description of the system model. Section Ⅲ analyzes the system capacity taking the channel clustering nature into consideration. Section Ⅳ shows the analytical and simulation results, and finally Section Ⅴ concludes the paper.

Ⅱ. System Model

2.1 A System Description

This paper considers a downlink of an HBF system with K users. As shown in Fig. 1, an M (the number of transceivers) by N (the number of antennas per transceiver) hybrid BF structure is investigated in the downlink. The BS consists of the total $M \cdot N$ antennas implemented as a type of UCA antenna. The circular radius of the UCA antenna is set above five times the wavelength at the center frequency in order to reduce the correlation among antennas[16]. Each transceiver consists of N antennas uniformly selected among $M \cdot N$ antennas. Each user is assumed to be equipped with a single antenna.

For every frame, the BS separately transmits data to M users at the same time by using a spatial multiplexing technique with M transceivers [17]. We assume that there is no interference between users that are served by the BS because the interference may be resolved by using the interference cancelation algorithms such as a zeroforcing beamforming technique[18,19]. When a single data stream from N antennas in a transceiver is considered, the received signal of the kth user who receives data from the mth transceiver can be expressed as

$$y_{m,k} = \sqrt{\rho_{m,k}}\boldsymbol{h}_{m,k}^T \boldsymbol{v}_N(\theta_m) x_{m,k} + n_k, \tag{1}$$

where $\rho_{m,k}$ is the large scale fading that was calculated taking the pathloss and the shadowing into consideration, $\boldsymbol{h}_{m,k}$, which is the $N \times 1$ multiple-input single-output (MISO) block-fading channel vector between N antennas in the mth transceiver and the kth user, is given by $\boldsymbol{h}_{m,k} = [h_1 h_2 \cdots \ h_N]^T$, θ_m is the AOD from the mth transceiver, $\boldsymbol{v}_N(\theta_m)$ is the UCA steering vector from N antennas in the mth transceiver, $x_{m,k}$ is the data signal from the mth transceiver to the kth users, n_k is the noise of the kth user, and $[\ \cdot\ ]^T$ is the transpose. The UCA steering vector from N antennas in a transceiver, $\boldsymbol{v}_N(\theta)$, which is known to both the BS and users, is given by

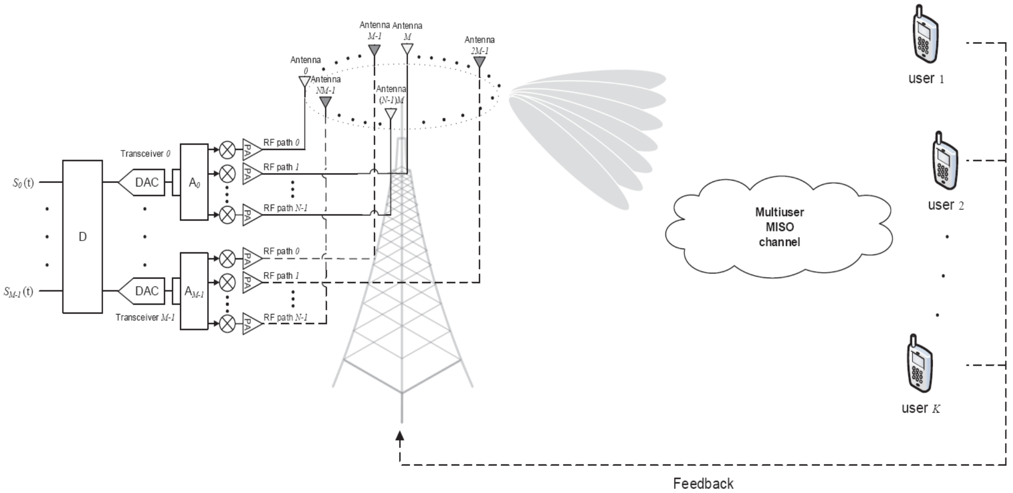

Fig. 1. An M by N HBF system model with a UCA antenna, where each of the M transceivers is connected with N antennas

