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대용량 데이터 전송을 위한 다중 셀 MISO 하향 능동 안테나 시스템에서 3D 빔포밍 기법

김 태 훈◆

3D Beamforming Techniques in Multi-Cell MISO Downlink Active Antenna Systems for Large Data Transmission

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요 약

본 논문은 다중 셀 다중입력 단일 출력 (MISO : multiple-input single-output) 하향링크 능동 안테나 시스템 (AAS : active antenna systems)에서 기지국의 수직 각도를 최적화하는 새로운 기법을 제시한다. 본 연구에서는 기존의 전역 탐색 방식 대신 간단하면서 최적의 값에 근사한 알고리듬들을 제안한다. 먼저, random matrix theory의 특성을 반영하여 평균 전송용량에 large system approximation이 적용된 수직적 빔포밍 알고리듬을 소개한다. 다음으로, signal-to-leakage-and-noise ratio (SLNR)을 기반으로 최적화 문제를 간단하게 만드는 수직적 빔포밍 알고리듬을 제안한다. 실험 결과를 통해 제안된 알고리듬들의 성능이 기존의 전역 탐색 알고리듬에 비해 복잡도가 매우 감소됨에도 불구하고 거의 비슷한 성능을 보임을 증명하였다.

Key Words : Active antenna system, vertical beamforming, multiple-input single-output (MISO) downlink, random matrix, large system approximation

ABSTRACT

In this paper, we provide a new approach which optimizes the vertical tilting angle of the base station for multi-cell multiple-input single-output (MISO) downlink active antenna systems (AAS). Instead of the conventional optimal algorithm which requires an exhaustive search, we propose simple and near optimal algorithms. First, we represent a large system approximation based vertical beamforming algorithm which is applied to the average sum rate by using the random matrix theory. Next, we suggest a signal-to-leakage-and-noise ratio (SLNR) based vertical beamforming algorithm which simplifies the optimization problem considerably. In the simulation results, we demonstrate that the performance of the proposed algorithms is near close to the exhaustive search algorithm with substantially reduced complexity.

Ⅰ. Introduction

Next generation communication system is known as fifth generation (5G) wireless networks and is required to produce higher data rates in the order of tens of giga bits per second(Gbit/s)[1-5]. To achieve this demand, multiple-input multiple-output (MIMO) methods and directional antenna techniques have been studied in the past[6-12]. Especially, the vertical beamforming in the three dimension (3D) shows much better performance compared

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to the horizontal beamforming in the two dimension because of much more interference cancellation[6].

In the 3D, there are two types of directional antenna system. The passive directional antenna system is adjusted by considering the practical cell architecture and field test[10]. This antenna system sets a fixed tilting angle which is indicated as the angle between the horizontal plane and the boresight direction of the antenna beam. Thus, this passive directional antenna cannot control the beam pattern dynamically and does not reflect the location of the users.

However, the active antenna systems (AAS) manage the directional antenna elements electronically and affect directional antenna pattern[11]. Thus, the AAS can optimize the tilting angle according to the individual user locations. In [10], the author has showed the optimal tilting angle of a single vertical sector in the single-cell multiple-input single-output (MISO) downlink systems as the closed form expression. With this result, the author in [13] has founded the two optimal tilting angles of the vertical sectors in a cell.

In this paper, we propose a new approach which finds the optimal tilting angles with non-exhaustive manner in multi-cell MISO downlink AAS. We set an optimization problem which maximizes the average sum rate and consider the exhaustive search based vertical beamforming (ES_VB) algorithm to obtain the solution. However, since this problem is non-convex, the optimal tilting angle can be found only by comparing the average sum rate over all possible combinations. Therefore, we will introduce other schemes to reduce the computation complexity.

First, we apply a large system approximation to the average sum rate where the properties of the random matrix theory are used. For the sake of this work, we increase the number of antennas per base station (BS) and the number of users per cell to infinity, such that their ratio goes constant. Then, the characteristic of the channel randomness disappears and wireless communication circumstance becomes deterministic network systems[14-17]. Thus, we propose a large system approximation based vertical beamforming (LA_VB) algorithm. This algorithm does not need the channel state information (CSI) to find the optimal tilting angle and shows considerable reduction of the whole computational complexity. But the LA_VB algorithm still requires exhaustive search to obtain the tilting angles.

