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Study on Multipath Propagation Characteristics toward the Fourth-Generation Mobile Communication Systems

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We have determined various radio wave propagation characteristics required for radio link design and cell design of 4G mobile communication systems and developed models for them. This article presents propagation loss prediction methods and multipath propagation models in urban areas, with the aim of identifying how they relate to system designs.

1. Introduction

Mobile communication systems utilize cable and radio transmission lines. The transmission quality of cable transmission lines such as optical fiber and high frequency cable lines is guaranteed. In contrast, a radio transmission line between a base station and a mobile station (user terminal) is, so to speak, in a situation where it borrows the space between transmitter and receiver freely, so the transmission quality is not guaranteed. However, it becomes possible to perform optimal transmission by determining the characteristics of radio transmission lines or the *radio wave propagation characteristics* generated by the geography and streetscape. Moreover, the optimal transmitter-receiver configuration can also be developed, allowing more cost efficient system designs.

Before explaining the current research issues related to radio wave propagation in Fourth-Generation (4G) systems, let us review the kinds of issues that have been addressed for various representative systems of each generation. From the time of the first analog narrowband systems, understanding the attenuation characteristics of radio waves, i.e., the *propagation loss*, has been the most important issue in system designs. For this reason, various methods for predicting the propagation loss in a system, for instance the Okumura-Hata model [1], [2], have been examined. Moreover, because the received levels tends to fluctuate considerably due to numerous radio waves generated by scattering effects in the vicinity of a mobile station, determination of such fluctuation characteristics has also been carried out. The Second-Generation (2G) digital systems, such as Personal Digital Cellular (PDC), adopt a method where multiple users are allocated to each time slot. The issue which should be considered on this system was the difference in arrival time of radio waves, the *channel impulse response*, scattering effect in a wide area, rather than in the immediate vicinity of the mobile station. Since the delay spread that indicates the degree of channel impulse response, in particular, is related to signal error rate, its characteristics have been investigated for each region. In the Third-Generation (3G) mobile communication systems (International Mobile Telecommunications-2000: IMT-2000), it became possible to effectively make use of radio waves whose arrival times were delayed by means of the RAKE reception method. Estimate of improvement effects brought by the RAKE reception become possible by determining the power delay profile that indicates received power with respect to arrival time of the radio waves.

As the mobile communication systems evolve, the usage of frequencies higher than 2 GHz is being examined for the 4G systems in order to increase the transmission rate even further. The Okumura-Hata model, the conventional propagation loss prediction formula, only applies to frequencies up to 2 GHz, which means that it is necessary to establish a prediction method for higher frequencies. Similarly, it is also necessary to analyze the channel impulse response characteristics at higher frequencies. Moreover, application of adaptive array antennas, which receive incoming radio waves by tuning in and focusing on the antenna beams, is also being considered for the 4G systems. In order to receive incoming radio waves efficiently with adaptive array antennas, it is also necessary to understand the radio wave distribution characteristics for the given incoming direction, i.e., the *direction channel impulse response*. The majority of the channel impulse response characteristics that have been determined thus far have been for cases where isotropic antennas were used. When considering the case where radio waves from a specific direction are received by beam antennas and utilizing delayed waves in the transmission, it is required to analyze the *scatter distribution* of radio wave caused by scattering object, that is, the scattering characteristics that generate both directional channel impulse response and channel impulse response. By analyzing the scatter distribution, it becomes possible to predict the channel impulse response characteristics etc. when beam antennas are used as well.

System designs include radio link design, where transmitting power and service area size are determined, and cell design, where the most efficient location of the base station is determined. Since knowledge about propagation characteristics are required for efficient 4G system designs, this article presents our research on propagation loss characteristics, channel impulse response characteristics, and directional channel impulse response characteristics, as well as their cause of generation, i.e., scatter distribution characteristics.

