Channel Capacity Evaluation for Urban MIMO Systems Using Path Visibility

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ABSTRACT

Multiple-Input Multiple-Output (MIMO) and Multi-User MIMO (MU-MIMO) systems are expected to improve the channel capacity over the limited bandwidth of existing wireless communication networks. The effects on the channel capacity characteristics of Single-User MIMO (SU-MIMO) systems in urban scenarios have been previously studied. In this paper, we first clarify that the larger number of antennas cannot contribute the improvement in the channel capacity in urban SU-MIMO scenarios due to the very high spatial correlation. Next, we focus on the MU-MIMO transmission because it can discriminate multiple users by the difference of Angle of Arrival (AOA). We compare the Multi Access Channel (MAC) capacity in the uplink to the capacity in SU-MIMO by considering the same total numbers of transmitting and receiving antennas between SU-MIMO and MU-MIMO. When the same numbers of the antenna elements are used, the better performance is obtained by urban MU-MIMO systems, unlike in the identical independent distributed (iid) scenarios which are generally assumed in MIMO transmission. Finally, the parameter called path visibility introduced in our previous study is playing an important role once again. It is defined as the probability that the direct wave can be received at the receiving antenna and has been used to determine the channel capacity characteristics and provide guidance in determining the appropriate range for the base station (BS) installation in urban SU-MIMO scenarios. In this study, we clarify that only this single parameter, *path visibility*, can also be used to determine the improvement in the channel capacity by MU-MIMO in urban scenarios, while both of SNR and spatial correlation must be considered as the indicative parameters on the performance of SU/MU-MIMO in conventional studies.

Keywords: MIMO, Channel Capacity, Urban Area, Multi-User Transmission, Path Visibility

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1. INTRODUCTION

Many studies have concluded that the MIMO wireless communication architecture is promising as an approach to achieve high bandwidth efficiency [1]-[4]. The channel capacity in future wireless networks can be improved by the potential of this advanced communication technology. However, the performance of MIMO wireless communication depends heavily on the propagation environment [5]-[7]. In outdoor wireless communications, the propagation environment becomes very complex because the height of the antennas among the surrounding buildings and the building height distribution itself in each urban area are different. The signal paths, especially the Line-of-Sight (LOS) between the transmitting antenna and respective receiving antenna, change according to the city environments [6]-[10].

Hence, we first prepare a building model, in order to determine the urban propagation characteristics between the transmitting and receiving arrays. Then, a ray-launching simulation is employed as a ray-tracing scheme, in order to evaluate the channel capacity in urban MIMO systems. This method can be used to estimate various propagation characteristics such as a complex electric field, the delay and angular profiles of emitted/arriving radio waves. The simulations based on these methods have been applied to the study of wireless communications for path-loss prediction as well as multipath characteristic prediction [11]-[15]. Moreover, concerning MIMO systems, ray-tracing models have been recently developed [16], [17] and have shown good agreement with measured channel characteristics [18], [19]. The ray-tracing simulation in MIMO systems is generally employed, in order to validate the effectiveness of measured results, because site specific problems might exist in measured results [18]. On the other hand, a building model is constructed case-by-case from the building height distribution generated using geographical data [20], and the channel capacity in

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urban MIMO scenarios can be obtained by employing this building model. To the best knowledge of the authors, there is no report in literature that uses a representative building model that is constructed from reasonable statistical parameters such as the building height distribution [20], the density of buildings [21], and the street width [22], as we use in this study. Hence, our building model can represent a statistical distribution of actual outdoor environment. Furthermore, with these simulations, all pertinent parameters, such as the building height distribution, BS height, mobile terminal (MT) location, and ray trajectory can be tightly controlled. The simulations can also be repeated to gain a statistical description of system performance in different scenarios.

The performance of urban SU-MIMO in terms of the channel capacity characteristics has been previously evaluated [10]. It has been shown that the channel capacity of urban SU-MIMO is improved by employing the EMTS (EigenMode Transmission System) algorithm as the MIMO transmission. The parameter "path visibility," which is the probability that the direct wave can be received at the receiving antenna or that a LOS exists, has been introduced therein. It has been clarified that the optimal capacity in urban SU-MIMO can be determined by only this single parameter. We also indicated that, at the optimal path visibility when considering 4×4 MIMO-EMTS transmission, the channel capacity is maximized because the appropriate combination of SNR and spatial correlation can be obtained.

In this paper, further evaluation concerning the antenna configurations is considered because such parameters affect the hardware scale in MIMO systems. Furthermore, the channel capacity in outdoor scenarios is compared to that in the iid scenarios which generally are the representative models in MIMO systems. Although the channel capacity of the iid channels is improved in proportion to the numbers of transmitting and receiving antennas, we clarify that it is different in urban MIMO scenarios where the channel capacity is not improved even if the numbers of antennas are increased. This occurs due to the high spatial correlation in outdoor scenarios compared to that in the indoor ones.

The Space Division Multiple Access (SDMA) transmission in urban propagation environment has been introduced to represent the total capacity in wireless communications [23]. When considering the uplink scenarios, the SDMA can discriminate multiple users by the *difference of AOA (AOA-diff)*, which is defined as the difference of the angle at which the signal from each MT arrives at the BS. The performance of urban SDMA in terms of the Signal-to-Interference-plus-Noise Ratio (SINR) has been studied only in the case that each MT is composed of single antenna element [24], [25]. For each user in such a system, the Single-Input Multiple-Output (SIMO) channel is generated, and the capacity is generally determined by the minimum number of antennas between the transmitting and receiving antennas. Hence, the capacity in such a SIMO channel is determined by the single transmitting antenna [24], [25]. In order to further improve the channel capacity in urban wireless communication systems, we introduce the multiple antennas at each MT herein, i.e., the MU-MIMO transmission is considered.

