An Analysis of the Performance of a Handset Diversity Antenna Influenced by Head, Hand, and Shoulder Effects at 900 MHz: Part II—Correlation Characteristics

Koichi Ogawa, Member, IEEE, Toshimitsu Matsuyoshi, and Kenji Monma

Abstract—In Part I of this two-part paper, we described the effective gain characteristics of the handset diversity antenna comprising a retractable whip antenna and a built-in planar inverted F antenna (PIFA). In order to achieve a high diversity effect, the correlation between the diversity branches must be small while at the same time maintaining a high effective gain, and this is contained in this paper—Part II. Further analysis includes an evaluation of the diversity gain with which the diversity effect shown by the analyses of the effective gain in Part I and the correlation in Part II is described. In addition, the mechanism for obtaining a small correlation coefficient is clarified by investigating the amplitude and phase radiation patterns when the whip length and the body inclination angle are changed. From these we obtain various numerical results that provide sufficient insight for design purposes. The validity of the analytical results is verified by an experiment in an indoor radio wave propagation environment.

Index Terms—Body effect, correlation coefficient, diversity, effective gain, moment method, planar inverted F antenna (PIFA), portable telephone.

I. INTRODUCTION

A MOBILE radio signal transmitted between a fixed base station and a moving hand-held terminal in a typical urban environment exhibits extreme variations in both amplitude and phase; fades of 30 dB or more below the mean level are typical. These effects are due to the random distribution of the field in which random multipaths exist due to reflection, diffraction, and scattering in land mobile propagation environments. Diversity reception techniques are commonly used in mobile communication systems to overcome deep faded [1], [2]. In Part I [3] of this two-part paper, we described the effective gain characteristics of a handset diversity antenna comprising a retractable whip antenna and a built-in planar inverted F antenna (PIFA). In order to achieve a high diversity effect, the correlation between the diversity branches must be small while at the same time maintaining a high effective gain, and this is contained in this paper—Part II.

The diversity gain is a measure of how effectively the diversity antenna functions in a practical propagation environment [1], [2] since a high diversity gain leads to a reduction of the carrier-to-noise power ratio (CNR) required to maintain a prescribed transmission quality; i.e., the average bit error rate (BER) in digital systems. It is known that the diversity gain is reduced when there is a difference in the received signal levels between the diversity branches even in the case of small correlation [4]. As with a handset diversity antenna, this unequal received signal condition is a common feature and is due to the complicated electromagnetic interaction between the two different types of antenna, which have different radiation patterns, and a human body in a normal talk situation. However, few theoretical approaches have been reported to evaluate the diversity gain taking into account this situation for this kind of antenna.

The purpose of this work (Part II) is to evaluate correlation coefficients with regard to the whip length, the head-to-radio separation, and the radio inclination angle from the vertical under various incident radio wave environments (Section III). Further analysis includes an evaluation of the diversity gain with which the diversity effect shown by the analyses of the effective gain in Part I [3] and the correlation in Part II is described. In Section IV, the mechanism for obtaining a small correlation coefficient is clarified by investigating the amplitude and phase radiation patterns when the whip length and the body inclination angle are changed. From these we obtain various numerical results that provide sufficient insight for design purposes. In Section V, an experiment was conducted in an indoor radio wave propagation environment to verify the analytical results of the correlation coefficient and diversity gain.

II. THEORETICAL MODEL AND DESCRIPTION

A. Antenna and Human Body Modeling

The diversity antenna comprises a whip antenna of length \(L_w\) mounted at the top of a metal case and a PIFA attached on the side plate adjacent to the upper plate. A resonant frequency of the PIFA is set to be nearly 900 MHz. A homogeneous human phantom model which includes a head, a hand and a left shoulder as shown in Fig. 1, that is identical with the model used in Part I [3], was employed in the analysis. This represents a practical use condition with a simplified structure assuming biological human tissue parameters. The head is approximated by a circular cylinder the dimensions of which are 18 cm in diameter and 25 cm in height. The hand is modeled by a simple parallelepiped holding a model of a radio with a thickness of the palm of 2 cm. The distance between the lower edge of the PIFA and the upper edge of the hand is set to be 0.5 cm. The radio

Manuscript received August 13, 1998; revised March 21, 2000.

