Improving Throughput by Multi-cell Coordinated Vertical Plane Beam Control with Pre-coding

Kenji Hoshino and Teruya Fujii
Wireless System Research Center
SOFTBANK MOBILE Corp.
Tokyo, Japan
kenji01.hoshino@g.softbank.co.jp

Abstract—**Cellular mobile communication systems reuse the same frequency channel in geographically distant areas to improve the spectrum efficiency. However, co-channel interference among cells remains a critical issue. Mitigating co-channel interference leads to a further improvement in spectrum efficiency. One technique for mitigating co-channel interference is antenna beam tilting, which controls the vertical plane beam of base station antennas. In cellular mobile communication systems, antenna beam tilting is generally used by setting fixed beams at each base station. If the vertical plane beam pattern is changed dynamically for each mobile station, it is possible to significantly improve the SINR (Signal-to-Interference plus Noise Ratio), which drastically improves the spectrum efficiency. We propose here a vertical plane beam control method that uses pre-coding; the vertical plane beam pattern for each mobile station is easily set by controlling the phase of the baseband signal. The proposed method can be easily implemented with little or no modification of the antenna configuration at the base station. This system is effective for improving not only cell edge capacity but also overall cell capacity at the same time. A computer simulation shows that the spectrum efficiency of the proposed system is approximately twice that of conventional antenna beam tilting.**

Keywords-OFDM; Cellular mobile communications; Antenna; Vertical plane beam control; Pre-coding; Cell configuration; System capacity

I. INTRODUCTION

Cellular mobile communication systems reuse the same frequency channel to improve the spectrum efficiency. To efficiently reuse the same frequency channel over geographically distant areas, it is necessary to suppress co-channel interference among co-channel reuse cells. Reducing the co-channel interference among cells leads to a further improvement in spectrum efficiency.

Radio resource allocation through the coordination of multiple cells, a key technology for controlling co-channel interference, has been studied in recent years. Multi-cell coordinated resource allocation coordinates the allocation of radio resources such as “transmit power”, “antenna” and “frequency” among multiple cells to better suppress their mutual co-channel interference, which greatly improves spectrum efficiency. These kinds of technologies are also being discussed animatedly in 3GPP and known as JP (Joint Processing) and CS/CB (Coordinated Scheduling / Coordinated Beam-forming) [1, 2].

Our solution to implementing this approach, ECO-OFDM (Enhanced COoperative-OFDM), ensures that the multiple base stations cooperate most effectively when allocating radio resources [3, 4].

In this paper, as one of the antenna resource control techniques in ECO-OFDM, we study vertical plane beam control of base station antenna.

The conventional vertical plane beam control involves antenna beam tilting as described in [5]. In antenna beam tilting, the tilt angle is generally fixed and set at the optimal value for each base station. The tilt angle is set so that the maximum directivity is directed to the cell edge. Since we cannot control antenna directivity for every mobile, it is impossible to configure the optimal value for the mobile stations inside the cell, i.e. away from the cell edge.

Given this background, this paper proposes a vertical plane beam control method that uses pre-coding to make vertical plane beam control possible for all mobile stations. The proposed method implements digital phase control of the baseband signal with pre-coding based on a known codebook. It is easy to implement since little or no modification of base station configuration is needed.

In this paper, we evaluate the throughput performance when the vertical plane beam control is applied in the multi-cell environment. In the evaluation, we consider both the decentralized and centralized approach for controlling users' pre-coding in each cell. In the decentralized method, the vertical plane beam is independently controlled for each cell; it is one of the easiest schemes to implement. On the other hand, in the centralized method, the vertical plane beam of each base station is optimally controlled by coordinating all base stations, which is computationally complex because exhaustive search is needed. However, we assess the centralized method to find the theoretical limits of the proposed method.

Because the proposed method uses vertical plane control, its performance depends on the size of the cell. Therefore, this paper focuses on an environment containing various cell sizes to better mirror actual environments.

Section II describes the vertical plane beam control method with pre-coding proposed in this paper. Section III introduces the model of the multi-cell environment with various cell sizes. Section IV presents the evaluation model for the proposed method and the results of evaluation. Finally, the conclusions are given in Section V.

