Analysis of Polarization Diversity Gain at Base Station in W-CDMA System

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Abstract

There have been many theoretical and experimental investigations on polarization diversity reception characteristics at base stations. The diversity gain was evaluated based on the distribution of the instantaneous received power in these investigations. The mainstream mobile communication systems are shifting to standardized IMT-2000 systems and the W-CDMA system is one of them. The effect using base station polarization diversity in W-CDMA must be evaluated by considering not only antenna diversity, but also RAKE reception / path diversity. Furthermore, Transmit Power Control (TPC) is applied to overcome the near-far problem of mobile units that maintain a fixed reception power level in W-CDMA systems. Therefore, traditional diversity gain cannot be used as an evaluation indicator. In this paper, we propose a theoretical analysis method for diversity gain using base station polarization diversity in W-CDMA. We also clarify the analytical results of practical diversity gain and verify the evaluation model used for theoretical analysis through a comparison with the experimental results.

1. INTRODUCTION

In base station (BS) diversity reception using multiple antenna branches, compared to Space Diversity (SD), polarization Diversity (PD) is also an effective technique to improve the quality of communications. In particular, PD comprising of only one antenna is appealing where the space to mount a diversity antenna is limited.

Polarization diversity reception characteristics were reported in many theoretical and experimental investigations [1-5]. Generally, the diversity effect is determined based on the difference in the average reception power between diversity branches and the change in the correlation coefficient of the received power between diversity branches. These values are determined using various factors. In the case of PD, these values are determined based on Cross Polarization Discrimination (XPD), inclination angle of the mobile station (MS) antenna, and the inclination angle of BS antenna branches (or polarization diversity branches). It was reported that XPD is approximately 6 to 8 dB in urban areas [1-3]. The advantages to applying diversity reception are given below.

- Diversity reception improves the average reception power because the signal is received at multiple antenna branches.
- Diversity reception reduces the changes in intensity of the reception power due to multi-path propagation.

Based on these advantages, the distribution of the instantaneous received power has been used to evaluate the diversity gain. To be more specific, The diversity gain is defined as the cumulative probability of the distribution, for example, an increase in the average reception power due to the application of diversity.

Mainstream mobile communication systems are shifting to the worldwide standard IMT-2000 systems, and the W-CDMA system is one of them [6]. In W-CDMA systems, RAKE reception is applied in which maximum ratio combining (MRC) is employed to separate the received multi-path signal into independent multiple paths. RAKE reception is a kind of diversity called path diversity. Therefore, the effect using BS polarization diversity in W-CDMA must be evaluated by considering not only antenna diversity, but also RAKE reception / path diversity. Transmit Power Control (TPC) is applied to overcome the near-far problem of mobile units that maintain a fixed reception power level in W-CDMA systems. Therefore, traditional diversity gain cannot be used as an evaluation indicator.

In this paper, we propose a theoretical analysis method for diversity gain using BS polarization diversity in W-CDMA. We also clarify the analytical results of practical diversity gain and verify the evaluation model used for theoretical analysis through a comparison with the experimental results.

2. THEORETICAL ANALYSIS

A. Propagation model

In this paper, we assume that the propagation delay time and arrival direction in the horizontal plane of the waves incident to the MS are characterized as an exponential distribution and Laplace distribution, respectively [10,11]. That is, power delay profile $p_D(\tau)$ is expressed as the following probability density function.

$$p_D(\tau) = \frac{1}{\sigma_D} \exp\left(\frac{-\tau}{\sigma_D}\right) \quad (1)$$

where σ_D is the delay spread. On the other hand, power angular spread $p_A(\phi)$ is expressed as the following probability density function.

$$p_A(\phi) = \frac{1}{\sqrt{2}\sigma_H} \exp\left\{ \frac{-|\phi - \phi_0|}{\frac{\sigma_H}{\sqrt{2}}} \right\} \qquad (2)$$

where σ_H is the angular spread and ϕ_0 is the average angle of arrival.

RAKE reception is used in W-CDMA systems. Discrete path model makes it easy to analyze the effect of RAKE reception. Therefore, the delay profile is estimated as the model shown in Fig. 1. Features of this model are given below.

- Each path is discrete and the number of paths, N_0, is finite.
- The decrease in the average received power of each path follows an exponential distribution provided that the power difference in decibels (dB) between successive paths is ΔL_p [dB].
- The instantaneous received power change in each path follows Rayleigh fading .