The authors are with the Devices Development Center, Matsushita Electric Industrial Company, Ltd., Osaka 571-8501, Japan.

Publisher Item Identifier S 0018–9545(01)06844-X.
is placed inclined at angle $\alpha$ from the vertical and at distance $D$ from the head so that it is positioned between the operator’s mouth and ear. The rotation center of the radio is located at a distance of 2 cm from the top of the metal case, and accords with the ear which is located at a height of 12.5 cm from the surface of the shoulder, corresponding to the rotation center of the head, as shown in Fig. 1. A detailed description for the wire-grid modeling is given in [3].

**B. Correlation Coefficient**

Assuming that the amplitude of the incident waves is of a Rayleigh distribution and the phase distribution is uniform, the correlation coefficient $\rho_e$ of the diversity antenna in Fig. 1 can be obtained as shown in (1) at the bottom of the page [5], [13], where $E_{\theta k}$ and $E_{\phi k}$ ($k = 1, 2$) are the complex expressions of the $\theta$ and $\phi$ components of an electric field pattern which includes the phase difference due to antenna displacement. $E_{\theta k}$ and $E_{\phi k}$ are calculated by the wire-grid model shown in [3, Fig. 2], in which simultaneous conjugate-matched condition for the two antennas in free space, as is discussed in Part I [3], is assumed. $P_{\theta}(\Omega)$ and $P_{\phi}(\Omega)$ are the $\theta$ and $\phi$ components of the angular density functions of incoming plane waves and XPR is the cross-polarization power ratio. $P_{\theta}(\Omega)$ and $P_{\phi}(\Omega)$ are from a statistical model in which the angular density functions are assumed to be Gaussian in elevation and uniform in azimuth given by [3, eqs. (18) and (19)].

**C. Diversity Gain**

In general, the cumulative probability distribution of received signals for two-branch selective diversity under unequal median values and correlated signal conditions is given by the following equation [4]:

$$P(\gamma) = 1 - \exp\left(-\frac{\gamma}{\Gamma}\right)Q\left(\sqrt{\frac{2\gamma}{\Gamma(1 - \rho_e)}}, \sqrt{\frac{2\rho_e \gamma}{\Gamma(1 - \rho_e)}}\right) - \exp\left(-\frac{\gamma}{\Gamma}\right) \left[1 - Q\left(\sqrt{\frac{2\rho_e \gamma}{\Gamma(1 - \rho_e)}}, \sqrt{\frac{2\gamma}{\Gamma(1 - \rho_e)}}\right)\right]$$

(2)

where

- $\gamma$: instantaneous CNR after selection,
- $\Gamma$: average CNR of branch #1, and
- $\rho_e$: correlation coefficient.
- $r$: ratio of the median values of branch #2 to branch #1, in which the median value of branch #1 is assumed to be greater than that of branch #2 ($0 < r < 1$).
- $Q$: Marcum’s $Q$ function defined by the following equation:

$$Q(\alpha, \beta) = 1 - \int_{\alpha}^{\beta} t I_0(\alpha t) \exp\left(-\frac{\alpha^2 + t^2}{2}\right) dt$$

(3)

where $I_0(x)$ is the modified Bessel function of zeroth order.

Since the average CNR $\Gamma$ and the median value $\Gamma_m$ are related by the equation $\Gamma_m = \Gamma \ln 2$, the cumulative probability distribution as a function of relative received signal level $\gamma/\Gamma_m$ is calculated from equations (2) and (3). Because the mean effective gain (MEG) [6] treated in Part I [3] is the ratio of the mean received power to the total power of incident waves [3, eq. (14)] when the radio moves in a multipath propagation environment, the median value ratio $r$ is given by the following equation:

$$r = r_m \quad (r_m \leq 1)$$

$$= 1/r_m \quad (r_m > 1)$$

(4)

where

$$r_m = \frac{G_{ex}}{G_{ew}}$$

(5)

