Interference Suppression Multiuser MMSE Multiplexing Combined with Optimal Joint Transmit/Receive Diversity for a Cellular Distributed MU-MIMO System

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Abstract— **In a cellular distributed multiuser MIMO (MU-MIMO) system, inter-cluster interference suppression is a challenge because user-cluster-wise distributed MU-MIMO is performed using the same radio resources in all user-clusters in each cell. Recently, we proposed the interference suppression multiuser minimum mean square error (IS-MU-MMSE) multiplexing for the single-antenna users case. In this paper, we extend IS-MU-MIMO multiplexing to the multiple-antenna users case. As the number of antennas per user increases, each user can transmit multiple streams using eigenmode transmission, however, the number of distributed antennas required increases and the antenna degrees of freedom for inter-cluster interference suppression decreases. We propose the IS-MU-MMSE multiplexing combined with optimal joint transmit/receive diversity (JTRD), where the concept of a virtual single antenna user is introduced, the number of required minimum distributed antennas at the base station is reduced to equal to the number of users, and the remaining antenna degrees of freedom are used for inter-cluster interference suppression. Through computer simulations, we evaluate the uplink user capacity and confirm that, in a high user-density environment, IS-MU-MMSE multiplexing combined with optimal JTRD is superior to that combined with eigenmode transmission.**

Keywords— Cellular distributed MU-MIMO, user-clustering, multiuser MMSE multiplexing, joint transmit/receive diversity, cell-free massive MIMO

I. INTRODUCTION

The mobile traffic volume has been increasing ever since the 5th generation (5G) system services started and is forecasted to reach 13.8 times the 2020 volume by 2030 [1]. Thus, it is essential to continuously enhance the system capacity even with the development of 5G-advanced and 6G systems [2][3]. In order to increase the system capacity while using the limited frequency resource, an effective approach is to densify the base station (BS) deployment. The densification of BS deployment shortens the transmitter-receiver distance and hence, makes it possible to utilize both millimeter-wave and terahertz bands. However, the ultra-high frequency band signals have a highly rectilinear propagation property, and this causes frequent radio link blockage by obstacles.

Rather than simply densifying the BS deployment, by keeping the signal processing and connection control functions at a conventional macro-cell BS (hereinafter, simply referred to as BS), a large number of antennas are deployed in each BS cell to achieve a higher-degree spatial diversity and to effectively avoid the aforementioned radio link blockage. The above radio signal transmission/reception system is called the distributed antenna or distributed multiuser multi-input multi-output (MU-MIMO) system [4][5]. Recently, the concept of the cell-free massive MIMO (CF-mMIMO) system [6] has emerged towards 6G systems. It should be noted that the concept of the CF-mMIMO system is basically equivalent to that of the large-scale distributed MU-MIMO system.

The challenge in realizing large scale distributed MU-MIMO systems is prohibitively high computational complexity. In order to address this challenge, we have proposed a cellular distributed MU-MIMO system [7], in which a wide communication service area is divided into a number of cells based on the location information of densely deployed distributed antennas to ensure the system scalability, multiple user-clusters are formed by grouping neighborhood users together in each cell based on the location information of users, and small-scale cluster-wise distributed MU-MIMO cooperative transmission/reception is performed using the same radio resources in all user-clusters in parallel, thereby enabling spatial multiplexing of a large number of users in each cell while keeping the computational complexity to an acceptable level. From the perspective of improving the system capacity while using the limited frequency resources, it is desirable to reuse the same radio resource in all cells, however, both the inter-cell interference and the inter-cluster interference are produced and limit the system capacity improvement achievable by cluster-wise distributed MU-MIMO. Thus, inspired by [8], we recently proposed the interference suppression multiuser minimum mean square error (IS-MU-MMSE) multiplexing to effectively suppress the inter-cluster interference for the case of single-antenna users [9].