2. Propagation Loss

The conventionally used Okumura-Hata model [1], [2] to predict propagation loss, is only valid for frequencies up to 2 GHz and transmitter-receiver distances of at least 1 km. Similarly, the frequency application range is 2 GHz or less for the COST Walfisch-Ikegami model [3] and the Sakagami model [4] as well. Since the 4G systems assume frequencies of 3 GHz or higher and cell radii of 1 km or less, they cannot be addressed by the conventional predictions models. For this reason, propagation experiments were performed in three regions in urban areas, the propagation loss characteristics were determined and the prediction formula was created. In the experiments, seven radio waves with frequencies of 0.457, 0.813, 2.2, 3.35, 4.7, 5.2, and 8.45 GHz, respectively, were used, the base station was placed at the highest possible location among the buildings in the vicinity, and the mobile station was placed on a road.

Before creating the prediction formula, important frequency characteristics were examined. As shown in **Figure 1**, it was found that if the measurement data is approximated by a function of the frequency f of the form $\alpha_f \log(f)$, the inclination α_f takes a value close to the case of free space loss ($\alpha_f = 20$) and the relative loss changes linearly with respect to the logarithmic value of the frequency. The results obtained when measuring in different regions using frequencies up to 15 GHz were similar to these [5], which demonstrate that the reliability of the results obtained is high.

The prediction formula was created by using multiple regression analysis, a multivariate analysis method. Specifically, the prediction formula was created by performing multiple regression on the measurement data. As parameters of the prediction formula, the transmitter-receiver distance d, base station height Hb, frequency f, and mobile station height Hm, which have large influence on the overall propagation loss, were used. **Table 1** shows the prediction formula proposed [6]. As can be seen, the proposed formula is formulated in a simpler form than conventional prediction formulae; this is because using formulae constructed from more complicated functions did not improve the prediction accuracy significantly.

Since the prediction error of the prediction formula must be taken into account as a margin in system designs, it is necessary to quantify the prediction error. Ideally, the prediction error should be evaluated using data obtained via measurement in each location, but such data was not available. Thus the measurement data of this study was used to estimate the prediction error. The difference between the value predicted by the proposed prediction formula and measurement data is called the regression residual, and was found to be 7 dB. This is not the true prediction error, but the prediction error will be likely to take a similar value if a sufficient amount of measurement data is available. Thus, the prediction error of the proposed formula is considered to be around 7 dB.

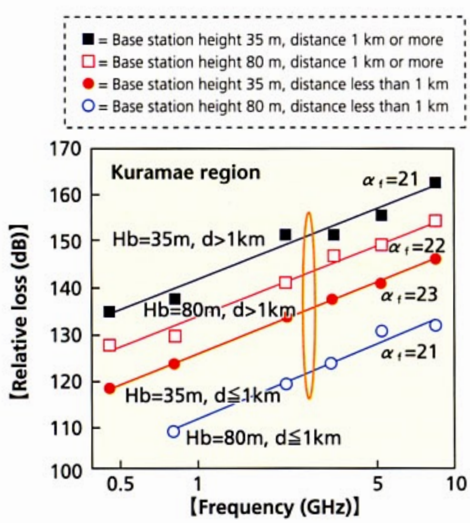


Figure 1 Frequency characteristics of propagation loss (measured values)

