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3-Cell 하향링크 MIMO 간섭 채널에서의 간섭 공간 재활용 및 QoS Constraint에 따른 그 적용 방안

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Interference Space Reuse and the Adoption Strategy through QoS Constraints in Three-Cell Downlink MIMO Interference Channels

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요 약

본 논문에서는 3-Cell 간섭 환경에서의 하향링크 MU-MIMO를 위한 간섭 공간 재활용 기술 (ISR)과 그 적용 방안을 제시한다. 멀티 셀 간섭환경의 셀 경계 사용자들의 안정적인 통신을 위해서는 효율적인 간섭 관리가 필요하다. 하지만 셀 중심부의 사용자들의 경우 간섭의 영향을 적게 받으며 적은 전송 전력으로도 안정적인 통신이 가능하다. 본 논문에서는 셀 경계 사용자의 간섭 공간을 재사용하여 셀 중심부 사용자에게 서비스를 제공하는 ISR 기반 전송 신호 설계 방법을 제시한다. ISR 방식은 간섭정렬(IA)과 결합된 부분적 주파수 재활용 (fractional frequency reuse : FFR) 방식과 비교하여 볼 때 셀 중심 사용자와 셀 경계 사용자에 대한 scheduling에 따라 전체 네트워크 데이터 전송용량 측면에서 20%의 성능 향상을 보이며 또한 셀 중심 사용자의 서비스 품질 (QoS) 요구조건이 고정되어 있는 경우 ISR 방식에 의해 기지국에서의 전송 신호 벡터를 설계함으로서 셀 경계 사용자의 데이터 전송 용량을 증가시킬 수 있다.

Key Words : interference space reuse, MU-MIMO, interference alignment, user pairing, 간섭 공간 재활용, 다중 유저 다중 안테나, 간섭 정렬, 사용자 스케쥴링

ABSTRACT

We propose an interference space reuse (ISR) algorithm for the MU-MIMO design in 3-cell downlink interference channels. Also, we provide a strategy for the adoption of the ISR scheme in the cellular network. In the multicell interference channels, the cell edge users may undergo severe interferences and their signals should be protected from the interferers for reliable transmissions. However, the intra cell users do not only experience small interferences but also they require small transmission power for stable communication. We provide a vector design algorithm based on ISR, where intra cell users are served through reusing the cell edge users' interference space. The performance enhancement reaches 20% compared to the fractional frequency reuse (FFR) scheme combined with IA through the scheduling between the cell edge users and the intra cell users. Also, it can be used to enhance the cell edge throughput when the quality of service (QoS) requirements of the intra cell users are fixed.

Ⅰ. Introduction

For decades, researches on wireless interference channels have been conducted to enhance the

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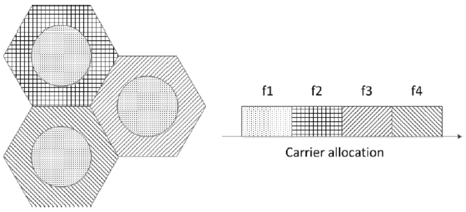

Fig. 1. Frequency resource allocation for FFR adoption in the 3-cell network

multiplexing gain and the achievable data rate in the interference network. The data symbol transmissions on the same radio resources can degrade the network throughput performance due to the uncertainties caused by the interferers. To transmit the data symbols with the reliabilities in the interference channel, the transmission symbols should be properly coordinated.

The interference can be dealt in two ways, the interference avoidance and the interference cancellation. In the interference avoidance, the radio resources are allocated for users not to undergo strong interference. Avoiding the strong interference, the resource can be reused among the network users and the achievable throughput can also be increased. Also, the interference can also be mitigated by the interference cancellation with the transmission signal coordination. The transmission vector coordination with the channel state information (CSI) enables the users to remove the interference components during the reception signal processing. Based on two aspects, the interference management can be done for the throughput enhancement in the interference channel using various dimensions such as the time resource, the frequency resource and the space resource using multiple antennas.

In many prior works, the methods for the interference management and the radio resource reuse schemes have been studied. We briefly review the related prior works and analyze the differences between their works and our work in the following subsections.

1.1. Related Works

In the previous works, the interference management schemes are studied to analyze the interference effects and enhance the network throughput. We review their works briefly in aspects of the interference management and radio resource reuse.

In the aspect of the interference management, the cooperative beamforming (BF) schemes such as the network MIMO and the interference alignment (IA) are studied to reduce the interference effects. In the case of the network MIMO, the transmission symbols and channel conditions for the network users are shared not to interfere each other. Related on the network MIMO, an architecture for the network MIMO based on the singular value decomposition (SVD) and the base station (BS) cooperation algorithms with limited feedbacks are proposed[1-4]. In IA, the transmission vectors are properly coordinated to be aligned into the interference spaces which have limited dimensions at the all receivers[5]. After the proposal of the concept of IA, the achievable multiplexing gain in the interference channels is rediscovered[6,7] and the adoption scenarios of IA in the cellular network are studied in several prior works[8-13]. Besides, the cooperative BF scheme are studied in many prior researches[14-24].

