Performance Evaluation of Active Propagation Control in a Three-Dimensional Indoor Environment

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***Abstract*—We can improve transmission performance of wireless communications by changing propagation environment actively and appropriately. We call such method "Active Propagation Control" (APC). In the previous studies we showed the fundamental effectiveness of APC by two-dimensional FDTD analysis, assuming an empty room where a metal plate is rotated as a device changing the propagation characteristics. In this paper, we analyze indoor propagation characteristics by using the three-dimensional FDTD method so as to discuss more accurate amount of the improvement of APC in a three-dimensional space. In addition, we change the position of the metal plate besides its size in order to evaluate the effect of the variations on the improvement of APC. In the evaluation, we assume a SISO wireless communication and show the reduction of path loss by APC quantitatively.**

***Keywords*— Radio propagation; Active propagation control; Path loss; FDTD**

I. Introduction

In recent years with the rapid spread of multifunctional wireless terminals typically represented by smartphones and tablet-type devices, higher speed and larger capacity wireless communication systems have become required. In wireless communication environments there are some positions where the transmission performance is severely degraded. For instance, an object blocking the transmitted radio wave forms a blind zone and multipath fading causes a local degradation of the propagation characteristics. In general it is difficult to realize high speed and large capacity wireless communications at such places. As one of the improvement methods for these situations, we proposed "Active Propagation Control" (APC), which improves the transmission performance of wireless communications by changing the propagation characteristics of the environment actively so that the transmission performance is improved. Also, we evaluated the improvement of the path loss of a Single-Input Single-Output (SISO) channel and the capacity of a 2×2 Multiple-Input Multiple-Output (MIMO) channel by APC [1, 2]. In the evaluations, we assumed an empty room where a metal plate is rotated to change the propagation characteristics for APC and analyzed the propagation characteristics quantitatively by the two-dimensional Finite Difference Time Domain (FDTD) method. These results represent a fundamental effectiveness of APC. However, since the analysis was in the two-dimensional, they do not show the precise amount of the improvement by APC in a realistic three-dimensional space. In this paper we evaluate indoor propagation characteristics by the three-dimensional FDTD method in order to discuss more accurate amount of the improvement by APC. For the evaluation, we assume an empty room environment where a rotatable metal plate is employed to change the propagation characteristics for APC in the same manner as before. We change the size and position of the metal plate in order to show the effect of the variations on the improvement of APC. In the evaluation, we assume a SISO wireless communication and show the reduction of the path loss by APC quantitatively.

II. Active Propagation Control

Fig. 1 schematically shows the basic concept of APC. The propagation characteristics at the receiver are appropriately configured by a propagation control device, by which characteristics of propagation path can be changed so that the transmission performance becomes better. The configuration of APC is relatively simple as shown in Fig. 1. However, there seem to be many subjects which should be considered to realize APC in actual wireless communications.

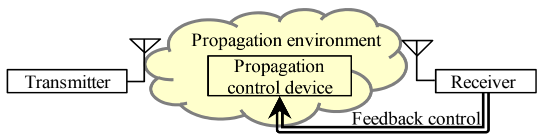


Fig. 1. Basic concept of APC.

A few relating techniques sharing the similar idea to APC have been presented. For instance, it is shown that the MIMO channel capacity can be increased by changing the environment to "multipath-rich" by using a reflect array antenna in an indoor Line-Of-Sight environment [3]. Also, it is reported that the blind spots between the buildings can be eliminated by using a reflect array antenna installed on the roof of a tall building [4]. In addition, it is shown that the degradation of a MIMO transmission performance caused by the key-hole effect can be improved by controlling propagation characteristics using a transmit-array antenna [5]. These results show the effectiveness of changing the propagation environment for enhancement of the transmission performance. On the other hand, Electrically-Steerable Parasitic Array Radiator (ESPAR) antenna has closer principle to APC than the above examples. The ESPAR antenna can control the antenna pattern by changing the reactance of parasitic elements loaded with variable reactor [6]. The principle of ESPAR antenna is similar to that of APC in that the propagation path is optimized without a radiating element. In contrast, we assume APC controls the propagation path itself in a larger-scale actively and appropriately so that the propagation characteristics between the transmitter and receiver are kept better intensively. We expect, for example, that APC performs well when the characteristics are degraded by the movement of a receiver or objects near the receiver in the case without APC. As the result of the assumption, it is desirable that the propagation control device can change a large range of the propagation characteristics. Besides, it is necessary that the receiver stays in the range. Meanwhile we assume feedback control in order to optimize the characteristic at the receiver. The optimization without the feedback control may be possible. However it requires high precise predictions of the propagation characteristics. Such predictions is not realized by currently-available propagation analysis methods. In addition, our purpose in this paper is to evaluate the improvement by APC quantitatively. Based on the above considerations, we assume that ideal optimization is realized in some ways. In other words, we evaluate the upper limit of the quantity of improvement by APC. On the other hand, there are many subjects to realize APC in actual environment as mentioned above and an actual method to realize APC is one of them. We show an example of a control method which can be realized simply and evaluate the improvement when the method is applied.