Table 1 Proposed formula for propagation loss prediction

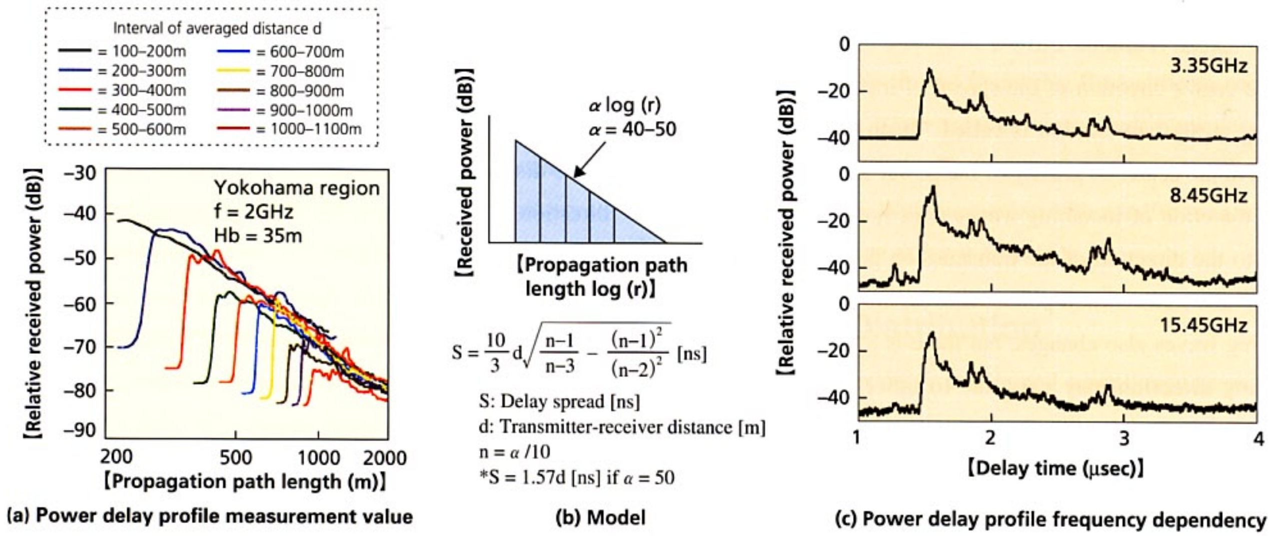
Proposed prediction formula	Loss = 42 log(d) – 32 log(Hb) + 20 log(f) – 5 log(Hm) + 55 [dB]	
Target range of prediction	Environment	Micro-cell in urban area
	Frequency	f = 0.4 to 8 [GHz]
	Transmitter-receiver distance	d = 100 to 1,000 [m]
	Base station height	Hb = 30 to 100 [m]
	Mobile station height	Hm = 1 to 5 [m]
	Prediction accuracy	Around 7 dB

3. Channel Impulse Response

Channel impulse response characteristics refer to characteristics where transmitted radio waves are reflected/scattered by buildings and similar, becoming multipath waves and causing differences in the arrival times at the receiving point. When examining the 2G and 3G systems, the channel impulse response characteristics up to 2 GHz have been more or less determined. For the 4G systems, it is necessary to examine what characteristics are seen at higher frequencies.

First of all, some of the channel impulse response characteristics at 2 GHz, which have been determined so far, are explained here. **Figure 2**(a) shows the power delay profile measured in the Yokohama region. This measurement result was obtained with the base station placed at the rooftop of a building and the mobile station placed on a road [7]. In order to obtain the average power delay profile with respect to the transmitter-receiver distance, the transmitter-reciever distance was divided into 100 m intervals and the power delay profiles obtained in each of the intervals were averaged. For example, the power delay profile shown in green in Fig. 2(a) is the average profile obtained in the interval where the transmitter-receiver distance is 400 m to 500 m. Moreover, the horizontal axis of Fig. 2(a) is indexed by propagation path length r so that power delay profiles of various transmitter-receiver distances can be shown in the same graph. From Fig. 2(a), the shape of the power delay profile P whose transmitter-receiver distance is d can be expressed by $P = \alpha \log(r)$ [dB] ($r \geq d$, $\alpha = 40$ to 50). The delay spread indicating the magnitude of delay time difference corresponds to the secondary moment of the power delay profile. It is also known from the shape of the power delay profile P above that the delay spread can be expressed by the formula shown in Fig. 2(b) [7].

