

LETTER

Analyses of Antenna Displacement in Short-Range MIMO Transmission over Millimeter-Wave

Ken HIRAGA^{†a)}, Member, Tomohiro SEKI[†], Kentaro NISHIMORI^{††}, Kenjiro NISHIKAWA[†], Ichihiko TOYODA[†], and Kazuhiro UEHARA[†], Senior Members

SUMMARY Short-range multiple-input and multiple-output (SR-MIMO) has attracted much attention, because the technique makes it possible to raise channel capacity to several hundred Gbit/s by utilizing the millimeter-wave band (e.g., 60 GHz band). Although the opposed transceiving antennas are assumed to be accurately positioned in previous studies regarding SR-MIMO, a very important issue is to evaluate the performance degradation due to displacement between MIMO transceivers. In SR-MIMO over the millimeter-wave band, any displacement is perceived as significant because the wavelength is small. This paper evaluates the influence on SR-MIMO transmission performance over millimeter-wave caused by displacement between the transmitting and receiving antennas. The channel capacity is found to degrade by 5% when the horizontal displacement is 1 mm and by 2.7% when the rotational displacement is 10 degrees. In addition, comparing performances obtained with a number of antenna array arrangements clarifies that a square pattern arrangement is suitable for short-range wireless transmission.

key words: short-range, MIMO, millimeter-wave, antennas, parallel transmission

1. Introduction

Recently, higher transmission speeds such as several Gbit/s are needed to support high definition images and video services. For such applications, the millimeter-wave band can be used since wide bandwidth is available. In particular, since the 60 GHz band has more unlicensed bands than other millimeter-wave bands; it is widely used for consumer wireless devices [1]. Although high signal-to-noise power ratio (SNR) is guaranteed in short-range communications, the transmission rate is saturated due to the limitations placed on modulation scheme level. To address this issue, multiple-input and multiple-output (MIMO) systems have been gathering much attention because they can increase the data rate without expanding the frequency bandwidth through the use of multiple antennas at the transmitter and receiver [2]. The use of a short-range MIMO (SR-MIMO) system with multiple data streams between the arrayed antennas is an effective transmission technique [3], [4]. Moreover, it has been shown that the channel capacity based on the optimal element spacing conditions in SR-MIMO exceeds the Ergodic capacity of the independent and identically distributed

(i.i.d.) channel when the same SNR conditions are assumed between the propagation channel of SR-MIMO and i.i.d. channels [4], [5]. In SR-MIMO over the millimeter-wave band, major displacement between the transmitting and receiving antennas is likely to occur because the wavelength is small. However, previous studies have not clarified the degree to which transmission rate performance degrades due to the displacement between MIMO transceivers. In this paper, we evaluate the influence on the SR-MIMO transmission performance over millimeter-wave band exerted by the displacement between the transmitting and receiving antennas. We also clarify the antenna arrangement suitable for SR-MIMO transmission when assuming such displacement.

The rest of the paper is organized as follows. Section 2 introduces the motivation and applications of this study and the basic characteristics of SR-MIMO transmission. The channel capacity with displacement between the transmitting and receiving antennas is shown in Sect. 3. Performances obtained with a number of antenna array arrangements are compared in Sect. 4.

2. Target Scenario and Basic Characteristics of SR-MIMO over Millimeter-Wave

SR-MIMO transmission over millimeter-wave is suitable for the application of short-range and ultra-high-speed data transmission using portable devices as shown in Fig. 1 because high-speed transmission and antenna array miniaturization can be achieved at the same time. Such systems can upload/download large-size movie or music files by putting the portable device close to the download kiosk or PC. Though a transmission speed of several Gbit/s is provided in IEEE802.15.3c for short-range transmission applications [6], more research on further high-speed transmission technology is needed, considering the larger file size of

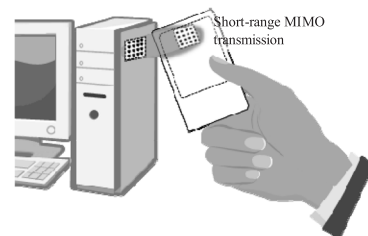


Fig. 1 Application of SR-MIMO over millimeter-wave band.

Manuscript received January 20, 2011.

Manuscript revised May 24, 2011.

[†]The authors are with NTT Network Innovation Laboratories, NTT Corporation, Yokosuka-shi, 239-0847 Japan.