In this paper, we consider the case where each user has multiple antennas. As a general linear control technique, MU-MIMO multiplexing, combined with block diagonalization and eigenmode transmission [10], is well known. This technique can transmit up to the same number of streams in parallel as the total number of antennas on the user side, while reducing inter-user and inter-stream interference. However, this technique requires the number of distributed antennas at the BS side to be greater than or equal to the total number of antennas on the users' side, and therefore, a huge number of distributed antennas is necessary when there are many users.

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In addition, strong inter-cluster interference occurs in a cellular distributed MU-MIMO system, so the number of distributed antennas at the BS side needs to be further increased to suppress inter-cluster interference. To solve these problems, we introduce the concept of a virtual single antenna user. MU-MIMO multiplexing of virtual single antenna users can reduce the required minimum number of distributed antennas at the BS side to the number of users. The next challenge is how to implement the concept of a virtual single antenna user. We utilize the optimal joint transmit/receive diversity (JTRD) technique [11], which is equivalent to maximum eigenmode transmission (or beamforming) [12]. We propose IS-MU-MMSE multiplexing combined with optimal JTRD, where the number of required minimum distributed antennas at the BS is reduced to the number of users, and the remaining antenna degrees of freedom are used for inter-cluster interference suppression. Through computer simulations, we evaluate the uplink user capacity achievable by the proposed IS-MU-MMSE multiplexing combined with optimal JTRD and that combined with eigenmode transmission and confirm that, in a high user-density environment, combining with optimal JTRD is superior to combining with eigenmode transmission.

The rest of this paper is organized as follows. Sect. II introduces the cellular distributed MU-MIMO system concept and describes the cell and user-cluster formation and the user-antenna association. In Sects. III and IV, the uplink transmission model and the proposed IS-MU-MMSE multiplexing combined with optimal JTRD are presented. In Sect. V, the uplink user capacities achievable by the proposed IS-MU-MMSE multiplexing combined with optimal JTRD and that combined with eigenmode transmission are evaluated by computer simulation. Sect. VI offers some conclusions and future works.

II. Cellular Distributed MU-MIMO System Concept

The concept of a cellular distributed MU-MIMO system is shown in Fig. 1.

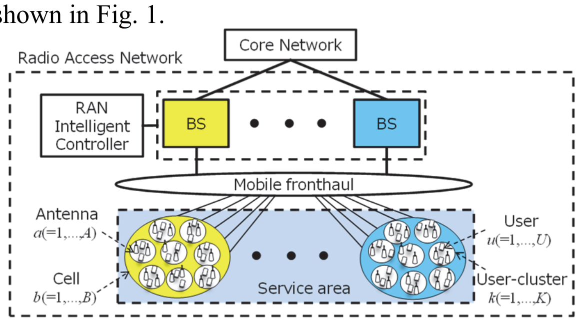

Fig. 1. Cellular distributed MU-MIMO system concept.

A wide communication service area consisting of randomly placed A distributed antennas (hereafter referred to as antennas) is divided into B cells. Antennas in a cell are connected with its BS via an optical mobile fronthaul so that each BS can cooperatively use the antennas in its cell. U user equipments having N antennas (hereafter referred to as users) are randomly distributed in the same service area, and users in each cell are grouped into user-clusters to perform small-scale cluster-wise distributed MU-MIMO in all user-clusters in parallel.

A. *Cell Formation*

Based on the location information of the antennas, the radio access network intelligent controller (RIC) takes a role of constructing the cellular structure. In order to make the number of antennas per cell uniform, the number of antennas per cell is constrained to be less than or equal to A_{cell} using the constrained K-means algorithm [7], and A antennas in the service area are divided into $B(= A / A_{\text{cell}})$ non-overlapped cells. Let $\mathcal{N}_b \subset \{1,\ldots,a,\ldots,A\}$ denote the subset of antennas ($|\mathcal{N}_b| = A_{\text{cell}}$) belonging to cell $b(=1,\ldots,B)$. Since cells do not overlap each other, $\mathcal{N}_b \cap \mathcal{N}_i = \varnothing$. Note that A_{cell} is determined based on the signal processing capability of the BS.

