Effects of Path Visibility on Urban MIMO Systems

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ABSTRACT

Multiple-Input Multiple-Output (MIMO) wireless communication technology is expected to improve the channel capacity over the limited bandwidth of existing networks. Since urban MIMO systems have complex propagation characteristics, the channel capacity cannot be estimated using a simple method. Hence, we introduce channel capacity characteristics to urban MIMO systems by using a combination of imaging and ray-launching methods as a ray-tracing scheme. A simulation based on these methods with variable parameters can reproducibly estimate various urban propagation characteristics and discriminate the effects of the urban model and antenna configurations. The characteristics of the Signal-to-Noise Ratio (SNR), the channel capacity, the spatial correlation, as well as the path visibility are then determined from the results of the simulation. The parameter called *path visibility* introduced in our previous study is considered again herein. We clarify that only this single parameter can be used to determine the channel capacity characteristics in urban MIMO scenarios. This parameter also provides guidance in determining the appropriate range for the base station (BS) height.

Keywords: MIMO, Path Visibility, Eigenmode Transmission, Channel Capacity, SNR, Spatial Correlation, Urban Area

1. INTRODUCTION

It has been concluded in many studies that the MIMO wireless communication architecture is promising as an approach to achieve high bandwidth efficiency [1]-[6]. MIMO wireless channels can be simply defined as a link where both transmitting and receiving ends are equipped with multiple antenna elements. This advanced communication technology has the potential to improve the channel capacity in future wireless networks. In our previous studies [7]-[9], we have shown that the performance of MIMO wireless communication depends heavily on the propagation environment which becomes very complex in outdoor wireless communications.

In order to determine the urban propagation characteristics between the transmitting and receiving arrays, a building model which represents a statistical distribution of actual outdoor environment is prepared following our studied model introduced in [7], as well as a ray-launching simulation which is employed to evaluate the channel capacity in urban MIMO systems. The performance of urban single-user MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO) in terms of the channel capacity characteristics has been previously evaluated [7]. It has been shown that more reliable services are obtained in SU-MIMO when more elements are added to the mobile terminal (MT) and BS antennas. However, the channel capacity is not increased in proportion to the increased number of the elements at the transmitting and receiving antennas. Furthermore, due to the very high spatial correlation in urban environment, the wider element spacing cannot enhance the performance of SU-MIMO. The parameter called *path visibility*, which represents a measure whether the direct path can be received at the BS when considering the uplink scenario, or that a line-of-sight (LOS) exists, has been introduced therein. It has been clarified that the ratio of the improvement in the capacity by MU-MIMO over SU-MIMO is relatively increased along with the increase in the path visibility. We also confirmed that the MU-MIMO transmission is effective because the spatial correlation can be reduced by the independent positions of the users.

Generally, the channel capacity in a MIMO channel can be represented by the SNR and the spatial correlation. However, since these propagation parameters are strongly affected by the heights of the BS and MT antennas as well as the surrounding buildings, it is very difficult to simply explain the relationship between the channel capacity characteristics of MIMO systems and these propagation parameters. Hence, the path visibility is considered again herein. Although it is clear that there is a relationship between the SNR and the path visibility in a Single-Input Single-Output (SISO) channel, the channel capacity characteristics in MIMO systems are affected

by not only the SNR but also the spatial correlation. In this study, the relationships among the characteristics of the SNR, channel capacity, and spatial correlation of urban MIMO systems and the path visibility are evaluated. We confirm that the channel capacity in urban MIMO systems can be estimated by using only the path visibility with the ray-tracing simulation.

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 the urban MIMO systems compared to that of the conventional independent identical distributed (iid) channels is then studied. The effects of model configurations are evaluated in Section 3. The effects of path visibility on the SNR, channel capacity and spatial correlation characteristics are then discussed in Section 4. Finally, the contribution of this paper is given in Section 5. It is shown that the channel capacity of urban MIMO systems can be directly derived from the path visibility. It is also shown that this parameter gives guidance concerning the appropriate height range for mounting the BS antenna.

