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# An Analysis of the Diversity Antenna Gain of a Handset Diversity Antenna Close to the Human Operator

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## 1. INTRODUCTION

Correlations and effective gains of a handset diversity antenna which include electromagnetic interaction by the existence of the antenna, the hand-held unit and the human operator in the land mobile communication environment have been reported [1]. 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 system, produced by the antenna correlation and effective gain characteristics. To this end, we propose a new figure-of-merit, named the Diversity Antenna Gain (DAG), based on a signal bit-error rate to estimate the effective performance of a handset diversity antenna [2].

This paper presents an analysis of the DAG of a handset diversity antenna influenced by head, hand and shoulder effects at 900 MHz. Evaluating the DAG for the π/4-shift QPSK signals, the diversity antenna for the PDC system with a postdetection two-branch selection combining and a maximum ratio combining scheme has been analyzed. The analytical results demonstarate the effective performance of the diversity antenna under practical use situation.

## 2. THEORETICAL MODEL AND METHOD

### 2.1 Antenna and Human Body Modeling [1]

Figure 1 shows a model of a handset diversity antenna close to a human phantom used for numerical calculations. This represents a practical use condition with a simplified structure assuming biological human tissue parameters. The head is approximated by a circular cylinder. The hand is modeled by a simple parallelepiped holding a model of a radio. The trapezoidal left shoulder is located at the side of a head giving a more realistic geometrical relationship between the human body and the radio during ordinary use [3].The radio is placed inclined at angle of 60° to the vertical and at distance $D$ from the head so that it was positioned between the operator's mouth and ear. A whip antenna of length $L_w$ is mounted at the top of the metal case and a PIFA is attached on the side plate adjacent to the upper plate.The wire-grid method was employed to calculate the antenna characteristics.

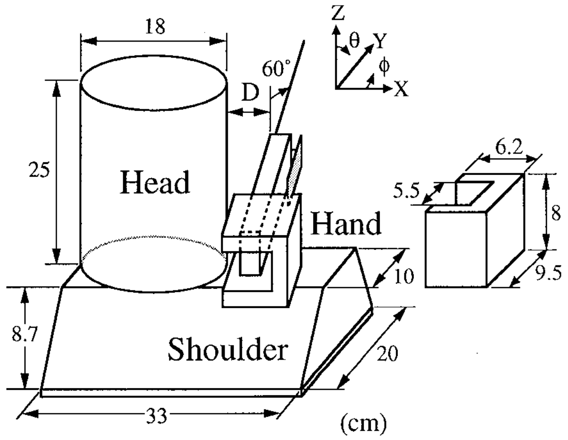

**Fig. 1 Diversity antenna close to the human operator.**

### 2.2 Diversity Combining Method

There are three main combining techniques; i.e. selection, maximum ratio, and equal gain. In a commercial portable telephone, however, antenna switching receiving method at an RF-stage is commonly used due to its simple configuration. In this paper, a postdetection two-branch selection combining (SC) at a baseband, which offers the maximum performance of the antenna switching receiving method, and a maximum ratio combining (MRC) scheme, which offers the optimum combining performance, are considered.

## 3. THEORY

### 3.1 ANTENNA CHARACTERISTICS

When a diversity antenna moves over a random route in a multiple radio wave environment of Rayleigh distribution in amplitude and uniform one in phase, the mean effective gain (MEG) $G_e$ and the correlation coefficient $\rho_e$ can be calculated using the complex radiation patterns of branch antennas [3],[4]. Since the MEG is basically defined as a ratio of receiving signal power to total power of incident waves at an observation point, the median value ratio $r$ can be obtained by the following equation:

$$r = r_m \qquad (r_m \le 1)$$
$$\quad = 1/r_m \qquad (r_m > 1) \tag{1}$$

where $$r_m = \frac{G_{ep}}{G_{ew}} \tag{2}$$

$G_{ep}$ and $G_{ew}$ are the MEG of the PIFA and the whip antenna. $r_m$ represents a ratio of MEG of respective antennas, in which the MEG of the whip antenna is greater than that of the PIFA in case of $r_m<1$ and vice versa in case of $r_m>1$.