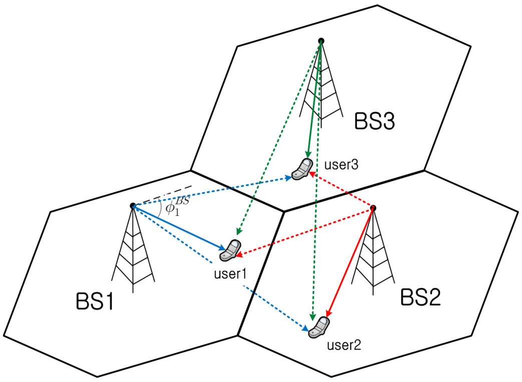

Fig. 1. System model for multi-cell MISO downlink AAS

Next, we approach the previous optimization problem from a signal-to-leakage-and-noise ratio (SLNR) point of view to solve the optimization problem simply. The conventional objective function involves the standard according to the signal-to-interference-plus-noise ratio (SINR) where calculation of the tilting angle in the particular BS needs the information of the other base stations (BSs). On the other hand, considering the current BS's leakage power, the SLNR approach does not require the information of the tilting angles in the other BSs[18]. Thus, we propose a SLNR based vertical beamforming (SLNR_VB) algorithm which independently optimizes the tilting angle in each cell. Simulation result confirms that our proposed algorithm exhibits performance close to the optimal exhaustive algorithm with much reduced complexity.

Ⅱ. System model

In this paper, we consider L-cell MISO downlink active antenna systems (AAS) where each BS is equipped with N directional antennas and supports a single user with a receive antenna in a cell as shown in Fig. 1. We assume that a BS with an active directional antenna radiates vertical beam to a single user sharply and sends a transmission signal toward the preferred direction. Then, the received signal $y_i \in \mathbb{C}$ at user i is given by

$$\begin{aligned} y_i = & \sqrt{r_{i,i}^{-\alpha} g_{i,i}(\phi_i^{BS},\phi_i^{U}) P_i}\, \mathbf{h}_{i,i}^{H} \mathbf{x}_i \\ & + \sum_{m \neq i}^{L} \sqrt{r_{m,i}^{-\alpha} g_{m,i}(\phi_m^{BS},\phi_i^{U}) P_m}\, \mathbf{h}_{m,i}^{H} \mathbf{x}_m + n_i \end{aligned} \quad (1)$$

where $\mathbf{h}_{m,i} \in \mathbb{C}^{N\times 1}$ and $r_{m,i}$ represent the channel vector and the distance from the antenna beam in the m-th BS to user i with the pathloss exponent α. Also, $\mathbf{x}_i(=\mathbf{v}_i s_i) \in \mathbb{C}^{N\times 1}$ is the transmit signal vector with the transmit power P_i where $\mathbf{v}_i \in \mathbb{C}^{N\times 1}$ and $s_i \in \mathbb{C}$ denote the beamforming vector with $\| \mathbf{v}_i \|^2 = 1$ and the transmit data symbol with unit variance, respectively. n_i is the complex additive Gaussian noise with variance $\sigma^2_{n_i}$. And $g_{m,i}(\phi_m^{BS}, \phi_i^U)\left(= g_{max} 10^{-1.2(\phi_i^U - \phi_m^{BS})/\phi_{3dB}^2}\right)$ is the antenna beam gain where ϕ_m^{BS} represents the vertical boresight angle of the BS indicated as the tilting angle, ϕ_i^U stands for the vertical angle of the user, and ϕ_{3dB} is the 3dB beam-width of the vertical patterns[10]. In here, ϕ_i^U is expressed as $\tan^{-1}(\triangle h / r_{m,i})$ where $\triangle h\left(= h_m^{BS} - h_{m,i}^U\right)$ is the height difference between a BS and a user. The second term in (1) represents the inter-cell- -interference (ICI).