2. ANALYSIS MODEL

2.1 Urban Propagation Model

The urban propagation model shown in Fig. 1 is simulated by a ray-tracing method as we employed in our studied model in [7]. The wireless communication system considered in this study is 4×4 MIMO, i.e., BS and MT antennas consist of 4 elements each. The element spacing at the BS and MT arrays herein is set to a half wavelength. For the BS which is located at the top of a building on one side of the model as shown in Fig. 1, a linear array is employed, as the MT antennas are set in a square array.
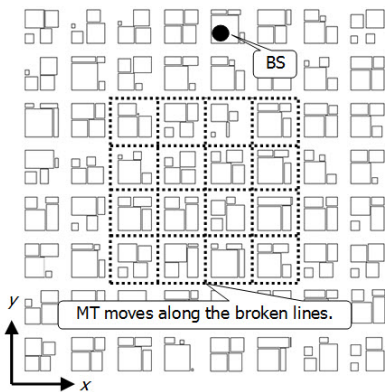

Fig.1: *Urban propagation model.*

2.2 Distribution of Building Height and Width

In this study, the chi-square is employed to assume the building height distribution as in our previous studies [7]. When the minimum height, h_{min}, is set to 4 m, the height of the building, h, can be expressed by [10]

$$h = h_0 \left(\chi^2(k) \right) + h_{min}, \qquad (1)$$

where $\chi^2(k)$ 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

$$h_0 = (h_{\mathrm{AVG}} - h_{min})/k. \qquad (2)$$

The width of each building, w_m, can also be determined from its height (h) in Eq.1 using [11]

$$w_m = w_0 \left(1 - \alpha \cdot \exp(-\beta h) \right), \qquad (3)$$

where w_0 is 55 m, α is 1.1, and β is -0.025 m^{-1}. The number of 20 different models is considered throughout this study to give the accuracy of the simulation results.

2.3 Evaluation Method

The channel capacity characteristics are herein introduced to urban MIMO systems by using a combination of imaging and ray-launching methods as a ray-tracing scheme. Imaging method is used to calculate the reflection and diffraction of the ray which arrives at the receiver. The locus of the ray is assumed by considering the transmitting point, receiving point, and all reflecting surfaces. Ray-launching method is a technique to calculate the field intensity of the ray arrives at the receiver. When the ray from the transmitter is passing the area near the receiver which is called the reception area, the field intensity can be then calculated. Both methods are generally employed as the simulation tools in the study of wireless communication.

In the next section, 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.

A.Signal-to-Noise Ratio (SNR)

From the simulation, the complex received voltage matrices are obtained and the channel response matrices can be calculated from those matrices. When the numbers of transmitting and receiving antennas are M and N, respectively, the channel response matrix, **H**, can be expressed by [12]

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1} & h_{N2} & \cdots & h_{NM} \end{bmatrix}, \quad (4)$$

where $h_{nm}(n = 1, 2, \ldots, N; m = 1, 2, \ldots, M)$ represents the complex received voltage between the m-th antenna of BS array and the n-th antenna of MT array.

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 [13]

$$\gamma_0 = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} |h_{nm}|^2}{NM\sigma^2} \quad (5)$$

B. Channel Capacity

The algorithms of MIMO systems employed herein are the Minimum Mean-Square Error (MMSE) and the Eigen-Mode Transmission System (EMTS) with equal power control. When the adaptive control for the weight coefficients is MMSE, the channel capacity can be obtained in units of bit/second/Hertz (bps/Hz) using [14], [15]

$$C_{MMSE} = -\sum_{m=1}^{M} \log_2 \left(1 - \mathbf{h}_m^H \left(\mathbf{HH}^H + \frac{M}{\gamma_0} \mathbf{I}_N \right)^{-1} \mathbf{h}_m \right). \quad (6)$$

The upper subscript H denotes the Hermite-transpose, $\mathbf{h}_m$ denotes the m-th column of $\mathbf{H}$, and $\mathbf{I}_N$ denotes the identity matrix of size N.

By using EMTS, the channel capacity of MIMO can be obtained using [13]

$$C_{EMTS} = \sum_{m=1}^{M} \log_2 \left(1 + \frac{\gamma_0}{M} \lambda_m \right). \quad (7)$$

The term λ_m represents the eigenvalue that is obtained by the matrix of $\mathbf{HH}^H$. The channel response matrices are obtained by the methods in which we have employed in [7]. The channel capacity is then obtained by deriving the average SNR (γ_0). 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. The cumulative density function (CDF) is considered to evaluate the performance of the systems statistically.

C. Spatial Correlation

In outdoor wireless communications, it is expected that the angular spread at the BS is narrower than that at the MT. In such a scenario, the capacity is degraded even if a high SNR is obtained [12], [16].

Hence, the spatial correlation is introduced. The spatial correlation between the i-th and the j-th elements of the BS array is evaluated using [12], [16]

$$\rho_{ij} = \left| \frac{\sum_{m=1}^{M} h_{im} h_{jm}^*}{\sqrt{\sum_{m=1}^{M} |h_{im}|^2} \sqrt{\sum_{m=1}^{M} |h_{jm}|^2}} \right| \quad (8)$$

We note that $i, j = 1,2,3,4$ in the case of 4×4 MIMO.