Furthermore, we focus on the uplink scenarios in which the MT and BS are performing as the transmitting and receiving antennas, respectively. In such scenarios, the analysis of channel is commonly referred to the Multi Access Channel (MAC) [26]. The MAC capacity (C_{MAC}) is considered as the total channel capacity at which the BS antenna can receive from the MT antennas moving in the propagation area. Then, we compare the CMAC to the capacity in SU-MIMO by considering the same total numbers of transmitting and receiving antennas between SU-MIMO and MU-MIMO. When the same numbers of antenna elements are used, the better performance is obtained in urban MU-MIMO scenarios, unlike in the iid ones which are generally used in MIMO transmission. Although we have clarified that the path visibility can be used as the performance index in SU-MIMO [10], this parameter is playing an important role once again in this paper. We clarify that, by only this single parameter, "path visibility," the improvement in the channel capacity by MU-MIMO in urban scenarios can be determined.

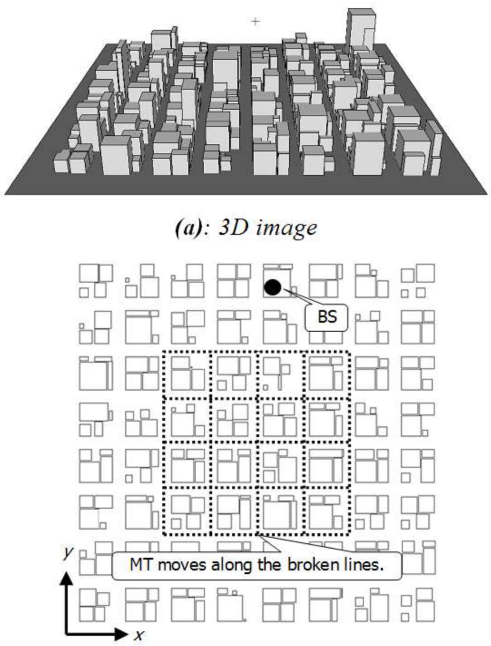
The rest of this paper is constructed as follows. First, all the analysis models such as the urban propagation model, the distribution of the building height and width, and the evaluation methods of the SNR, channel capacity, spatial correlation, and path visibility are respectively described in Section 2. The performance of urban SU-MIMO systems is then studied. The effects of the MT and BS antenna configurations on the channel capacity characteristics are then discussed in Section 3. After that, the effects of model configurations and path visibility on the characteristics of the spatial correlation between users and channel capacity of urban MU-MIMO systems are evaluated in Section 4. Finally, the contribution of this paper is given in Section 5.

2. ANALYSIS MODEL

2.1 Urban Propagation Model

The urban propagation model is simulated by a ray-tracing method, including the characteristics and the locations of the transmitting and receiving antenna arrays. The downtown area of an idealized large city is considered in this study. It is represented as an urban propagation model in Fig. 1. In reality, the city blocks in the downtown area differ in size, but typically there are 20 square city blocks per mile (≈12 per km) [21]. Since the entire space of the model covers the area of 640 m×640 m, the model is formed of 8×8=64 blocks of 50 m×50 m. Each block consists of four buildings. Since the standard width of the street including the sidewalk studied in [22] is approximately 65 ft (19.5 m), the street width herein is set to 20 m. The buildings are assumed to be constructed of concrete and the relative dielectric constant and conductivity are set to 5 and 0.01 S/m, respectively. We note that the simulated models determined from these reasonable statistical parameters can be considered as a representative model of actual outdoor environment. Hence, the characteristics of the Signal-to-Noise Ratio (SNR), channel capacity, spatial correlation, and path visibility, obtained in this study can be applied to the evaluation of MIMO systems in actual propagation environment.

The uplink scenarios are considered throughout this study. The MT and BS antennas are respectively performing as the transmitting and receiving antennas. In Section 3, the $M \times N$ SU-MIMO systems are considered. This means that the MT and BS antennas respectively consist of M and N elements. In Section 4, the $(M_1+M_2)\times N$ MU-MIMO systems are considered. In this case, the characters M_1 and M_2 represent the numbers of elements of the first and second MT antennas, respectively. It is noted that M_1+M_2 is supposed to be not greater than N.



(a): 3D image

(b): Top-view image

Fig.1: *Urban propagation model.*

In some actual cellular environments in which the effectiveness of an adaptive array was evaluated, the element spacing is narrowly set at a half wavelength ($\lambda/2$) even when a 4-element array antenna is used [27]. As a general understanding, MIMO and adaptive arrays need more than two antenna elements while only two antennas are generally used for space diversity in cellular systems, it is difficult to establish array antennas with a wide element spacing in such limited space. It has been shown that wider antenna spacing at the BS does not improve the channel capacity of urban MIMO systems [28], and compact multi-antenna terminals with closely spaced antenna elements are practical [29]. Hence, the element spacing at the BS and MT arrays herein is set to a half wavelength. For the BS, a linear array is employed. It is located at the top of a building on one side of the model as shown in Fig. 1(b). Since an accurate reflection or diffraction cannot be obtained at the edge of the analysis model in Fig. 1, the MT is assumed to move on the street in the area of 280 m×280 m around the center of the model along the broken lines in Fig. 1(b) at the height of 1.5 m. The MT antennas are set in a symmetrical array depending on their numbers of elements.