Then, applying the maximal ratio transmission (MRT), the received SINR at the user i can be expressed as

$$\mathrm{SINR}_i = \frac{r_{i,i}^{-\alpha} g_{max} 10^{-1.2(\phi_i^U - \phi_i^{BS})/\phi_{3dB}^2} P_i \left|\mathbf{h}_{i,i}^H \mathbf{v}_i\right|^2}{\mathrm{ICI}_i + \sigma^2_{n_i}} \tag{2}$$

where $\mathrm{ICI}_i = \sum_{m \neq i}^{L} r_{m,i}^{-\alpha} g_{max} 10^{-1.2(\phi_i^U - \phi_m^{BS})/\phi_{3dB}^2} P_m \left|\mathbf{h}_{m,i}^H \mathbf{v}_m\right|^2$ for user i. Now we can formulate the optimization problem for the L-cell network which maximizes the average sum rate to find the optimal tilting angle as follows,

$$\begin{aligned} &\max_{\phi_m^{BS}} E\left[\sum_{i=1}^{L} \log_2\left(1 + \mathrm{SINR}_i\right)\right] \\ &\text{s.t. } \phi_{min} \le \phi_m^{BS} \le \phi_{max} \ \text{ for } m = 1, \ldots, L \end{aligned} \tag{3}$$

where ϕ_{min} and ϕ_{max} are the minimum and the maximum tilting angles. Our goal is to obtain the optimal tilting angle ϕ_m^{BS} by using the exhaustive search based vertical beamforming (ES_VB) algorithm. However, because this optimization problem (3) is non-convex, it is hard to find the solution. The ES_VB algorithm taking into account all possible value of the tilting angles has too much complexity. Thus, we will offer alternative algorithms to solve this problem in the following sections.

Ⅲ. Large system approximation based vertical beamforming

In this section, we first introduce a method to reduce the complexity of the ES_VB algorithm by using a large system approximation of the average sum rate. This large system approximation is associated with the useful results of random matrix theory developed in [14]-[17] and the assumption that our system dimensions standing for the number of antennas N in a BS and the number of users K in a cell expand to infinity with a fixed ratio (i.e., $\lim_{N,K\to\infty} \frac{N}{K} = \beta$). In particular, random matrix theory has the property which makes the randomly elements of the random matrix deterministic. Based on this result, large system approximation reduces the probabilistic feature of the wireless channel and leads to the deterministic system. Also, this approximation shows accurate performance for the finite dimensional system, even for small dimension[14]. Thus, through the following lemma and theorem, we will make the multi-cell MISO system efficiently with reduced complexity. First, we introduce the following lemma to utilize the large system approximation.

Lemma1[16] : Let $\mathbf{A} \in \mathbb{C}^{N\times N}$ be a random matrix and $\mathbf{x} \in \mathbb{C}^{N\times 1}$ be a random vector of independent identically distributed (i.i.d) entries with zero mean, variance $\frac{1}{N}$, and finite eight-order moment, which is independent of $\mathbf{A}$. Then,

$$\begin{aligned} &(i)\ \mathbf{x}^H\mathbf{A}\mathbf{x} - \frac{1}{N}\mathrm{tr}(\mathbf{A}) \xrightarrow{N\to\infty} 0, \\ &(ii)\ \mathrm{E}\left[\left|(\mathbf{x}^H\mathbf{A}\mathbf{x})^2 - \left(\frac{1}{N}\mathrm{tr}(\mathbf{A})\right)^2\right|\right] \xrightarrow{N\to\infty} 0. \end{aligned}$$

Next, with this lemma1, we can apply the large system approximation to the average sum rate denoted as $R_{sum}(\phi^{BS})\left(= E\left[\sum_{i=1}^{L} \log_2\left(1 + \mathrm{SINR}_i\right)\right]\right)$.

Theorem1 : As N and K grow large with fixed ratio $\beta\left(= \lim_{N,K\to\infty} \frac{N}{K}\right)$, the SINR of user i converges as follows,

$$\mathrm{SINR}_i \xrightarrow{N\to\infty} \mathrm{SINR}_i^o$$

where $\mathrm{SINR}_i^o \triangleq \dfrac{r_{i,i}^{-\alpha} \mathrm{g}_{max} 10^{-1.2(\phi_i^U - \phi_i^{BS})/\phi_{3dB}^2} P_{i,i} N}{\mathrm{ICI}_i^o + \sigma_{n_i}^2}$ with

$$\mathrm{ICI}_i^o = \sum_{m \neq i}^{L} r_{m,i}^{-\alpha} \mathrm{g}_{max} 10^{-1.2(\phi_i^U - \phi_m^{BS})/\phi_{3dB}^2} P_{m,i} .$$