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$$v_N(\theta) = \frac{1}{\sqrt{N}} \begin{pmatrix} e^{j\nu R\cos(\theta - \varphi_1)} \\ e^{j\nu R\cos(\theta - \varphi_2)} \\ \vdots \\ e^{j\nu R\cos(\theta - \varphi_n)} \\ \vdots \\ e^{j\nu R\cos(\theta - \varphi_N)} \end{pmatrix}, \tag{2}$$

where ν is the wavenumber, R is the circular radius of a transceiver that is implemented as a type of UCA antenna, θ is the AOD of the user, and φ_n is the angular position of the nth antenna in a transceiver[20]. The channel environment is assumed to change independently and identically between consecutive frames. Moreover, this paper assumes that the BS successfully receives the feedback information without error from users.

This paper considers AODs in the horizontal plane but does not consider them in the vertical plane[21]. In addition, we assume a narrowband channel. As shown in Fig. 2, each downlink frame consists of a pilot period and a data transmission period[13]. The length of a downlink frame is T and the length of the pilot period is τ. Therefore, the BS transmits data to users for the duration of $T-\tau$. The BS transmits M pilot signals at M transceivers during the pilot period and each user estimates the M channel states from M transceivers of the BS on the basis of the received M pilot signals. Each user reports its CSI to the BS via the feedback channel, where the CSI consists of two kinds of information, the AOD and SNR of the strongest beam among M received pilot signals.

2.2 CSI Feedback

The CSI reported by the kth user consists of pairs of the AOD and SNR of the strongest beam among M received pilot signals. Let the CSI of the kth user be denoted by $\mathrm{CSI}_k = \{(\theta^*_{1,k}, \mu^*_{1,k}), (\theta^*_{2,k}, \mu^*_{2,k}), \cdots, (\theta^*_{M,k}, \mu^*_{M,k})\}$, where

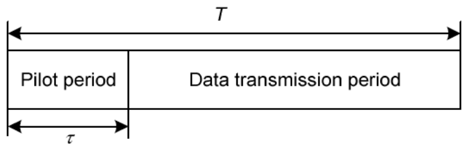

Fig. 2. A downlink frame structure

$\theta^*_{m,k}$ and $\mu^*_{m,k}$ respectively represent the AOD and SNR of the strongest beam among the pilot signals received from N antennas of the mth transceiver.

If N antennas in the mth transceiver at the BS send a pilot symbol s_m, then the received signal of the kth user who receives a pilot signal from the mth transceiver is given by

$$y_{m,k} = \sqrt{\rho_{m,k}}\, \boldsymbol{h}^T_{m,k} \boldsymbol{v}_N(\theta^{pilot}_m) s_m + n_k, \tag{3}$$

The channel vector $\boldsymbol{h}_{m,k}$ is given by

$$\boldsymbol{h}_{m,k} = \sum_{l=1}^{L_k} \begin{pmatrix} \alpha_{l,m,1,k} e^{j\phi_{l,m,1,k}} \\ \alpha_{l,m,2,k} e^{j\phi_{l,m,2,k}} \\ \vdots \\ \alpha_{l,m,n,k} e^{j\phi_{l,m,n,k}} \\ \vdots \\ \alpha_{l,m,N,k} e^{j\phi_{l,m,N,k}} \end{pmatrix}, \tag{4}$$

where L_k is the number of all multi-path components between the BS and the kth user. L_k is the same for all transceivers because the transceivers are located in the same BS. Let the symbols $\alpha_{l,m,n,k}$ and $\phi_{l,m,n,k}$ respectively represent the amplitude and phase of the lth multi-path component between the nth antenna of the mth transceiver and the kth user[22]. Each user is assumed to know the pilot symbols and the AODs of M pilot signals. The estimated channel between the mth transceiver and the kth user, $\hat{\boldsymbol{h}}_{m,k}$, is given by

$$\hat{\boldsymbol{h}}^T_{m,k} = \frac{y_{m,k}}{s_m} \boldsymbol{v}_N(\theta^{\pi lot}_m)^{\dagger}, \tag{5}$$

where θ^{pilot}_m is the pilot signal's AOD from the mth transceiver and $(\cdot)^{\dagger}$ is pseudoinverse. By using the simple beamscan algorithm on the basis of the space-alternating generalized expectation-maximization (SAGE)[23], the AOD of the beam that has the highest channel state between the mth transceiver and the kth user can be expressed as follows:

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$$\theta^*_{m,k} = \arg\max \left|\hat{\boldsymbol{h}}^T_{m,k}\boldsymbol{v}_N(\theta_{m,k})\right|^2, \quad (6)$$

where $|\cdot|$ is the absolute value. In (6), $\hat{\boldsymbol{h}}^T_{m,k}\boldsymbol{v}_N(\theta_{m,k})$ represents the channel state between the mth transceiver and the kth user at the AOD of $\theta_{m,k}$ without consideration of the large scale fading. Consequently, the received SNR of the strongest beam at the kth user who receives the pilot symbol from the mth transceiver is given by

$$\mu^*_{m,k} = \rho_{m,k}\left|\hat{\boldsymbol{h}}^T_{m,k}\boldsymbol{v}_N(\theta^*_{m,k})\right|^2, \quad (7)$$

For every frame, each user reports the AODs and SNRs of the strongest beam at each transceiver to the BS, where a pair of ($\theta^*_{m,k}$, $\mu^*_{m,k}$) are respectively calculated from (6) and (7) for $m = 1,2,\cdots,M$.

2.3 User Selection

The BS serves up to M users among K candidate users via M transceivers by using the spatial multiplexing technique. In order to maximize the system capacity, for every frame, a user who the highest SNR at each transceiver is respectively selected for downlink data service where the SNRs of users are calculated taking the AOD-based channel clustering nature into consideration according to (7). The BS transmits multiple data to the selected M users through M data streams formed by using the AODs reported by the selected users.

Ⅲ. Capacity Analysis

For the mth transceiver, the selected user's SNR is the maximum value among the SNRs of the strongest beams of the users who receive data from the mth transceiver, i.e. $\gamma^*_m = \max\left(\mu^*_{m,1}, \mu^*_{m,2}, \cdots, \mu^*_{m,K}\right)$. Let the probability density function (pdf) of the SNR of the selected user at the mth transceiver be denoted by $f_{\gamma^*_m}(\gamma)$. The system capacity can then be expressed as follows:

$$C = (T-\tau)\sum_{m=1}^{M}\int_0^\infty \log_2(1+\gamma) f_{\gamma^*_m}(\gamma)\, d\gamma, \quad (8)$$

Because of the assumption of the i.i.d channel among transceivers, this paper focuses on the single stream generated from N antennas of the mth transceiver. For simplicity of notation, we omit the scripts m and k, which respectively denote the mth transceiver and the kth user, in $\mu_{m,k}$, $\theta_{m,k}$, $\rho_{m,k}$, and $\boldsymbol{h}_{m,k}$. Each transceiver selects a user who has the highest SNR and it transmits data to that user by using the AOD of the strongest beam between the transceiver and that user. Hence, the received SNR at the user can be expressed as follows:

$$\mu = \frac{\rho}{N}\max|\zeta_N(\theta)|^2, \quad (9)$$

where $\zeta_N(\theta)$, which is derived in Appendix Ⅰ, is the channel state that does not consider the large scale fading of the AOD of θ. $\zeta_N(\theta)$ is given by

$$\begin{aligned}\zeta_N(\theta) = &\underbrace{\sum_{n=1}^{N}\left(a^2_{h,n}+b^2_{h,n}\right)}_{\zeta_N^{const}} + \\ &\underbrace{2\sum_{n'=1}^{N-1}\left(\sum_{n=1}^{N-n'}\alpha_h\cos(\delta(\theta))\right)}_{\zeta_N^{var}(\theta)} - \\ &\underbrace{2\sum_{n'=1}^{N-1}\left(\sum_{n=1}^{N-n'}\beta_h\sin(\delta(\theta))\right)}_{\zeta_N^{var}(\theta)},\end{aligned} \quad (10)$$