In this study, the carrier frequency is set to 3 GHz. A ray-launching method is employed as the ray-tracing scheme. To obtain the reflecting points for the diffraction, an image method is used. The numbers of reflections and diffractions considered in all simulations are up to 30 and 2, respectively. The average building heights of 20 m to 40 m are considered throughout this study as the representative cases of a downtown area.

2.2 Distribution of Building Height and Width

Different studies have assumed various building height distributions from uniform and random distributions [30] to the Rayleigh distribution [20]. However, the building height distribution taken from geographical data in [20] can be better fitted by a chi-square distribution. Hence, the chi-square is employed to assume the building height distribution in this study. The minimum height of these buildings, h_{min}, is set to 4 m. The height of the building, h, can be expressed by [31], [32]

$$h = h_0(x^2(k)) + h_{min}, \tag{1}$$

where $x^2(k)$ is the chi-square distribution with k degrees of freedom (DOF) which is set to 5 herein. The term h_0 denotes the scaling parameter which can be obtained when the average building height, h_{AVG}, is set, as

$$h = (h_{AVG} - h_{min})/k \tag{2}$$

The width of each building, w_m, can be determined from its height using [31]

$$w_m = w_0(1 - \alpha \cdot \exp(-\beta h)), \tag{3}$$

where w_0 is 55 m, α is 1.1, and β is -0.025 m^{-1}. These values are considered applicable to universal cases [31]. We note that the total number of buildings in each simulated model is 64×4=256 buildings. Each of four buildings is packed one-by-one into each street block. The first building (the bottom left square in each block in Fig. 1(b)) is packed into the block with its full width. However, for the three remaining buildings, to refrain from exceeding the margin of the block (50 m×50 m), their widths may need to be decreased so that they fit (three other squares/rectangles in each block in Fig. 1(b)).

Figure 2 shows the building height distribution when h_{AVG} is set to 30 m. The grey bar graph shows an example of the distribution of h of the model, and the solid line shows the distribution of the average of h of 20 different models, which approaches the chi-square distribution (dashed line) corresponding to Eq.(1). An acceptable building height distribution can be obtained when this number of models is considered. Although the accuracy is improved when the trial number of models is increased, the simulation time is relatively increased. Hence, the number of 20 different models is selected for use throughout this study. The deviation in the building height as well as other statistical data can be calculated from the basic characteristics of the chi-square distribution.

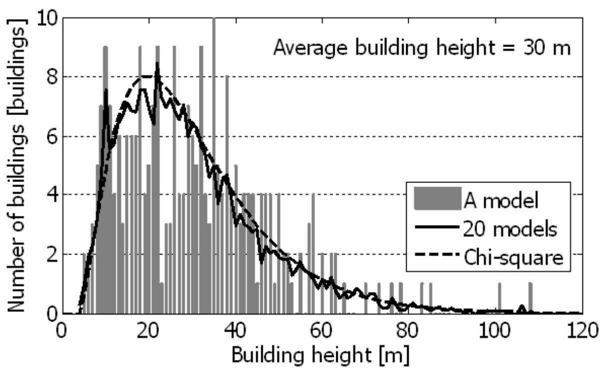


Fig.2: *Building height distribution.*

2.3 Evaluation Method

The relationships among the path visibility, SNR, channel capacity, and spatial correlation, are considered throughout this study. The definitions of these parameters are first introduced in this section.

2.3.1 Signal-to-Noise Ratio (SNR)

The channel response matrices are obtained from the complex received voltage matrices, which are calculated at intervals of 14 m in length along the broken lines in Fig. 1(b). This means that the number of calculated points in each model is 185. When the numbers of transmitting and receiving antennas are M and N, respectively, the channel response matrix, $\mathbf{H}$, can be expressed by [33]

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1} & h_{N2} & \cdots & h_{NM} \end{bmatrix}. \tag{4}$$

When σ^2 denotes the power of additive complex Gaussian noise, the average SNR at each receiving antenna, γ_0, of the receiving array can be calculated from $\mathbf{H}$'s elements by [34]

$$\gamma_0 = \frac{\sum_{N-1}^{N}\sum_{M-1}^{M}|h_{nm}|^2}{NN\sigma^2} \tag{5}$$

2.3.2 Channel Capacity

A. **SU-MIMO Systems**

In this paper, the uplink scenarios are considered. It is assumed that the Channel State Information (CSI) between the transmitting and receiving antennas is not known by the transmitting antenna. In such a case, the channel capacity of SU-MIMO can be obtained in units of bit/second/Hertz (bps/Hz) using [34]

$$C = \log_2 \det[\mathbf{I} + \gamma_\mathbf{0}\mathbf{H}\mathbf{H}^H]. \tag{6}$$

The upper subscript H denotes the Hermite-transpose, and $\mathbf{I}$ denotes the identity matrix. The channel response matrices are determined from the matrices of amplitude and phase of the received signal at each receiving antenna from each transmitting antenna, and obtained by tracing the ray into the propagation model. The channel capacity is then obtained by deriving the average SNR. Here, the transmission power is set at a value that would yield the SNR of 20 dB for the transmission distance of 400 m over a free space connection.