Proof) Since the large system based on the random matrix deals with huge dimensions, we enlarge the conventional systems into the multi-user systems where each cell has K users. Then, we can express the average sum rate of LK users as

$$R_{sum}(\phi^{BS}) = E\left[\sum_{i=1}^{L}\sum_{k=1}^{K} \log_2\left(1 + \mathrm{SINR}_{k_i}\right)\right]$$

where k_i denotes the k-th user of the i-th cell with

$$\mathrm{SINR}_{k_i} = \frac{r_{i,k_i}^{-\alpha} \mathrm{g}_{i,k_i}(\phi_i^{BS}, \phi_{k_i}^U) P_{i,k_i} \left|\mathbf{h}_{i,k_i}^H \mathbf{v}_{k_i}\right|^2}{\mathrm{IUI}_{k_i} + \mathrm{ICI}_{k_i} + \sigma_{k_i}^2} . \qquad (4)$$

Here, inter-user-interference (IUI) and ICI can be denoted as

$$\mathrm{IUI}_{k_i} = \sum_{m \neq k}^{K} r_{i,k_i}^{-\alpha} \mathrm{g}_{i,k_i}(\phi_i^{BS}, \phi_{k_i}^U) P_{i,k_i} \left|\mathbf{h}_{i,k_i}^H \mathbf{v}_{m_i}\right|^2 \quad \text{and}$$

$$\mathrm{ICI}_{k_i} = \sum_{l \neq i}^{L} \sum_{m=1}^{K} r_{l,k_i}^{-\alpha} \mathrm{g}_{l,k_i}(\phi_l^{BS}, \phi_{k_i}^U) P_{l,k_i} \left|\mathbf{h}_{l,k_i}^H \mathbf{v}_{m_i}\right|^2 .$$

The multi-cell multi-user systems has the interference among the users and the cells, respectively. Then, we use the MRT beamforming scheme to cancel these interferences. The beamforming vector based on the MRT is written by

$$\mathbf{v}_{k_i} = \sqrt{\mu}\,\mathbf{h}_{k_i} \quad \text{with} \quad \mu = \frac{P_i}{\mathrm{tr}(\mathbf{P}_i \mathbf{V}_i \mathbf{V}_i^H)},$$

where $P_i > 0$ is the total available transmit power in the i-th cell, $\mathbf{V}_i = [\mathbf{v}_{1_i}, \cdots, \mathbf{v}_{K_i}]$, and $\mathbf{P}_i = diag\{p_{i,1_i}, \cdots, p_{i,K_i}\}$ with $p_{i,k_i} > 0$ is the signal power of user k of the i-th cell. In order to disappear the randomness of the channel, by using the deterministic approximations in [15] and [16], we achieve the below result,

$$\frac{1}{N}\left|\mathbf{h}_{i,k_i}^H \mathbf{h}_{i,k_i}\right|^2 \xrightarrow{N \to \infty} N \ ,$$

$$\frac{1}{N}\left|\mathbf{h}_{l,k_i}^H \mathbf{h}_{i,k_i}\right|^2 \xrightarrow{N \to \infty} 1 \ . \qquad (5)$$

Also, for large N, K such that $0 < \lim\inf_N \frac{K}{N} \leq \lim\sup_N \frac{K}{N} < \infty$, we expect to have

$$\mathrm{tr}(\mathbf{P}_i \mathbf{V}_i \mathbf{V}_i^H) - NP_i \to 0. \qquad (6)$$

Applying the results in (5) and (6) to (4), we have

$$\mathrm{SINR}_{k_i} - \mathrm{SINR}_{k_i}^o \xrightarrow{N \to \infty} 0.$$

Since the large system approximation is well matched for the small dimensional system, the above value of the SINR_i^o for a single-user case is also valid. This concludes the proof.

Using the result in the theorem1, the above optimization problem (3) can be written as

$$\begin{aligned} &\max_{\phi_m^{BS}} E\left[\sum_{i=1}^{L} \log_2\left(1 + \mathrm{SINR}_i^o\right)\right] \\ &\text{s.t. } \phi_{min} \leq \phi_m^{BS} \leq \phi_{max} \quad \text{for } m = 1, \ldots, L \end{aligned} . \qquad (7)$$

In this new optimization problem, the asymptotic sum rate can be expressed as

$$R_{sum}^o(\phi^{BS}) \left(= E\left[\sum_{i=1}^{L} \log_2\left(1 + \mathrm{SINR}_i^o\right)\right]\right).$$