where $\alpha_{h,n}$ and $\beta_{h,n}$ are the real part and the imaginary part of the channel vector between the nth antenna and the user. The distribution of $\alpha_{h,n}$ and $\beta_{h,n}$ is determined by the channel environment. Additionally, α_h, β_h, and $\delta(\theta)$ are

$$\alpha_h = a_{h,n}a_{h,n+n'} + b_{h,n}b_{h,n+n'}, \quad (11)$$

$$\beta_h = a_{h,n}b_{h,n+n'} - a_{h,n+n'}b_{h,n+n'}, \quad (12)$$

$$\delta(\theta) = \frac{4\pi R}{\lambda}\sin\left(\frac{\varphi_{n+n'}-\varphi_n}{2}\right)\sin\left(\theta - \frac{\varphi_{n+n'}+\varphi_n}{2}\right), \quad (13)$$

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where λ is the wavelength at the center frequency. Therefore, the optimal value of θ, θ^*, is given by

$$\theta^* = \arg\max \zeta_N(\theta) \\ = \arg\max \left(2\sum_{n'=1}^{N-1}\left(\sum_{n=1}^{N-n'} \alpha_h \cos(\delta(\theta))\right) - 2\sum_{n'=1}^{N-1}\left(\sum_{n=1}^{N-n'} \beta_h \sin(\delta(\theta))\right) \right), \quad (14)$$

For the particular case of $N=2$, i.e., the number of antennas per transceiver is two, $\zeta_2(\theta)$ can be simplified as

$$\zeta_2(\theta) = \underbrace{a_{h,1}^2 + b_{h,1}^2 + a_{h,2}^2 + b_{h,2}^2 +}_{\zeta_N^{const}} \underbrace{2\alpha\cos\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right)\right) -}_{\zeta_N^{var}(\theta)} \underbrace{2\beta\sin\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right)\right),}_{\zeta_N^{var}(\theta)} \quad (15)$$

where α is $a_{h,1}a_{h,2} + b_{h,1}b_{h,2}$ and β is $a_{h,1}b_{h,2} - a_{h,2}b_{h,1}$. In (15), $\zeta_2^{var}(\theta)$ can be expressed by

$$\zeta_2^{var}(\theta) = 2\alpha\cos\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right)\right) - 2\beta\sin\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right)\right) \\ = 2\sqrt{\alpha^2 + \beta^2} \cdot \cos\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right) - \tan^{-1}\left(\frac{\beta}{\alpha}\right)\right). \quad (16)$$

Because $\zeta_2^{var}(\theta)$ is the general form of a cosine function, $|\zeta_2^{var}(\theta)|$ has the maximum value when the $d\zeta_2^{var}(\theta)/d\theta = 0$. Therefore, the optimal value of θ that maximizes the SNR in (9) is obtained by solving $d\zeta_2(\theta)/d\theta = 0$. The derivation of (15), which is derived by Appendix II, is given by

$$\frac{d\zeta_2(\theta)}{d\theta} = -\frac{8\alpha\pi}{\lambda}\sin\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right)\right)\cos\left(\theta - \frac{\pi}{2}\right) - \frac{8\beta\pi}{\lambda}\cos\left(\frac{4\pi R}{\lambda}\sin\left(\theta - \frac{\pi}{2}\right)\right)\cos\left(\theta - \frac{\pi}{2}\right). \quad (17)$$

Hence, the optimal value of θ, θ^*, can be expressed as follows:

$$\theta^* = \arg\max \zeta_2(\theta) \\ = \sin^{-1}\left(\frac{\lambda}{4\pi R} tan^{-1}\left(-\frac{\beta}{\alpha}\right)\right) + \frac{\pi}{2} \quad (18)$$

Consequently, from (9), if the kth user receives data from the mth transceiver, the received SNR of the strongest beam of the kth user is given by

$$\mu_{m,k}^* = \frac{\rho_{m,k}}{N}\left|\zeta_N\left(\theta_{m,k}^*\right)\right|^2 \quad (19)$$

where $\theta_{m,k}^*$ is obtained from (18).