B. *User-Cluster Formation*

Based on user location information, each BS forms non-overlapped user-clusters. In order to make the number of users per cluster uniform, the constrained K-means algorithm is also used here. The number of users per cluster is constrained to be less than or equal to U_{cls}. As a consequence, a total of K (= U / U_{cls}) non-overlapped user-clusters are formed in the service area. Note that, for simplicity, in the computer simulation in this paper, we generate U_{cell} (= U / B) users in each cell so as to make the total number of users in the service area becomes U. Let $\mathcal{S}_k \subset \{1,\ldots,u,\ldots,U\}$ denote the subset of users ($|\mathcal{S}_k| = U_{\text{cls}}$) belonging to user-cluster $k(=1,\ldots,K)$. Since user-clusters do not overlap, $\mathcal{S}_k \cap \mathcal{S}_i = \varnothing$. Let $\mathcal{C}_b \subset \{1,\ldots,k,\ldots,K\}$ denote the subset of user-clusters ($|\mathcal{C}_b| = K_{\text{cell}}$) belonging to cell b. Note that U_{cls} is also determined based on the signal processing capability of the BS.

C. *Antenna Association*

In order to make the signal processing complexity per user-cluster uniform, the same number A_{cls} of antennas from A_{cell} antennas of a cell of interest are associated with each user-cluster belonging to this cell, and antenna overlap is allowed between different user-clusters. The antenna association for each user-cluster is done as follows. Firstly, the same number $A_{\text{cls}}/U_{\text{cls}}$ of antennas with the lowest pathloss are selected for each user. It should be noted that A_{cls} must be a multiple integer of U_{cls} and that the same antenna is not allowed to be shared by different users. Then, if different users in the same user-cluster select the same antenna, the user whose selected antenna has the lowest pathloss keeps it, and the other users select another antenna with the next lowest pathloss. Let $\mathcal{M}_k \subset \{1,\ldots,a,\ldots,A\}$ denote the subset of antennas ($|\mathcal{M}_k| = A_{\text{cls}}$) belonging to user-cluster k. If user-cluster k belongs to cell b, $\mathcal{M}_k \subset \mathcal{N}_b$.

Let S denote the number of streams per user, then the minimum required A_{cls} is $A_{\text{cls}} = S \cdot U_{\text{cls}}$. In the proposed IS-MU-MMSE multiplexing combined with optimal JTRD, since each user transmits single-stream (S = 1), the minimum required A_{cls} is the same number as U_{cls} (i.e., A_{cls} = U_{cls}), however, by intentionally associating twice as many antennas as U_{cls} to each user cluster (i.e., A_{cls} = $2U_{\text{cls}}$), the remaining antenna degrees of freedom $(A_{\text{cls}} - U_{\text{cls}})$ becomes U_{cls}, which can be utilized for suppression of inter-cluster interference.

III. Uplink Transmission Model

Fig. 2 shows the uplink transmission model for a cellular distributed MU-MIMO system. Assuming that user u belongs to user-cluster k in cell b (i.e., $u \in \mathcal{S}_k, k \in \mathcal{C}_b$), the uplink received signal vector $\mathbf{y}_u \in \mathbb{C}^S$ after IS-MU-MMSE reception for user $u \in \mathcal{S}_k$ transmitting S streams is represented as

$$\mathbf{y}_u = \mathbf{W}_u^{\mathrm{H}} \mathbf{D}_k \left(\mathbf{H}_u \boldsymbol{\beta}_u \mathbf{s}_u + \sum_{v=1, v \neq u}^{U} \mathbf{H}_v \boldsymbol{\beta}_v s_v + \mathbf{n} \right), \tag{1}$$