In a view of the radio resource reuse, the fractional frequency reuse (FFR) scheme is a well known reuse algorithm in the interference channel. In Fig. 1, the resource allocation structure for FFR is shown. In the FFR scheme, the radio resources are divided into two parts for the intra cell area users and the cell edge users respectively. The intra cell users can use the same resource because of the small effect of the inter-cell interference (ICI). However, the cell edge users may undergo the severe throughput degradation if they use the same radio resource. Therefore, the radio resources for the cell edge users should be coordinated properly among the interfering cells.

Based on the FFR scheme, many algorithms to enhance the network throughput are proposed. For examples, the interference characteristics of the femtocell network based on FFR are analyzed[25].

With the analysis, the femtocell deployment schemes based on FFR are suggested[26-28]. Also, an algorithm to control the reuse factor of the radio resource is proposed[29] and the authors show that the network throughput can be enhanced by the adaptive reuse factor control.

The radio resource reuses in the interference channels also have been considered in several researches on cognitive radio networks (CRN). In CRN, the wireless terminals find and reuse the available radio resources not to disturb the primary networks or the pre-existing communications. In IEEE 802.22 system, the geographical and sensing information can be used for the radio resource reuse[30,31].

However, there are some missed considerations in the previous works. Many of works do not consider the user scheduling aspect for the BS cooperation in multicell environments. In the case of MU-MIMO, the user selection can yields critical improvement on the network throughput. Besides, the radio resource allocations with MU-MIMO can be complex and hard to implement with previously proposed schemes.

In this paper, we study the three-cell downlink interference channels and propose a interference space reuse (ISR) scheme. Also, we suggest an adoption strategy of the ISR scheme through the user location and the quality of service (QoS) requirement. In addition, we show that the cell edge users' throughput can be increased by the QoS parameter control without the loss of the intra cell users' throughput compared to the FFR scheme.

The remaining part of the paper consists as the follows. In Section II, we describe the system model. In Section III, we propose the ISR algorithm for the cellular downlink channel and suggest an algorithm for the adoption of our proposing algorithm. Then, we show the enhancement of the network throughput in Section IV. Finally, the conclusion is derived in Section V.

Ⅱ. System Model

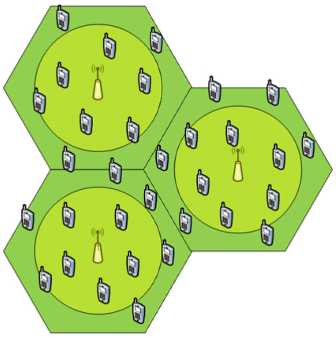

Fig. 2. The user distribution in the 3-cell interference network

The three-cell interference channel is shown in Fig. 2. Generally, the cell edge areas and the intra cell areas can be divided by the distance between the users and their belonging cell BSs. We assume that users are distributed with a uniform distribution through the cell area and each user is served one symbol stream per each MU-MIMO transmission.

In the cellular downlink channel, the received signal for user a who belongs to cell g is given as the following equation,

$$\underline{r}_a = H_g^a V_g \underline{s}_g + \sum_{j \neq g} H_i^a V_j \underline{s}_j + \underline{n}_a, \tag{1}$$

where $\underline{r}_a$ is the received signal vector at user a, H_j^a indicates the channel matrix between the jth BS and user a, V_j is the precoding matrix of the jth BS, $\underline{s}_i$ is the transmission symbol vector of the ith cell, and $\underline{n}_a$ is the noise vector at user a. Here, the transmission precoding matrix V_g consists of multiple vectors which are aimed to serve users of the gth cell. For example, if user a, b and c belong to the gth cell, the precoding matrix V_g is given as $V_g = [\underline{v}_a, \underline{v}_b, \underline{v}_c]$, where $\underline{v}_a$, $\underline{v}_b$, and $\underline{v}_c$ are the transmission vectors for user a, b, and c respectively. The magnitudes of all vectors are controlled through the QoS requirements or the channel environments.

When users receive the signal vectors from the multiple BSs, they should remove the major

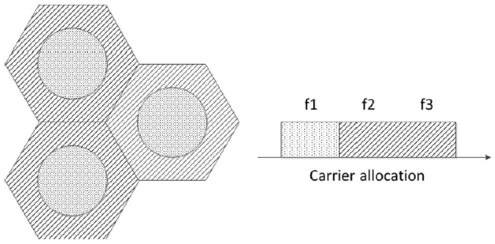

Fig. 3. The FFR structure combined with IA

interference to decode their symbol successfully. When a receiving vector which nulls the major interference component is multiplied with the received signal vector, the decoded symbol can be expressed as:

$$\hat{s}_a = \underline{w}_a^H \underline{r}_a = \underline{w}_a^H H_g^a V_g \underline{s}_g + \underline{w}_a^H \left(\sum_{j \neq g} H_i^a V_j \underline{s}_j + \underline{n}_a \right), \tag{2}$$

where $\underline{w}_a$ is the receiving vector at user a. The achievable throughput depends on the magnitudes of the signal processing gain of the desirable signal, the remaining interference levels, and the noise.