A. Evaluation Environment and Method

In order to present the improvement of APC we evaluate the changes of the path loss generated by rotating the metal plate in a 3-dimensional indoor environment.

Fig. 2 schematically shows the overview of the assumed indoor environment model and Fig. 3 presents a plane of the model including the transmitting point. The parameters used in the evaluation are summarized in Table 1. In the environment, the propagation characteristics are analyzed by using the 3-dimensional FDTD. The position in the model is expressed by using rectangular coordinates whose origin is at one of the corners of the room as shown in Fig. 2. The environment is a 10m (*x*-axis) × 8m (*y*-axis) × 3m (*z*-axis) closed room. There are no objects such as furniture in the room. In the model we assume concrete walls having 0.2m thickness outside the room. Also, we apply the Mur 1st-order absorbing boundary condition outside the wall in the FDTD calculation. The transmitter is fixed at (1.0, 1.0, 1.5) and transmits a vertical polarization wave which is perpendicular to the *x*-*y* plane. A rotatable square-shaped metal plate whose thickness is 0.1m is placed in the room. We assume the three kinds of the side-length *W*, where *W* is 1.0m, 2.0m, and 2.9m. Moreover, we assume in each case of *W* that the center of the metal plate is located at one of the three points as P_1(3.5, 2.5, 1.5), P_2(5.0, 3.0, 1.5), and P_3(7.0, 4.0, 1.5). They are shown in Fig. 3. The metal plate is set perpendicular to the *x*-*y* plane and rotated on the rotation axis which passes through the center of the metal plate and parallels *z*-axis as shown in Fig. 2. The rotation angle θ is 0° when the square-shaped aspects of the plate are parallel to the *z*-*x* plane and the counter-clockwise rotation is the positive direction as shown in Fig. 3. The assumed carrier frequency is 1.0GHz and the grid size of the FDTD calculation is 0.025m, which corresponds to [wavelength/12]. The receiving points are at all available grid positions of the FDTD analysis in the room. In order to present the improvement by APC, we calculate the path loss in a SISO channel by taking the ratio of the source signal at the transmitting point to the calculated received signals at the receiving points.

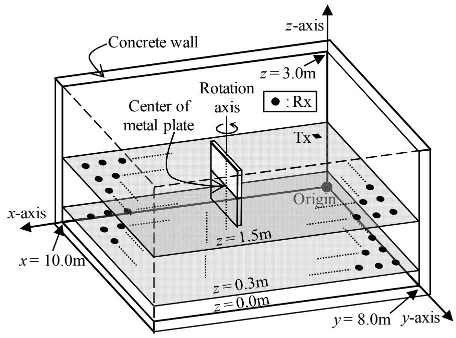


Fig. 2. Overview of assumed indoor environment.

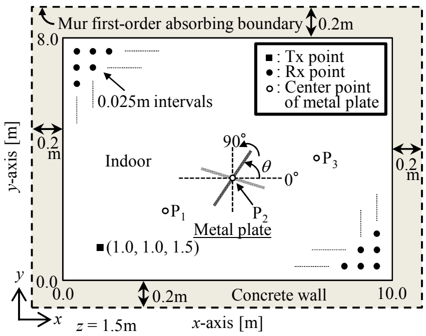


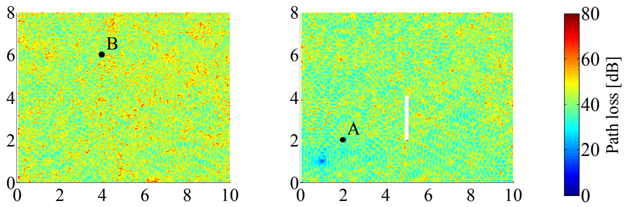
Fig. 3. A view of plane (z = 1.5m) in assumed indoor environment.