Then, we propose a large system approximation based vertical beamforming (LA_VB) algorithm in the following.

```
LA_VB algorithm:

Initialize $\hat{R}_{sum} = 0$ and $\Delta\phi$ is the step size between $\phi_{\min}$ and $\phi_{\max}$ for searching $\phi^{BS}$,
For $\phi_1^{BS} = \phi_{\min} : \Delta\phi : \phi_{\max}$
  For $\phi_2^{BS} = \phi_{\min} : \Delta\phi : \phi_{\max}$
    ... For $\phi_L^{BS} = \phi_{\min} : \Delta\phi : \phi_{\max}$
        Calculate the asymptotic sum rate $R_{sum}^o(\phi_1^{BS}, \ldots, \phi_L^{BS})$
        If $R_{sum}^o(\phi_1^{BS}, \ldots, \phi_L^{BS}) \geq \hat{R}_{sum}$
          Update $\hat{R}_{sum} = R_{sum}^o(\phi_1^{BS}, \ldots, \phi_L^{BS})$
                 $\hat{\phi}_1^{BS} = \phi_1^{BS}, \ldots, \hat{\phi}_L^{BS} = \phi_L^{BS}$
        End
    ... End
  End
End
```

In the simulation results, we will show that the proposed LA_VB algorithm yields the performance close to the ES_VB algorithm. Since there is no necessity for knowing the CSI in the LA_VB algorithm, this method has less complexity than ES_VB algorithm. This deterministic effect on the system channel results from the random matrix property. Thus, we can simplify the optimization problem much more which maximizes the asymptotic sum rate. However, the LA_VB algorithm still must execute the exhaustive search for finding the tilting angles ϕ_i^{BS} for $i=1,\ldots,L$ and consider the tilting angles in the other BSs due to the ICI. Thus, in the following section, we will offer an algorithm to resolve these problems.

Ⅳ. SLNR based vertical beamforming

In this section, we introduce a new technique based on the SLNR criterion for estimating an optimum tilting angle. Since the LA_VB algorithm has complicated computation, we will use the following approach to overcome this issue. From the perspective of SLNR, we reconstruct the above optimization problem (7) which maximizes the instantaneous rate as

$$\max_{\phi_i^{BS}} E\left[\log_2\left(1+\mathrm{SLNR}_i^o\right)\right] \qquad ,$$

$$\text{s.t. } \phi_{min} \le \phi_i^{BS} \le \phi_{max} \quad \text{for } i=1,\ldots,L$$

where $\mathrm{SLNR}_i^o = \dfrac{r_{i,i}^{-\alpha} g_{max} 10^{-1.2(\phi_i^U-\phi_i^{BS})/\phi_{3dB}^2} P_i N}{\sum_{m\neq i}^{L} r_{i,m}^{-\alpha} g_{max} 10^{-1.2(\phi_m^U-\phi_i^{BS})/\phi_{3dB}^2} P_i + \sigma_i^2}$

and the instantaneous rate $\widetilde{R}_{SLNR,i}^o(\phi_i^{BS})$ of the user in the i-th cell is expressed as $E\left[\log_2\left(1+\mathrm{SLNR}_i^o\right)\right]$.

Now, using these results, we offer a SLNR based vertical beamforming (SLNR_VB) algorithm in the following.

In this SLNR_VB algorithm, we can optimize the tilting angle independently in each cell. Unlike the SINR, since the leakage power of a BS is the interference from other BSs' circumstances, the ICI term of SLNR does not have to know other BSs' both beamforming vectors and tilting angles. Also, the SLNR_VB algorithm related to the large system approximation has the deterministic channel property. Thus, this algorithm has the complexity $O(M)$, whereas the ES_VB algorithm has the complexity $O(M^2)$. In the next section, we will confirm that SLNR_VB algorithm achieves the near optimal performance compared to the exhaustive method. Therefore this SLNR approach algorithm contributes a considerable complexity reduction.

```
SLNR_VB algorithm:

Initialize $\hat{R}_{inst,i}=0$ and $\Delta\phi$ is the step size between $\phi_{\min}$ and $\phi_{\max}$ for searching $\phi^{BS}$,
For $i=1,\ldots,L$
    For $\phi_i^{BS}=\phi_{\min} : \Delta\phi : \phi_{\max}$
        Calculate the instantaneous rate $\widetilde{R}_{SLNR,i}^o(\phi_i^{BS})$
        If $\widetilde{R}_{SLNR,i}^o(\phi_i^{BS}) \ge \hat{R}_{inst,i}$
            Update $\hat{R}_{inst,i}=\widetilde{R}_{SLNR,i}^o(\phi_i^{BS})$
            $\hat{\phi}_i^{BS}=\phi_i^{BS}$
        End
    End
End
```

Ⅴ. Simulation Results

In this section, we present numerical results to confirm the effectiveness of the proposed algorithms by running Monte Carlo simulations. We assume that the elements of the channel have an i.i.d complex Gaussian distribution with zero mean and unit variance. Also, the noise variance σ_n^2 is set to be 1.