For the 4G systems, the channel impulse response characteristics were measured at higher frequencies. Fig. 2(c) shows the power delay profiles measured in one location in an urban area [5]. The measurement was performed at 3 GHz, 8 GHz, and 15 GHz in order to observe the differences due to frequency. Since each power delay profile has the same shape, it is understood that the profile does not depend on frequency. The delay spread within the area where the measurement was performed did not depend on frequency



$$S = \frac{10}{3} d \sqrt{\frac{n-1}{n-3} - \frac{(n-1)^2}{(n-2)^2}} \text{ [ns]}$$

Figure 2 Power delay profile model and frequency dependency

either; the cumulative distribution of delay spread is the same for each of the three frequencies [5]. Fig. 2(c) does not show any measurement results at 2 GHz, but the results mentioned earlier indicate that the same characteristics are obtained at frequencies 3 GHz to 15 GHz; thus, the channel impulse response characteristics at 2 GHz will most likely be the same as well. This can easily be predicted from the fact that the frequency difference from 3 GHz to 2 GHz is smaller than the difference from 3 GHz to 15 GHz. From these results, it was found that the previous results can be applied as is for 4G system designs with frequencies higher than 2 GHz.

4. Directional Channel Impulse Response

Directional channel impulse response characteristics refer to angular distribution characteristics of incoming waves as seen from the reception point. Whereas the channel impulse response represents the temporal spread of incoming waves, the directional channel impulse response refers to the spatial spread of incoming waves. In the same way as for the channel impulse response, the indices determining the directional channel impulse response are power angular profile and angular spread.

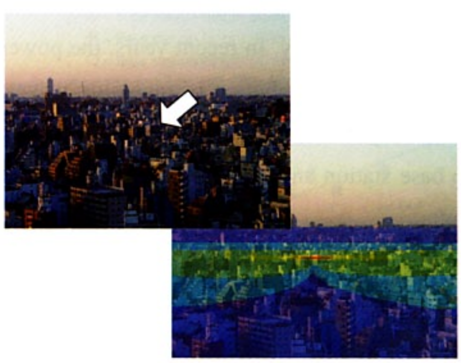
4.1 Incoming Waves at the Base Station

In the 4G systems, the frequencies used will be higher and, accordingly, the propagation loss will be larger. It is thus necessary to increase the system gain by using methods in one way or another. The current base station antennas are typically sector antennas whose half-power width in the horizontal direction pattern is broad, 120° or 60°. Switching to adaptive array antennas that narrow down the horizontal direction pattern and direct the beam in the direction of the mobile stations is an effective method to increase the system gain. To design the adaptive array antennas, it becomes necessary to figure out the directional channel impulse response characteristics of incoming waves at the base station. The directional channel impulse response characteristics have been examined in the past as they are related to the correlation coefficient between the received signals when utilizing space diversity. In recent years, the power angular profile, which is the distribution of incoming waves, along with its dependency on the distance to the base station, the height of the base station and frequency has become the target of examination.

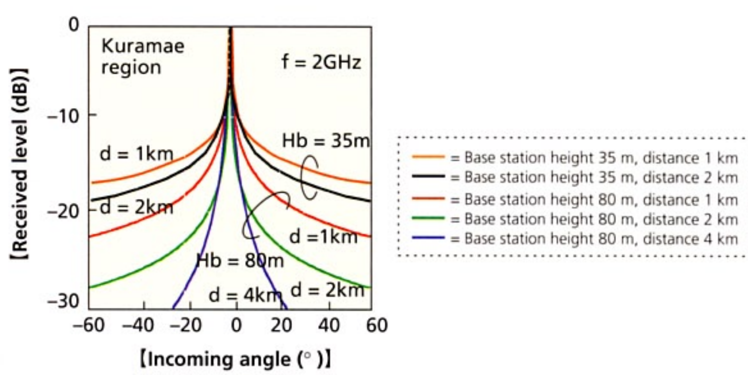
Figure 3(a) shows the incoming direction and power level of radio waves seen from the base station. The calculation is performed using a model where it is assumed that the radio waves are irradiated from the location indicated by the arrow in the top photo in Fig. 3(a) (on the road 1 km ahead). The lower photo in Fig. 3(a) shows the same image, color coded according to the power level of incoming waves. From this figure, it can be seen that radio waves tend to scatter in the horizontal direction due to reflections from the surrounding building before they arrive at the station. Fig. 3(b) shows the power angular profile in the horizontal direction of radio waves arriving at the base station [8]. The transmission point was placed on a road and the height of the receiving base stations Hb was set to 35 m (rooftop height) and 80 m (steel tower height), respectively. The frequency was set to 2 GHz. It can be seen that the shape of the graph becomes sharper as the transmitter-receiver distance d becomes larger or the base station height becomes higher. The angular spread is around 2 to 5°.