where $\mathbf{s}_u \in \mathbb{C}^S$, $\boldsymbol{\beta}_u \in \mathbb{C}^{N \times S}$, and $\mathbf{W}_u \in \mathbb{C}^{A \times S}$ are the uplink transmit signal vector with transmit power p_u, the transmit weight matrix and the IS-MU-MMSE weight matrix for user $u \in \mathcal{S}_k$, respectively. $\mathbf{H}_u = [\mathbf{h}_1^{(u)\mathrm{T}} \ldots \mathbf{h}_n^{(u)\mathrm{T}} \ldots \mathbf{h}_N^{(u)\mathrm{T}}]^{\mathrm{T}} \in \mathbb{C}^{A \times N}$ is the propagation channel matrix of user $u \in \mathcal{S}_k$, where $\mathbf{h}_n^{(u)} = [h_{n1}^{(u)} \ldots h_{na}^{(u)} \ldots h_{nA}^{(u)}]^{\mathrm{T}} \in \mathbb{C}^A$ is the propagation channel vector associated with user $u \in \mathcal{S}_k$ between antenna n and all A antennas in the service area. $\mathbf{n} \in \mathbb{C}^A$ is the complex Gaussian noise vector with each element being an independent zero-mean complex Gaussian variable having variance $2\sigma^2$. $\mathbf{D}_k = \mathrm{diag}(d_1, \ldots, d_a, \ldots, d_A) \in \mathbb{C}^{A \times A}$ is the antenna association matrix for user-cluster $k \in \mathcal{C}_b$, and its diagonal element d_a is given as

$$d_a = 1(0) \text{ if } a \in \mathcal{M}_k \text{(otherwise)}. \tag{2}$$

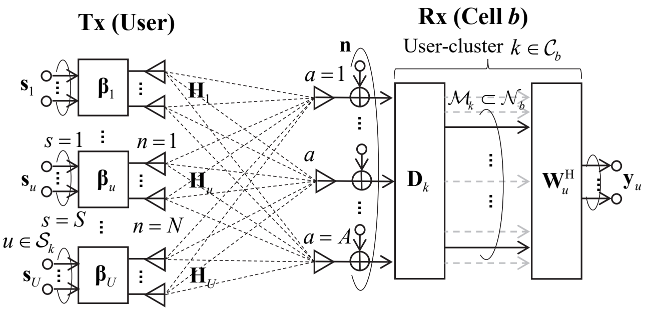

Fig. 2. Uplink transmission model for user u.

IV. IS-MU-MMSE Multiplexing Combined with Optimal JTRD

In this section, the optimal JTRD weight, proposed IS-MU-MMSE weight combined with optimal JTRD, and the relationship between optimal JTRD and eigenmode transmission for the uplink are described.

A. *Optimal JTRD Weight* [11]

Optimal JTRD weight vector of user $u \in \mathcal{S}_k$ belonging to user-cluster $k \in \mathcal{C}_b$ in cell b is denoted by $\boldsymbol{\beta}_u^{\mathrm{JTRD}} \in \mathbb{C}^N$ with $(\boldsymbol{\beta}_u^{\mathrm{JTRD}})^{\mathrm{H}} \boldsymbol{\beta}_u^{\mathrm{JTRD}} = 1$, which is the solution of the following eigenequation:

$$\left\{ \left(\mathbf{D}_k \mathbf{H}_u \right)^{\mathrm{H}} \mathbf{D}_k \mathbf{H}_u \right\} \boldsymbol{\beta}_u^{\mathrm{JTRD}} = \omega_u^{+} \boldsymbol{\beta}_u^{\mathrm{JTRD}}, \tag{3}$$

where $\mathbf{D}_k \mathbf{H}_u$ is the u-th user's propagation channel matrix and ω_u^{+} is the maximum eigenvalue. The transmit signal multiplied by $\boldsymbol{\beta}_u^{\mathrm{JTRD}}$ is regarded as a single-stream transmission from a virtual single-antenna user.