Let the pdf and the cumulative distribution function (cdf) of $\mu_{m,k}^*$ be denoted by $g_{\mu_{m,k}^*}(\gamma)$ and $G_{\mu_{m,k}^*}(\gamma)$, respectively. Because each transceiver selects the user who reports the highest SNR for each transceiver, the pdf of the SNR of the selected user can be expressed as

$$f_{\gamma_m^*}(\gamma) = \sum_{k=1}^{K} g_{\mu_{m,k}^*}(\gamma) \prod_{l=1, l\neq k}^{K} G_{\mu_{m,k}^*}(\gamma) \quad (20)$$

by the statistical order. By substituting (20) into (8), we can calculate the system capacity.

Ⅳ. Numerical and Simulation Results

The system capacity of the downlink of the HBF system with K users has been evaluated. The BS has M UCA transceivers, where each transceiver consists of N antennas, and therefore the BS has a total of $M \cdot N$ antennas. Each user is equipped with a single antenna. The parameters used in the simulation are summarized in Table 1.

Figure 3 shows the capacity of the HBF system when the total number of antennas is $M \cdot N = 16$. As the number of users increases, the system capacity increases because of the user diversity. As the number of transceivers, M, increases, the HBF system achieves spatial multiplexing gain because it

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Table 1. Simulation parameters

Item	Value
Center frequency, $1/\lambda$	2 GHz
The radius of a UCA antenna	1 meter
Distribution of large scale fading, ρ_k	Gaussian (0,1) dB
Channel model	Winner model
Propagation condition	Suburban and NLOS
The number of multi-path components per link, L_k	20
Ratio of the pilot period to the frame duration, τ/T	0.92

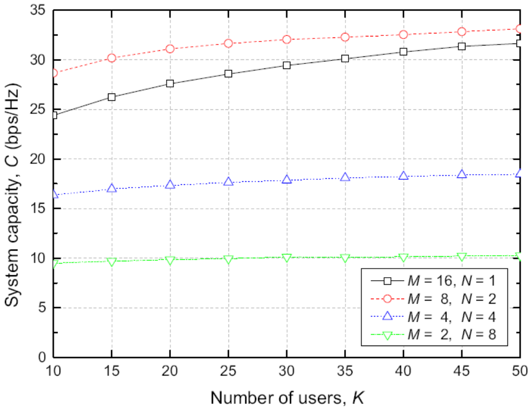

Fig. 3. The system capacity when the total number of antennas is 16

serves multiple users at the same time. Additionally, as the number of antennas per transceiver, N, increases, the HBF system achieves beamforming gain. When the total number of antennas, $M \cdot N$, is fixed, there may be a tradeoff between the spatial multiplexing gain and the beamforming gain. However, the spatial multiplexing gain is superior to the beamforming gain for $M \geq 2$. For example, when $K=50$, the HBF system with ($M=8$, $N=2$) improves the capacity by about 79% in comparison with the system with ($M=4$, $N=4$), and by about 223% in comparison with the system with ($M=2$, $N=8$), respectively. However, the capacity of the HBF system with ($M=16$, $N=1$) is less than that of the HBF system with ($M=8$, $N=2$) because the system does not achieve beamforming gain due to the AOD based channel clustering nature. Hence, when the total number of antennas is fixed, the values of M and N can be adjusted according to the trade-off between the spatial multiplexing gain and the beamforming gain, taking the implementation complexity into consideration.