^{††}The author is with Faculty of Engineering, Niigata University, Niigata-shi, 950-2181 Japan.

a) E-mail: hiraga.ken@lab.ntt.co.jp

DOI: 10.1587/transcom.E94.B.2891

contents that will be seen in the near future. The position of the opposed transceiving antennas is important to form the transmission path to obtain a high channel capacity when SR-MIMO transmission is performed. Since users adjust the portable terminal's position manually, the antenna's positional precision is limited. In the millimeter-wave band, degradation caused by the displacement is larger than that in the microwave band because of the shorter wavelength. In SR-MIMO transmission over millimeter-wave, therefore, the influence exerted on the channel capacity by displacement between antenna arrays should be analyzed quantitatively.

For the work described in this paper, channel capacity C is calculated using the following equation:

$$C = \log_2 \det \left(\mathbf{I} + \frac{P_s}{\sigma^2 M} \mathbf{H} \mathbf{H}^H \right) \quad (1)$$

where \mathbf{I} and \mathbf{H} denote the unit matrix ($M \times M$ matrix, M : the number of antenna elements) and the channel matrix, respectively, P_s is total transmission power at the transmitter, and σ^2 is noise power at the receiver side. When the same transmitting power at each antenna element is assumed, maximum channel capacity is calculated by using Eq. (1) whether the channel information is known or unknown at the transmitter [7]. The transmission characteristics between the transmitting and receiving antenna elements are calculated as S-parameters by electromagnetic field simulation. This simulation was performed at 60 GHz using the method of moments as described in [8]. The S-parameters are then converted to the channel matrix. The channel capacity is calculated from the transmission characteristics by using Eq. (1).

Figure 2 shows the analysis model used to investigate the performances of SR-MIMO over millimeter-wave. In the model, the distance between the transmitting (TX) and receiving (RX) antenna arrays is D . Total transmission power at the transmitter P_s is 20 dBm, noise power at the receiver σ^2 is -30 dBm. Antenna elements for both arrays are arranged in the same square pattern with element spacing d and M is the number of antenna elements for both arrays. The arrays are formed on dielectric substrates of a finite size whose thickness is 0.2 mm and the dielectric constant ϵ_r is 2.6. The analysis includes the effects of the coupling between TX and RX antenna elements, the effects of the mutual coupling between elements in the same array, and the effects of the edge of a dielectric substrate. The elements formed on the dielectric substrate are rectangular microstrip antennas $1.44 \text{ mm} \times 1.44 \text{ mm}$ in size.

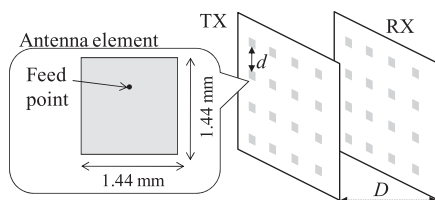


Fig. 2 Analysis model.

Figure 3 shows the calculated relationship between transmission distance D and channel capacity. Here, M is 16. In SR-MIMO transmission, as d increases the received power decreases and therefore SNR also decreases. On the other hand, the spatial correlation rises as d decreases [4]. Therefore, there is optimum element spacing where the channel capacity is the maximum. The dotted line in the figure shows the channel capacity with d of 2.5 mm (half wavelength) and the solid line shows the channel capacity with optimum element spacing, d_{opt} . With D of 1 mm, the channel capacity is 192 bit/s/Hz. Thus, transmission of several hundred Gbit/s is possible in the 60 GHz band, which has wide (around 2 GHz) bandwidth.

Figure 4 shows the calculated relation between M and channel capacity at $D=1$ mm. Here, the element spacing is fixed at $d = 2.5 \text{ mm} = 0.5\lambda_0$. The solid line shows the channel capacity of SR-MIMO transmission. As M increases, the number of data streams also increases and consequently the channel capacity becomes large. To compare the channel capacity of SR-MIMO transmission with that in usual MIMO transmission, it also plots the channel capacity of an i.i.d. channel in which each path between the TX and RX antenna elements is independently Rayleigh-distributed. The elements of the i.i.d. channel matrix are zero-mean and unit-variance complex Gaussian random variables. To perform fair comparison of these channels, the pathloss is given for i.i.d. channel so that the average received SNR in the i.i.d. channel is the same as that in SR-MIMO transmission. In both cases, total transmission power at the transmitter P_s is 20 dBm, noise power at the receiver σ^2 is -30 dBm. The channel capacity of SR-MIMO is higher than that of the i.i.d. channel. As the figure shows, the channel capacity for SR-MIMO increases almost in proportion to M when