B. *IS-MU-MMSE Weight Combined with optimal JTRD*

The IS-MU-MMSE weight vector $\mathbf{w}_u^{\mathrm{JTRD}} \in \mathbb{C}^A$ combined with optimal JTRD of user $u \in \mathcal{S}_k$ belonging to user-cluster $k \in \mathcal{C}_b$ in cell b is given as

$$\mathbf{w}_u^{\mathrm{JTRD}} = p_u \left(\begin{array}{l} \sum_{v \in \mathcal{P}_k} p_v \mathbf{D}_k \mathbf{H}_v \boldsymbol{\beta}_v^{\mathrm{JTRD}} \left(\mathbf{D}_k \mathbf{H}_v \boldsymbol{\beta}_v^{\mathrm{JTRD}} \right)^{\mathrm{H}} \\ + \mathrm{diag}\left(\sum_{v \in \mathcal{P}_k} p_v \mathbf{D}_k \mathbf{q}_v \right) + \sigma^2 \mathbf{D}_k \end{array} \right)^{-1} \mathbf{D}_k \mathbf{H}_u \boldsymbol{\beta}_u^{\mathrm{JTRD}}, \tag{4}$$

where $\mathbf{D}_k \mathbf{H}_u \boldsymbol{\beta}_u^{\mathrm{JTRD}}$ is the $u(\in \mathcal{S}_k)$-th user's equivalent channel matrix which is a concatenation of propagation channel matrix and optimal JTRD transmit weight.

$\mathcal{P}_k$ is the subset of U_{cls} desired users to be multiplexed in user-cluster k and interfering users that give dominant inter-cluster interference to user cluster k. $\mathcal{P}_k$ is expressed as

$$\mathcal{P}_k = \bigcup_{v \in \mathcal{S}_k} \mathcal{I}_v, \tag{5}$$

where $\mathcal{I}_v = \{ i : \mathbf{G}_v \mathbf{G}_i \neq \mathbf{0}_A \}$ is the subset of users whose antennas overlap with the antennas selected for user v. $\mathbf{G}_v = \mathrm{diag}(g_1, \ldots, g_a, \ldots, g_A) \in \mathbb{C}^{A \times A}$ is the antenna association matrix for user v (note that $\mathbf{D}_k = \sum_{v \in \mathcal{S}_k} \mathbf{G}_v$).

$\mathbf{q}_v$ is the vector of short-term average channel gain between user v and all antennas in the service area, and is given as

$$\mathbf{q}_v = \left[\mathbb{E}\left\{ \left| h_1^{(v)} \right|^2 \right\} \ldots \mathbb{E}\left\{ \left| h_a^{(v)} \right|^2 \right\} \ldots \mathbb{E}\left\{ \left| h_A^{(v)} \right|^2 \right\} \right]^{\mathrm{T}}, \tag{6}$$

where $\mathbb{E}\{ |h_a^{(v)}|^2 \}$ is the short-term average channel gain between user v and antenna a. The short-term average means to take averaging over fading for the given the pathloss and shadowing loss. Since N antennas of user v are close to each other, $\mathbb{E}\{ |h_a^{(v)}|^2 \} = \mathbb{E}\{ |h_{1a}^{(v)}|^2 \} = \ldots = \mathbb{E}\{ |h_{na}^{(v)}|^2 \ldots = \mathbb{E}\{ |h_{Na}^{(v)}|^2 \}$ is assumed.

By using the IS-MU-MMSE weight vector of Eq. (4), the interference from dominant ($A_{\mathrm{cls}} - U_{\mathrm{cls}}$) inter-cluster interfering users can be suppressed by the help of the remaining ($A_{\mathrm{cls}} - U_{\mathrm{cls}}$) antenna degrees of freedom while spatially multiplexing U_{cls} users in user-cluster k. In contrast, inter-cluster interference from users (represented by the user set $\overline{\mathcal{P}_k}$) other than the user set $\mathcal{P}_k$ is treated as the equivalent noise. This improves the received signal-to-interference plus noise power ratio (SINR) when the remaining antenna degrees of freedom is limited.