Figure 4 compares the capacity of the HBF system with and without AOD. In the HBF w/o AOD, each user reports the received SNR to the BS, where the SNR is calculated on the basis of only the estimated channel without consideration of the UCA steering vector. Hence, in the HBF w/o AOD, the beamforming gain decreases because the system does not take the channel clustering nature into consideration. When $M=8$ and $N=2$, the capacity of the HBF w/ AOD is greater than that of the HBF w/o AOD by about 24.9%; when $M=4$ and $N=4$, the capacity of the HBF w/ AOD is greater than that of the HBF w/o AOD by about 52.8%.

Figure 5 shows the capacity of the HBF system with four transceivers as the number of antennas per transceiver increases. As the number of antennas increases, the accuracy of the estimation of AOD and the beamforming gain increase. Consequently, the capacity also increases. In particular, when $K=50$, the capacity of the HBF system with $N=8$ is greater than that of the HBF system with $N=4$ by about 11.2% and it is greater than that of HBF system with $N=2$ by about 23.8%, respectively.

Figures 6 and 7 show the capacity of the HBF

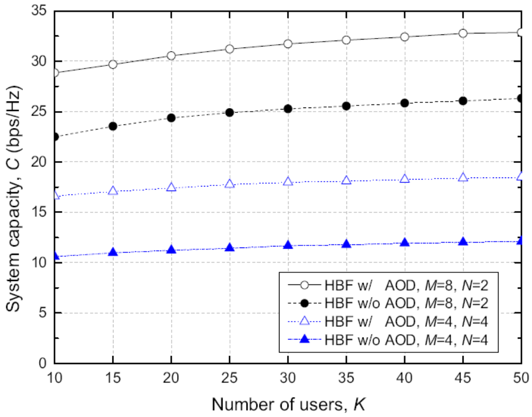

Fig. 4. The system capacity according to the consideration of AOD

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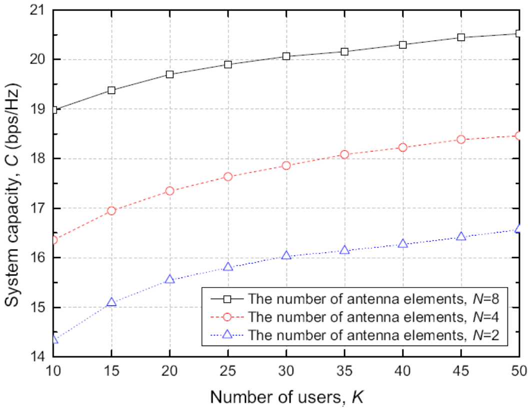

Fig. 5. The system capacity when the BS has four transceivers

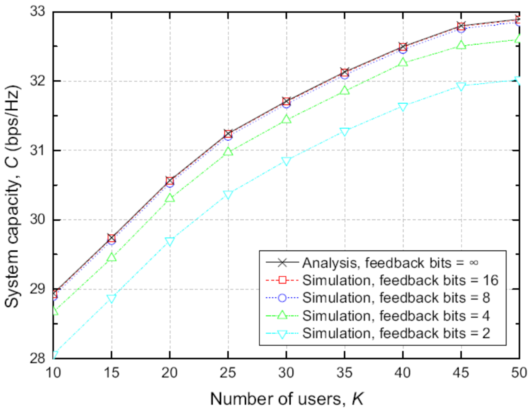

Fig. 6. The system capacity according to the number of AOD representation bits when $M=8$ and $N=2$

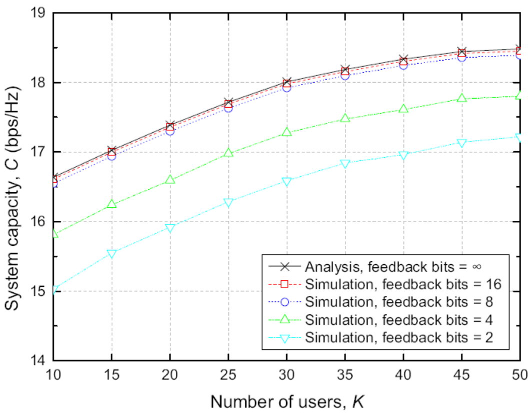

Fig. 7. The system capacity according to the number of AOD representation bits when $M=4$ and $N=4$