Ⅲ. Interference Space Reuse Algorithm

Before the explanation of our algorithm, we propose a FFR scheme which is combined with IA for the achievable throughput performance comparison. After that, we explain the transmission vector design algorithm based on ISR. Then, we suggest the adoption scenario of the ISR algorithm in the cellular networks.

We note the user group for the users who locate in the cell edge area and belong to the g th cell as Φ_g^e. In the case of the intra cell user group we use the notation Φ_g^i for the users who are located in the intra cell area and belong to the gth cell.

3.1. FFR with IA

As the simplest structure of FFR combined with IA, we suggest a resource allocation scenario like Fig. 3. In the scenario, the radio resource can be divided into two parts for the intra cell users and the cell edge users.

In the case of the intra cell users, the resource can be reused without the consideration of the interference. If we analyze the channel matrix between intra cell user $\phi_g^i(k) \in \Phi_g^i$ using SVD, then the result is given by the following,

$$H_g^{\phi_g^i(k)} = U_g^{\phi_g^i(k)} \Sigma_g^{\phi_g^i(k)} \left(T_g^{\phi_g^i(k)}\right)^H, \tag{3}$$

where $U_g^{\phi_g^i(k)} \in C^{M_r \times M_r}$ and $T_g^{\phi_g^i(k)} \in C^{M_t \times M_t}$ are given as unitary matrices, and $\Sigma_g^{\phi_g^i(k)} = diag[\lambda_g^{[\phi_g^i(k),1]}, \cdots, \lambda_g^{[\phi_g^i(k),M_r]}] \in C^{M_r \times M_t}$ is a diagonal matrix which is composed by ordered singular values of the channel matrix, $\lambda_g^{[\phi_g^i(k),1]} \geq \lambda_g^{[\phi_g^i(k),2]} \geq \cdots \geq \lambda_g^{[\phi_g^i(k),M_r]}$. Here, M_r and M_t mean the numbers of the receive antennas and transmit antennas respectively. To maximize the MU-MIMO gain, the interference space of each user can be determined by the receive vectors which correspond to smaller singular values than $\lambda_g^{[\phi_g^i(k),1]}$. Therefore, the interference at user $\phi_g^i(k)$ is determined as

$$\mathrm{A}_{\phi_g^i(k)} = \mathrm{C}\left(U_g^{\phi_g^i(k)} \begin{bmatrix} \underline{0}_{M_r}^H \\ I_{M_r-1} \end{bmatrix} \right), \tag{4}$$

where $\mathrm{C}(\cdot)$ is the column vector space, $\mathrm{A}_{\phi_g^i(k)}$ is the interference space of user $\phi_g^i(k)$, $\underline{0}_{M_r}^H$ is a zero column vector whose size is given as M_r, and I_{M_r-1} is the identity matrix whose size is given as $M_r - 1$. Hence the all transmission vectors for the g-th cell users except user a should be mapped into A_a, the conditions for the transmission vector spaces of the other intra cell users in cell g except user $\phi_g^i(k)$ are given by

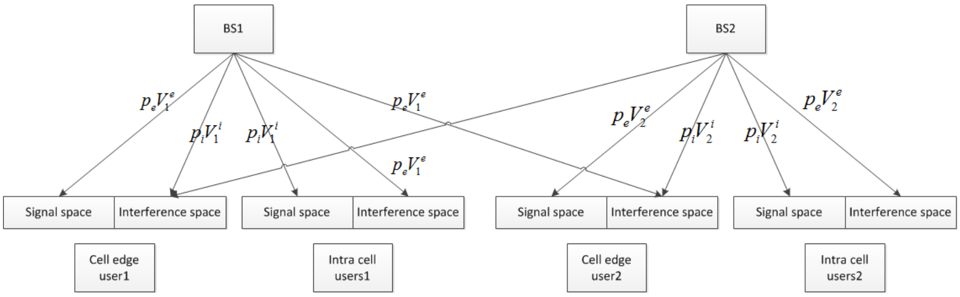

Fig. 4. Transmission signal vector design based on ISR

$$T_{\phi_g^i(1)}, T_{\phi_g^i(2)}, \cdots T_{\phi_g^i(M_r)} \subset \mathrm{C}\left(T_g^a \begin{bmatrix} 0_{M_t}^H \\ I_{M_t-1} \end{bmatrix}\right),$$

$$\text{for } \phi_g^i(1), \phi_g^i(2), \cdots, \phi_g^i(M_r) \in \Phi_g^i \text{ except } \phi_g^i(k) \quad (5)$$

where $T_{\phi_g^i(l)}$ is the transmission vector space for user $\phi_g^i(l)$. Similarly, the interference spaces and the conditions for the transmission vector spaces of the other intra cell users can be found. Therefore, the number of the conditions for the vector space of each user is given as $M_i - 1$, where M_i is the number of the symbols transmitted from the BS using MU-MIMO at the same time.