To evaluate the performance of the systems statistically, the cumulative probability (Cumulative Density Function or CDF) is considered. In order to obtain reliable results, the propagation characteristics between the MT and BS antennas are simulated in 20 different urban propagation models for each setting. This means that the CDF of the channel capacity is calculated from the total number of 185×20=3,700 different channel response matrices. This number of models is considered in Section 2.2 and it is adequate to give an accurate value of channel capacity of the evaluated systems.

B. **MU-MIMO Systems**

In the cases of MU-MIMO, two MTs are assumed to move independently along the broken lines in Fig. 1(b). For each paired location of these MTs, we obtain the channel matrix from the simulation. The channel capacity is then calculated using this channel matrix. In order to evaluate the statistical performance, we evaluate the channel capacities of different paired locations of the MT_1 and MT_2.

When considering the uplink scenarios, the analysis of the channel is commonly referred to the MAC

[26]. The MAC capacity (C_{MAC}) is considered as the total channel capacity at which the BS antenna can receive from the MTs moving in the propagation area. In such a MAC, the BS can estimate all the CSIs from the transmitting antennas. In the cases of 2-user MIMO systems evaluated in Section 4, this C_{MAC} can be obtained by the substitution of the combined CSI ($\mathbf{H_{MAC}}$) into (6). This means that the number of calculated cases is 185?185=34,225 for each model, and the CDF of the channel capacity is calculated from the total number of 34,225×20= 684,500 different channel response matrices for each setting. For example, in the cases of (2+2)×4, the CSI of the MAC is the combination of the CSIs of two MTs as shown in Fig. 3.

2.3.3 Spatial Correlation

Since the spatial correlation has played an important role in the evaluation of urban SU-MIMO [10], its effect can be applied for the MU-MIMO. In order to evaluate the spatial correlation between users, the following definition is given. In this case, there are 2×2=4 combinations of spatial correlation, between 2 antenna elements of MT1 and the other 2 of MT2. They can be obtained by [33], [35]

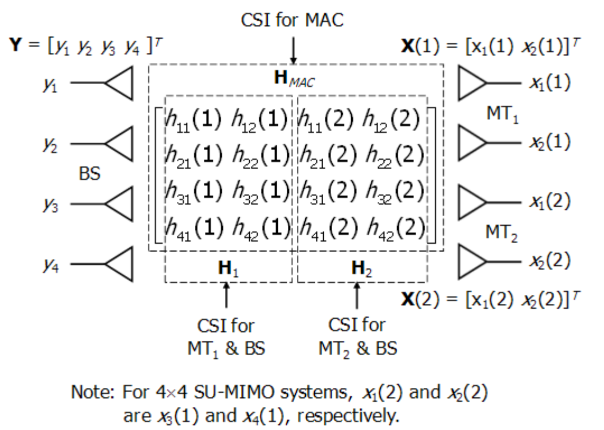


Fig.3: *The CSI of MAC of (2+2)×4 MU-MIMO systems.*

$$\rho_{i(1)j(2)} = \frac{\sum_{k=1}^{N} h_{ki}(1)h_{kj}(2)^*}{\sqrt{\sum_{k=1}^{N} |h_{ki}(1)|^2}\sqrt{\sum_{k=1}^{N} |h_{kj}(2)|^2}}. \quad (7)$$

where N is the number of BS antennas, $i(1)$ and $j(2)$ are the i-th element of MT_1 and j-th element of MT_2, respectively. In the cases of (2+2)×4 MU-MIMO, i, j = 1, 2.

The spatial correlation for each paired location of two MTs is also calculated using the channel matrix mentioned in Section 2.3.2-B. The statistical characteristics of this spatial correlation are also obtained by the same method as in Section 2.3.2-B. The spatial correlation characteristics plotted in Fig. 8 are averaged from these values. It is noted that Eq. (7) can also be adopted to calculate the spatial correlation of SU-MIMO.

2.3.4 Path Visibility

To evaluate the performance of outdoor wireless communication systems, not only the signal obstacles (in this case, the surrounding buildings) and the height of the BS must be considered, but also the location of the MT in such a propagation environment. The signal path between the transmitting and receiving antennas is directly and strongly affected by these parameters. Hence, the path visibility is introduced as a representative term for these effects. It is defined as the probability that a direct wave can be received at the receiver or that a LOS exists, i.e.,

$$path\ \ visibility[\%] = \frac{N_{\mathrm{LOS}}}{N_{\mathrm{OP}}} \times 100. \quad (8)$$

The terms N_{LOS} and N_{OP} denote the number of observed points at which a LOS exists and the total number of observed points, respectively.

We note that, in general, the relative strength of the direct and scattered components of the received signal in wireless communications is expressed by the Ricean K-factor, which provides an indication of the link quality. Although the K-factor is generally used as the propagation parameter in mobile communication, it is difficult to estimate the K-factor exactly when the BS installation is considered in actual outdoor environment because a delay profile measurement is required. On the other hand, when the building structure around the BS is determined, the path visibility can be relatively easily obtained. Moreover, even if we use the K-factor as the index on the channel capacity of SU-MIMO/MU-MIMO, the SNR must also be clarified. Hence, instead of using the complicated K-factor, we herein use the path visibility as the indicative parameter to determine the channel capacity in urban MIMO scenarios.