Therefore, the received power of each path, P_i, is expressed as the following equation.

$$P_i = \frac{P_{total}}{\sum_{i=1}^{N_0} 10^{-\frac{\Delta L_p}{10} \cdot i}} \cdot 10^{-\frac{\Delta L_p}{10} \cdot i} \quad (i = 1 \ldots N_0) \qquad (3)$$

where P_{total} is the total received power.

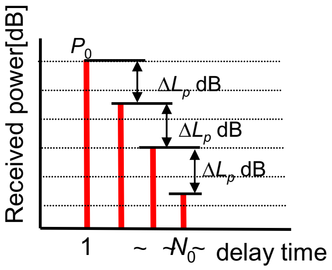

Fig. 1: Delay profile model

B. Evaluation model of polarization diversity

Figure 2 shows the model for evaluating the polarization diversity in this paper. In this model, θ is the polarization angle of a MS antenna, and α and β are the polarization angles for the two antenna branches at the MS antenna. Generally, these are defined as $\beta = \alpha$ -90 deg. in polarization diversity. Term Γ is the XPD, and ϕ is the arrival angle of the incident wave when the main beam direction of the antenna branch is 0 deg. Equations that are used to derive average powers P_α and P_β received at both antenna branches and correlation coefficient ρ between received powers at both antenna branches when the angular spread σ_H is 0 deg. were previously reported in [1] and [2]. When considering angle σ_H in the horizontal plane, these equations can be extended by using power angular profile $p_A(\phi)$ as shown in the following equation.

$$P_\alpha = A^2\left(\cos^2\theta + \frac{1}{\Gamma}\sin^2\theta\right)\cdot f + B^2\left(\frac{1}{\Gamma}\cos^2\theta + \sin^2\theta\right)\cdot g$$
$$P_\beta = C^2\left(\cos^2\theta + \frac{1}{\Gamma}\sin^2\theta\right)\cdot f + D^2\left(\frac{1}{\Gamma}\cos^2\theta + \sin^2\theta\right)\cdot g \qquad (4)$$

$$\rho = \frac{\left\{AC\left(\cos^2\theta + \frac{1}{\Gamma}\sin^2\theta\right)\cdot f + BD\left(\frac{\cos^2\theta}{\Gamma} + \sin^2\theta\right)\cdot g\right\}^2}{P_\alpha \cdot P_\beta} \qquad (5)$$

where

$$A = \cos\alpha, \quad B = \sin\alpha$$
$$C = \cos\beta, \quad D = \sin\beta \qquad (6)$$

and

$$f = \int_{\phi_0-\pi}^{\phi_0+\pi} p_A(\phi)d\phi, \quad g = \int_{\phi_0-\pi}^{\phi_0+\pi} \cos^2(\phi)\cdot p_A(\phi)d\phi \qquad (7)$$

When assuming that $p_A(\phi)$ is a Laplace distribution expressed as Eq. (2), with some straightforward manipulations taking $\sigma_H/\sqrt{2} << \pi$ into consideration, we obtain

$$f = 1, \quad g = \frac{1}{2}\left(1 + \frac{\cos 2\phi_0}{2\sigma_H{}^2 + 1}\right) \qquad (8)$$

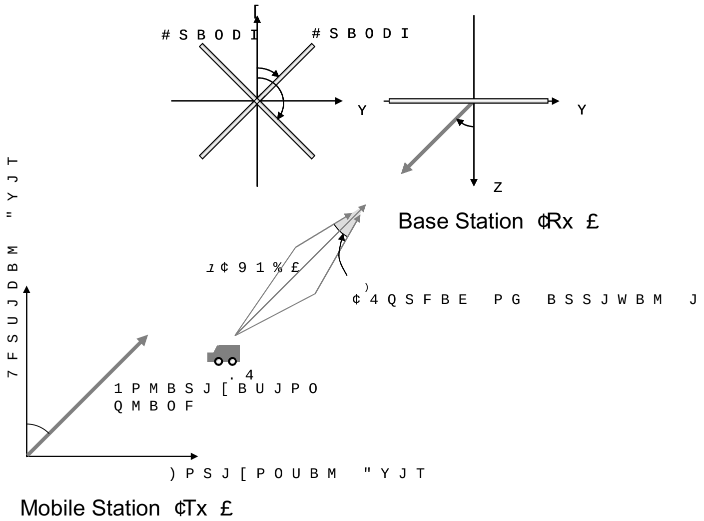

Fig. 2: Polarization diversity evaluation model at base station

C. Diversity model in W-CDMA system

When the effect of diversity in W-CDMA is evaluated, as mentioned above, the effect of path diversity using RAKE reception must be considered. Therefore, in this paper we use the diversity model shown in Fig. 3 [8,9]. In this model, MRC is applied to the signals received at the two antenna branches by selecting the path in order from the higher received power after separating and detecting the paths from each delay profile. Here, the delay profile at each branch is assumed as follows.

