MIMO Capacity Expansion Antenna Pattern

Collaboration Projects

Base-station Antenna Pattern Design for Maximizing Average Channel Capacity in Indoor MIMO System

We present an antenna-pattern design method for maximizing average channel capacity for an indoor 2 × 2 MIMO base station using propagation-characteristics analysis based on geometric optics. This research was conducted jointly with the Arai Laboratory (Professor Hiroyuki Arai), Division of Physics, Electrical and Computer Engineering, Graduate School of Engineering, Yokohama National University.

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1. Introduction

Multiple-Input Multiple-Output (MIMO)[*1] multiplex transmission is a scheme for increasing transmission bit rate by transmitting different data over multiple transmit antennas using the same radio resources (time, frequency, code) and by extracting receive signals over multiple receive antennas. The MIMO scheme is currently being adopted in standards such as wireless LAN, Worldwide interoperability for Microwave Access (WiMAX), and Long Term Evolution (LTE) [1]-[3]. The technique to achieve a MIMO multiplex transmission can be broadly divided into two types depending on whether propagation-channel[*2] information is used on the transmit side. These are eigenmode transmission[*3] and space division multiplexing transmission[*4] [4], both of which are being specified into standards. In this article, we deal with the space division multiplexing transmission system considering its relative ease of deployment. Although this system itself includes a variety of demodulation techniques [5], our discussion here examines channel capacity corresponding to ideal demodulation results.

While base stations used in MIMO multiplex transmission generally use omni-directional antennas, it has been reported that transmission characteristics can be improved by using directional antennas [6]. At the same time, antenna patterns capable of improving transmission characteristics depend on the environment where the base station is installed. There have been reports on an improvement effect in transmission characteristics by directional antennas in a specific environment, but no studies have been reported on specific design guidelines for antenna pattern. The recent spread of broadband Internet connections, moreover, has only increased the demand for faster wireless communications particularly in indoor environments such as offices and homes making design guidelines for antenna pattern an important technical issue [7].

In this article, with the aim of establishing a design method for directional antennas in an indoor environment, we present a design method for directional-antenna half-power beam width[*5] and beam direction such that transmission bit rate is maximum with respect to the room's aspect ratio (horizontal to vertical ratio) for an indoor base station in a 2×2 MIMO system. We arrived at this method by applying propagation-characteristics analysis using geometric optics[*6]. This research was conducted jointly with Professor Hiroyuki Arai of Yokohama National University, who is

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[*1] **MIMO**: Wireless communications technology for expanding transmission capacity by using multiple transmit/receive antennas.

[*2] **Propagation channel**: An individual communication path in wireless communications. In this article, a communication path between transmit/receive antennas.

[*3] **Eigenmode transmission**: A MIMO multiple transmission system that transmits signals by arranging the pattern on the transmit side based on propagation-channel information estimated in advance.

[*4] **Space division multiplexing transmission**: A MIMO multiplex transmission system that inputs different data into each antenna element.

an acknowledged leader on the application of directional antennas to MIMO systems.

2. Proposed Antenna Pattern Design Method

2.1 Room Model Used in This Analysis

Figure 1 shows an overhead view of the room used in this study. The room constitutes a cuboid in space measuring 6.0 m wide (x direction), t × 6.0 m deep (y direction), and 2.7 m high (z direction). The walls are assumed to be made of concrete. Here, t represents the room's aspect ratio. As shown in Fig. 1, the base-station antenna unit is placed on one of the walls (zx plane) centered with respect to the x direction. It is fixed 0.2 m from the ceiling and 0.24 m from the wall with the element interval set to 3.0 cm, which is half the wavelength of the 5 GHz carrier frequency. The mobile-station antenna unit is situated at a height of 1.0 m from the floor. This unit can be moved in intervals of 1/6 the room size in either the x or y direction making for a total of 25 measuring points inside the room.