978-1-4673-0990-5/12/$31.00 ©2012 IEEE

II. VERTICAL PLANE BEAM CONTROL OF BASE STATION ANTENNA WITH PRE-CODING

A. *Conventional vertical beam control*

The key vertical plane beam control technologies are antenna beam tilting and AAA (Adaptive Array Antenna).

Antenna beam tilting fixes the vertical plane beam of a base station antenna to a specific direction. Hence, the performance of antenna beam tilting depends on the directional characteristics and the antenna tilt angle. The tilt angle is normally set toward the cell edge so that the main lobe of the tilted beam intersects the cell edge. Since antenna beam tilting has only one beam pattern, it is impossible to configure optimal beams for every mobile station within the cell.

On the other hand, since AAA can yield an optimal beam for each mobile station, it is possible to increase the desired signal power at each mobile station in the coverage area and decrease the interference signal power at the surrounding cells. However, since it is necessary to prepare the same number of feeders and amplifiers (AMPs) as the number of antenna elements, the device configuration is exceedingly complex, especially when there are many antenna elements. For example, a 16-element antenna needs 16 feeders and 16 AMPs.

B. *Vertical plane beam control with pre-coding*

Fig. 1 shows an example of the proposed antenna structure. 16 half-wave dipole antennas are vertically spaced under an antenna hood. As described in Fig. 1 (a), the 16 elements are equally split into element group A and B. Equal phase and equal amplitude are supplied to each element group. We regard these element groups as one antenna combining them. By setting a different phase to each element group, various beams can be configured as shown in Fig. 1 (b). With respect to the phase patterns to be used, we define a codebook that holds several combination patterns for groups A and B. Each mobile station selects a specific pattern from the predefined codebook. The proposed system implements phase control by digital control of the baseband signal, "pre-coding", rather than by analog control via a phase shifter, i.e. codebook-based beam-forming.

C. *Analytical model*

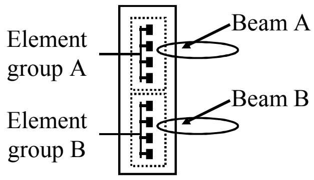
We examine a linear array antenna here. We denote the number of antenna elements as N, the wavelength as λ, and the interval between elements as Δd. The horizontal plane directivity is set at 0deg.. The vertical plane directivity, $g_N(\theta)$, and the power directivity, $G_N(\theta)$, of this linear array antenna can be represented as follows.

$$g_N(\theta)=\sum_{k=0}^{N-1} g_e(\theta)\cdot\exp\left(j\frac{2\pi k\Delta d\sin\theta}{\lambda}\right) \tag{1-1}$$

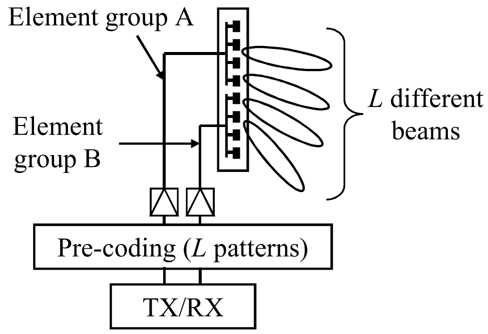
$$G_N(\theta)=\left|g_N(\theta)\right|^2=\left|\sum_{k=0}^{N-1} g_e(\theta)\cdot\exp\left(j\frac{2\pi k\Delta d\sin\theta}{\lambda}\right)\right|^2 \tag{1-2}$$

where $g_e(\theta)$ is the vertical plane directivity of the antenna element. For simplicity, we assume that the element itself has no directivity, i.e. $g_e(\theta)\equiv 1$.

In the proposed method, if we denote the number of antenna elements in antenna group A and B as N_1 and N_2 (=N-N_1), and their vertical plane directivity as $g_{N1}(\theta)$ and $g_{N2}(\theta)$, respectively, $g_{N1}(\theta)$ and $g_{N2}(\theta)$ can be represented as follows.



(a) Antenna element structure.



(b) Antenna structure.

Figure 1. Vertical plane beam control by using pre-coding.