- Shapes of the delay profiles obtained from both antenna branches are equal to each other.
- The shape of the delay profile is defined as Eq. (3).
- Power changes between paths in co-antenna branches are uncorrelated.
- Power difference ΔL [dB] (= P_α[dB] - P_β[dB]) and changing correlation ρ between co-delay time paths at 2 antenna branches (#1 and #4; #2 and #5; and #3 and #6) are the same among all these paths, and these are defined as shown in (4) through (6) and (8).
- Power changing between paths where the delay time is different between the two antenna branches is uncorrelated.

Here, when the number of paths for MRC is N, Path #i (i = 1…N/2) is at the α branch, and Path #i (i = N/2…N) is at the β branch. The average received power of each path is expressed from Eq. (3) as

$$P_i = \begin{cases} \dfrac{P_\alpha}{\sum_{i=1}^{N/2} 10^{-\frac{\Delta L_p}{10}\cdot i}} \cdot 10^{-\frac{\Delta L_p}{10}\cdot i} & (i = 1 \dots N/2) \\ \dfrac{P_\beta}{\sum_{i=1}^{N/2} 10^{-\frac{\Delta L_p}{10}\cdot i}} \cdot 10^{-\frac{\Delta L_p}{10}\cdot i} & (i = N/2+1 \dots N) \end{cases} \quad (9)$$

Furthermore, covariance matrix $\mathbf{R}$ of the complex amplitude between paths is given by the following equation.

$$\mathbf{R} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,N} \\ \vdots & \ddots & \vdots \\ a_{N,1} & \cdots & a_{N,N} \end{bmatrix} \quad (10)$$

where

$$a_{i,j} = \begin{cases} \sqrt{P_i \cdot P_j} \cdot \delta_{i,j}, & (i = 1 \dots N/2,\ j = 1 \dots N/2) \\ & (i = N/2+1 \dots N,\ j = N/2+1 \dots N) \\ \sqrt{P_i \cdot P_j} \cdot \sqrt{\rho} \cdot \delta_{i,j-N/2}, & (i = 1 \dots N/2,\ j = 1 \dots N/2) \\ & (i = N/2+1 \dots N,\ j = N/2+1 \dots N) \end{cases} \quad (11)$$

In (11), $\delta_{i,j}$ is the Kronecker delta defined by

$$\delta_{i,j} = \begin{cases} 0, & (i \neq j) \\ 1, & (i = j) \end{cases} \quad (12)$$

When the eigenvalue obtained after eigen decomposition in (11) is λ_1 to λ_N, instantaneous changing distribution $E(\gamma)$ of the received power after MRC is given by

$$E(\gamma) = \frac{1}{\prod_{j=1}^{N} \lambda_j} \sum_{j=1}^{N} \frac{e^{-\gamma/\lambda_j}}{\prod_{k=1, k\neq j}^{N} \left(1/\lambda_k - 1/\lambda_j\right)} \quad (13)$$

where TPC is not applied [7-9].

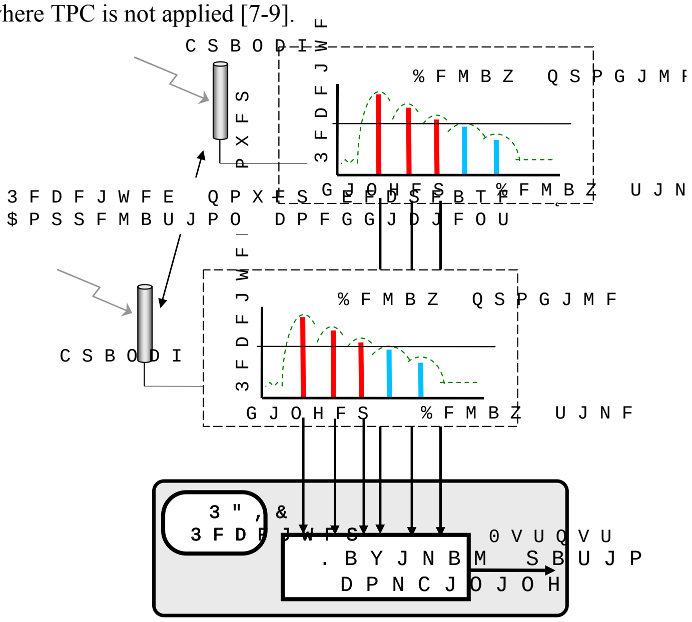

Fig. 3: Diversity model in W-CDMA system

D. Definition of Diversity Gain

In this section, the diversity gain considering TPC is described.