$G_{ex}$ and $G_{ew}$ are the MEG of the PIFA and the whip antenna. $r_m$ represents the ratio of the MEG’s of the respective antennas, in which the MEG of the whip antenna is greater than that of the PIFA in the case of $r_m < 1$ and vice versa in the case of $r_m > 1$. By calculating $\rho_e$ and $r$ from Eqs. (1)–(5), the diversity gain of the diversity antenna in Fig. 1 under unequal median values and correlated signal conditions is given by the following equation:

$$G_{div} = \frac{(\gamma/\Gamma_m)_{\text{Rayleigh}}}{(\gamma/\Gamma_m)_{\text{Rayleigh}}}$$

(6)
where the numerator represents a relative signal level corresponding to a probability of 1%, a criterion commonly used in mobile communications, in (2), and the denominator represents a relative signal level of a probability of 1% in the case of the Rayleigh distribution (0.0146: -18.35 dB).

III. ANALYTICAL RESULTS

A. Correlation Coefficient

Portable telephones are used practically at various inclinations from the horizontal to the vertical and the average inclination angle from the vertical is reported to be about 60° for a normal talk position [7]. Thus, for the purpose of design of the diversity antenna analyses were made with the telephone upright and with an inclination angle of 60° as basic configurations.

Fig. 2 shows the correlation coefficient with respect to whip length $L_w$, with mean elevation angles, $m_V$ and $m_H$, and standard deviations, $\sigma_V$ and $\sigma_H$, of the $\theta$ and $\phi$-component incident wave distributions as parameters. Here, XPR is set to be 6 dB since the measured cross-polarization power ratio in urban areas is known to be 4 to 9 dB [8]. $m_V$ and $m_H$ are determined from the measured results of mean elevation angles (0°−40°) in a propagation environment for portable telephones at 900 MHz [9].

Fig. 2(a) indicates that for an elevation angle of 0° (horizontal) a small correlation coefficient of less than 0.3 is obtained at any whip length. However, for elevation angles more than 20° the correlation coefficient increases with increasing elevation angle and large correlation coefficients of 0.6 to 0.7 are observed when $m_V = m_H = 60°$. Since the incident waves in the 900-MHz land mobile environment mostly arrive at elevation angles of less than 20° in rural areas more than 1 km away from a base station [9], Fig. 2(a) suggests that the diversity antenna should show a good diversity effect at any whip length in these environments. However, the incident waves arrive at relatively high elevation angles, from 20° to 40°, in urban areas, and thus in these environments, the diversity effect may be lower.

Fig. 2(b) shows the effect of the standard deviation of the incident wave distribution on correlation coefficient. It can be seen from the figure that correlation coefficients of less than 0.5 are obtained for standard deviations of more than 20°, in which the waves are spread over a wide angle, whereas the correlation coefficients become large for a standard deviation of 1°, in which the waves are concentrated in a narrow angle. From the viewpoint of the actual propagation environment, however, the incident wave angles are not narrow, so that the correlation coefficient does not exceed 0.5 under the conditions assumed in Fig. 2(b).

Fig. 2(c) and (d) show the correlation coefficients with an inclination angle of 60°. From the figures, small correlation coefficients of less than 0.3 are obtained regardless of the elevation angle and standard deviation. Note that a half-wave-length whip antenna gives an almost uncorrelated condition. It
can be understood from the results that a correlation coefficient during talking with commercial telephones is expected to be sufficiently small.

By comparison between the calculated results in Fig. 2 and those in free space (see reference [10, Fig. 12, p. 1009], [14]), it is found that there is a significant discrepancy in the correlation behavior with changing elevation angle of the incident waves when \( D = 2 \) cm. From the literature [10], [14], it was found that a quarter-wavelength whip antenna gives a small correlation of 0.3 at all elevation angles. In Fig. 2(a), however, the correlation becomes large at high elevation angles. This is accounted for by changes in the radiation pattern due to a human body. The mechanism for this phenomenon will be considered in Section IV.