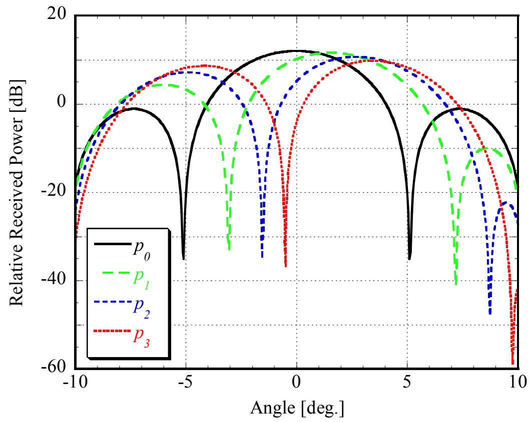


Figure 2. Relative received power vs. Angle.

$$g_{N1}(\theta)=\sum_{k=0}^{N_1-1} g_e(\theta)\cdot\exp\left(j\frac{2\pi k\Delta d\sin\theta}{\lambda}\right) \tag{2-1}$$

$$g_{N2}(\theta)=\sum_{k=N_1}^{N_1+N_2} g_e(\theta)\cdot\exp\left(j\frac{2\pi k\Delta d\sin\theta}{\lambda}\right) \tag{2-2}$$

Here, if we denote the i-th pre-coding vector (PV) that includes the combination of upper and lower phases as $p_i=(p_i^U, p_i^L)$, the vertical plane directivity and power directivity with applying i-th PV are given as follows.

$$g_{N,i}(\theta)=g_{N1}(\theta)\exp(jp_i^U)+g_{N2}(\theta)\exp(jp_i^L) \tag{3-1}$$

$$G_{N,i}(\theta)=\left|g_{N1}(\theta)\exp(jp_i^U)+g_{N2}(\theta)\exp(jp_i^L)\right|^2 \tag{3-2}$$

As an example of antenna directivity, we consider a codebook with L patterns. For example, when four PVs, p_0=(0, 0), p_1=(2π/5, 0), p_2=(7π/10, 0) and p_3=(9π/10, 0), are applied, antenna vertical plane directivity $G_{N,i}(\theta)$ is as shown in Fig. 2, where the element interval, Δd, normalized by wavelength λ, equals 0.7. If p_0 is applied, the antenna gain is the maximum

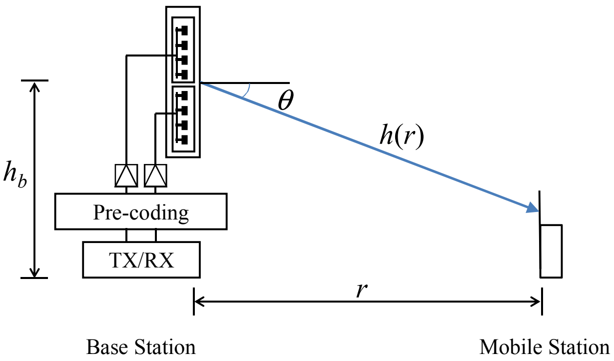


Figure 3. System model.

when θ=0[deg.] since all elements have the same phase. When PV is set at p_0, the antenna configuration is the same as the conventional antenna configuration without vertical pre-coding. On the other hand, if p_2 is applied, the gain is maximum at θ=3[deg.] with the null at θ=-1.5[deg.].

Next, we discuss the characteristics from the viewpoint of propagation distance in the proposed system. As an example, when we denote the base station height as h_b, and the distance between base station and mobile station as r, elevation angle θ can be expressed by the following equation.

$$\theta = \tan^{-1}(h_b / r) \tag{4}$$

As described in Fig. 3, if we denote the propagation channel between the antennas of base station and mobile station as $h(r)$, and the transmission signal as s_d, the received signal $e_{N,i}(r)$ when applying i-th PV is expressed as follows.