C. *Relationship Between Optimal JTRD and Eigenmode Transmission*

Optimal JTRD is a single-stream transmission technique, while eigenmode transmission is an S (= N)-stream transmission one. The transmit weight matrix $\boldsymbol{\beta}_u \in \mathbb{C}^{N \times S}$ for the u-th user eigenmode transmission is given as

$$\boldsymbol{\beta}_u = \frac{1}{\sqrt{S}} \left[\boldsymbol{\beta}_1^{(u)} \ldots \boldsymbol{\beta}_s^{(u)} \cdots \boldsymbol{\beta}_S^{(u)} \right], \tag{7}$$

where $\boldsymbol{\beta}_s^{(u)} \in \mathbb{C}^N$ with $(\boldsymbol{\beta}_s^{(u)})^{\mathrm{H}} \boldsymbol{\beta}_s^{(u)} = 1$ is the solution corresponding to the s-th largest eigenvalue of the eigenequation of Eq. (3).

The IS-MU-MMSE weight matrix $\mathbf{W}_u \in \mathbb{C}^{A \times S}$ combined with eigenmode transmission is given as

$$\mathbf{W}_u = \left[\mathbf{w}_1^{(u)} \ldots \mathbf{w}_s^{(u)} \cdots \mathbf{w}_S^{(u)}\right] = p_u \begin{pmatrix} \sum_{v\in\mathcal{P}_k} p_v \mathbf{D}_k \mathbf{H}_v \boldsymbol{\beta}_v \left(\mathbf{D}_k \mathbf{H}_v \boldsymbol{\beta}_v\right)^{\mathrm{H}} \\ +\mathrm{diag}\left(\sum_{v\in\mathcal{P}_k} p_v \mathbf{D}_k \mathbf{q}_v\right) + \sigma^2 \mathbf{D}_k \end{pmatrix}^{-1} \mathbf{D}_k \mathbf{H}_u \boldsymbol{\beta}_u . \quad (8)$$

Note that the eigenmode transmission using $S = 1$ is called the maximum eigenmode transmission (or beamforming) and is equivalent to optimal JTRD.

V. Computer Simulation

We evaluate the uplink user capacity achievable by IS-MU-MMSE multiplexing combined with optimal JTRD in a cellular distributed MIMO system by computer simulation and confirm that IS-MU-MMSE multiplexing combined with optimal JTRD is superior to that combined with the eigenmode transmission.

A. Simulation Settings

An example of cellular structure and user-clusters formed in the center cell is illustrated in Figs 3(a) and 3(b), respectively. A = 3200 antennas are randomly placed in a 5×5 normalized squared service area while keeping minimum distance of 0.0625 from each other. The number of antennas per cell is constrained to A_{cell} = 128, and antenna clustering is performed to form B (= A / A_{cell}) = 25 cells. U = 3200 users are randomly placed in the same service area while keeping minimum distance of 0.0625 from each other. For simplicity, U users are placed equally in each cell (i.e., U_{cell} = U / B = 128). The number of users per user-cluster is constrained to U_{cls} = 8, forming K = U / U_{cls} = 400 user-clusters and accordingly, the number of clusters per cell is K_{cell} (= K / B) = 16. The number A_{cls} of antennas per user-cluster is set to $A_{\mathrm{cls}} = 2U_{\mathrm{cls}}$, resulting in the remaining antenna degrees of freedom of A_{cls} - U_{cls} = 8.

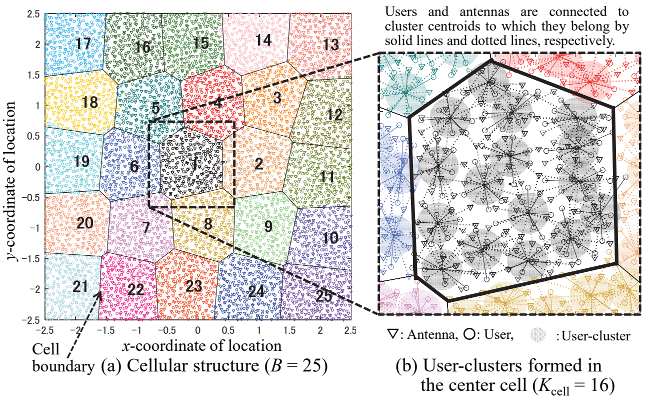

Fig. 3. An example of cellular structure and formed user-clusters.