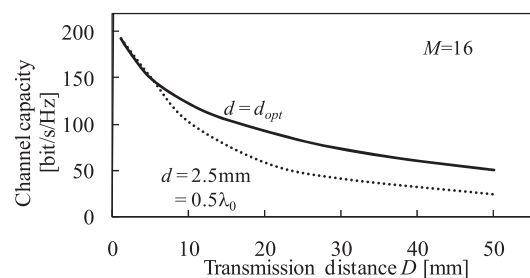


Fig. 3 Relationship of channel capacity to transmission distance D .

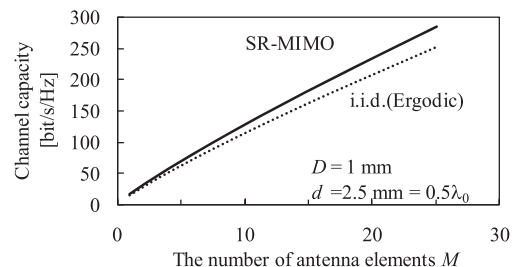


Fig. 4 Relationship of channel capacity to number of antenna elements M .

$D=1$ mm.

3. The Influence of Positional Precision of the Antenna

To investigate the influence of the displacement between transceiver antennas, electromagnetic field analyses were performed using the models shown in Fig. 5. In these models, the distance between the TX and RX antenna arrays is D . The elements for both arrays are arranged in the same square pattern with element spacing $d = 0.5 \lambda_0$ and the

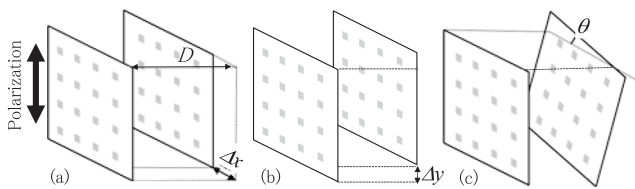
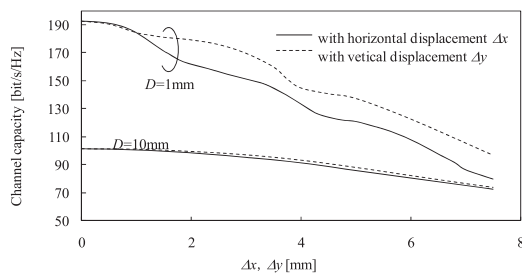
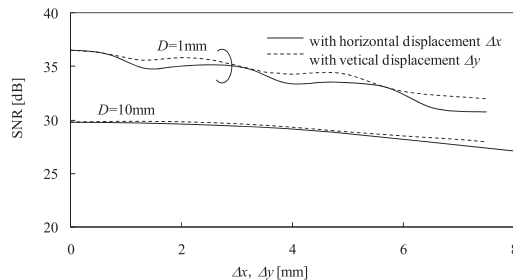


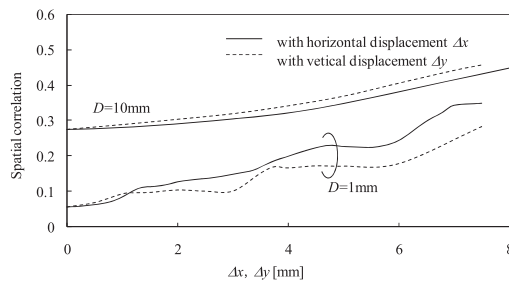
Fig. 5 Analysis model. (a) Horizontal displacement, (b) vertical displacement, and (c) rotational displacement.