When the instantaneous received power after MRC is γ, the transmission power is controlled in order to ensure that γ is fixed as shown in Fig. 4. When the target received power is γ_0, the instantaneous transmission power value, which increases or decreases, is given by γ_0/γ because its power increases or decreases based on TPC. The average value, T, of the instantaneous transmission power value, which increases or decreases, is expressed as follows based on (13) [8,9].

$$T = \gamma_0 \int_0^\infty \frac{1}{\gamma} E(\gamma) d\gamma \quad (14)$$

Hereafter, we call this average value the transmission power increase ratio.

Next, we describe the relationship between the antenna diversity and the transmission power increase ratio. When not applying TPC, the received power distribution with antenna diversity is more limited than that without antenna diversity. Therefore, when applying TPC, the transmission power increase ratio with antenna diversity is lower than that without antenna diversity. In other words, we can restrict the transmission power increase by using antenna diversity. In this paper, we define polarization diversity (or antenna diversity) gain G as follows.

$$G = T_1 / T_2 \tag{15}$$

Here, T_1 and T_2 are the transmission power increase ratios with and without polarization diversity, respectively.

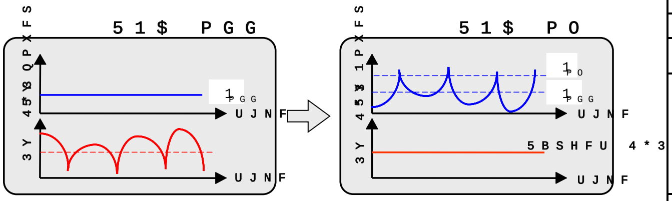

Fig. 4: Definition of diversity gain

3. PROPAGATION MEASUREMENT

Narrowband measurement was performed in order to verify the polarization diversity evaluation model described in Section 2B, and to evaluate the practical diversity gain.

The measurement area is Aoyama in Tokyo, Japan, which is considered to be a typical urban area. A transmitter is established in a test vehicle as a MS and a 2-GHz CW is transmitted with a 45 deg. polarization. The transmission power is 43 dBm and the MS antenna height is 3 m. In order to transmit the 45 deg. polarized wave (θ= 45 deg.), a vertically (V) polarized wave from a sleeve antenna and a horizontally (H) polarized wave from a slotted cylinder antenna are transmitted at the same time. The advantage of this method is that the 45 deg. polarized wave, which is independent of the antenna radiation pattern, can be transmitted uniformly throughout the horizontal plane. On the other hand, at the MS, data are obtained using four sleeve antennas installed on a rooftop. The angle of each antenna from the vertical axis is set to 0, 90, +45, and –45 deg. Therefore, VH polarization (VH-PD) diversity can be evaluated because the antennas at 0 and 90 deg. are considered to be a V polarized branch and H polarized branch, respectively. Furthermore, ± 45 deg. polarization diversity (45-PD) can be evaluated because the antennas at +45 and –45 deg. are considered to be a +45 deg. polarized branch and –45 deg. polarized branch, respectively. Table I gives the measurement conditions. In this measurement, the test vehicle is driven in an area with a radius of approximately 1.5 km from the BS. In the test vehicle, the position information was recorded by GPS in order to recognize the transmission position each time for data processing.

In the processing of the data, first the received power data at the MS is fitted to the transmission position information for each measurement. Next, the difference in the received power, ΔL, and the correlation coefficient, ρ, between the V polarized branch and H polarized branch, and that between the +45 deg. polarized branch and –45 deg. polarized branch, are calculated over a 10-m interval along the measurement course. The average arrival angle of the incident wave, $_0$, is assumed to be the same as the direction of the MS, and it is calculated from the position of the MS.