3. PROBLEM IN SU-MIMO TRANSMISSION IN URBAN MIMO SCENARIOS

The performance of urban SU-MIMO has been previously evaluated [10], [28]. The effects of urban model configurations on the channel capacity characteristics have been discussed. Beside those studies, the effects of the antenna configurations in such urban propagation environment where the spatial correlation becomes very high and strongly affect the channel capacity, are quite interesting to be considered. The channel capacity of conventional iid channels, which is herein calculated using the random-generated channel matrix with the average SNR obtained from the simulation results of each urban propagation model, is referred to show the effectiveness of our studied systems.

3.1 Effect of Number of Antenna Element

In this section, the effects of the numbers of the MT and BS antenna elements are evaluated. Figure 4 represents the effect of the number of the antenna elements on the channel capacity of M×N SU-MIMO, when M=N. The height of the 4-element BS antenna is varied among 60 m, 80 m and 100 m. The MT antennas are set in a square array with the spacing of a half wavelength ($\lambda/2$). It clearly indicates that the channel capacity of the systems is improved along with the increase in the numbers of antenna elements. However, even if the numbers of antenna elements is increased, the channel capacity is not increased in proportion to the numbers of elements at the transmitting and receiving antennas as in the conventional iid scenarios. Moreover, adding more elements to the antenna array seems to deteriorate the channel capacity compared to that in the iid cases.

3.2 Effect of Antenna Element Spacing

In this section, the effect of the element spacing between each antenna element is evaluated for both MT and BS antennas, separately.

Figure 5 represents the effect of the element spacing of the BS antenna on the channel capacity characteristics. The BS antenna height is varied among 60 m, 80 m, and 100 m. The linear array of 4 antenna elements is employed at the BS, as 4 antenna elements are set in a square array at the MT. Since the carrier frequency employed herein is 3 GHz, one wavelength (λ) becomes 10cm. As the results, the variation of the element spacing at the BS antenna, among the values of $\lambda/2, 1\lambda, 2\lambda$ and 3λ,

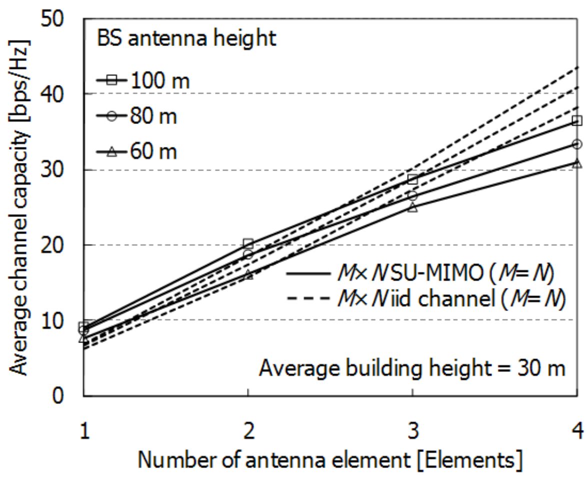


Fig.4: Effects of number of antenna element.

merely affects the channel capacity, unlike the effects of other previously-studied parameters [10]. Even if

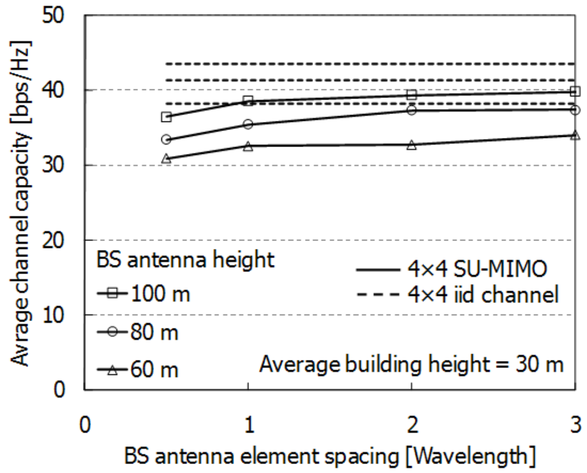


Fig.5: Effects of antenna element spacing.

the spacing between each antenna element is wider, the average channel capacity is not improved. Moreover, the channel capacity of these SU-MIMO systems is deteriorated compared to those of the iid cases. This is because the very high spatial correlation in urban propagation environment, in which the signals arrive at the receiving antenna from the limited directions. In such iid channels, the channel capacity characteristics are not affected by the antenna element spacing. In consequence, we assume that there is a challenge to obtain the higher capacity when the MU-MIMO with the same total number of antennas with the SU-MIMO is employed. Hence, the MU-MIMO transmission is introduced in Section 4, in order to reduce the spatial correlation and its effect on the channel capacity characteristics of urban MIMO systems.

Additionally, we note that there are other antenna configurations, such as the antenna polarization, the radiation pattern, which are not considered herein. Even if the directional antennas have promised good performance in many indoor MIMO systems [36], it seems not to be appropriate for the urban ones where the user terminals are supposed to move in wide propagation environment. Some simulated results about the effects of these parameters look too complicate to be discussed. Hence, the omni-directional antennas are employed at both transmitting and receiving antennas throughout this study.