Fig. 3 exhibits the correlation coefficients as functions of radio body inclination angle from the vertical at \( D = 2 \) cm with XPR as a parameter. The whip antenna is of a quarter-wavelength [Fig. 3(a), (b)] or a half-wavelength [Fig. 3(c), (d)]. The standard deviation of the incident waves is 40° and elevation angles are 0° and 20°. When \( L_w = \lambda/4 \), a small \( \rho_e \) of less than 0.3 is obtained for all inclination angles in the case of XPR = 0 and 9 dB while \( \rho_e \) becomes large for the upright configuration when XPR = -9 dB, in which the \( \phi \)-components of the incident waves are dominant in the propagation environment of interest. Thus the reason for this large \( \rho_e \) may be related to the \( \phi \)-components of the radiation patterns, which is discussed in Section IV. When \( L_w = \lambda/2 \), an almost uncorrelated situation is seen at inclination angles of more than 60°, which is also discussed in Section IV.

Fig. 4 exhibits the correlation coefficients with respect to radio-to-head separation with elevation angles of incident waves as parameters. \( \rho_e \) changes little with changing \( D \) and a small \( \rho_e \) of less than 0.3 is obtained.

### B. Diversity Gain

Fig. 5 presents the diversity gain versus head-to-radio separation at \( D = 0.5 \) cm and XPR = 6 dB calculated from the correlation coefficients in Fig. 4 and the mean effective gains in [3, Fig. 11(b)]. The handset has a quarter-wavelength whip antenna. When the handset approaches a head (\( D = 0.5 \) cm) a diversity gain of 9 to 9.5 dB is obtained for elevation angles of incident waves of 0° to 40° and the gain decreases gradually as \( D \) increases. When \( D = 5 \) cm, \( G_{\text{div}} = 8 \) to 8.5 dB for \( m_V = m_H = 0° \) to 40°. As shown in Fig. 4, \( \rho_e \) remains at an almost constant value of 0.2 regardless of \( D \) under the conditions assumed in Fig. 5. As for the MEG in [3, Fig. 11(b)], on the other hand, the two antennas offer different behavior; the MEG of the whip antenna increases as \( D \) increases while that of the PIFA changes little due to an effect of the hand (see [3]). From this, an increase in \( D \) gives rise to a decrease in the median value ratio \( \gamma \) between the diversity branches, which in turn leads to a degradation of the diversity gain shown in Fig. 5. Fig. 5 also shows that the diversity gain is lower at low elevation angles of the incident
The reason for this behavior is also due to a decrease in the median value ratio \( \gamma \) at low \( m_{\lambda Y} \) and \( m_{\lambda H} \) values as can be seen in [3, Fig. 11(b)]. Described in this manner, with regard to the handset diversity antenna, the diversity gain is influenced by an unequal median value condition caused by a difference in the electromagnetic interaction between the antennas and the human body.

Fig. 6 shows the diversity gain versus whip length at \( \alpha = 60^\circ \) and XPR = 6 dB. After a half-wavelength whip antenna is expected to have a high diversity effect since it offers a high effective gain and at the same time a high diversity gain.

Fig. 7 exhibits the diversity gain as a function of inclination angle of the radio. The reason for a high diversity gain at XPR = 0 dB in Fig. 7(a) is due to a small \( \rho_e \), in Fig. 3(a) and a small difference in the MEG values in [3, Fig. 13(a) and (b)]. The reason for a low diversity gain at XPR = 9 dB with \( \alpha > 30^\circ \) in Fig. 7(a) is a large difference in the MEG values in [3, Fig. 13(a) and (b)]. Variations in the diversity gain in Fig. 7(b) correspond to the unequal median value caused by the MEG behavior in [3, Fig. 13(c) and (d)] since sufficiently small \( \rho_e \) is obtained as shown in Fig. 3(c).

IV. CONSIDERATIONS

In order to consider the correlation coefficient behavior described in Section III, the radiation patterns were investigated. If the amplitude radiation characteristics for half-wavelength and quarter-wavelength whip antennas, and (c) and (d) show the phase differences between the two antennas, which are defined as the phase of the PIFA minus the phase of the whip antenna, when radio waves are received far from the source. In the figure \( \delta \) represents the elevation angle from the horizontal plane \( (x-y) \).