D. Path Visibility

The path visibility introduced in our previous study [7] is considered herein, as

$$path\ visibility\ [\%] = \frac{N_{LOS}}{N_{OP}} \times 100. \quad (9)$$

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.

3. EFFECTS OF MODEL CONFIGURATIONS

Figure 2 shows examples of the channel capacity distribution around the observed area along the broken lines in Fig. 1. Four different cases are shown to clarify the difference in the channel capacity distribution of urban MIMO systems. The average building heights of 20 m to 40 m are considered throughout this study as the representative cases of a downtown area as mentioned in Section 2.1.

Figures 2(a) and 2(b) show cases of weight coefficients in a MIMO system controlled using the MMSE algorithm. The average building height (h_{AVG}) is set to 20 m and the BS antennas are mounted at the height (h_{BS}) of 40 m and 80 m, respectively. Figures 2(c) and 3(d) represent the cases when the EMTS algorithm is employed for urban MIMO transmission. Term h_{BS} is set to 80 m and h_{AVG} is set to 20 m and 40 m in Figs. 2(c) and 2(d), respectively.

These figures clarify that, for all settings, the further the distance the MT moves away from the BS, the more degraded the channel capacity becomes. It is also quite clear that the urban MIMO systems, in which the EMTS algorithm is employed, have a higher channel capacity compared to that using the MMSE algorithm (Figs. 2(b) and 2(c)). Furthermore, the figures show that MIMO users can obtain more reliable service when moving around the area with a higher-mounted BS (Figs. 2(a) and 2(b)) or in an area in which the average building height is lower (Figs. 2(c) and 2(d)).

Figure 3 shows the improvement in the channel capacity of MIMO-EMTS over MIMO-MMSE compared to those for conventional iid channels. This is illustrated in terms of the channel capacity ratio
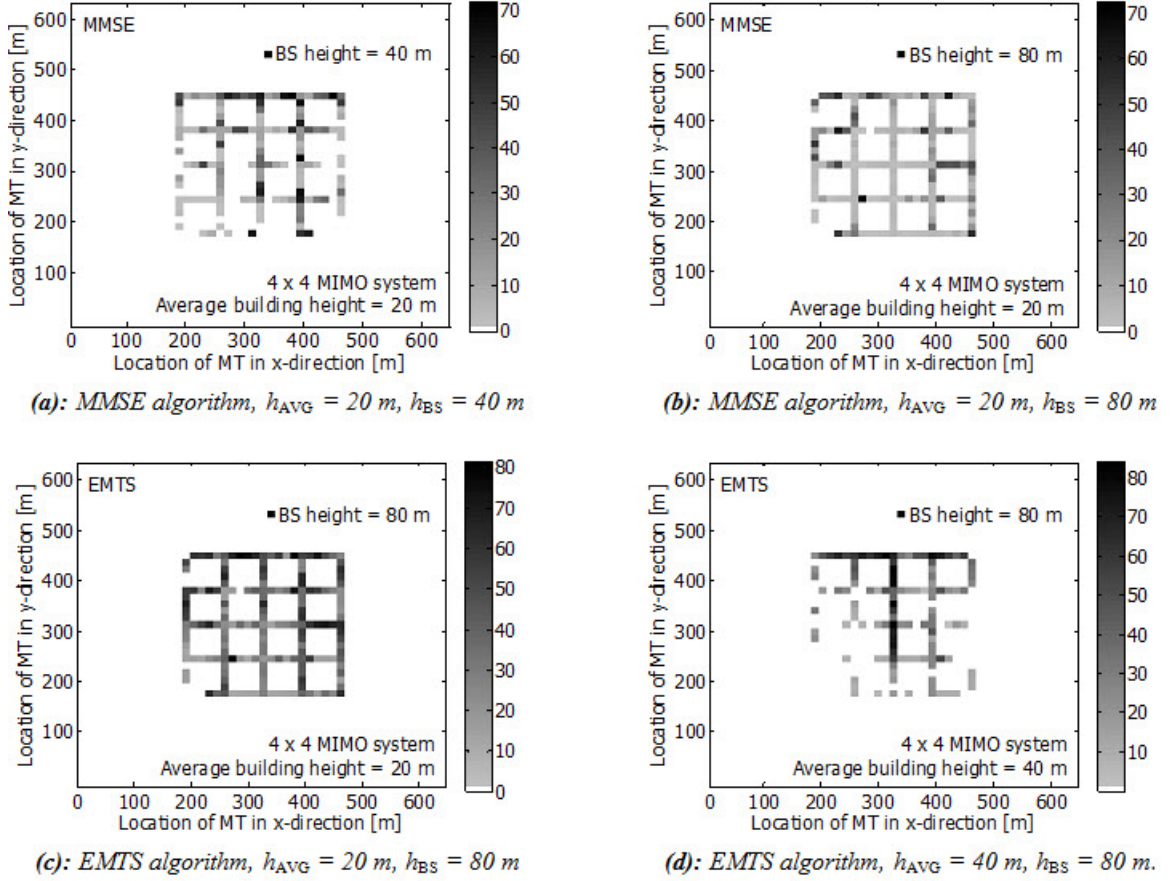
(a): MMSE algorithm, $h_{AVG} = 20 m$, $h_{BS} = 40 m$