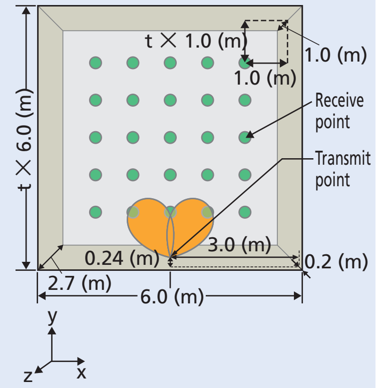


Figure 1 Room model and antenna arrangement (overhead view)

Antenna directivity $D(\theta)$ of each antenna element of the base station assumes the pencil beam[*7] given by equation (1). An isotropic antenna[*8] is used for each antenna element of the mobile station.

$$D(\theta)=\begin{cases}\cos^{\Theta}(\theta) & (0\le\theta\le\pi/2,\ 3\pi/2\le\theta\le 2\pi)\\ \alpha_{F/B}\cos^{\Theta}(\theta) & (\pi/2\le\theta\le 3\pi/2)\end{cases}\qquad(1)$$

$$\Theta=-\frac{\log_{10}2}{\log_{10}\cos(\theta_H/2)}$$

Here, $\alpha_{\mathrm{F/B}}$ represents the reciprocal of the front-to-back (F/B) ratio[*9]. In this article, we assume an ideal antenna with no backward radiation (F/B ratio $=\infty, \alpha_{\mathrm{F/B}}=0$). The symbol θ_{H} indicates half-power beam width of the antenna pattern. In this study, the half-power beam widths of the two transmit elements are the same, and as shown in **Figure 2**, the beam directions of these two elements are symmetrical about the normal to the wall where the base station is installed. Antenna gain can be calculated by equation (2) using the same θ_{H} for half-power beam width for both xy and yz planes [8].

$$Gain = 10\log_{10}\frac{4\pi}{{\theta_H}^2}\qquad(2)$$

Figure 3 shows the pencil-beam pattern calculated from equations (1) and (2) for various half-power beam width values.

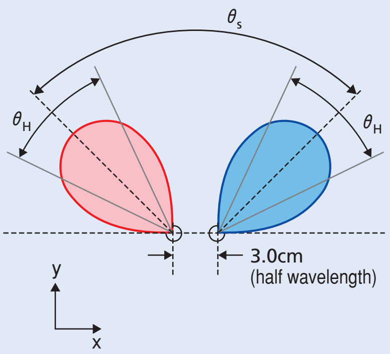


Figure 2 Setting the transmit antenna pattern (half-power beam width and inter-beam angle)

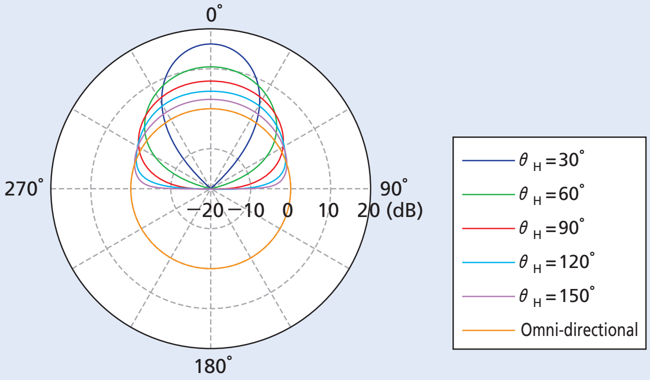


Figure 3 Pencil-beam antenna pattern (horizontal and vertical planes)

[*5] **Half-power beam width**: The angular range from the maximum power emitted from an antenna to the half of that value. Indicates the sharpness of the antenna pattern.

[*6] **Geometric optics**: A technique that handles the propagation of electromagnetic waves as geometrical lines without consideration of their wave properties.

[*7] **Pencil beam**: An antenna pattern that is strong in one direction in three-dimensional space.

[*8] **Isotropic antenna**: An antenna that uniformly radiates an electromagnetic field in all directions, and acts as a criterion when evaluating gain. It is a virtual antenna and does not exist in reality.

We calculated propagation characteristics at each measurement point by propagation-characteristics analysis using geometric optics, and calculated channel capacity C for MIMO multiplex transmission using equation (3) based on the propagation characteristics so obtained. Channel capacity indicates the maximum amount of information that can be transmitted per unit time on a propagation channel of a certain frequency. For a fixed total transmission power, a higher channel capacity means better spectral efficiency enabling high-speed data communications.

$$C=\log_2\left[\det\left[\mathrm{I}+\frac{P_t}{m\sigma^2}\mathrm{HH}^H\right]\right]$$
$$=\sum_{i=1}^{m}\left(1+\log_2\frac{P_t\lambda_i}{m\sigma^2}\right)\ [\text{bit/ s /Hz}] \qquad (3)$$

In equation (3), m indicates the number of base-station antennas (m=2 in this study). The symbol P_t and σ^2 stand for total transmission power and noise power, respectively. H represents the channel matrix*10 and H^H its complex conjugate transpose, λi the ith eigenvalue of channel matrix H, and I a unit matrix. **Table 1** shows basic specifications in propagation-characteristics analysis.