system according to the number of AOD representation bits for the following two cases: ($M=8$, $N=2$) and ($M=4$, $N=4$). The value of the user's AOD is equally quantized in a range from 0 to 360 degrees according to the number of AOD representation bits. The analytical results assume that the number of AOD representation bits is infinite. The quantization error due to the limitation of the AOD representation bits leads to performance degradation. As shown in Fig. 6, in the HBF system with ($M=8$, $N=2$), the system capacity degrades by about 2.7%, 1.0%, 0.2%, and 0.1% when the number of AOD representation bits is 2 bits, 4 bits, 8 bits, and 16 bits, respectively. Moreover, the performance degradation due to the limited AOD representation bits is dependent on the number of transceivers and the number of antennas. As shown in Fig. 7, in the HBF system with ($M=4$, $N=4$), the system capacity degrades by about 7.3%, 3.8%, 0.5%, and 0.2% when the number of AOD representation bits is 2 bits, 4 bits, 8 bits, and 16 bits, respectively. However, as shown in Fig. 6 and Fig. 7, the performance degradation due to the AOD representation bits is negligible.

V. Conclusion

This paper analyzed the capacity of an HBF system taking the channel clustering nature between the BS and users into consideration. The downlink performance of the HBF system with a UCA antenna was evaluated in terms of the number of UCA transceivers, the number of antennas per transceiver, and the number of AOD representation bits used by users. As the number of transceivers increases, the system capacity linearly increases with adoption of a spatial multiplexing technique. Similarly, as the number of antennas increases, the system capacity also increases. For the case where the number of transceivers is 4 and the number of antennas per transceiver is 4, the BS increases the capacity by about 52.8% when the BS selects users taking the AOD based channel clustering nature into consideration compared to when the BS selects users without considering the AOD based channel clustering nature. Moreover, as the number of AOD representation bits increases, the estimation accuracy

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of the AOD of the strongest beam increases, and therefore the system capacity also increases.

Appendix Ⅰ: The derivation of the received SNR at each user

From (7), the received SNR at the kth user who receives data from the mth transceiver is given by

$$\mu^{*}_{m,k} = \rho_{m,k} \max \left| \boldsymbol{h}^{T}_{m,k} \boldsymbol{v}_{N}(\theta_m) \right|^2 \quad , \tag{A·1}$$

where complex values of $\boldsymbol{v}_N(\theta_m)$ and $\boldsymbol{h}_{m,k}$ can be expressed as a complex form, $a+bi$.

For simplicity of notation, we omit the subscripts m and k, which respectively denote the mth transceiver and the kth user. When the number of antennas per transceiver is N, the received SNR at each user can then be expressed as

$$\gamma = \frac{\rho}{N} \max \left| \underbrace{\left(a_{v,1} + b_{v,1} i \ \cdots \ a_{v,N} + b_{v,N} i \right) \cdot \begin{pmatrix} a_{h,1} + b_{h,1} i \\ \vdots \\ a_{h,N} + b_{h,N} i \end{pmatrix}}_{\zeta(\theta)} \right| \quad , \tag{A·2}$$

where $a_{v,n}$ and $b_{v,n}$ are the real part and the imaginary part of the steering vector between the n th antenna and the user, respectively. Also, $a_{h,n}$ and $b_{h,n}$ are the real part and the imaginary part of the channel vector between the nth antenna and the user, respectively. The parameter $\zeta_n(\theta)$ can be expanded as

$$\begin{aligned} \zeta_n(\theta) = & \sum_{n=1}^{N} \left(a^2_{h,n} + b^2_{h,n} \right) + \\ & 2 \sum_{n'=1}^{N-1} \left(\sum_{n=1}^{N-n'} \alpha_h \left(a_{v,n} a_{v,n+n'} + b_{v,n} b_{v,n+n'} \right) \right) - \\ & 2 \sum_{n'=1}^{N-1} \left(\sum_{n=1}^{N-n'} \beta_h \left(a_{v,n} b_{v,n+n'} - a_{v,n+n'} b_{v,n} \right) \right), \end{aligned} \tag{A·3}$$