TABLE I. PARAMETERS AND ASSUMPTIONS IN EVALUATION

Carrier frequency	1.0GHz
Environment	10m×8m×3m, No objects
FDTD	Cell size : 0.025m (1/12 wavelength) Absorbing boundary condition : Mur 1st-order absorption boundary
Metal plate	Shape : Square Thickness : 0.1m Side-length : 1.0m, 2.0m, 2.9m Center position : P_1(3.5, 2.0, 1.5), P_2(5.0, 3.0, 1.5), P_3(7.0, 4.0, 1.5)
Wall	Thickness : 0.2m Material : Concrete Material parameters of concrete Relative permittivity : 6.76 Conductivity : 0.0023(S/m)

B. Influence of Metal Plate to Propagation Characteristics

We firstly show the propagation characteristics in the room. Fig. 4(a) and Fig. 4(b) show the spatial distribution of the path loss on the planes at z = 0.3m and 1.5m, respectively in the environment shown in Fig. 2. In this evaluation the center of the metal plate is at P_2 and W is 2.0m. In the figures the metal plate θ is fixed to 90°. We can find from Fig. 4 that the random and rugged variations of the path loss appear.



(a) z = 0.3, θ = 90° (b) z = 1.5, θ = 90°

Fig. 4. Spatial distribution of path loss. (Horizontal axes: x coordinate vale [m], vertical axes: y coordinate vale [m])

Fig. 5 shows the variations of the path loss by the metal plate's rotation at two receiving points A(2.0, 2.0, 1.5) and B(4.0, 6.0, 0.3) in Fig. 4(b) and Fig. 4(a), respectively. A is located at a relatively closer position to the transmitting point while B is farther. The center of the metal plate is fixed at P_2 and W is 2.0m. In this figure, θ changes from 0° to 180° with every 1° separation. We can find from the figure the influence of the rotation at A is smaller than that at B. The variation widths at the two points A and B are approximately 18dB and 24dB, respectively. In this paper APC improves the path loss at the receiving point by adjusting the rotation angle of the metal plate to the best one. Note that we assume in the later quantitative evaluation the rotation angle θ giving the smallest path loss is ideally obtained at each receiving point for APC. Unless otherwise noted, the best rotation angle at each receiving point is picked up by calculating the path loss in every case where θ changes every 3° from 0° to 180°.

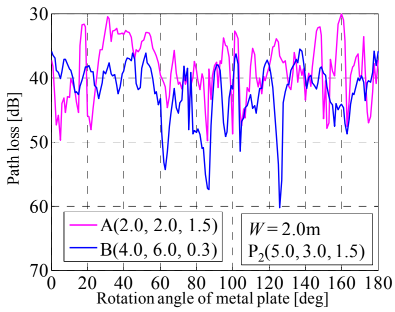


Fig. 5. Variation of path loss when metal plate is rotated.

C. Improvement of Path Loss

Fig. 6 shows the variations of the path loss where the receiving point moves on the line from (8.0, 0.0, 1.5) to (8.0, 8.0, 1.5) straightly in Fig. 4(b). In the figure two results are presented. "w/ APC" shows the path loss where the rotation angle is adjusted so that the path loss at the receiving points becomes the smallest, while "w/o APC" is where the plate angle is fixed to 90°. "w/o APC" in the later also means the same configuration. In the figure we can find that the improvement of the path loss by APC at each receiving point depends on the positions. However, at the most of the receiving points the path loss is significantly improved by APC. Moreover, we can find in the figure that the spatial dependency of the path loss caused by multipath fading is reduced by APC.

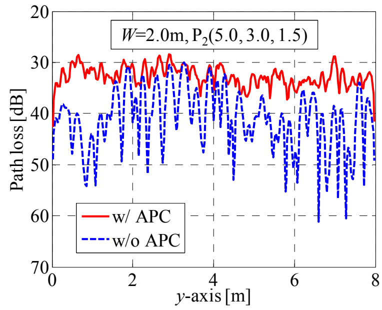


Fig. 6. Variation of path loss with and without APC.

In order to present the improvement by APC quantitatively, we define the difference of the path loss between w/ and w/o APC as the maximum improvement of the path loss. Fig. 7 shows the cumulative distribution function (CDF) of the maximum improvement of the path loss over the whole room. Note that we suppose the assumed receiving points are on the planes where z is from 0.3m to 2.7m with 0.3m separation. Fig. 7(a)-(c) shows CDFs in the case where W = 1.0m, 2.0m, and 2.9m. Also, we assume three cases where the center of the metal plate is located at the three points P_1, P_2, and P_3.