The center direction of the spread of incoming radio waves arriving at the base station is called "mean angle," and corresponds to the center of gravity of the power angular profile. The center direction of incoming waves does not necessarily correspond to the direction of the transmission point. As the mobile station—the transmission point—moves, the center direction of incoming waves also changes, but there is a possibility that the incoming direction may vary due to other reasons than this. When adaptive array antennas are used at the base station, controlling the antenna beam becomes difficult if the center direction of incoming waves keeps changing. This also has an adverse influence on the handover between sectors of the current systems. A current base station uses sector antennas to measure the received level of signal which is transmitted at a mobile station and hands over the communication to the sector antenna yielding the higher received level. If the center direction of incoming waves varies, differences of the received level between sectors fluctuates and the handover may not be carried out efficiently in some cases. By understanding the fluctuation of the center direction of incoming waves, it also becomes possible to obtain the optimal threshold value to be used in handover among sectors.

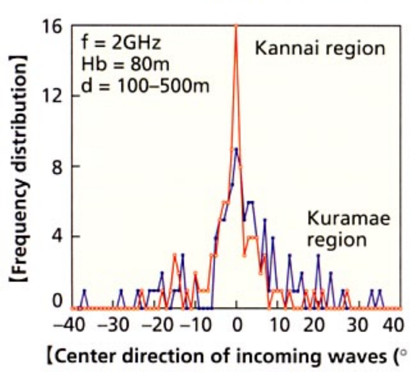
Fig. 3(c) shows an example of measurements of incoming wave distribution in center direction based on mobile station direction as in reference [9]. The measurement was conducted with a frequency of 2 GHz in the Kuramae region in Tokyo and the Kannai region in Yokohama, and the base station height Hb was 80 m for both regions. Since the fluctuation of the center direction of incoming waves becomes prominent in the vicinity of the base station, the measurement was made for the transmitter-receiver distances d between 100 and 500 m. Twenty to thirty percent of the measured center directions of incoming waves matched with the mobile station direction, but the rest did not match the mobile station direction. By analyzing the variation of the center direction of incoming waves, the standard deviation was found to be approximately 15°. This variation is characteristic for 2 GHz, but this kind of data can also be used in 4G system for threshold values for adaptive array antenna beam control and handover. The future issue is to be examined for higher frequencies as well.



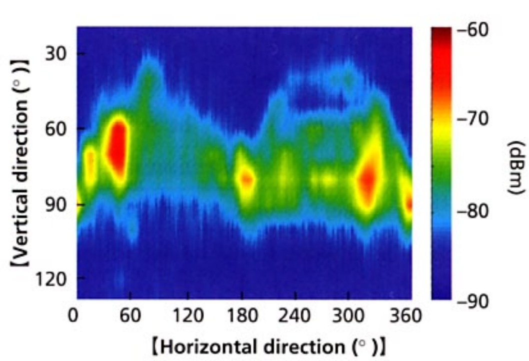
(a) Incoming waves at the base station (calculated values)