As can be seen from Fig. 8(a), when \( L_w = \lambda/2 \) the amplitude characteristics of both antennas are similar in shape and vary little with changing elevation angles in the range from \( \delta = 0^\circ \) to \( 60^\circ \). In the phase characteristics of Fig. 8(c), on the other hand, the maximum phase variation, defined as the difference between the maximum and minimum phases, is \( 240^\circ \) for \( \delta = 0^\circ \) (x-y plane), \( 80^\circ \) for \( \delta = 30^\circ \) and \( 45^\circ \) for \( \delta = 60^\circ \). This shows that the maximum phase variation decreases with increasing elevation angle. This is accounted for by a decrease in the spacing of two antennas in terms of phase when they are seen from a high elevation angle. This phase variation behavior corresponds to the correlation coefficient behavior in Fig. 2(a), in which, for a half-wavelength whip antenna, incident waves at a low elevation angle (less than \( 20^\circ \)) result in small correlation coefficients, whereas those at a high elevation angle (more than \( 40^\circ \)) result in large correlation coefficients. Consequently, by considering a small variation in the amplitude characteristics in Fig. 8(a), the decrease in correlation coefficients in the low elevation angle region can be best explained in terms of the phase characteristics. In Fig. 8(c) the phase characteristics are drawn for intervals of \( 15^\circ \) in \( \delta \); the spacing between the curves increases as \( \delta \) decreases. Thus phase variation as a function of \( \delta \) increases in the low-elevation-angle region. These results describe the correlation coefficient behavior in Fig. 2(b), in which the correlation coefficient decreases as the standard deviation of each component of the wave distribution increases. These relationships between the correlation coefficients and the radiation patterns at \( L_w = \lambda/2 \) mentioned above are compared to those in free space [10], [14].

Fig. 8(b) and (d) exhibit the radiation characteristics for a quarter-wavelength whip antenna. Comparing these to the half-wavelength case, sidelobes in the pattern are observed. In the an-
alytical results in free space [10], [14], it was shown that a small correlation coefficient is obtained for a quarter-wavelength whip antenna regardless of the incident wave parameters because at the sidelobes the radiation patterns of the two antennas become opposite in phase, resulting in large phase variations. However, there is no such abrupt phase change in Fig. 8(d) as shown in reference [10, Fig. 16(d)], [14], and Fig. 2(a) shows that large correlation coefficients of more than 0.5 are obtained for elevation angles of more than $40^\circ$. Thus, a possible cause of this large correlation is considered to be the mitigation of the phase variation, resulting from the reduction of radiated power from the radio body due to an effect of the hand, since the radiation pattern changes regarding whip length are caused by the currents induced on a radio body [11]. To verify the validity of this assumption, the correlation and radiation characteristics for the handset with only a hand (no head and shoulder) being attached are investigated.

Fig. 7. Diversity gain versus the inclination angle of the radio body at $D = 2$ cm: (a) $L_w = \lambda/4$ and (b) $L_w = \lambda/2$.

Fig. 8. Radiation characteristics of the whip antenna and the PIFA ($\theta$-component, $\alpha = 0$, $D = 2$ cm).

Fig. 9. Correlation coefficient versus the whip length when the handset with a hand is located in an upright configuration for $XPR = 6$ dB, $\sigma V = \sigma H = 20^\circ$, and $\alpha = 0^\circ$.