(b): MMSE algorithm, $h_{AVG} = 20 m$, $h_{BS} = 80 m$

(c): EMTS algorithm, $h_{AVG} = 20 m$, $h_{BS} = 80 m$

(d): EMTS algorithm, $h_{AVG} = 40 m$, $h_{BS} = 80 m$.

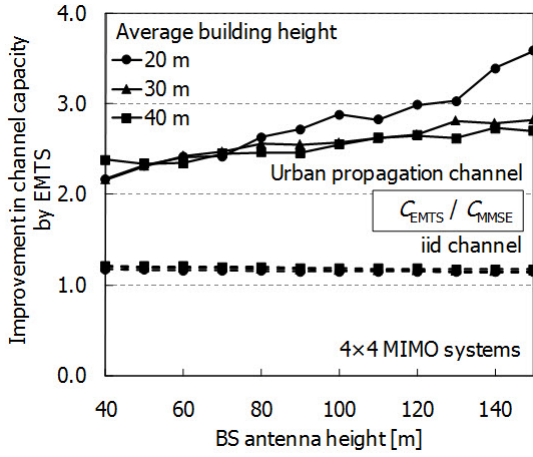**Fig.2:** *Examples of channel capacity (bps/Hz) distribution around the observed area.*

**Fig.3:** *Improvement in channel capacity by EMTS.*

(C_{EMTS}/C_{MMSE}). The dashed lines, which represent the capacity ratio of the conventional iid channels, clearly indicate that EMTS can improve the channel capacity only slightly over MMSE $(C_{EMTS}/C_{MMSE} \approx 1.2)$ for all the variations in the model configurations. In the case of the MIMO channels, which are represented by the solid lines, it is clear that the capacity can be significantly improved

by employing EMTS $(C_{EMTS}/C_{MMSE} > 2)$. This is due to the very high spatial correlation, which is described hereafter. Hence, the EMTS is considered to be effective for urban MIMO communications. Further details regarding the low channel capacity when MIMO-MMSE is employed and why MMSE is considered unsuitable for urban MIMO scenarios are discussed in Section 3.2. It was also indicated in [17] that the channel capacity of urban MIMO systems is maximized when the EMTS algorithm is employed. Hence, hereafter the focus of the discussion is on MIMO-EMTS.

To discriminate these results, the performance of the systems is evaluated statistically by calculating the CDF of the SNR as well as of the channel capacity. Herein, the SNR of the MIMO systems is determined from the average SNR of four antenna elements, which is almost the same level as that for the SISO systems. Figures 4(a) and 4(b) respectively represent the effects of the BS antenna height on the SNR and channel capacity characteristics. The BS antenna height is varied among 60 m, 80 m, and 100 m as the average building height is set to 30 m. In Fig. 4(a), the characteristics of the SNR (per element) of the MIMO systems are illustrated. As shown in this figure, the SNR is increased along with the average
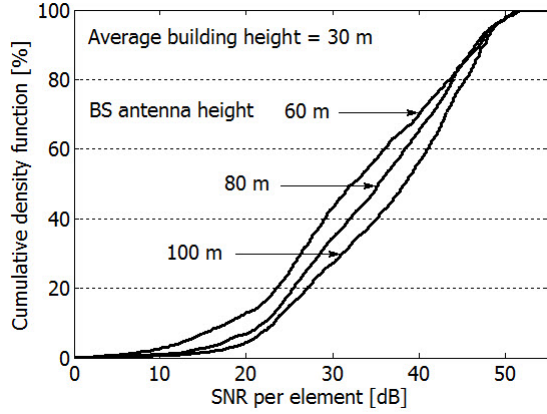
(a): Effect on SNR characteristics
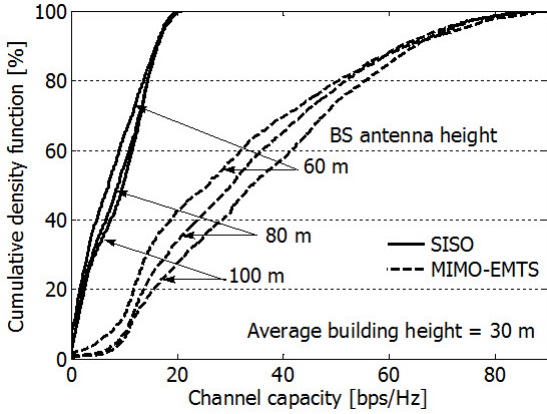
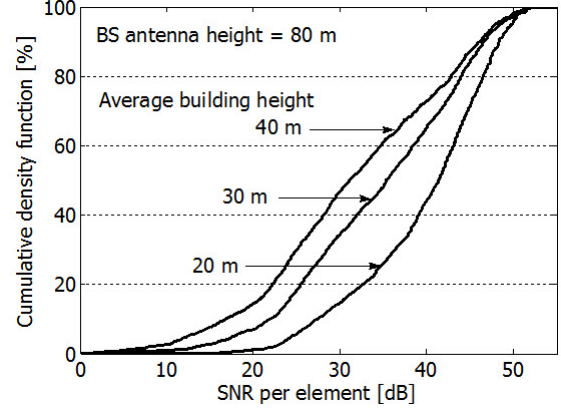*(b): Effect on channel capacity characteristics*