$$\begin{aligned} e_{N,i}(r) &= h(r) g_{N1}(\tan^{-1}(h_b / r)) \cdot \exp(jp_i^U) \cdot s_d \\ &\quad + h(r) g_{N2}(\tan^{-1}(h_b / r)) \cdot \exp(jp_i^L) \cdot s_d \\ &= h(r)\left(g_{N1}(\tan^{-1}(h_b / r)) \exp(jp_i^U) + g_{N2}(\tan^{-1}(h_b / r)) \exp(jp_i^L) \right) \cdot s_d \end{aligned} \tag{5}$$

The received power $E_{N,i}(r)$ when applying i-th PV is expressed as follows.

$$\begin{aligned} E_{N,i}(r) &= \left| e_{n,i}(r) \right|^2 \\ &= \left| h(r) \right|^2 \left| g_{N1}(\tan^{-1}(h_b / r)) \exp(jp_i^U) + g_{N2}(\tan^{-1}(h_b / r)) \exp(jp_i^L) \right|^2 \end{aligned} \tag{6}$$

where we assume the transmit signal power is $|s_d|^2 \equiv 1$. This paper assumes the propagation characteristics (distance characteristic) $|h(r)|^2$ obeys the following equation.

$$|h(r)|^2 = A \cdot r^{-\alpha} \quad (\alpha \geq 2) \tag{7}$$

where A is a constant that depends on the transmit power and antenna characteristic of each base station. α, a propagation constant, is approximately 3.5 in a typical urban area. We set α=3.5 hereafter.

Here, we examine a distance characteristic when we set the base station height at h_b=50[m] and cell radius at R=1[km] as an example. If we assume that the fixed tilt angle equals the elevation angle at the cell edge, we can express tilt angle θ_{Tilt} as θ_{Tilt}=tan^{-1}(50/1000)=2.9[deg.]. When the fixed tilt is applied, the received power is given as follows.

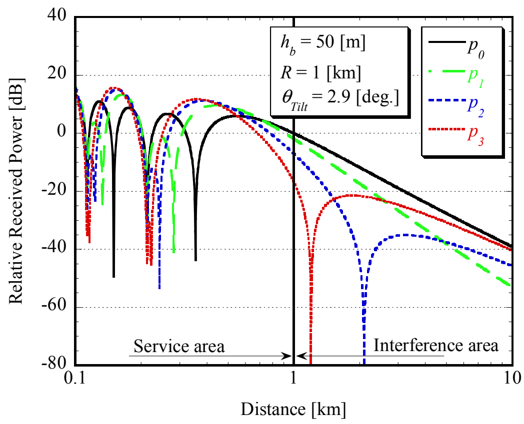


Figure 4. Relative received power vs. Distance.

$$E_{N,i}(r) = |h(r)|^2 \left| \begin{aligned} & g_{N1}(\tan^{-1}(h_b / r) - \theta_{Tilt}) \exp(jp_i^U) \\ & + g_{N2}(\tan^{-1}(h_b / r) - \theta_{Tilt}) \exp(jp_i^L) \end{aligned} \right|^2 \tag{8}$$

Here, assuming $E_{N,0}(R)$=1(=0dB) with p_0=(0, 0), when four PVs (p_0=(0, 0), p_1=(2π/5, 0), p_2=(7π/10, 0), p_3=(9π/10, 0)) are applied, the relative received power vs. distance for four PV patterns are described as shown in Fig. 4. In this figure, we set N=16, N_1=N_2=8, Δd=0.7, θ_{Tilt}=2.9[deg.]. As shown in Fig. 4, the variation in received power depends on PV. From the result of Fig. 4, for example, if the mobile station is in the range of 0.3[km]<r<0.6[km], by selecting p_2 or p_3, the received signal power at the mobile station can be increased, and the interference signal power can be considerably decreased at the same time. Moreover, by selecting p_3 if there is a neighboring mobile station in the interference area at the range of 1.0[km]<r<1.5[km], and p_2 if 1.5[km]<r<3.0[km], then the interference signal power at the neighboring mobile station can be significantly decreased, i.e. more than 20dB.

The optimal PV generally depends on cell size R, base station height h_b and fixed tilt angle θ_{Tilt}. Therefore, PV selection must consider all parameters.