For the above environment and 2 × 2 MIMO space division multiplexing transmission, we investigated the conditions for a base-station antenna pattern having a half-power beam width and inter-beam angle for which average channel capacity is maximum.

2.2 Results of Transmission-characteristics Evaluation

Figure 4 shows the relationship between average channel capacity and maximum beam direction of the base-station antenna pattern for different room aspect ratios. The horizontal axis in the graphs shown represents maximum beam direction in terms of inter-beam angle θ_s. Fig. 4(a) - (c) show results for aspect ratios 0.5, 1 and 2, respectively, with each graph giving results for half-power beam widths 30°, 60°, 90°, 120° and 150° and the omni-directional case (isotropic antennas).

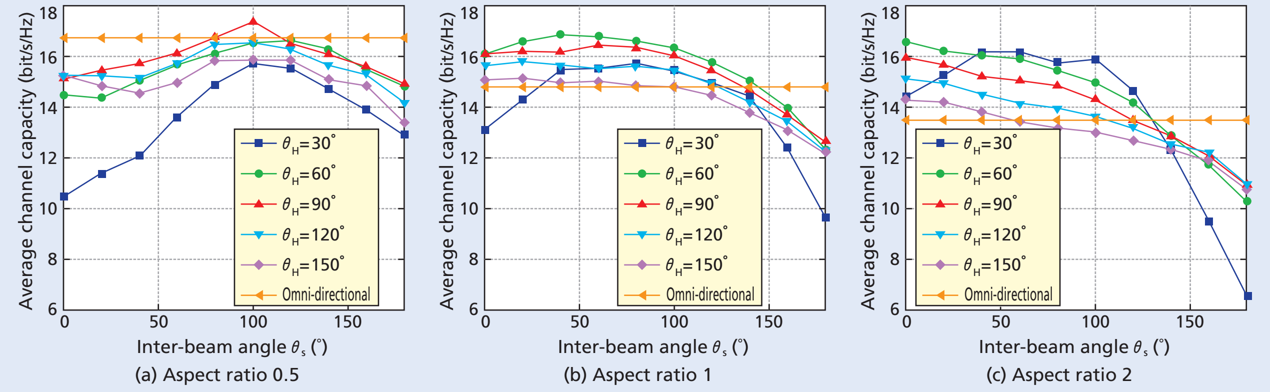
Table 1 Basic specifications of simulation

MIMO	2 × 2
Carrier frequency	5 GHz
Transmit/receive antenna interval	Half-wavelength
Symbol rate	4 Msps
Modulation scheme	QPSK (header)
	16QAM (data)
Transmit power of each antenna	–5 dBm
Noise power	–85 dBm
Channel modeling	Ray-trace method
Wall material	Concrete
Relative permittivity	6.76
Conductivity	0.0023 S/m
No. of reflections (upper limit)	5

QPSK: Quadrature Phase Shift Keying
16QAM: 16 Quadrature Amplitude Modulation
sps: symbol per second

The results of Fig. 4 show that an antenna pattern exists for which average channel capacity is better than that of the omni-directional case regardless of the aspect ratio and that this tends to be particularly true for aspect ratios of 1 and greater.

Figure 5 shows half-power beam width and maximum beam direction maximizing average channel capacity versus room aspect ratio. It can be seen here that half-power beam width maxi-