Fig.4: *Effect of BS antenna height.*

(a): Effect on SNR characteristics

(b): Effect on channel capacity characteristics

Fig.5: *Effect of building height distribution.*

building height. Moreover, the range of the SNR becomes 0 to 50 dB regardless of the distribution of the building height.
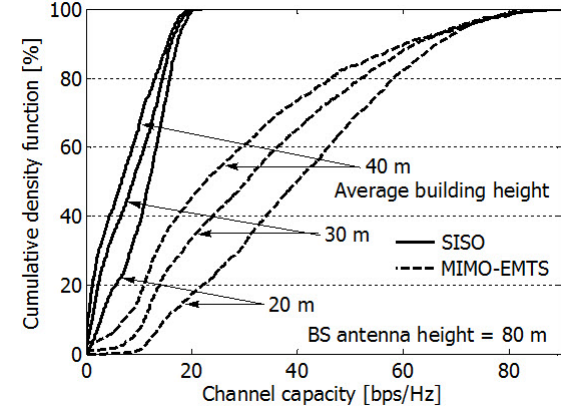
In Fig. 4(b), comparisons between 4×4 MIMO-EMTS and conventional SISO systems are shown. By considering the difference in the systems, we see that the area under the CDF curves of the channel capacity of MIMO-EMTS systems is much smaller than that for SISO systems. That is to say, the effectiveness in the MIMO systems is improved over the conventional SISO systems. When the BS antenna is mounted higher, the channel capacities for both SISO and MIMO are increased. Although it is well known that the capacity in SISO channels is increased by the SNR, these results confirm that the capacity in urban MIMO systems is also increased by the increase in the SNR.

3.1 Effect of Building Height Distribution

Figures 5(a) and 5(b) represent the effects of building height distribution on the SNR and channel capacity characteristics, respectively. The same comparisons among the different systems as in Fig. 4 are considered. The average building height is varied among 20 m, 30 m, and 40 m as the BS is mounted at a height of 80 m. Considering the variation in the

average building height, it is clear that when the average building height becomes low, the area under the CDF curves of the SNR and channel capacity decreases, i.e., for all systems. A user moving in the area in which the average height of the surrounding buildings is lower can obtain more reliable services.

Figures 6(a), 6(b), and 6(c) represent the effects of the building height distribution and BS antenna height on the SNR, the channel capacity and the spatial correlation characteristics, respectively. The average building height is varied among 20 m, 30 m, and 40 m as the BS antenna height is varied from 40 m to 150 m in steps of 10 m. We note that the algorithms employed for urban MIMO transmission do not affect the SNR characteristics of the systems. However, at any average building height, the average SNR increases when the BS antenna is mounted higher.