Hence the transmission vector space for user $\phi_g^i(k)$ should be aligned to the interference spaces of all the other users belonging to Φ_g^i except user $\phi_g^i(k)$, the transmission vector space of user $\phi_g^i(k)$ can be computed as the intersection spaces of the found candidate spaces. Therefore, the transmission vector space of user $\phi_g^i(k)$ can be decided like the following equation,

$$\mathrm{T}_{\phi_g^i(k)} \subset \bigcap_{l \in \{1,2,\cdots,\mathrm{M_i}\} l \neq \mathrm{k}} \mathrm{C}\left(T_g^{\phi_g^i(l)} \begin{bmatrix} 0_{M_t}^H \\ I_{M_t-1} \end{bmatrix}\right) . \quad (6)$$

In the case of the cell edge users, they use different radio resources from the intra cell users in the FFR scheme. To protect the cell edge users from the itnerferences, IA can be adopted and it can help enhancing the multiplexing gains in the interferene channel. For the IA techniques for the cell edge users, there are many skills as mentioned in the previous section[5]-[11].

In the FFR scheme, the throughput controls for the QoS constraint between the intra cell users and the cell edge users only depend on the radio resource. Due to the fact, the power consumption can be inefficient for the users near the BS. Near the BS, the bandwidth is much more important than the signal power. The proper power-resource allocation can yield more enhanced throughput in the interference channels.

3.2. Transmission Vector Design based on ISR

In this subsection, we describe ISR scheme. The overall signal transmission process of the ISR scheme is shown in Fig. 4. In ISR, the interference management is aided by the transmission precoding matrix and the power control instead of the interference avoidance using different radio resources. Thus, the overall precoding matrix at BS g is composed like the following equation,

$$V_g = \left[\sqrt{p_e^g}\, V_g^e, \ \sqrt{p_i^g}\, V_g^i\right], \quad (7)$$

where p_g^e is the signal power for the cell edge users, p_g^i is the signal power for the intra cell users of the gth cell, V_g^e and V_g^i are the precoding matrices for the cell edge users and the intra cell users respectively. In ISR, by serving the intra cell users through the cell edge users' interference space with small power, the QoS requirements for the intra cell users can be satisfied with small additional interferences due to channel features.

We describe the detailed transmission vector design method. We consider the cell edge users at first whose channel features are harsh in the aspects of the interference and the channel gain from the belonging cell BS. In the case of the cell edge users, they may undergo severe interferences from other cells. Therefore, one cell edge user's transmission signal should be designed to be aligned to the other users' interference spaces. By aligning the users' signals, cell edge users can easily remove strong interferences from other BSs. That is, V_g^e can be designed by IA to establish the reliable link between the BS and the cell edge users similarly with FFR in Section Ⅲ-1.

To serve the intra cell users additionally, we should consider the interference cancellation process at the cell edge users. When the cell edge users decode their message symbols, they should not be able to remove their ICI only, but they should also be able to remove the inter-user interferences (IUI) which are aimed to the intra cell users. Therefore, the transmission vector space for the intra cell users should be aligned to the interference spaces or the null spaces of the cell edge users. Thus, the signal spaces for the intra cell users are given as the following equation,

$$V_g^i \subset \left[\bigcap_{k=1}^{M_e}\left\{\left(H_g^{\phi_g^e(k)}\right)^{-1}\mathrm{A}_{\phi_g^e(k)} \cup \mathrm{N}\left(H_g^{\phi_g^e(k)}\right)\right\}\right] \quad , \qquad (8)$$

where $(\cdot)^{-1}$ indicates pseudo inverse matrix, and $\mathrm{N}(\cdot)$ indicates the null space of the matrix.

To maximize the achievable throughput of MU-MIMO, we should also consider the major interference component at the intra cell users. Because the intra cell users also receive the signals for the cell edge user belonging to the same cell, the interference spaces for the intra cell users should include the spaces caused by the signals for the cell edge users of their own cell. In other words, for user $k \in \{1,2,\cdots,\mathrm{M_i}\}, \phi_\mathrm{g}^\mathrm{i}(\mathrm{k}) \in \Phi_\mathrm{g}^\mathrm{i}$,

$$H_g^{\phi_g^i(k)}\mathrm{V}_{\boldsymbol{g}}^{\boldsymbol{e}} \subset \mathrm{A}_{\phi_g^i(k)}. \qquad (9)$$

At the intra cell users, the IUIs caused by the signals for the cell edge users should be removed successfully. Therefore, the receiving vector at each intra cell users can be transformed into a cascaded form like $\underline{w_{g_{\phi_g^i(k)}}} = N(H_g^{\phi_g^i(k)} V_g^e)\underline{\widetilde{w_{\phi_g^i(k)}}}$, where $N(\cdot)$ is the orthonormal null matrix, and $\underline{\widetilde{w_{\phi_g^i(k)}}}$ is a decoding vector at user $\phi_g^i(k)$ after nulling IUIs caused by the signals for the cell edge users. Therefore, we can model the signal decoding process at the intra cell user like the following equation,