(a) Channel capacity



(b) SNR

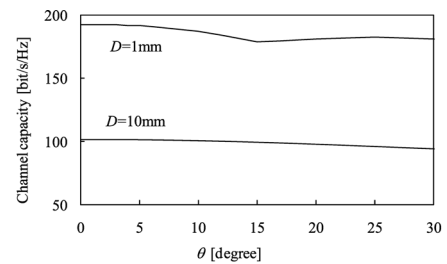


(c) Spatial correlation

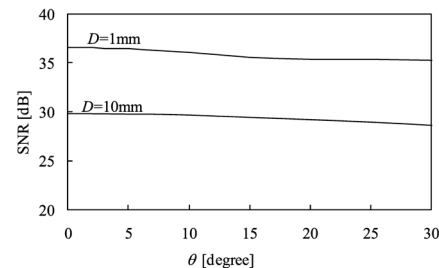
Fig. 6 Relationship to vertical/horizontal antenna displacement.

number of TX and RX antenna elements M is 16. The elements are the same as those shown in Fig. 2. The array size is 10 mm^2 . Three types of antenna displacement situations were modeled: (a) horizontal displacement Δx , (b) vertical displacement Δy , and (c) rotational displacement θ . The vertical arrow in the figure indicates the polarization direction. The electromagnetic field analysis was performed at 60 GHz using the method of moments. Other conditions are the same as in the analysis presented in Sect. 2.

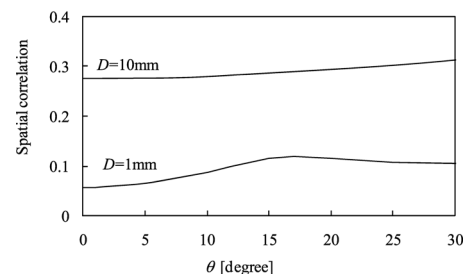
Figure 6 shows the influence of Δx and Δy on the channel capacity. In this figure, we can see that the channel capacity decreases as the displacement increases. When the displacement increases, SNR decreases mainly because the total transmission distance between TX and RX antenna elements increases and the transmission loss becomes larger. Moreover, the spatial correlation increases because the differences between each path length become small. In SR-MIMO, which cannot utilize a multipath environment, spatial correlation increases because the phase differences between each path become small when the differences between each path length become small. Consequently, channel capacity decreases. At D of 10 mm, the influence of displacement is smaller than in the case of $D=1$ mm. This is because



(a) Channel capacity



(b) SNR



(c) Spatial correlation

Fig. 7 Relationship to rotational antenna displacement.

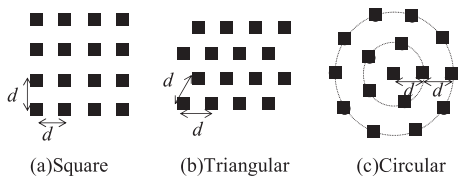


Fig. 8 Antenna arrangements. ($M=16$)

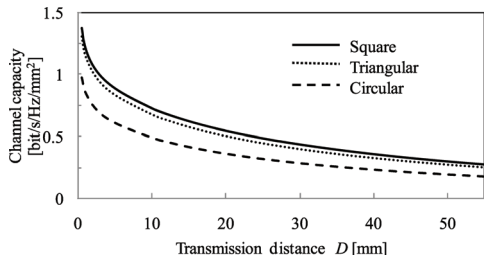


Fig. 9 Relationship of channel capacity to antenna arrangements vs. transmission distance D . ($d=2.5\text{ mm}=0.5\lambda_0$)

the amount of change in the transmission route by displacement is relatively small when D is long. For $D=1\text{ mm}$, the channel capacity decreases by 5% at $\Delta x=1\text{ mm}$, and similarly decreases at $\Delta y=1\text{ mm}$. When Δx and Δy are larger than 1 mm, the influence of the former is larger than that of the latter. In the case of far-field transmission, the influence of Δy must be larger than that of Δx because we assume the polarization of the antenna is vertical in this analysis model. However, the influence of Δy is smaller than that of Δx in this analysis.

Figure 7 shows the influence of rotational antenna displacement θ . Channel capacity decreases as θ increases, because SNR decreases and spatial correlation increases. The channel capacity degradation is 2.7% at $\theta=10$ degrees for D of both 1 mm and 10 mm. The channel capacity degradation caused by θ is gradual.

4. Performance Comparison of The Antenna Array Arrangements

In applications such as that shown in Fig. 1, it is practical to arrange antenna elements on the same plane. In the technical field of adaptive antenna arrays, a variety of antenna arrangements has been examined [9]. The methods considered for arranging the elements on a planar antenna array include the (a) square pattern, (b) triangular pattern, and (c) concentric circle pattern arrangements shown in Fig. 8. In our microwave-band studies [4], [5], only (a) was modeled and other arrangements were not studied. Therefore, a concrete comparison with other arranging methods should be performed. In this work, we analyzed and compared channel capacity performances for three antenna element arrangements. The interelement spacing d is 2.5 mm ($=0.5\lambda_0$), the number of elements M is 16, and other conditions are the same as in the analysis presented above.