Figure 6(b) shows that when 4×4 MIMO-EMTS is employed, it achieves approximately 4-times higher channel capacity over the conventional SISO systems. The elements added to the BS and MT antennas seem to be fully beneficial since the channel capacity of MIMO-EMTS is only slightly influenced by the spatial correlation and it promises to be more applicable to urban MIMO transmission. On the other hand, as
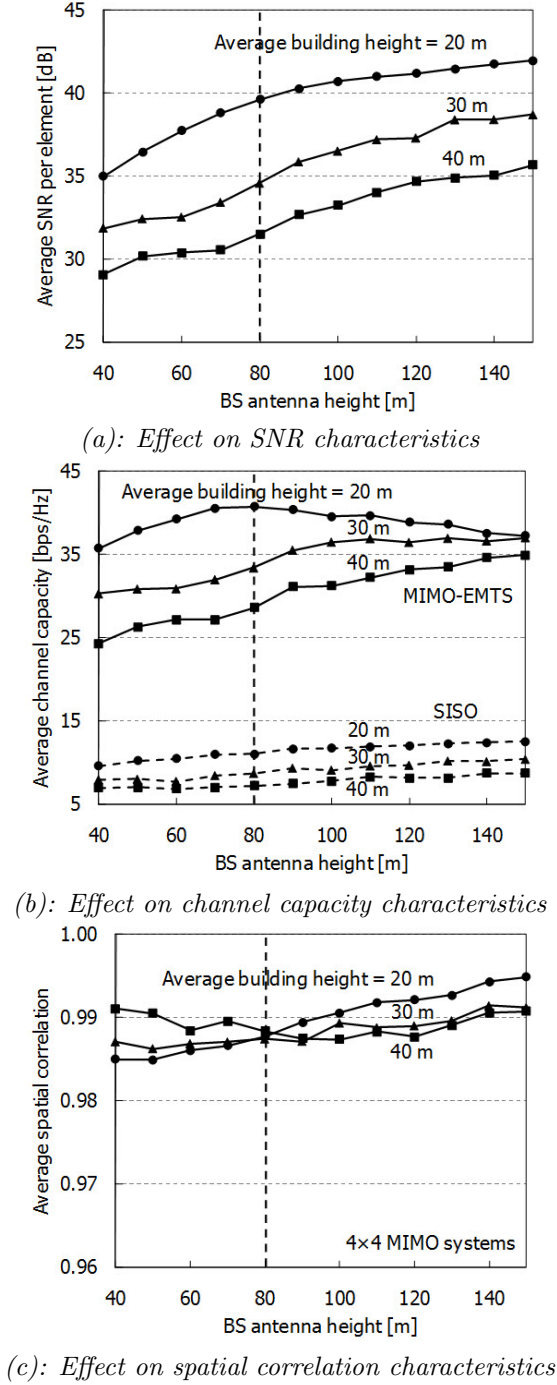
(a): Effect on SNR characteristics

(b): Effect on channel capacity characteristics

(c): Effect on spatial correlation characteristics

Fig.6: *Effect of building height distribution and BS antenna height.*

discussed regarding Fig. 3, the performance of MIMO-MMSE severely degrades and it is considered inapplicable to urban wireless communications. In such cases, the performance of the systems is distinctly influenced by high spatial correlation environments as shown in Fig. 6(c). The spatial correlations for all settings of urban propagation models are really high. These results are confirmed by the situations with the high spatial correlation measured in actual MIMO environments when only vertical polarization

is used [12]. In general MIMO transmission, the channel capacity is affected by two factors, the multiplexing gain and the spatial diversity gain. In such high correlation scenarios, the second and the remaining eigenvalues are very small compared to the first one. However, the effect of the spatial diversity gain considering the first eigenvalue can be achieved because the diversity effects exist at the transmitting and receiving arrays. Hence, the channel capacity can still be improved.

Considering the intersection between the curves and the vertical dash lines in Fig. 6, when the average building height is 20 m, the average SNR on the right-hand side gradually increases compared to the other side. The highest level of the average channel capacity is obtained when the BS antenna is mounted at 80 m height. At this average building height, the average spatial correlation keeps increasing throughout the variation of the BS height.

In urban wireless communications, the performance of the MIMO systems in terms of the channel capacity characteristics is influenced by not only the reflection and diffraction of the propagation model itself, but also the SNR and the spatial correlation. When the average building height is not so high (20 m) and the BS antenna is mounted low, the influence of the SNR seems to be larger than that of the spatial correlation. Thus, the average channel capacity of MIMO-EMTS can be improved along with the increase in the height of the BS antenna and the average SNR. However, when the BS antenna is mounted very high compared to the average building height (> 80 m), the spatial correlation still gradually increases. The influence of high correlation then begins to affect the channel capacity. Consequently, the channel capacity of the systems cannot be improved and gradually degrade. These situations are more clearly described in Section 4.2 by additionally considering the effects of path visibility.
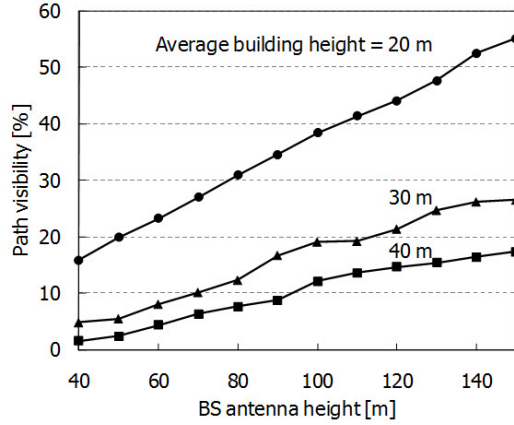
4. EFFECTS OF PATH VISIBILITY