$$\begin{aligned}\widehat{s_{\phi_g^i(k)}} &= \underline{w_{\phi_g^i(k)}} H_g^{\phi_g^i(k)}(V_g^e \underline{s_{g,e}} + V_g^i \underline{s_{g,i}}) \\ &= \underline{\widetilde{w_{\phi_g^i(k)}}} N(H_g^{\phi_g^i(k)} V_g^e)^H H_g^{\phi_g^i(k)}(V_g^e \underline{s_{g,e}} + V_g^i \underline{s_{g,i}}) \\ &= \underline{\widetilde{w_{\phi_g^i(k)}}} N(H_g^{\phi_g^i(k)} V_g^e)^H H_g^{\phi_g^i(k)} V_g^i \underline{s_{g,i}},\end{aligned} \qquad (10)$$

where $\widehat{s_{\phi_g^i(k)}}$ is the decoded message symbol at user $\phi_g^i(k)$. Let us define the effective channel matrix $\widetilde{H}_g^{\phi_g^i(k)}$ as $N(H_g^{\phi_g^i(k)} V_g^e)^H H_g^{\phi_g^i(k)} V_g^i$. Then we can find the minimum gain vectors in the desired channel by using SVD like following equation,

$$\widetilde{H}_g^{\phi_g^i(k)} = \widetilde{U}_g^{\phi_g^i(k)}\,\widetilde{\Sigma}_g^{\phi_g^i(k)}\,(\widetilde{T}_g^{\phi_g^i(k)})^H, \qquad (11)$$

where $\widetilde{U}_g^{\phi_g^i(k)}$ and $\widetilde{T}_g^{\phi_g^i(k)}$ are orthonormal matrices, and

$\widetilde{\Sigma_g^{\phi_g^i(k)}} = diag[\lambda_{\widetilde{g,\phi_g^i(k),1}}, \lambda_{\widetilde{g,\phi_g^i(k),2}}, \cdots, \lambda_{\widetilde{g,\phi_g^i(k),M_r}}]$ is a diagonal matrix whose elements are sorted by $\tilde{\lambda}_{g,\phi_g^i(k),1} \geq \tilde{\lambda}_{g,\phi_g^i(k),2} \geq \cdots \geq \tilde{\lambda}_{g,\phi_g^i(k),M_r}$. By using SVD, the channel matrix is transformed into orthogonal transmission channels which have different channel gains. To minimize the gain loss during the interference cancellation, the interference space at user $\phi_g^i(k)$ should be decided by the right part of the $\tilde{U}_g^{\phi_g^i}(k)$ because that part has smaller channel gains than the maximum singular value $\tilde{\lambda}_{g,\phi_g^i(k),1}$. Because the interference space at inter cell user $\phi_g^i(k)$ include the interference space caused by the precoding matrix for the cell edge users and the minimum gain space, the interference space at user $\phi_g^i(k)$ is given by

$$\mathrm{C}\left(\left[H_g^d V_g^e,\ H_g^d V_g^i X_g^{\phi_g^i(k)}\right]\right), \tag{12}$$

where $X_g^{\phi_g^i(k)}$ is computed as:

$$X_g^{\phi_g^i(k)} = \tilde{T}_g^{\phi_g^i(k)} \begin{bmatrix} 0^H \\ I \end{bmatrix}. \tag{13}$$

In (12), the first term is caused by IUIs which are aimed to the cell edge users, and the second term can be decided to minimize the gain loss during the interference cancellation.

Similarly with Section III-1, there exist $M_i - 1$ conditions for the transmission vector space of user $\phi_g^i(k)$. The transmission vector space of user $\phi_g^i(k)$ should be mapped to all the interference spaces of all users belonging to Φ_g^i except user ϕ_g^i. Therefore, the transmission vector space for the intra cell user $\phi_g^i(k)$ is given by

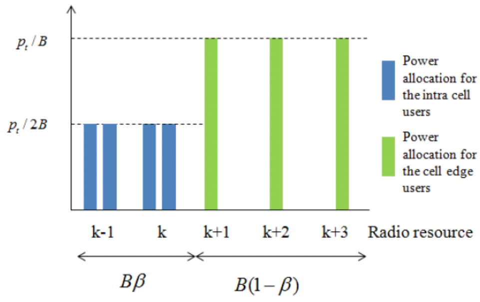

Fig. 5. Resource-power allocation method for FFR combined with IA

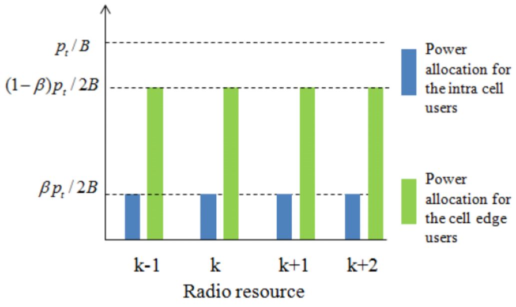

Fig. 6. Resource-power allocation for the ISR method

$$\bigcap_{\phi_g^i(l) \in \Phi_g^i\, l \neq k} \mathrm{C}\left(\left(H_g^{\phi_g^i(l)}\right)^{-1} \left[H_g^{\phi_g^i(l)} V_g^e,\ H_g^{\phi_g^i(l)} V_g^i X_g^{\phi_g^i(l)}\right], \atop N\left(H_g^{\phi_g^i(l)}\right)\right). \tag{14}$$

3.3. ISR Adoption and User Scheduling in Cellular Networks

In this subsection, we discuss an adoption strategy of the ISR scheme in the cellular network. Before the discussion on the adoption scenario of the ISR scheme, we discuss the resource-power allocation method at first.