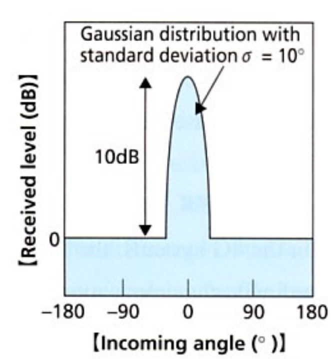
(b) Angular profile of incoming waves at the base station (measured values)



(c) Center direction of incoming waves seen from the base station (measured values)



(d) Incoming waves distribution at the mobile station (measured values)



(e) Incoming waves distribution at the mobile station (model)

Figure 3 Spread of radio waves incoming at the base station and mobile station

4.2 Incoming Waves at the Mobile Station

Improvement of reception gain can be expected by using antennas that control the beam direction at mobile stations as well. To quantify the amount of gain improvement, it is necessary to determine the waves' incoming direction characteristics seen from the mobile station. For this reason, it is necessary to measure and clarify the actual incoming wave spread characteristics.

Fig. 3(d) shows an example of distribution of incoming waves measured in a residential district [10]. Radio waves with a frequency of 3 GHz were transmitted from a height of 15 m and received in a 3-dimensional manner at a receiver placed on a road, using micro strip antennas with a half-power beam width of 10°. From the figure, it can be seen that there were some clusters in the incoming waves. It was found out that these main directions of incoming waves correspond to specific directions, such as the road direction and the directions of normal reflections from houses on the roadside.

In the antenna beam control method at the mobile station, it is assumed that the beam is restricted to the horizontal direction and faces the direction at which the received level becomes the maximum. To obtain the directional channel model in this case, each incoming wave patterns in the horizontal direction measured at each location can be normalized with the direction in which the received level becomes the maximum as reference and those normalized patterns were averaged. Fig. 3(e) shows the incoming wave pattern model calculated from the measurement result. The direction in which the received level attains the maximum has a received level of 10 dB higher than other directions. Thus, by using this approach model, it is possible to obtain improvement effects of gain by means of antenna beam control. For example, it was found that if ideal beam control is performed using a beam antenna with a half-power width of 120°, an improvement effect of 2 dB compared to isotropic antenna is obtained. With an antenna with a half-power width of 60°, the improvement effect is 4 dB [11].

5. Scatter Distribution

From the power delay profile and power angular profile of radio waves transmitted from the mobile station and incoming at the base station, it is possible to know at which locations each wave is scattered before arrival. In cities, radio waves are scattered by buildings; such scattering conditions may be predicted using scatter distribution models. Several scatter distribution models have already been proposed in the past as well [12], [13].

Figure 4 shows the scattering conditions obtained from a scatter distribution model [8]. The calculation conditions are: the distance between transmitter and receiver is 1 km, the base station height is 80 m, the mobile station is placed on a road and the frequency is 2 GHz. Assuming that a radio wave emitted from the transmission point is reflected only once by any given building before reaching the reception point, the power level of the radio wave is indicated at the position of the reflection point. The scatter distribution is shown from three different angles, which is shaped like the outer rim of a crater with a crater lake.