TABLE 1: MEASUREMENT CONDITIONS

Measurement area	Aoyama (Tokyo)
Frequency	2.2 GHz
Transmission power	43 dBm
BS antenna height	70 m (G.L.)
MS antenna height	3 m (G.L.)
BS antenna (Rx)	Sleeve antenna •4 (V-polarization, H-polarization, ·45 deg. polarization, 45 deg. polarization, Gain: 2 dBi)
MS antenna (Tx)	Sleeve antenna (V-polarization, Gain: 2 dBi) Slotted cylinder antenna (H-polarization, Gain: 2 dBi)
Tx polarization	45 deg. polarization (V and H-polarization transmission)

4. EVALUATION

A. *Verification of polarization diversity evaluation model*

The polarization diversity evaluation model described in Section 2B is verified through comparison to measurement results. These results are as follows.

Figure 5 shows the dependence of ΔL on the arrival angle, $_0$. Markers represent measurement results, and lines represent theoretical results. In the theoretical analysis, the XPD between the MS and BS is Γ = 6 dB (generally observed in urban areas [1, 2]), and arrival angular spread σ_H is set as a parameter. Figure 5 shows that the theoretical and measurement results agree relatively well pertaining to the following characteristics.

1) For VH-PD, when $_0$ increases, ΔL becomes large.
2) For 45-PD, ΔL is approximately 0 dB and independent of $_0$.

Figure 6 shows the dependence of ρ on arrival angle $_0$. Similar to Fig. 5, the markers represent the measurement results and the lines represent the theoretical results. In the theoretical analysis, Γ= 6 dB and σ_H is set as a parameter. Figure 6 shows that the theoretical and measurement results agree relatively well pertaining to the following characteristics.

1) On VH-PD, ρ is independent of $_0$ and it is uncorrelated.
2) On 45-PD, when $_0$ increases, ρ becomes high.

As stated above, the theoretical and measurement results agree relatively well pertaining to both ΔL and ρ. Therefore, the results show that the polarization diversity evaluation model described in this paper is valid.

B. Evaluation of polarization diversity gain

Figure 7 shows polarization diversity gain G calculated from the results of Figs. 5 and 6, provided that σ_H is 5 deg. based on the measurement results reported previously [11]. Measurement values in this paper are obtained from CW measurements. Accordingly, we assume that (N_0, ΔL_p) = (3, 4.5 dB) in the delay profile model, in both the theoretical and measurement data. From Fig. 7, we understand the following points.

1) VH-PD and 45-PD are in agreement concerning the diversity gain.
2) When $_0$ increases, diversity gain G becomes low.

When $_0$ = 0 deg., G is approximately 4 dB. When $_0$ = 90 deg., G is almost 0 dB. Here, in the measurement, G for VH-PD is slightly higher than that for 45-PD. For this reason the average reception power at each branch is normalized by the average reception power, P_α, at branch V($\alpha = 0$ deg.).
Figure 7 shows that the theoretical and measurement results agree relatively well. Therefore, Figs. 8 and 9 show only the theoretical results for VH-PD. Figure 8 shows the dependence of G on the angular spread and Fig. 9 shows the dependence of G on the delay spread (or delay profile). As shown in these figures, when $_0$ increases, G becomes low. However in Fig. 8, when there is a large angular spread, G increases slightly. when $_0$ = 90 deg. As shown in Fig. 9, as the number of delay paths decreases, in other words, as the largest power path becomes dominant, G increases.