In the case of the FFR scheme, the radio resources can be allocated through the QoS constraint like Fig. 5. In the figure, β is the resource-power allocation ratio of the intra cell users and B is the available total bandwidth of the cellular networks. The resource ratio between the intra cell users and the cell edge users can be adopted differently through the QoS constraint of the users. In FFR, the bandwidth for the intra cell users is given as βB through the QoS constraint.

In the case of the ISR scheme, the power and resource allocation scheme is adopted differently from the FFR scheme. The resource-power allocation scheme for ISR is shown in Fig. 6. In the ISR scheme, the same radio resource is used for the intra cell user and the cell edge user. However, the transmission powers of the cell edge users and the intra cell users can be controlled through the QoS constraints.

Now, we consider the adoption scenario of the ISR scheme. If we compute the achievable throughputs for the intra cell users and the cell edge users when the FFR scheme and the ISR scheme used respectively, then we can decide which scheme is favorable. The achievable throughputs for FFR and ISR schemes can be computed as the following equations,

For $a \in \Phi_g^i$

$$r_{ISR}^a = M_i \log_2 \left(1 + \frac{\beta x_{a,a} p_t / M_i}{\sigma_{n,a}^2 + (1-\beta) \sum_{k \in \Phi_j^{e}, j \neq g} \frac{x_{a,k} p_t}{M_e} + \beta \sum_{k \in \Phi_j^{i}, j \neq g} \frac{x_{a,k} p_t}{M_i}} \right), \quad (15)$$

$$r_{FFR}^a = M_i \beta \log_2 \left(1 + \frac{x_{a,a} p_t / M_i}{\sigma_{n,a}^2 + \sum_{k \notin \Phi_g} p_t / M_i} \right), \quad (16)$$

For $b \in \Phi_g^e$

$$r_{ISR}^b = M_e \log_2 \left(1 + \frac{p_t (1-\beta) x_{b,b} / M_e}{\sigma_{n,b}^2 + \beta \sum_{k \in \Phi_g^i, j \neq g} x_{b,k} p_t / M_i} \right), \quad (17)$$

$$r_{FFR}^b = (1-\beta) M_e \log_2 \left(1 + x_{b,b} p_t / (M_e \sigma_{n,b}^2) \right), \quad (18)$$

where r_{ISR}^a and r_{FFR}^a are the achievable throughput for user a with ISR and FFR respectively, M_i and M_e are the number of the transmission symbols for the intra cell users and the cell edge users, and M_t is the number of the transmitter antennas. The term $x_{j,k}$ denotes the signal processing gain, $\left| \underline{w_j} / |\underline{w_j}|)^H H_{g'}^j \underline{v_k} / |\underline{v_k}| \right|^2$, where $\underline{v_k}$ is the transmission vector for user k and $\underline{w_j}$ is the receiving vector at user j. Here, the maximum value of M_e is determined through the numbers of the BSs antennas and users' antennas[8]. For $M_r = M_t$ and $M_t > M_r$, the maximum value of M_e are given as $M_t/2$ and $\lfloor \frac{M_t + 1}{3} \rfloor$, respectively. In the case of the intra cell users, M_i is determined as $M_t - M_e$ and M_t for FFR and ISR respectively.

At the intra cell users, only IUIs are considered as the dominant interferences and removed during the decoding processes. Thus, the ICI components remain as the interference leakage. In the aspect of the power-resource allocation ratio, the QoS parameter β is controlled by the transmission power and the channel gain. In ISR, β is reflected in the transmission power while FFR reflects β in the bandwidth scheduling. In (15) and (16), each achievable throughput for FFR and ISR at the intra cell user is derived in the aspect of the QoS parameter and the channel gain.

In (17) and (18), the achievable throughputs with FFR and ISR at the cell edge users are shown. For the cell edge users, ICIs caused by the signals for the other cell edge users are designed to be aligned to the limited spaces. Thus, the interferences caused by the signals aimed to the other cell edge users can be successfully removed by multiplying zero-forcing receiving filter. In FFR, all the interferences are removable because there is no additional interferences caused by the signals for the intra cell users. In ISR, however, the interference spaces of the cell edge users are reused for the