where α_h is $a_{h,n} a_{h,n+n'} + b_{h,n} b_{h,n+n'}$ and β_h is $a_{h,n} b_{h,n+n'} - a_{h,n+n'} b_{h,n}$. Additionally, $a_{v,n}$ and $b_{v,n}$ can be derived from the UCA steering vector function. Hence, $a_{v,n}$ and $b_{v,n}$ can be expressed as follows:

$$a_{v,n} = \cos\left(\frac{2\pi R}{\lambda} \cos\left(\theta - \varphi_{\mathrm{n}} \right) \right), \tag{A·4}$$

$$b_{v,n} = \sin\left(\frac{2\pi R}{\lambda} \cos\left(\theta - \varphi_{\mathrm{n}} \right) \right), \tag{A·5}$$

where λ is the wave length at the center frequency and $\varphi = 2\pi n / N$ is the angular position of the nth antenna for $n = 1, 2, \cdots, N$. From (A·4) and (A·5), we can simplify (A·2) as

$$\begin{aligned} \zeta_n(\theta) = & \sum_{n=1}^{N} \left(a^2_{h,n} + b^2_{h,n} \right) + \\ & 2 \sum_{n'=1}^{N-1} \left(\sum_{n=1}^{N-n'} \alpha_h \cos\left(\delta(\theta) \right) \right) - \\ & 2 \sum_{n'=1}^{N-1} \left(\sum_{n=1}^{N-n'} \beta_h \sin\left(\delta(\theta) \right) \right), \end{aligned} \tag{A·6}$$

where $\delta(\theta)$ is given by

$$\begin{aligned} \delta(\theta) = & \frac{4\pi R}{\lambda} \sin\left(\frac{\varphi_{\mathrm{n+n'}} - \varphi_{\mathrm{n}}}{2} \right) \cdot \\ & \sin\left(\theta - \frac{\varphi_{\mathrm{n+n'}} + \varphi_{\mathrm{n}}}{2} \right). \end{aligned} \tag{A·7}$$

Appendix Ⅱ: The derivation of the received SNR at each user when $N = 2$

When the number of antennas per transceiver is two ($N = 2$), the user's SNR is

$$\gamma = \frac{\rho}{2} \max \left| \underbrace{\left(a_{v,1} + b_{v,1} i \ \ a_{v,2} + b_{v,2} i \right) \cdot \begin{pmatrix} a_{h,1} + b_{h,1} i \\ a_{h,2} + b_{h,2} i \end{pmatrix}}_{\zeta_2(\theta)} \right|^2 \quad , \tag{A·8}$$

The parameter $\zeta_2(\theta)$ can be expanded as

$$\begin{aligned} \zeta_2(\theta) = & a^2_{h,1} + b^2_{h,1} + a^2_{h,2} + b^2_{h,2} + \\ & 2\alpha\left(a_{v,1} a_{v,2} + b_{v,1} b_{v,2} \right) - \\ & 2\beta\left(a_{v,1} b_{v,1} - a_{v,2} b_{v,1} \right), \end{aligned} \tag{A·9}$$

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where α is $a_{h,1}a_{h,2}+b_{h,1}b_{h,2}$ and β is $a_{h,1}b_{h,2}-a_{h,2}b_{h,1}$. From (A·4) and (A·5), we can simplify (A·9) as

$$\begin{aligned}\zeta_2(\theta)=&a_{h,1}^2+b_{h,1}^2+a_{h,2}^2+b_{h,2}^2+\\&2\alpha\cos\left(\frac{4\pi R}{\lambda}\sin\left(\theta-\frac{\pi}{2}\right)\right)-\\&2\beta\sin\left(\frac{4\pi R}{\lambda}\sin\left(\theta-\frac{\pi}{2}\right)\right).\end{aligned} \tag{A·10}$$

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