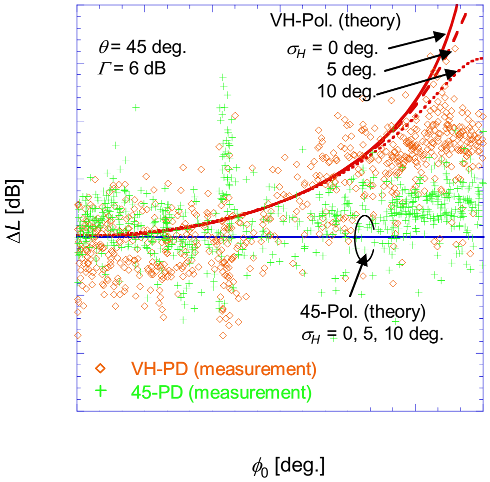

Fig. 5: Dependence of difference in received power, ΔL, on arrival angle $_0$

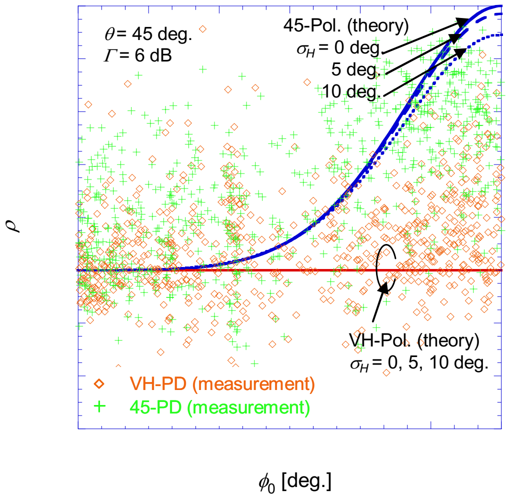

Fig. 6: Dependence of correlation coefficient on arrival angle $_{00}$

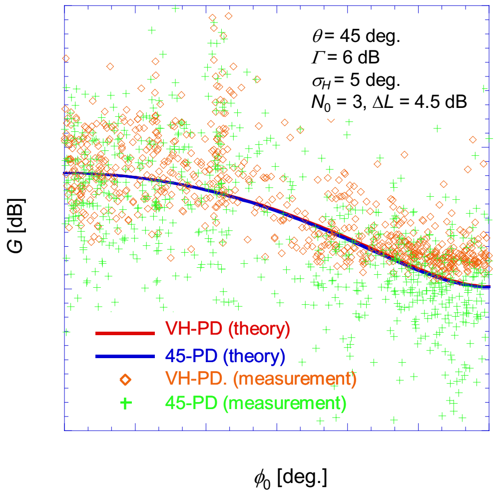

Fig. 7: Polarization diversity gain G

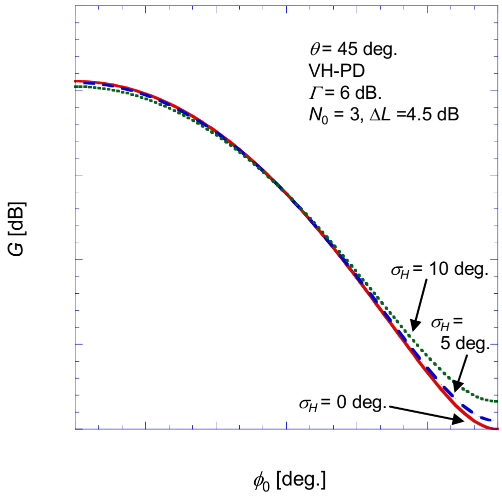

Fig. 8: Polarization diversity gain G
(dependence on arrival angular spread σ_H)

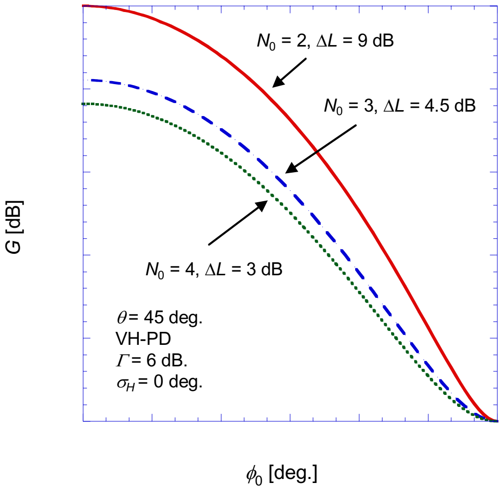

Fig. 9: Polarization diversity gain *G* (dependence on delay profile model)

5. CONCLUSION

This paper proposed the analytical method for BS polarization diversity gain in a W-CDMA system. The feature of this method is that we define the diversity gain as a transmission power value, which increases or decreases, when TPC is applied using the following model.

1) Propagation model: the delay profile and arrival angular profile are characterized as an exponential distribution and Laplace distribution, respectively.
2) Polarization diversity evaluation model: considers the arrival angle of the incident wave, the angular spread with the inclination angle of the MS and BS antennas, and XPD.
3) Diversity model in W-CDMA system: considers path diversity using RAKE reception with antenna diversity.

We also clarified the analytical results of practical diversity gain and verified the evaluation model used for theoretical analysis through comparison with 2-GHz experimental results. The results are as follows.

1) The diversity gain calculated from theoretical analysis agrees well with the measured diversity gain.
2) VH polarization diversity and ± 45 deg. polarization diversity agree concerning the diversity gain.
3) Polarization diversity gain is the largest at the main beam direction of the antenna branch array, and it is approximately 4 to 5 dB.
4) Polarization diversity gain is increased as the angular spread is increased and as the number of delay paths decreases.

However, for these features, sleeve antennas are used as antenna branches for polarization diversity. Therefore, for different constructions of antenna branches, it is anticipated that results 2) and 3) may be different from those presented in this paper.

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