The transmit power is set to be equal for all users. Normalized transmit SNR is defined as the received SNR when the distance between the transmitter and receiver is the normalized distance $1/\sqrt{2}$, which is equivalent to half the diagonal distance of a square-shaped cell when the service area is regularly divided into B = 25 square-shaped cells. In this simulation, the normalized transmit SNR is set to 0 dB, adding 42 dB to which is equal to the received SNR when the distance between the transmitter and receiver is half the average distance between immediately neighborhood antennas. The transmission environment under the assumption of the normalized transmit SNR = 0 dB is interference-limited.

The propagation channel is assumed to be characterized by distance-dependent pathloss with pathloss exponent of 3.5, log-normally distributed shadowing loss with standard deviation of 7 dB, and Rayleigh fading. The perfect knowledge of MIMO propagation channels as well as user and antenna locations is assumed.

B. Uplink User Capacity

The uplink user capacity C_u [bps/Hz] of user u belonging to user-cluster k in cell b is calculated using

$$C_u = \sum_{s=1}^{S} \log_2\left(1+\mathrm{SINR}_s^{(u)}\right), \quad (9)$$

where $\mathrm{SINR}_s^{(u)}$ is the received SINR of the u-th user's stream s and is obtained from Eqs. (1), (7), and (8) as

$$\mathrm{SINR}_s^{(u)} = \frac{p_u \left|\left(\mathbf{w}_s^{(u)}\right)^{\mathrm{H}} \mathbf{D}_k \mathbf{H}_u \boldsymbol{\beta}_s^{(u)}\right|^2}{\begin{pmatrix} \sum_{r=1, r\neq s}^{S} p_u \left|\left(\mathbf{w}_s^{(u)}\right)^{\mathrm{H}} \mathbf{D}_k \mathbf{H}_u \boldsymbol{\beta}_r^{(u)}\right|^2 + \\ \sum_{v=1, v\neq u}^{U} \sum_{r=1}^{S} p_v \left|\left(\mathbf{w}_s^{(u)}\right)^{\mathrm{H}} \mathbf{D}_k \mathbf{H}_v \boldsymbol{\beta}_r^{(v)}\right|^2 + \sigma^2 \left(\mathbf{w}_s^{(u)}\right)^{\mathrm{H}} \mathbf{w}_s^{(u)} \end{pmatrix}} . \quad (10)$$

The cumulative distribution function (CDF) of the uplink user capacity is obtained as follows. First, placing users randomly and generating pathlosses, shadowing losses, and fading gains for each user, the link capacity is obtained using Eq. (9). Fading gains are changed 10 times to obtain the short-term average capacity for each user. This is done 100 times by changing locations of users to obtain a total of $100\times U_{\mathrm{cell}}$ samples of the short-term average user capacity for users in the cell of interest, from which the CDF of uplink user capacity is obtained (note that the cell of interest is the central cell shown in Fig. 3(b) to take into account the effect of inter-cell interference as accurately as possible).

C. Simulation Results

The CDF of the uplink user capacity is shown with the number of antennas per user N = {1, 2, 4} as a parameter in Fig. 4. The link capacity with IS-MU-MIMO multiplexing combined with optimal JTRD for N = 2 increases compared to the link capacity without optimal JTRD (i.e., N = 1). Increasing N to N = 4 further increases the link capacity. This is because higher diversity gain is obtained as by increasing N while keeping the total transmit power per user the same.

The CDF of the uplink user capacity with N = 2 is shown with the number of streams per user S = {1, 2} as a parameter in Fig. 5. The result for S = 1 represents the case of combining with optimal JTRD (equivalent to maximum eigenmode transmission) and the result for S = 2 the case of combining with eigenmode transmission. The result for N = S = 1 is also shown for comparison. IS-MU-MIMO multiplexing combined with optimal JTRD (S = 1) achieves the highest link capacity. Combining with eigenmode transmission (S = 2) has the highest probability of falling into a low capacity region of lower than approximately 3 bps/Hz (equivalent to the received SINR region of lower than 8.5 dB). In a high user-density environment such as U_{cell} (= A_{cell}) = 128, user-clusters are very close to each other, and strong inter-cluster interference occurs. Thus, it is effective to utilize each user's multiple transmit antennas solely as spatial diversity as in optimal JTRD so as to suppress the inter-cluster interference.