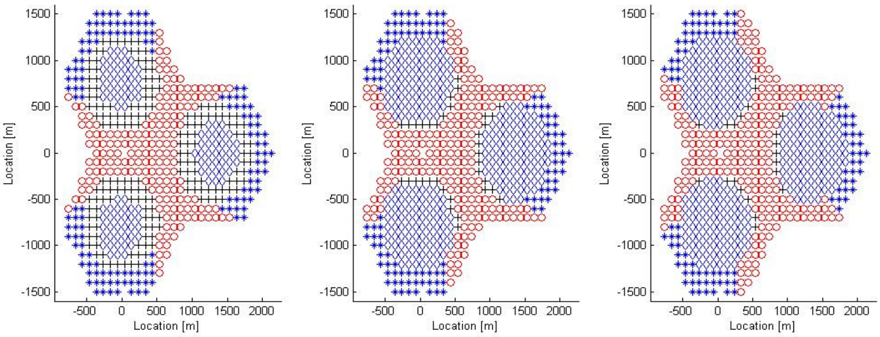

Fig. 7. Transmission scheme adoption strategy through the user location in the three-cell interference networks, $1/\beta$=3, $1/\beta$=6, $1/\beta$=9

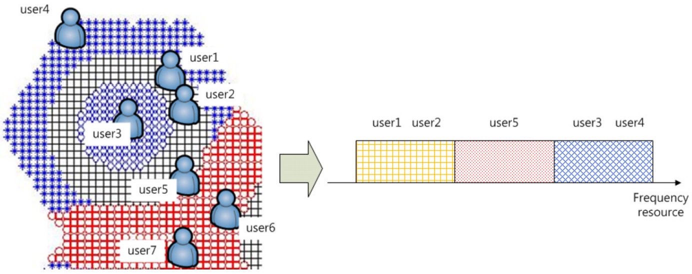

Fig. 8. The adoption of the ISR scheme and the FFR scheme in the OFDMA system.

intra cell users with small power, the interference leakages remain and the achievable throughput may slightly degraded.

However, computing the achievable throughputs for the all pairs of MU-MIMO to determine a favorable scheme requires lots of time because there may be lots of user pairs through the cell area. Instead of the exact achievable throughput, we can find the expected achievable throughput using the pathloss gain and the transmission power roughly. The simplified achievable throughput based on the pathloss for each user and scheme is given as the following equations,

For $a \in \Phi^i_g$,

$$\widetilde{r^a_{ISR}} = M_i \log_2\left(1+\frac{G(M_t-M_e)\beta l^a_g p_t/M_i}{\sigma^2_{n,a}+\sum_{i\neq g} p_t l^a_i}\right), \qquad (19)$$

$$\widetilde{r^a_{FFR}} = M_i \beta \log_2\left(1+\frac{G(M) p_t l^a_g}{\sigma^2_{n,a}+\sum_{i\neq g} p_t l^a_i}\right), \qquad (20)$$

For $b \in \Phi^e_g$,

$$\widetilde{r^b_{ISR}} = M_e \log_2\left(1+\frac{(1-\beta) l^b_g p_t/M_e}{\sigma^2_{n,b}+\beta\sum_{i\neq g} p_t l^b_i/M_i}\right), \qquad (21)$$

$$\widetilde{r^b_{FFR}} = (1-\beta) M_e \log_2\left(1+p_t l^b_g/\sigma^2_{n,b}\right), \qquad (22)$$

where l^a_g is the pathloss between BS g and user a, and $G(\cdot)$ is the MU-MIMO gain. Equations from (19) to (22) is simplified versions of Equations from (15) to (18) assuming that the signal processing gains are dominantly determined by the MU-MIMO gain and the pathloss between the BSs and the users. The MU-MIMO gain for the remaining degree of freedom is given in Table. I. Using the above equations, we can set the criteria for the selection of the reuse schemes, FFR and ISR.

The selection between FFR and ISR through the resource-power allocation ratio and the user location can be done like Fig. 7. In the figure,

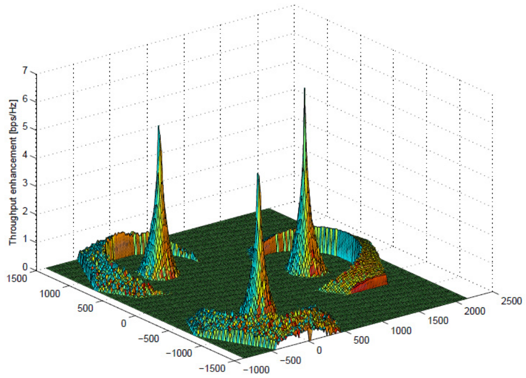

Fig. 9. Throughput enhancement through the cell area, $\beta=1/3$.

Table 1. MU-MIMO gain evaluation through the number of antennas

x	$G(x)$
1	0.5
2	1.7553
3	3.2771
4	4.8990

the number of antennas for the BS and the users are set to two. The distance between two BSs are set to 1.5km and the transmission power at the BS is assumed as 20 W. In the figure, the stars indicate the cell edge transmission scheme with ISR, the circles indicate the pure IA scheme usage, and the diamonds indicate the ISR scheme for the intra cell users.

As the figure shows, the ISR scheme is efficient near the BS. In the case of the intra cell users, the achievable throughputs increase slowly as the received power increase. However, the ISR increases the available bandwidth for intra cell users and the network throughput can increase linearly through the increment of the bandwidth. In the case of the cell edge users, ISR can be partially effective through the overall network. The users who are located at the border of the each cell undergo severe interference from other cells. Therefore, they should be protected from the interferences caused by other cells. However, the other cell edge users do not suffer from the interference because they are far from the interfering BSs. Therefore, the interference space reuse enhance their throughput and is helpful for increasing the network throughput.