4. CHANNEL CAPACITY CHARACTERISTICS OF URBAN MULTI-USER MIMO SYSTEMS

As mentioned in Section 3 as well as in [10] and [28], the channel capacity of urban SU-MIMO is deteriorated compared to that of the iid cases due to the very high spatial correlation in urban propagation environment. The performance of SU-MIMO systems is degraded because the multipath rich environment cannot be created. Hence, in order to reduce the effect of the spatial correlation, the MU-MIMO transmission is introduced in this section. In order to compare the MAC capacity to the channel capacity in SU-MIMO, the total numbers of transmitting and receiving antennas of both SU-MIMO and MU-MIMO are set to be the same, i.e., the channel capacity characteristics of urban (2+2)×4 MU-MIMO are evaluated throughout this section.

4.1 Channel Capacity Comparison between MU-MIMO and SU-MIMO

When considering the uplink scenarios in urban MU-MIMO transmission, C_{MAC} is considered as the total channel capacity at which the BS antenna can receive from the MTs moving in the propagation area.

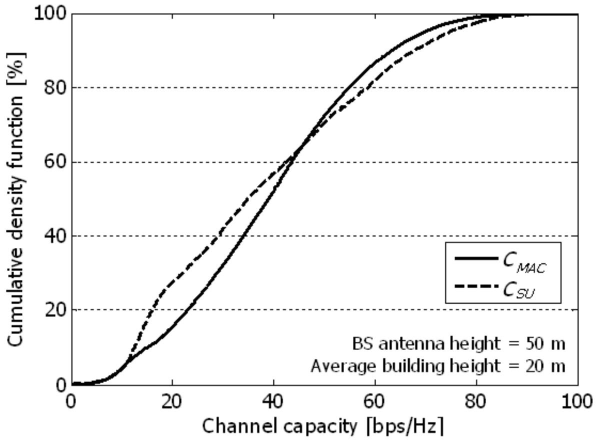
Figure 6 represents the examples of the CDFs of C_{MAC} of (2+2)?4 MU-MIMO compared to those of the channel capacity of 4×4 SU-MIMO (C_{SU}). Figure 6(a) shows the case when the average building height (h_{AVG}) is 20 m, and the BS antenna height (h_{BS}) is 50 m, in which CMAC is almost as same as $C_{SU}(C_{MAC} \approx C_{SU})$. Figure 6(b) shows another case when the BS antenna is mounted higher at 100 m height, in which C_{MAC} is clearly greater than C_{SU}. This characteristic reasonably lies in the same direction and agrees with those of measured MU-MIMO channels in both outdoor and indoor scenarios which are clearly evaluated in [37].

These results promise a very significance to be considered, since the MU-MIMO transmission is effective when the BS antenna is mounted higher, while the SU-MIMO one is not. When considering the cases of conventional iid channels, the C_{MAC} are always equal to the C_{SU}, i.e., the SU-MIMO seems to be also effective in iid scenarios.

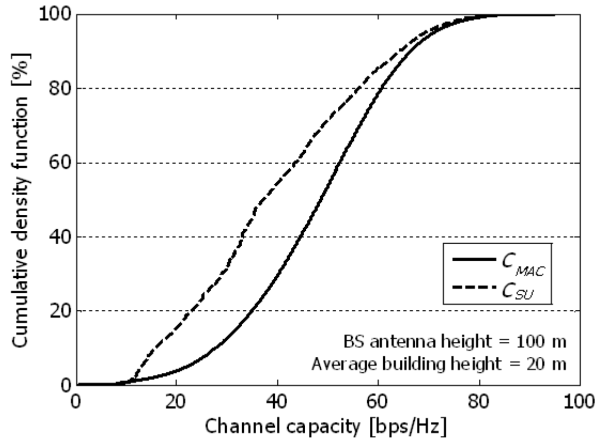
4.2 Effects of Urban Model Configurations

To evaluate the performance of urban MU-MIMO further, the variation of the model configurations are considered. Figure 7 shows the effects of the model configurations on the channel capacity of SU-MIMO and MU-MIMO systems mentioned in Section 4.1. The average building height is varied among 20 m, 30 m and 40 m, respectively.

When considering the channel capacity of MU-MIMO compared to that of SU-MIMO, the results promise a very significance, since there are the situations that the C_{MAC} becomes greater than the $C_{SU}(C_{MAC}¿\, C_{SU})$, i.e., the MU-MIMO transmission presents the
effectiveness. Further discussion about this is expressed in Section 4.3. These results confirm that the channel capacity characteristics of MU-MIMO are greatly different from those in the iid scenarios, in which the C_{MAC} is normally equal to the C_{SU}, when the total number of antennas is the same. These are



(a): h_{AVG} = 20 m, h_{BS} = 50 m



(b): h_{AVG} = 20 m, h_{BS} = 50 m.

Fig. 6: *Examples of CDFs of C_{SU} and C_{MAC}.*

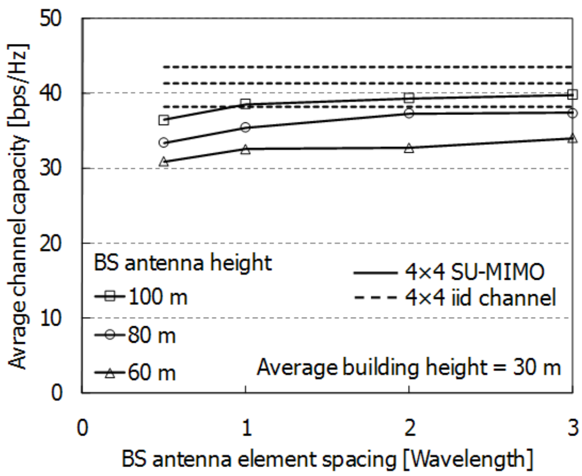


Fig. 7: *Effects of model configurations on C_{MAC} and C_{SU}.*

clearly supported by Fig. 8. The average spatial correlation between the users of (2+2)×4 MU-MIMO in which two MTs moving independently in the propagation area is much lower than the average spatial correlation between each antenna element of 4×4 SU-MIMO in which all MT antenna elements always stay close. Since the spatial correlation becomes low, its effect on the channel capacity is also deteriorated [10].