Fig. 9 shows the correlation coefficient vs. the whip length relationship when the handset with a hand is located in an upright configuration as shown in an inset in the figure. Comparing Fig. 9 with the correlation coefficient in free space (in reference [10, Fig. 12(a), p. 1009], [14]), an increase in correlation coefficient at $\theta$ can be observed regardless of the incident wave parameters. Fig. 10 exhibits the amplitude and phase radiation characteristics for the $E_\theta$-component for the same configuration. Comparing a quarter-wavelength whip case in Fig. 10(b) and (d) with those in free space ([10, Fig. 16(b) and (d), p. 1010], [14]), the radiation patterns of the PIFA change considerably and there is a significant reduction in phase variation with respect to $\phi$. For example, the maximum phase variations for $\delta = 0^\circ$, $30^\circ$ and $60^\circ$ are changed from $42^\circ$, $185^\circ$ and $120^\circ$ in reference [10, Fig. 16(d)], [14] to $20^\circ$, $80^\circ$ and $74^\circ$ in Fig. 10(d). It should be noted specifically that in Fig. 10(d) there is no abrupt phase change for $\delta = 30^\circ$. In addition, the spacing between the curves in Fig. 10(d) is smaller than that of in [10, Fig. 16(d)], [14], indicating a smaller phase variation with respect to the elevation angle. Judging from the fact that the radiation pattern changes of the PIFA in Fig. 10(b) from the free space case in [10, Fig. 16(b)], [14] could contribute to a decrease in correlation coefficient, an increase in correlation coefficient in Fig. 9 at $L_w = \lambda/4$ can be attributed to the reduction of the phase variation with respect to both $\phi$ and $\delta$ as...
shown in Fig. 10(d). It is concluded from these considerations that the hand offers an increase in correlation coefficient due to the mitigation of the phase variation, resulting from the reduction of radiated power from the radio body due to a shadowing effect by the hand. This explanation is also supported by the fact that at $L_w = \lambda/2$ no significant difference between the correlation coefficient in Fig. 9 and those in [10, Fig. 12(a)], [14] can be seen, since the variation in the radiation characteristics in Fig. 10(a), (c) from those in free space in [10, Fig. 16(a), (c)], [14] is very little compared to the $L_w = \lambda/4$ case, implying less electromagnetic coupling between the antennas and the hand. This is accounted for by small current flows on the radio body as shown in [3, Fig. 17].

Fig. 8(d) shows that the maximum phase variations for $\delta = 0^\circ$, $30^\circ$, and $60^\circ$ are $82^\circ$, $88^\circ$, and $87^\circ$ respectively, arising from the total effect of the head, hand and shoulder. In comparison with Fig. 10(d), there is an increase in the maximum phase variation for $\delta = 0^\circ$, leading to a correlation reduction at $L_w = \lambda/4$ for $m_V = m_H = 0^\circ$ in Fig. 2(a), and for $\delta = 30^\circ$ and $60^\circ$ no significant change in the phase variation can be seen, resulting in almost the same correlation in Fig. 2(a) as in Fig. 9 for $m_V = m_H = 40^\circ$ and $60^\circ$.

Fig. 11 exhibits the radiation characteristics when the telephone body is inclined. Comparing Fig. 11 to the upright case in Fig. 8, a greater variation in phase is observed particularly for a half-wavelength whip antenna. This leads to a small correlation coefficient, as illustrated in Fig. 2(c) and (d).

Fig. 12 shows the $\phi$-component radiation characteristics for the upright configuration. From the figure, the radiation patterns of both antennas are similar in shape and the phase variations are very small with respect to both $\phi$ and $\delta$. This is the reason for a high correlation coefficient at $\alpha = 0$ and XPR = $-9$ dB in Fig. 3(a) and (b).

V. EXPERIMENTAL STUDY IN AN INDOOR MULTIPATH ENVIRONMENT

An experiment was conducted in an indoor radio wave propagation environment at 900 MHz to verify the analytical results of the correlation coefficient and diversity gain. Fig. 13 shows the experimental setup, which is identical with that of [3, Section VI]. The experiment was conducted in a typical laboratory with concrete walls, and plastic boards on a concrete base for the floor and ceiling. The transmitting antenna was located vertically on the floor and the receiving signals were sampled by an A/D converter simultaneously with the receiving whip antenna and PIFA close to the human phantom (Fig. 1) which was moving around on a rotating arm of 1.5 m. A partition wall was placed between the transmitting and receiving antennas so that the out-of-sight condition was maintained. Both antennas were located at the same height of 1.5 m from the floor, which was the ceiling–floor center position.

The experimental procedure and method for incident wave parameter measurement is explained in detail in the literature.
Table I shows the measured incident wave parameters, assuming the incident wave distribution to be Gaussian in elevation and uniform in azimuth.

Fig. 14 shows the measured correlation coefficients when the human phantom was directed to $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$ relative to the tangential direction of the rotating arm. The average value for the four measurements is also shown. A solid line in the figure shows the calculated correlation coefficient. For the same reason mentioned in [3, Section VI], the measured result in Fig. 14 that should be compared with the analytical result is the average value of the four directions. The average values show a good agreement with the calculated ones, indicating the validity of the analysis of correlation coefficient conducted in this paper.