It can be seen from the figure that the largest maximum improvement in total over the whole room among the all cases is obtained where the metal plate having 2.9m side-length is placed at P_2. In this case over 8dB and 16dB of the improvement of the path loss are obtained by APC at 50% and 10% receiving points in the room, respectively. Even in the smallest improvement case, when the metal plate with 1.0m side-length is employed at P_3, over 4dB and 12dB of the improvement at 50% and 10% receiving points are realized by APC, respectively. Also, Fig. 7(a) shows that when the center position of the plate is closer to the transmitter, the more improvement is obtained. In contrast, comparing CDFs of the P_1 and P_2 cases in Fig. 7(b) and Fig. 7(c), the total maximum improvement of the P_2 case is larger than that of the P_1 case in the both figures. That is, it is not always true that the closer to the transmitter the metal plate is, the more improvement we can obtain.

D. Application of More Practical APC

We evaluated the upper limit of the improvement performance by APC assuming that the best rotation angle to achieve the smallest path loss is ideally realized at each receiving point. However, it is difficult to obtain such an optimum solution in an actual environment. In contrast, in order to evaluate the improvement characteristics of more practical APC, now we assume a new scheme where the better rotation angle at each receiving point is chosen among a limited number of rotation angles. We call this scheme "limited angle APC". In this paper, the number is assumed five and the five rotation angles are fixed. They are 0°, 36°, 72°, 108°, and 144°. In limited angle APC (LA-APC), the angle giving the smallest path loss is selected among the five. Note that we assume the process is performed quickly enough compared with the time variations of the propagation characteristics.

Fig. 8 shows CDF of the maximum improvement by LA-APC. In this figure, we pick up two cases where the improvement becomes the largest and smallest among all combinations of W and position of the plate shown in Fig. 7. In the figure, zero improvement case exists for some ratio of the receiving points. It is a case where the rotation angle of w/o APC (90°) is the best over the five angles. It can be seen from the figure that the zero improvement occurs at about 22% and 15% receiving points in the room when the plate having 2.9m side-length is placed at P_2 and the 1.0m plate is at P_1 respectively. In other words, positive improvement values are obtained at other 78% and 85% receiving points in each case. Also, the improvement of over 2.5dB and 5dB is obtained at 50% receiving points in each case.

III. Conclusion

In this paper, we evaluated the improvement of Active Propagation Control (APC) in a three-dimensional indoor environment. We assumed a rotatable metal plate as the propagation control device and evaluated the effect of the variations of the size and position on the improvement of APC. We carried out quantitative evaluations based on the 3-dimensional FDTD method. As a consequence, we can find that over 8dB and 16dB of the improvement of the path loss are obtain by APC at 50% and 10% receiving points in the best of all cases considered in this paper. Also, we evaluated more practical APC where the better rotation angle of the metal plate is chosen among the limited and fixed rotation angles. Consequently, positive improvement is obtained at 85% receiving points in such a case.

In this paper, we assumed APC using a rotatable metal plate. However, the rotation of the metal plate is unsuitable for the control device from the viewpoint of physically interfering with people and furniture. We have to consider more effective and safe ways.

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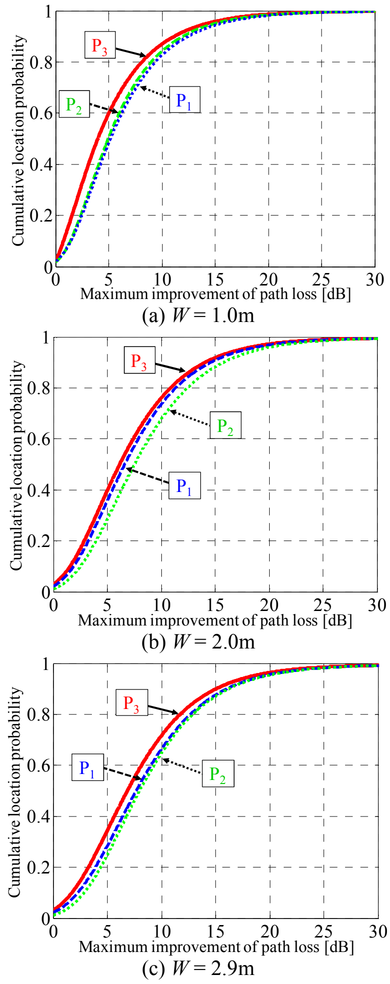

Fig. 7. CDF of maximum improvement of path loss.

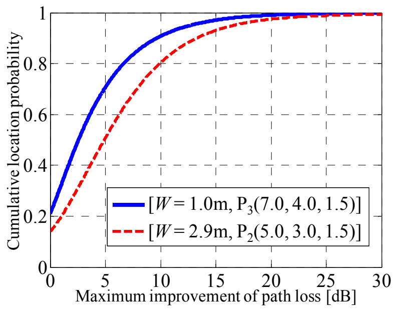

Fig. 8. CDF of maximum improvement of path loss by LA-APC.