Here, we explain about the received power estimation using pilot signals in the SISO (Single-Input and Single-Output) system shown in Fig. 3. In the PV selection based on pilot signal, the pilot signals, s_{p1} and s_{p2}, are transmitted from element group A and B, respectively. The pilot signals are assumed to be transmitted at the tilt angle, θ_{Tilt}. In this case, the pilot signals received at the mobile station, $P_{N1}(r)$ and $P_{N2}(r)$, are expressed by the following equations.

$$\begin{aligned} P_{N1}(r) &= h(r) g_{N1}(\tan^{-1}(h_b / r) - \theta_{Tilt}) \cdot s_{p1} \\ P_{N2}(r) &= h(r) g_{N2}(\tan^{-1}(h_b / r) - \theta_{Tilt}) \cdot s_{p2} \end{aligned} \tag{9}$$

Since the pilot signals are known to the mobile stations, the mobile station can obtain the propagation channel from $P_{N1}(r)$ and $P_{N2}(r)$ as follows.

$$\begin{aligned} h(r) g_{N1}(\tan^{-1}(h_b / r) - \theta_{Tilt}) &= P_{N1}(r) / s_{p1} \\ h(r) g_{N2}(\tan^{-1}(h_b / r) - \theta_{Tilt}) &= P_{N2}(r) / s_{p2} \end{aligned} \tag{10}$$

By substituting (10) into (8), the received power of each PV can be estimated by the following equation.

$$E_{N,i}(r) = \left| P_{N1}(r) / s_{p1} \cdot \exp(jp_i^U) + P_{N2}(r) / s_{p2} \cdot \exp(jp_i^L) \right|^2 \tag{11}$$

Mobile stations select the appropriate PV by utilizing $E_{N,i}(r)$.

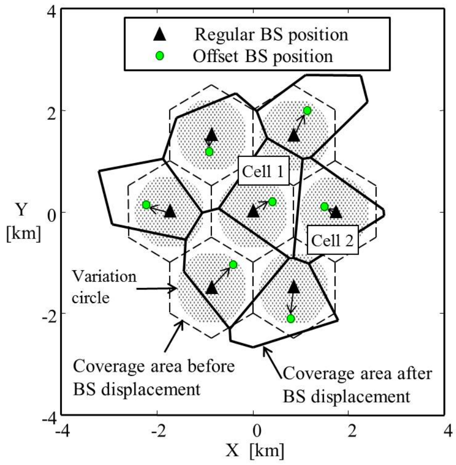


Figure 5. Model of an environment consisting of various cell sizes.

D. PV selection method

In this paper, we introduce both the decentralized and centralized approach to PV selection for each mobile station.

In decentralized control, each user selects the PV that yields the highest received power from the serving cell. That is to say, we change i of (11) and select the PV that has the highest $E_{N,i}(r)$. Assuming the highest received power at the mobile station in k-th cell as E_k, the thermal noise as $N_{0,k}$ and the interference signal power as I_k, the Shannon capacity at the mobile station, C_k, can be represented as the following equation.

$$C_k = \log_2\left(1 + E_k / (N_{0,k} + I_k)\right) \tag{12}$$

On the other hand, the centralized control selects PV of each mobile station so that the throughput of whole coverage area is maximal. Therefore, the selected PV is not always the PV with highest received power at the mobile station. If we denote the received power realized by applying the i-th PV to the mobile station in the k-th cell as $E_{k,i}$, the Shannon capacity of the mobile station, $C_{k,i}$, is given as follow.

$$C_{k,i} = \log_2\left(1 + E_{k,i} / (N_{0,k} + I_k)\right) \tag{13}$$

Moreover, the Shannon capacity in the coverage area, C, is given as follow.

$$C = \sum_{k=1}^{M} C_{k,i} \tag{14}$$

where M is the number of cells in the coverage area. In the centralized control, the set of PVs that make C of (14) maximal is selected by exhaustive search; L^M.

III. Cell configuration model

This paper clarifies the performance of the proposed method in a multi-cell environment containing various cell sizes. To examine this kind of environment, we employ the BS displacement model discussed in reference work [6], it is called the irregular cell configuration hereafter.