From the view of the receiving antenna (BS), the *AOA-diff* is defined and its effect on the channel capacity characteristics is indicated. Figure 9 shows the average CMAC and CSU at each AOA-diff. In the cases of MU-MIMO in which the MTs stay far from each other, along with the increase in the AOA-diff, the channel capacity is relatively increased. Even if the BS antenna is mounted at 50 m height at which the MU-MIMO transmission is not much more effective than the SU-MIMO (see Fig. 7), the channel capacity is also increased when the locations of two MTs are far apart and the spatial correlation becomes low. Moreover, when the MTs stay at the very near locations, or the AOA-diff is small, the (2+2)×4 MU-MIMO can be approximately regarded as the 4×4 SU-MIMO, and the channel capacity becomes low due to high correlation.

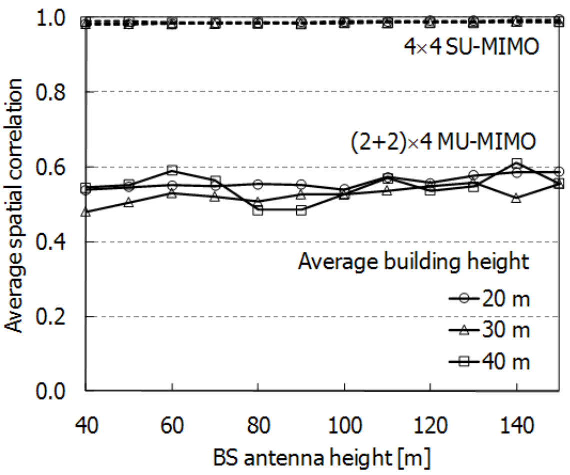


Fig.8: *Spatial correlation characteristics.*

4.3 Channel Capacity Improvement in MU-MIMO

The results in Fig. 7 are very interesting as discussed. However, the turning points at which the C_{MAC} becomes greater than the C_{SU} cannot be distinctly noticed. Hence, Fig. 10 shows the clearer figure by illustrating in terms of the channel capacity ratio of the C_{MAC} to the C_{SU}, which indicates the improvement in the channel capacity of MU-MIMO over SU-MIMO. The intersections between these lines and the horizontal dashed line indicate the turning points at which the C_{MAC} becomes greater than the C_{SU} (C_{MAC} / C_{SU} > 1). As the average building

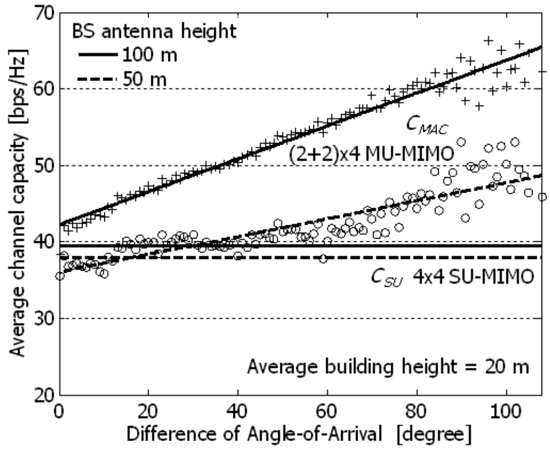


Fig.9: *Effects of difference of AOA on C_{SU} and C_{MAC}.*

height is higher, the turning points relatively present at the higher BS antenna height, for example, when h_{AVG} = 40 m and h_{BS} ≈100 m.

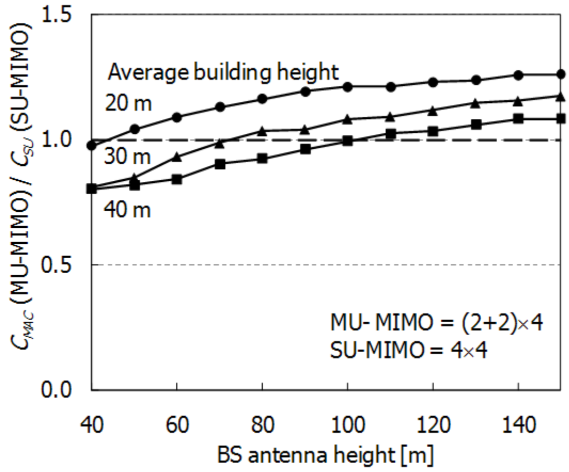


Fig.10: *Improvement in channel capacity by MU-MIMO.*

To explain these more relatively, the path visibility introduced in our previous study [10], [28] seems to be playing an important role once again. The path visibility has been defined as the probability that the direct wave can be received at the receiving antenna or that a LOS exists. Consequently, Fig. 11 shows the effect of the path visibility on the characteristics of the C_{MAC}/C_{SU}. As the results, along the increase in the path visibility, the ratio of the C_{MAC}/C_{SU} is relatively increased. It is clarified that the C_{MAC} becomes greater than the C_{SU}, when the path visibility is about 13 percent. That is to say, to obtain the effectiveness of urban wireless communication, not only the MU-MIMO transmission is supposed to be employed, but also the BS antenna should be mounted at the height so as the path visibility is greater than 13%. This result will be very useful when considering the installation of the BS in urban SU/MU-MIMO systems. Furthermore, when the average building height is varied from 20 m to 40 m, the optimal height of the BS antenna which yields 13% path visibility can be estimated as shown in Fig. 12. In general words, when the building structure in each urban area is given and the BS antenna is installed, the path visibility can be estimated. By only this single parameter, path visibility, the improvement in the channel capacity by MU-MIMO in urban scenarios can be determined.