(a) Aspect ratio 0.5

(b) Aspect ratio 1

(c) Aspect ratio 2

Figure 4 Channel capacity

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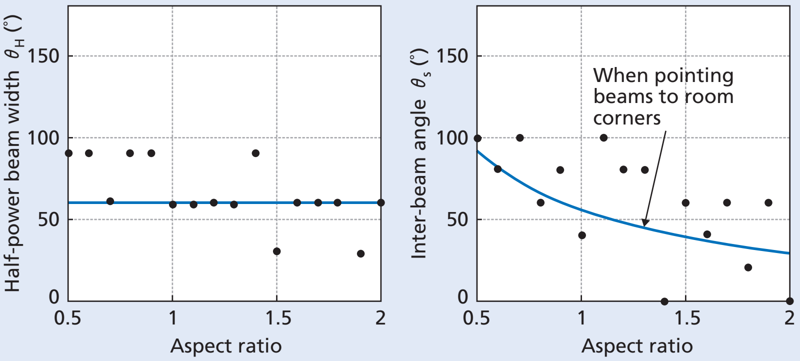
*9 **F/B ratio**: Ratio of power in the antenna's maximum-radiation direction to the maximum value of undesired radiation power in a certain angular range in the opposite direction.

*10 **Channel matrix**: A matrix representing the channel response between transmit/receive antennas. The eigenvalues of the channel matrix affect the receive Signal to Noise Ratio (SNR) of each transmit signal.



(a) Half-power beam width (b) Inter-beam angle

Figure 5 Beam settings maximizing average channel capacity

mizing average channel capacity tends to narrow as the aspect ratio becomes larger eventually becoming a value of about 60°, and that inter-beam angle θ_s likewise tends to narrow as the aspect ratio becomes larger. Figure 5(b) also shows the plot for angle θ_c when pointing the beams to the room corners opposite the base station. This plot exhibits the same decreasing tendency as above. On the basis of these results, we see that average channel capacity can be maximized by setting half-power beam width to 60° and setting the maximum beam direction of each beam to the corresponding room corner.

3. Reasons for Improvement in Transmission Characteristics by Directional Antennas

We consider the main factors behind the improvement in transmission characteristics in a MIMO system through the use of directional antennas at the base station to be an increase in antenna gain and a decrease in spatial correlation[*11].

Among eigenvalues λ_i in equation (3), we define the maximized eigenvalue to be the primary eigenvalue and the next largest one to be the secondary eigenvalue. Now, in an indoor environment in which direct waves exist, the primary eigenvalue will be dominant and larger compared to the secondary eigenvalue [9]. Increasing antenna gain here will have the effect of making the primary eigenvalue larger and improving characteristics.

At the same time, a decrease in spatial correlation by pointing each of the directional antennas in a different direction will have the effect of increasing channel capacity even in the case of a small element interval, which, in the case of omni-directional antennas, would mean an increase in spatial correlation.

In this study, antenna elements were separated by a half-wavelength, a condition under which spatial correlation would be low even if omni-directional antennas were to be used. For this reason, we consider the improvement effect in average channel capacity to be mainly due to increase in antenna gain.

To give an example, **Figure 6** shows the cumulative probability distribution of the primary and secondary eigenvalues for a half-power beam width of 60° and an aspect ratio $t = 2$. These results confirm that the primary eigenvalue is dominant and that its value tends to improve with change in inter-beam angle θ_s.

4. Conclusion

In this article we clarified a base-station antenna-pattern design method that maximizes the average channel capacity with respect to the room's aspect ratio in 2×2 MIMO space division multiplexing transmission by applying propagation-characteristics analysis using geometric optics, assuming an indoor mobile communications environment. It was found that average channel capacity could be maximized

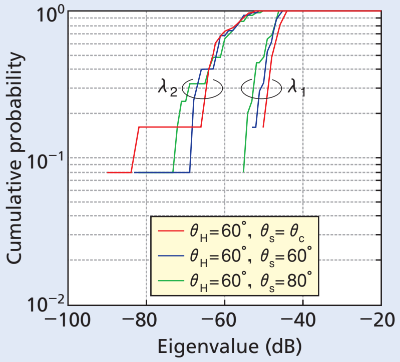


Figure 6 Cumulative probability of eigenvalues

[*11] **Spatial correlation**: Fading correlation between two spatially separated channels. It depends on signal arrival conditions and the positional relationship between the two channels. A higher spatial correlation makes it more difficult to separate signals and reduces MIMO channel capacity.

by setting beam half-power beam width to 60° and the beam direction of each antenna element to room corners on the opposite wall.

In future research, we plan to study systems with a greater number of antenna elements and implementation methods for antennas. We also plan to document the results of our research in base-station antenna design specifications, installation manuals, etc., for use in constructing efficient areas in indoor environments where high-speed mobile communications is expected to diffuse and to apply our study results to business applications.

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