In the regular cell configuration, base stations are located at the centers of hexagonal cells, the "Regular BS position" described in Fig. 5. In the irregular cell configuration, on the other hand, base stations are randomly distributed within circles (variation circles) centered on "Regular BS position", represented as "Offset BS position" in Fig. 5. Here, we define the radius of the variation circle normalized by the cell radius (regular cell configuration) as eccentricity ξ. ξ=0 represents the regular cell configuration. The larger ξ is, the more strongly the cell structure differs from the regular cell configuration. Fig. 5 shows an example when we set ξ=0.8. As shown in the coverage area after BS displacement in Fig. 5, cells of different size can be created in the irregular cell configuration.

IV. Evaluation by computer simulation

A. Evaluation model

(i) Cell configuration

We assume M=7 cells. In the regular cell configuration (ξ=0), cell radius is set at R=1[km]. In the irregular cell configuration, we set ξ=0.8.

(ii) Antenna configuration

The horizontal directivity of base stations is assumed to be omnidirectional. The vertical and horizontal directivity of mobile station is also assumed to be omnidirectional. This paper assumes SISO transmission to evaluate fundamental performance by applying the proposed method. The other parameters are the same as in Section II-*C*. In the irregular cell configuration, fixed tilt angle without pre-coding control is set so that the maximum gain of antenna directivity intersects the farthest cell edge, $R_{\max}$, from the base station. For example, in Fig. 5, $R_{\max}$ of cell 1 and 2 is 1.2km and 1.7km, respectively. Thus, the tilt angle of the fixed beam is $\tan^{-1}(50/1200)$ =2.3[deg.] and $\tan^{-1}(50/1700)$=1.7[deg.], respectively.

(iii) Pre-coding setting

PV patterns (codebook) are assumed to be defined individually for every cell. The patterns depend on $R_{\max}$. Table 1 shows an example of PV configuration according to $R_{\max}$ where the antenna height of base station is 50m. The maximum cell radius is set in steps of 0.5km in the proposed method. Regarding the PV selection, we employ the decentralized and centralized control as stated in Section II-*D*.

(iv) User model

This paper assumes an OFDMA-based system. Transmission is conducted in such a way that users' data are orthogonal to each other, thus there is no interference among mobile stations in a cell. In this paper, therefore, we assume one mobile station per cell. Each mobile station is uniformly distributed in its coverage area.

(v) Propagation model

The propagation characteristic between the base station and its mobile station is defined as long-term variation for simplicity as described in (7). We set α=3.5 in this paper. In addition, the transmit power and the noise power of base stations is set so that the average SNR (Signal-to-Noise Ratio) at the cell edge, SNR_R is 10[dB] in the regular cell

Table 1. Example of codebook

R_{max}	PV pattern			
R_{max}<0.75km	(π, 0)	(9π/10, 0)	(7π/10, 0)	(2π/5, 0)
0.75km≦R_{max}<1.25km	(9π/10, 0)	(7π/10, 0)	(2π/5, 0)	(0, 0)
1.25km≦R_{max}<1.75km	(9π/10, 0)	(4π/5, 0)	(2π/5, 0)	(0, 0)
1.75km≦R_{max}	(9π/10, 0)	(4π/5, 0)	(2π/5, 0)	(0, 0)

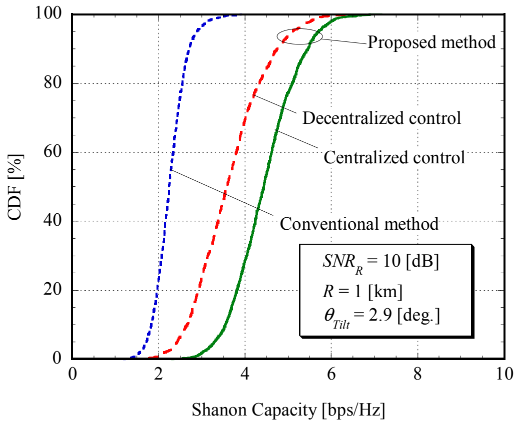


Figure 6. Throughput performance in regular cell configuration.