To investigate the best transmission technique for different user densities, the uplink sum capacity (50% point of the CDF is shown as a function of U_{cell} in Fig. 6. Here, the sum capacity is calculated by summing the link capacities of all U_{cell} users in the cell. When U_{cell} is greater than 32 (i.e., U_{cell} / A_{cell} is greater than 1/4), IS-MU-MIMO multiplexing combined with optimal JTRD achieves the highest sum capacity. In contrast, when U_{cell} is less than 16 (i.e., U_{cell} / A_{cell} is less than 1/8), combining with eigenmode transmission achieves the highest sum capacity.

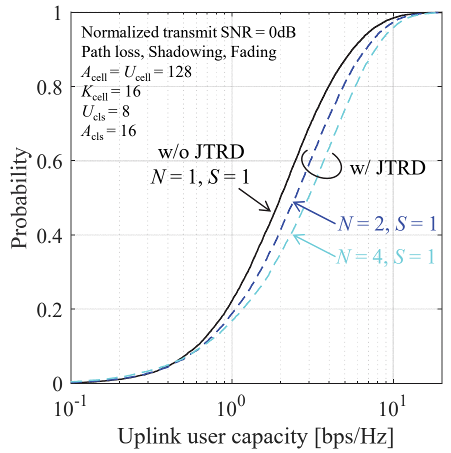

Fig. 4. The CDF of user capacity with N as a parameter.

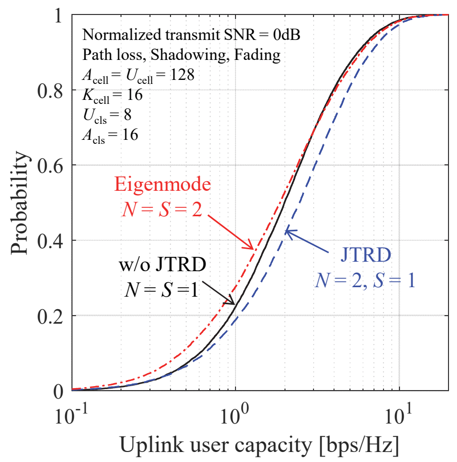

Fig. 5. The CDF of user capacity with S as a parameter.

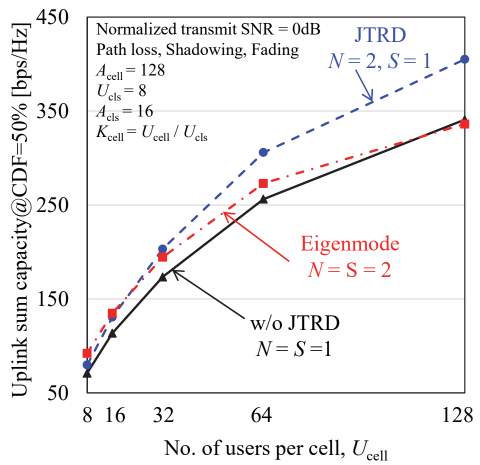

Fig. 6. Sum capacity as a function of U_{cell}.

VI. Conclusion

In this paper, we proposed IS-MU-MMSE multiplexing combined with optimal JTRD for the case of multiple-antenna users in a cellular distributed MIMO system. Through computer simulations, we compared the uplink user capacity achievable by IS-MU-MMSE multiplexing combined with optimal JTRD and that combined with eigenmode transmission and confirmed that combining with optimal JTRD is superior to combining with eigenmode transmission in a high user-density environment.

In a low user-density environment with weak inter-cluster interference, multiple-stream eigenmode transmission is superior. Therefore, in a service area with non-uniform user-density, IS-MU-MMSE multiplexing combined with adaptive eigenmode transmission that changes the number of streams according to the user-density within a cluster is suitable, and this is our future study issue.

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