With the criteria, ISR can be adopted selectively in the wireless systems. For example, the frequency resource allocation can be done through the user locations and interference conditions like Fig. 8 in OFDMA systems. In the figure, user 1 and user 2 can use same radio resources using multiuser MIMO. In the case of user 3 and user 4, they can be served by the ISR scheme using same radio resource. In the radio resource, the transmission vector of user 4 is designed by IA considering other cell edge users belonging to other cells. Then, user 3 can served by the BS using the vector which is mapped to the interference space of user 3 to avoid the IUI at the user 3. In the case of user 5, the interference environment may cause severe throughput degradation. Thus, the user 5 can be served by the IA scheme considering other cell users such as user 6 and user 7 using other radio resources.

Ⅳ. Performance Evaluation

The parameters for the performance evaluation are given in TABLE II. The simulation parameters are selected from the IEEE 802.16m evaluation methodology[32]. In the reference, the pathloss model is given as the following equation,

$$l[dB]=130.62+37.6\log_{10}(d), \tag{23}$$

where l is the pathloss gain in dB, and d is the distance between the user and the BS in km. The channel fading coefficients are generated with complex Gaussian random distribution, $C(0,\ 1)$.

The spectral efficiency enhancement through the user location is shown in Fig. 9. The throughput enhancements near the BS increase drastically when the ISR scheme is used. Near the BS, the increment of the throughput caused by the increment of the SINR is less than the throughput increment caused by the increment of the bandwidth. In the case of the ISR, the intra cell

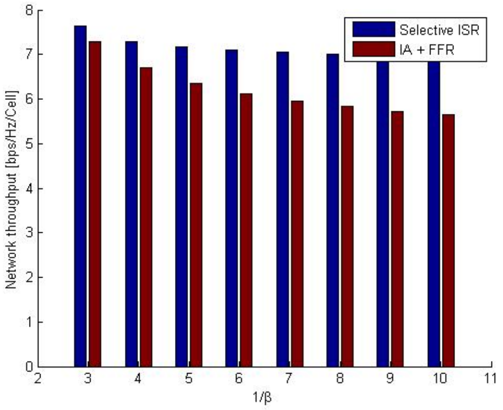

Fig. 10. The network throughput through the resource-power ratio, β

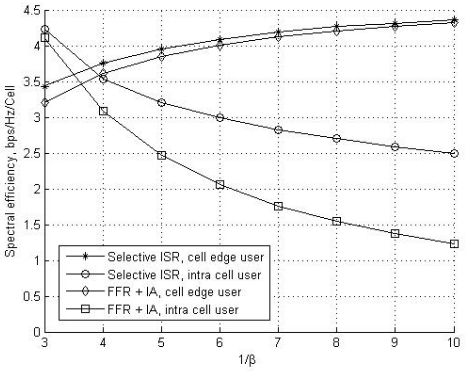

Fig. 11. Spectral efficiency of the intra cell sers and the cell edge users through the resource-power allocation, β

user can have higher bandwidth compared to the FFR scheme with same power allocation, where the user in the intra cell area can only use small bandwidth.

The network capacity increment through the power-resource allocation ratio is shown in Fig. 10. As the graph shows, the selective adoption of the ISR scheme can yield the enhancement of the network throughput in the interference cellular networks.

The network throughput difference between the selective ISR adoption and FFR with IA becomes larger as β becomes smaller. The performance difference reaches 20% of the throughput of the FFR scheme when β is less than $1/8$. In the case of FFR, the throughput for the intra cell user decrease linearly when the resource-power ratio becomes small. However, in the case of the ISR scheme, the throughput for the intra cell user decrease through the log function.

The detailed throughput enhancements of the intra cell users and cell edge users are shown in Fig. 11. As the graph shows, the throughput enhancement at the intra cell user is remarkable through the resource-power allocation ratio. From the result, we can conclude that the selective adoption of the ISR scheme through the user location yields better throughput performance than the FFR scheme combined with IA.

The control of the resource-power allocation ratio can also enhance the throughput of the cell edge users by using ISR. When the QoS requirements for the intra cell users are fixed, the resource-power allocation ratio can be reduced when the ISR scheme is adopted. For example, if the QoS requirement for the intra cell users is given as the spectral efficiency of 2.5 bps/Hz, then the resource-power ratio can be reduced to 0.1 which yields 12.5% throughput improvement at the cell edge users.

V. Conclusion

In this paper, we propose the ISR scheme for the 3-cell interference networks. As the simulation result shows, the ISR scheme can increase the overall network throughput. The selective adoption of the ISR scheme can increase up to 20% of the network throughput through the resource-power allocation ratio between the intra cell users and the cell edge users. Also, the ISR scheme allows more flexible control of the resource-power allocation ratio between the intra cell users and the cell edge users.

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