4.1 Effects of Model Configurations on Path Visibility

Before discussing the effects of path visibility, we note that the results in this section do not depend on the algorithm employed in the systems. We also clarify that the path visibility around the observed area is significantly influenced by the surrounding buildings, the BS height, as well as the location of the MT in the propagation area.

Figures 7(a) and 7(b) show the effects of the building height distribution and the BS antenna height on the path visibility, respectively. In Fig. 7(a), the BS antenna height is varied from 40 m to 120 m in steps of 20 m. The figure shows that, at any BS antenna height, the path visibility reasonably decreases when the average building height is higher. Furthermore, when the average building height is 40 m, the path
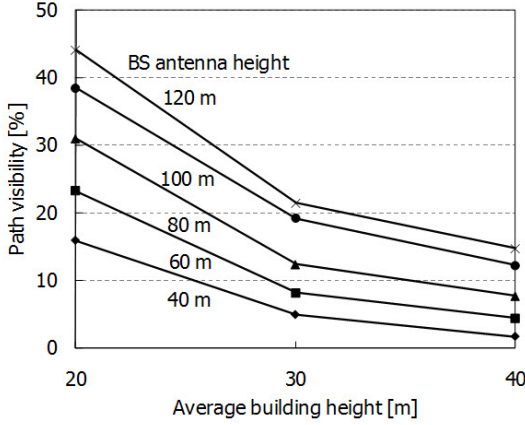
(a): Effect of building height distribution

(b): Effect of BS antenna height

Fig.7: *Effect of model configurations on path visibility.*

(a): Effect on SNR characteristics

(b): Effect on channel capacity characteristics

(c): Effect on spatial correlation characteristics
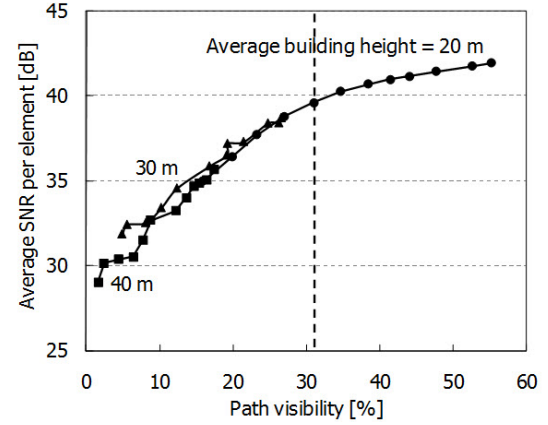
Fig.8: *Effect of path visibility.*

visibility changes in only a small range, or approximately only 12%, even the BS is mounted at three times the average building height (120 m).

In Fig. 7(b), the average building height is varied among 20 m, 30 m, and 40 m. The figure shows that, at any average building height, the path visibility reasonably increases when the BS antenna is mounted higher. Moreover, the relationship between the path visibility and BS antenna height seems to be ably and roughly approximated as linear functions, i.e., it appears linear with a constant slope for each average building height.
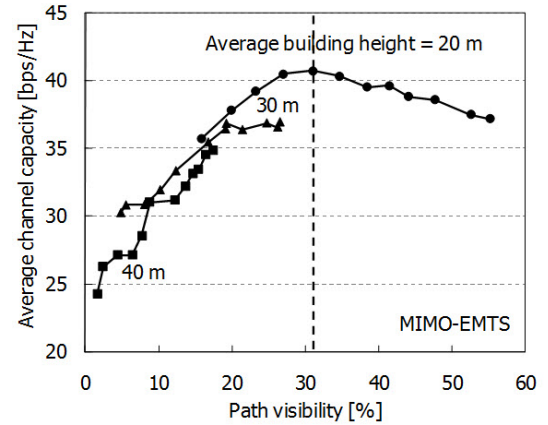
4.2 Effects of Path Visibility on SNR, Channel Capacity and Spatial Correlation