Figure 9 shows the relationship between channel capacity C and transmission distance D for the three antenna

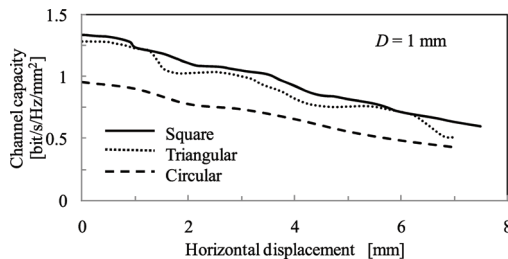


Fig. 10 Relationship of channel capacity to antenna arrangements with horizontal displacement.

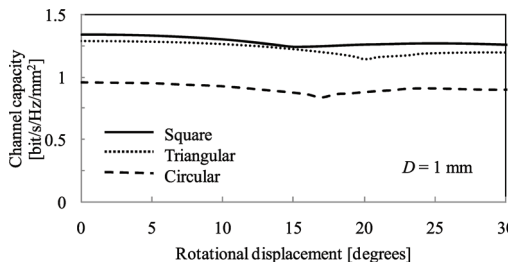


Fig. 11 Relationship of channel capacity to antenna arrangements with rotational displacement.

arrangements. Figures 10 and 11 show the influence of horizontal displacement and rotational displacement respectively when D is 1 mm. Since each arrangement has a different aperture size, channel capacities per mm^2 are compared. No large difference is seen in the performances of these three arrangements. Therefore, it can be concluded that the square pattern antenna arrangement is suitable for the applications shown in Fig. 1.

5. Conclusion

In this paper we clarified the influence of an antenna's positional precision on performance, which is an important factor in SR-MIMO systems. Performance degradation due to horizontal, vertical, and rotational antenna displacement was analyzed for vertical polarization antennas. The channel capacity for a transmission distance of 10 mm degraded by 5% when the horizontal displacement was 1 mm and by 2.7% when the rotational displacement was 10 degrees. By analyzing performances for three kinds of antenna array arrangements, we confirmed that a square pattern antenna arrangement is suitable because of its simple structure.

References

- [1] J.M. Gilbert, et al., "A 4-Gbps uncompressed wireless HD A/V transceiver chipset," *IEEE Micro*, vol.28, no.2, pp.56-64, March-April 2008.
- [2] D. Gesbert, et al., "From theory to practice: an overview of MIMO space-time coded wireless systems," *IEEE J. Sel. Areas Commun.*, vol.21, no.3, pp.281-302, April 2003.
- [3] I. Sarris and A.R. Nix, "Design and performance assessment of high-capacity MIMO architectures in the presence of a line-of-sight component," *IEEE Trans. Veh. Technol.*, vol.56, no.4, pp.2194-2202, July 2007.

- [4] N. Honma, K. Nishimori, T. Seki, and M. Mizoguchi, "Short range MIMO communication," 3rd European Conference on Antennas and Propagation (EuCAP 2009), Wed-S21J4-5 in CD-ROM, March 2009.
- [5] K. Nishimori, T. Seki, K. Hiraga, and N. Honma, "Experimental evaluation in short range MIMO communication with simple transmission scheme," Proc. IEEE Antenna & Propagation symposium, (AP-S), Session 401.8 in CD-ROM, July 2010.
- [6] A. Sadri, "Summary of the usage models for 802.15.3c," IEEE802.15.3c WPAN Task Group <http://www.ieee802.org/15/pub/TG3c.html>, Nov. 2006.
- [7] T. Ohgane, T. Nishimura, and Y. Ogawa, "Applications of space division multiplexing and those performance in a MIMO channel," IEICE Trans. Commun., vol.E88-B, no.5, pp.1843–1851, May 2005.
- [8] <http://www.zeland.com/ie3d.htm>
- [9] K. Hirata, S. Matsuda, K. Nishizawa, H. Miyashita, and T. Numazaki, "Antenna arrangement method for the suppression of grating lobes of the distributed array antenna," IEICE Technical Report, A-P2005-15, May 2005.
-