It is seen that the radio waves were scattered more in the

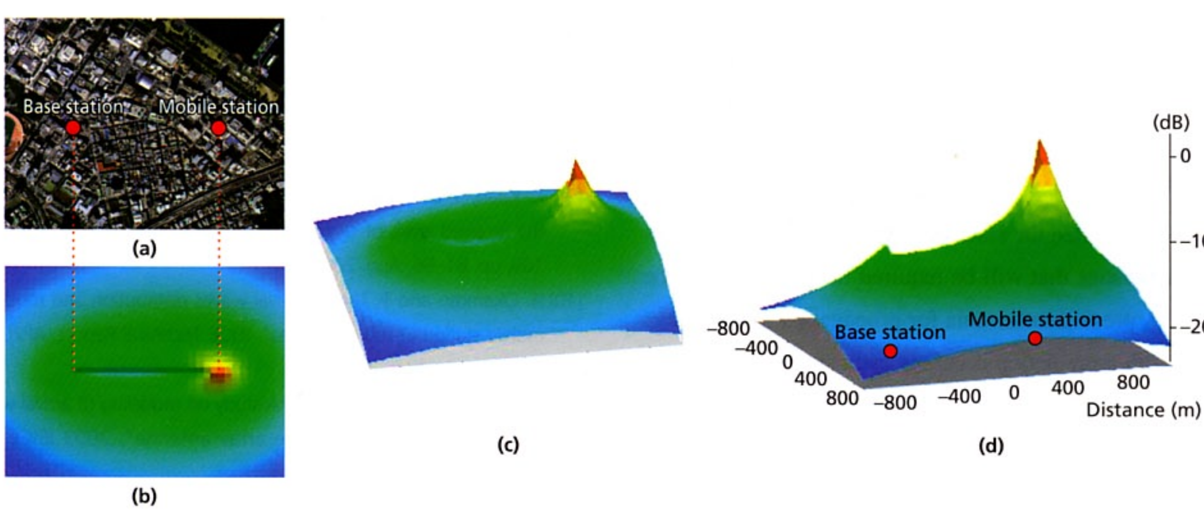


Figure 4 Radio wave scatter distribution in a city (model)

vicinity of the mobile station than in the vicinity of the base station, because the mobile station is located in a valley of buildings, where the many buildings on the road side scatter radio waves. The results presented in Fig. 4 are generated without taking the direction of the road on which the mobile station is placed into consideration in the model, but it has also been illustrated that the scattering distribution where the shape around the mobile station extends in the road direction could be obtained [13]. Not so much scattering occurred around the straight line connecting the base station and mobile station. This is because buildings can hardly reflect radio waves right behind them.

With this scatter distribution model, power delay profiles and power angular profiles shown in Fig. 2(a) and 3(b), respectively, can be obtained. Moreover, since the areas of the power delay and power angular profiles are equal to the received power, they can thus be associated with propagation loss as well; distance characteristics of propagation loss in Table 1 can also be obtained. In this way, multipath propagation characteristics in a city can be expressed in a comprehensive manner.

Furthermore, since this scatter distribution model can present both channel impulse response characteristics and directional channel impulse response characteristics at the same time, it allows evaluation of the following items, which could not be obtained in the past.

1) Channel impulse response characteristics when directional antennas are used at the base station can be obtained. These characteristics become necessary when using adaptive array antennas at the base station.
2) Correlation coefficients between received signal levels when waves of the same delay time are received with space diversity can be obtained. This correlation becomes necessary at evaluation when the RAKE reception method is used in combination with space diversity.

6. Conclusion

This article reported the results of our research on the propagation characteristics that will be required in link design of the 4G systems. A prediction formula for propagation loss in urban areas along with a prediction accuracy estimate targeted for the 4G system were provided. Regarding the channel impulse response characteristics, it was shown that the characteristics are not dependent on frequency and determined that the characteristics up to 2 GHz can thus be applied to the 4G systems.

In the same way as for directional channel impulse response characteristics and scatter distribution, the dependency on frequency must be examined. Since a base station type that can be installed at the height of power line poles has been examined internationally, propagation loss prediction formula for low base station heights are necessary as well. In order to cover the entire Japan, it is required to examine the conditions not only within urban areas but also in suburban areas. These are issues to be addressed in the future. Moreover, although this article did not touch upon the subject of Multiple Input Multiple Output (MIMO) technologies, which are expected to improve transmission speed, we plan to model propagation characteristics related to the technologies in the future as well.

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ABBREVIATIONS

IMT-2000: International Mobile Telecommunications-2000
MIMO: Multiple Input Multiple Output
PDC: Personal Digital Cellular