From the results in Figs. 6 and 7, it is anticipated that some relationships exist among the path visibility, SNR, channel capacity, and spatial correlation. In order to clarify the relationships among these parameters, the effects of path visibility on the SNR, channel capacity, and spatial correlation characteristics are represented in Fig. 8(a), 8(b), and 8(c), respectively.
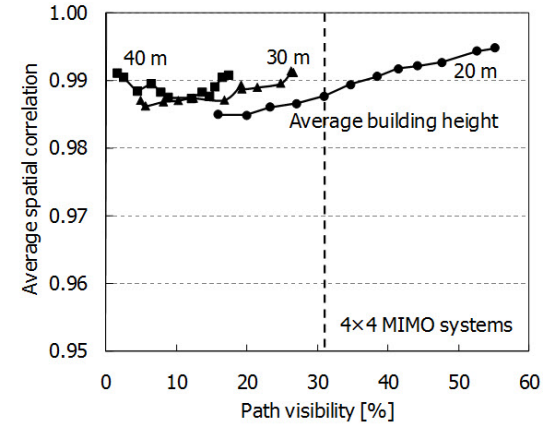
Figure 8(a) indicates that the SNR characteristic

of urban MIMO systems can be approximated from the path visibility without the need to derive it from the model configuration, neither the building height distribution nor the BS antenna height. On the right-hand side of the vertical dashed line, i.e., when the path visibility is greater than 30 percent, it is noticed that the SNR is not increased in a proportional to the path visibility. Furthermore, a very interesting result is obtained in Fig. 8(b), as the channel capacity is maximized when the path visibility is approximately

30%. When the path visibility is greater than 30%, the channel capacity is decreased while it is proportionally improved on the other side or when the path visibility is less than 30%. The reason why the optimal channel capacity exists can be explained by using Figs. 8(a) and 8(c).

In such cases where the BS antenna is mounted very high compared to the height of the surrounding buildings, although the path visibility increases, the influence of the spatial correlation, which still gradually increases as shown in Fig. 8(c), becomes affecting the channel capacity. On the other hand, we note that the SNR is not increased in a proportional to the path visibility when the path visibility is greater than 30% as shown in Fig. 8(a). In other words, the channel capacity is determined by not only the SNR but also the spatial correlation, although the effect on the channel capacity by the SNR is basically stronger than that by the spatial correlation.

Therefore, the channel capacity is decreased even if the SNR and path visibility are increased, when the spatial correlation is very high. As a result, the appropriate combination of the SNR and spatial correlation, which maximizes the channel capacity in 4×4 MIMO-EMTS transmission, is obtained when the path visibility is approximately 30%. Furthermore, we found that the appropriate channel capacity in urban MIMO scenarios can be determined by only a single parameter, path visibility.

5. CONCLUSIONS

In this paper, the channel capacity in urban MIMO systems was evaluated by using a simulation based on the ray-tracing method.

First, the effects of urban model configurations on the SNR and channel capacity of urban MIMO systems were evaluated. Even if the spatial correlation is very high in an urban outdoor scenario, the MIMO communication systems were more effective than the conventional SISO systems. When the average building height decreased or the BS antenna was mounted higher, more reliable services were provided to users moving in the urban area.

Second, in urban MIMO communications in which the spatial correlation is very high, the EMTS algorithm was suitable for urban MIMO transmission. The MMSE algorithm was unsuitable because its channel capacity is strongly affected by a high spatial correction and degraded in such a scenario. It was confirmed by a comparison with conventional iid channels that the channel capacity of urban MIMO systems could be significantly improved by the use of EMTS.

Third, the effects of the urban model configurations on the path visibility were evaluated. It was clarified that the path visibility reasonably increased when either the average height of the surrounding buildings was lower or the BS antenna was mounted higher.

Fourth, the effects of the path visibility on the SNR, channel capacity and spatial correlation characteristics were evaluated. It was clarified that the SNR and channel capacity characteristics of urban MIMO systems could be derived directly from the path visibility between the BS and MT antennas. Neither a high SNR nor a high BS antenna location was necessarily optimal for the channel capacity in urban MIMO-EMTS scenarios. Hence, from the viewpoint of the base station installation in urban MIMO systems, not only the SNR but also the spatial correlation must be carefully considered. We found that the appropriate channel capacity in urban MIMO scenarios can be determined by only a single parameter, path visibility. Furthermore, this parameter provided guidance in terms of the BS antenna height reaching optimality at the path visibility of 30 percent when considering 4×4 MIMO-EMTS transmission. At this optimal path visibility, the channel capacity is maximized because the appropriate combination of SNR and spatial correlation can be obtained.

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