In such urban propagation scenarios in which the spatial correlation is very high, the independent positions of the users in MU-MIMO can reduce the spatial correlation. That is the reason why MU-MIMO transmission can present the effectiveness while the SU-MIMO cannot. These results also confirm that the channel capacity characteristics in urban MU-MIMO are greatly different from those in neither indoor nor iid scenarios as discussed in Section 4.1. On the other hand, although the spatial correlation can be reduced in the cases of MU-MIMO, the change in the difference of the spatial correlation is very small (see Fig. 8). Moreover, it is shown in [10] that the path visibility becomes high as the average building height is lower. When considering these facts together with the results in Fig. 9, it is clarified that the most of the capacity improvement in the cases of MU-MIMO is because of the enlargement of AOA-diff. This is reinforced by that the performances of SU-MIMO and MU-MIMO become approach as the average building height becomes higher (see Fig. 7). Namely, when the LOS path is blocked, the AOA-diff does not work as a dominant factor anymore.

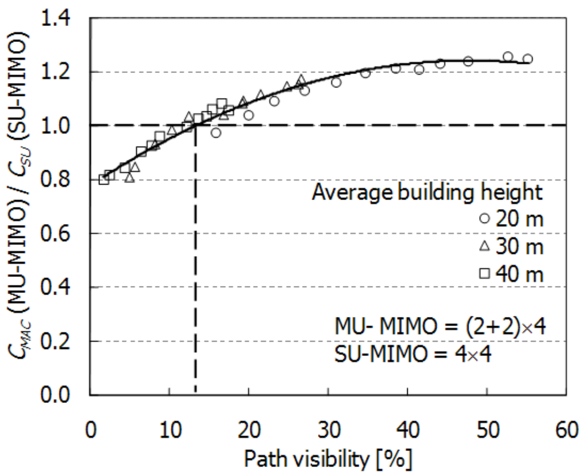


Fig.11: *Effect of path visibility on the characteristic of* C_{MAC}/C_{SU}.

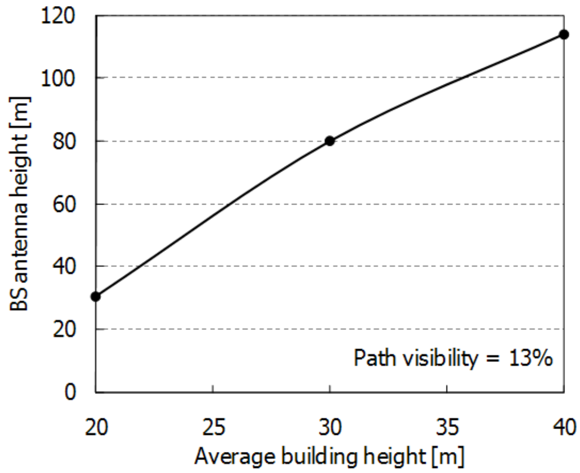


Fig.12: *BS antenna height and average building height which yield 13% path visibility.*

5. CONCLUSION

Throughout this paper, the channel capacity characteristics of urban SU-MIMO and MU-MIMO systems considering the uplink scenario were studied.

The effects of the antenna configurations on the channel capacity of SU-MIMO were evaluated. It was clarified that more reliable services were obtained in SU-MIMO when more elements were added to the MT and BS antennas. However, the channel capacity was not increased in proportion to the increased number of the elements at the transmitting and receiving antennas as in conventional iid scenarios. Furthermore, the wider element spacing could not enhance the performance of SU-MIMO, due to the very high spatial correlation in urban environment.

Then, the MU-MIMO transmission was introduced to reduce the spatial correlation. The MAC capacity in ((2+2)×4) MU-MIMO was compared to the capacity in 4×4 SU-MIMO. It was clarified that the spatial correlation between users of MU-MIMO in which two MTs moved independently in the propagation area was much lower than that of the SU-MIMO in which all MT antennas stayed close all the times. Its effect on the channel capacity was also lowed. By the definition of the AOA-diff, it was clarified that when the MTs stayed far from each other in which the spatial correlation becomes low, the channel capacity was increased. Moreover, when the AOA-diff was small or the MTs stayed very near, the (2+2)×4 MU-MIMO channels could be approximately regarded as the 4×4 SU-MIMO.

Finally, the ratio of the C_{MAC} / C_{SU} which indicates the improvement in the capacity by MU-MIMO was relatively increased along with the increase in the path visibility. It was confirmed that the MU-MIMO transmission was effective because the spatial correlation can be reduced by the independent positions of the users. In such urban scenarios, the MU-MIMO transmission was supposed to be employed.

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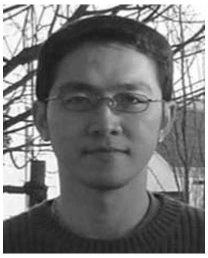

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