The total transmit power is denoted as P. The cell-edge SNR standing for the received SNR at the cell boundary is defined as $\mathrm{SNR}=\dfrac{r_{max}^{-\alpha}P}{\sigma_n^2}$ where r_{max} is the radius of a cell. And due to the MRT, the BS knows the perfect CSI to make the beamforming vectors. Table 1 shows the simulation settings. In this settings, we consider 3-cell $(L=3)$ model and there is a single BS and a single

Table 1. Simulation Settings

$\Delta h\ [m]$	$r_{\min}\ [m]$	$r_{\max}\ [m]$	$\phi_{3dB}(^o)$
28.5	30	500	6.2
$G_{\max}$ [dBi]	N	L	α
17	3	3	3.4

user in each cell where a BS has 3 antennas $(N=3)$ and a user has a single antenna. The height of a BS and a user is set as 30 $[m]$ and 1.5 $[m]$, respectively. Three BSs are located appropriately where we denote each BS as BS1, BS2, and BS3. Also, we use (x,y) notation which presents x-dimensional position and y-dimensional position. First, BS1 is set to $(0,0)$ position. Next, BS2 and BS3 are located at $(\sqrt{3}r_{\max}\cos(30^o), \sqrt{3}r_{\max}\sin(30^o))$ and $(\sqrt{3}r_{\max}\cos(-30^o), \sqrt{3}r_{\max}\sin(-30^o))$, respectively. And three users are located at $(250,0)$, $(500,100)$, and $(550,-300)$ with the variance 3000, 500, and 4000. And the maximum value $\phi_{\max}$ is set to 25^o and the minimum value $\phi_{\min}$ can be calculated as $\tan^{-1}(\Delta h/r_{\max})$. Also, the step size $\Delta\phi$ is 0.01^o.

Figure 2 shows the average sum rate in terms of the cell-edge SNR. In this plot, we can confirm that the proposed LA_VB and SLNR_VB algorithms exhibit the near optimal performance to the ES_VB algorithm. And the SLNR_VB scheme has the important advantage of the reduction in complexity for finding the optimal tilting angles. In this simulation circumstance, the minimum value $\phi_{\min}$ of BS tilting angle is obtained as 3.2623^o. Thus, the numbers of the candidate tilting angle is roughly 2170 and SLNR_VB algorithm has the $6510(=3\times 2170)$ search size. However, ES_VB algorithm needs the full search to find the optimal tilting angle and has the 3^{2170} complexity. In addition, the SLNR_VB algorithm has a tiny performance loss compared to the ES_VB algorithm. Throughout the simulation, we verify that our proposed vertical beamforming algorithms are very effective for multi-cell MISO downlink AAS.

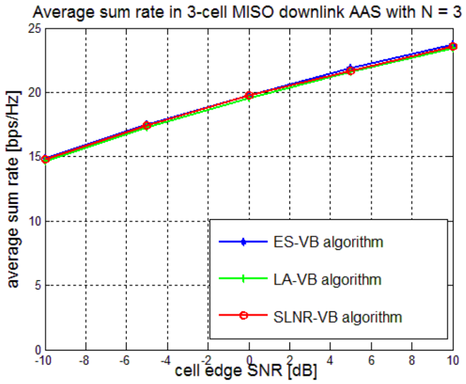

Fig. 2. Average rate performance comparison as a function of cell-edge SNR

Ⅵ. Conclusion

In this paper, we have proposed the 3D vertical beamforming technique with the reduced complexity which obtains the optimal tilting angle for multi-cell MISO downlink AAS. First, we have suggested the LA_VB algorithm which reflects the large system approximation. In this work, the randomness of the system channel disappears. Next, the SLNR_VB algorithm utilizing the concept of SLNR has been introduced to reduce the search size for optimizing the tilting angles. From numerical results, we have verified that the proposed algorithms represent the near optimal performance compared to the exhaustive algorithm with significantly reduced complexity.

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