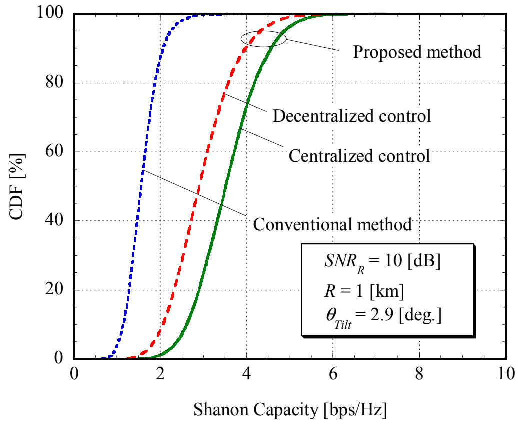


Figure 7. Throughput performance in irregular cell configuration.

configuration (R=1[km]) when the main lobe points to the cell edge. All base stations transmit signals at the same power.

(vi) Evaluation item

We evaluate the total Shannon capacity of M=7 cells for simplicity as expressed by the following equation.

$$C = \sum_{k=1}^{M} C_k = \sum_{k=1}^{M} \log_2(1+\gamma_k) \tag{12}$$

where γ_k represents the received SINR at mobile station in i-th cell after applying PV.

B. Evaluation result

This paper denotes the vertical plane beam control with pre-coding and the simple antenna beam tilting without pre-coding as "Proposed method" and "Conventional method", respectively.

(a) Throughput performance in regular cell configuration

Fig. 6 shows CDF of throughput in the regular cell configuration. The proposed method (both types) significantly improves the throughput compared to the conventional method. Regarding average throughput, centralized and decentralized control have 2.0 and 1.6 times higher throughput than the conventional method, respectively.

(b) Throughput performance in irregular cell configuration

Fig. 7 plots the throughput performance in the irregular cell configuration; ξ=0.8 with 100 iterations. Centralized and decentralized control offer 2.2 and 1.9 times higher average throughput than the conventional method, respectively.

These results show that the proposed method can achieve high performance in throughput and offers a drastic improvement, especially in the irregular cell configuration.

V. CONCLUSION

This paper proposed a method for realizing vertical plane beam control with pre-coding and clarified its throughput improvement when applied to the multi-cell environment. We considered, for the proposed method, centralized and decentralized control for PV selection. The results are summarized as follows.

(1) In the regular cell configuration, centralized and decentralized control improve cell throughput by 2.0 and 1.6 times compared to the conventional method.

(2) In the irregular cell configuration with eccentricity of 0.8, centralized and decentralized control improve cell throughput by 2.2 and 1.9 times compared to the conventional method.

Especially in the irregular cell configuration, the proposed method dramatically increases the throughput possible.

ACKNOWLEDGEMENT

Part of this work is carried out under the grant, "R&D on the cooperative control technologies for multiple base stations in an environment consisting of various cell sizes," which is funded by the Ministry of International Affairs and Communications of Japan.

REFERENCES

[1] ITU-R, "Requirements related to technical performance for IMT-Advanced radio interface(s)," Recommendation M.2134, 2008.

[2] 3GPP TR36.814: "Further advancements for E-UTRA physical layer aspects; Coordinated multi point transmission and reception," 2010.

[3] K. Hoshino and T. Fujii, "Multi-cell Coordinated Power Control with Adjacent Cell Cooperative Transmission Considering Actual Environment," *Proc. of IEEE Vehicular Technology Conference*, Budapest, May 2011.

[4] M. Mikami and T. Fujii, "Cooperative MIMO Transmission Based on Multiple Base Station Coordination for OFDM Cellular Systems," *Proc. of IEICE 2008 International Symposium on Antenna and Propagation*, Taiwan, Oct. 2008.

[5] T. Fujii, "Optimum Antenna Beam Tilting for Cellular Mobile Radio Systems," *IEICE Trans. on Communications*, Vol. J77-B2, No. 3, pp. 166-170, 1994 (in Japanese).

[6] K. Nakano, T. Fujii and N. Nakajima, "Outage Probability for Mobile Radio Considering the Ambiguity of the Base Station Location and Antenna Height," *IEICE Trans. on Communications*, Vol. J75-B2, No. 3, pp. 157-162, 1992 (in Japanese).