Fig. 15 shows the cumulative probability distribution for $L_w = \lambda/2$. Two dashed lines indicate the theoretical curves for Rayleigh distribution and a two-branch selective diversity in (2) when XPR = 4.4 dB, $\sigma_V = 27^\circ$, $\sigma_H = 58^\circ$, and $\mu_V = \mu_H = 0^\circ$. From Fig. 15 the receiving signals for both antennas exhibit nearly Rayleigh distributions and the signals combining after diversity show good agreement with the theoretical curve. The diversity gain can be obtained from a difference between the average receiving signal level for the two antennas and the signal level after combining at 1% probability. The diversity gain is determined to be 9 dB as shown in Fig. 15, which is only 0.5 dB smaller than the theoretical value. The experimental results show that an analysis of the diversity gain was performed with a high accuracy and the diversity antenna dealt with in this paper has a high performance in reducing deep signal fades encountered in the cellular communication environment.

VI. CONCLUSION

In Part II of this two-part paper, an evaluation of correlation coefficients with regard to the whip length, the head-to-radio separation, and the radio inclination angle from the vertical under various incident radio wave environments is given. Further analysis includes an evaluation of the diversity gain with which the diversity effect shown by the analyses of the effective gain in Part I [3] and the correlation in Part II is described. From these we obtain various numerical results that provide sufficient insight for design purposes.

To discuss the optimum structure of the diversity antenna, one important consideration involves the transmission quality prescribed in the system design, which is the average bit error rate (BER) in digital systems, produced by the antenna correlation and effective gain characteristics, and this is left for further studies [15], [16].

REFERENCES


Mr. Matsuyoshi is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Kenji Monma was born in Kanagawa, Japan, on August 27, 1973. He received the B.S. degree in communication engineering from Tohoku University, Sendai, Japan, in 1996.

He joined Matsushita Electric Industrial Company, Ltd., Osaka, Japan, in 1996 and has been engaged in research and development work on microwave circuits and antennas for mobile communication systems.

Koichi Ogawa (M’89) was born in Kyoto, Japan, on May 28, 1955. He received the B.S. and M.S. degrees in electrical engineering from Shizuoka University, Japan, in 1979 and 1981, respectively, and the Dr.E. degree in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan, in 2000.

He joined Matsushita Electric Industrial Company, Ltd., Osaka, Japan, in 1981, where he was engaged in research and development work on a 50-GHz millimeter-wave integrated circuit and a 12/14-GHz very small aperture terminal (VSAT) satellite communication system. He is currently a Research Group Leader of Mobile Communication RF-Devices. His research interests include diversity antennas for portable handsets, compact antennas for mobile communication systems, and other related areas of radio propagation.

Dr. Ogawa received the OHM Technology Award from the Promotion Foundation for Electrical Science and Engineering in 1990. He also received the TELECOM Systems Technology Award from the Telecommunications Advancement Foundation (TAF) in 2001. He was a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan Committee on Electromagnetic Human Phantom. He was a Chairman of the technical session for antenna human interactions at the IEEE AP-S ’99 International Symposium, Orlando, FL. He also chaired technical sessions for mobile station antennas/ human interactions with mobile communication antennas at the IEEE VTC2000 and IEICE ISAP2000 International Symposia in Japan. He is listed in Who’s Who in the World.


Toshimitsu Matsuyoshi was born in Hyogo, Japan, on February 10, 1970. He received the B.S. and M.S. degrees in communication engineering from Osaka University, Osaka, Japan, in 1992 and 1994, respectively.

He joined Matsushita Electric Industrial Company, Ltd., Osaka, in 1994 and has been engaged in research and development work on microwave filters and amplifiers. He is presently engaged in research and development on antennas for mobile communication systems.

Kenji Monma was born in Kanagawa, Japan, on August 27, 1973. He received the B.S. degree in communication engineering from Tohoku University, Sendai, Japan, in 1996.

He joined Matsushita Electric Industrial Company, Ltd., Osaka, Japan, in 1996 and has been engaged in research and development work on microwave circuits and antennas for mobile communication systems.