## 3.2 AVERAGE BIT-ERROR RATE

The average bit-error rate of the diversity antenna due to time-varying attenuation can be obtained:

$$\overline{P_e} = \int_0^\infty p_e(\gamma)p(\gamma)d\gamma \tag{3}$$

where $p_e(\gamma)$ is the conditional BER when the instantaneous carrier-to-noise power ratio (CNR) at the detector input is $\gamma$ in the Rayleigh fading channel. $p(\gamma)$ is the probability density function (pdf) of the instantaneous CNR after combining. From eq. (3), the average BER for SC and MRC can be calculated in the followings:

### *A. Selection Combining*

$p(\gamma)$ of receiving signals for the two-branch selective diversity under unequal median value and correlated signal condition is given by the following equation [5]:

$$p(\gamma) = \frac{d}{d\gamma} p_r(\gamma) \tag{4}$$

$$p_r(\gamma) = 1 - \exp(-\frac{\gamma}{\Gamma})Q(\sqrt{\frac{2\gamma}{r\Gamma(1-\rho_e)}}, \sqrt{\frac{2\rho_e\gamma}{\Gamma(1-\rho_e)}})$$
$$-\exp(-\frac{\gamma}{r\Gamma})\left[1 - Q(\sqrt{\frac{2\rho_e\gamma}{r\Gamma(1-\rho_e)}}, \sqrt{\frac{2\gamma}{\Gamma(1-\rho_e)}})\right] \tag{5}$$

where $\Gamma$ is the average CNR of branch #1, $\rho_e$ is the correlation coefficient of signal envelopes. $r$ is the median value ratio defined by eq. (1). $Q$ is the Marcum's $Q$ function.

$p_e(\gamma)$ of the π/4-shift QPSK signals with delay detection in the AWGN channel is calculated by the following equation:

$$p_e(\gamma) = \frac{1}{4\pi\sqrt{2}} \int_0^{2\pi} \frac{\exp\left[-\gamma\left(1 - \frac{\cos t}{\sqrt{2}}\right)\right]}{1 - \frac{\cos t}{\sqrt{2}}} dt \tag{6}$$

Substituting eqs. (4)-(6) to eq. (3), the average BER is calculated by numerical integral.

### *B. Maximum Ratio Combining*

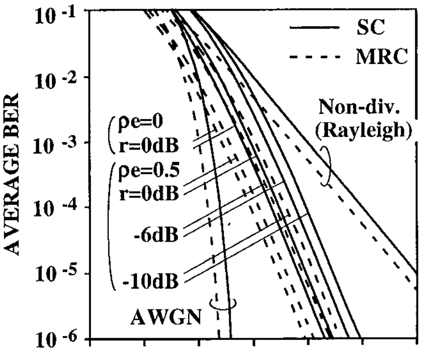

Fig. 2 BER performance of π/4-shift QPSK.

$p(\gamma)$ of receiving signals for the two-branch maximum ratio combining diversity under unequal median value and correlated signal condition can be expressed as [6]

$$p(\gamma) = \frac{1}{\lambda_1 - \lambda_2}\left\{\exp\left(-\frac{\gamma}{\lambda_1}\right) - \exp\left(-\frac{\gamma}{\lambda_2}\right)\right\} \tag{7}$$

where $\lambda_1$ and $\lambda_2$ are the eigen values for the covariance matrix of complex receiving signals and found from the following equations:

$$\lambda_1 = \frac{1}{2}\left[\Gamma_1 + \Gamma_2 + \sqrt{(\Gamma_1 + \Gamma_2)^2 - 4\Gamma_1\Gamma_2\left(1 - |\rho|^2\right)}\right] \tag{8}$$

$$\lambda_2 = \frac{1}{2}\left[\Gamma_1 + \Gamma_2 - \sqrt{(\Gamma_1 + \Gamma_2)^2 - 4\Gamma_1\Gamma_2\left(1 - |\rho|^2\right)}\right] \tag{9}$$

where $\Gamma_1$ and $\Gamma_2$ are the average CNR of each branch and expressed as $\Gamma_2=r\Gamma_1$. $r$ is the complex correlation coefficient and related to the envelope correlation coefficient $\rho_e$ as $\rho_e \fallingdotseq |\rho|^2$.

$p_e(\gamma)$ of the π/4-shift QPSK signals with coherent detection in the AWGN channel is obtained from the following equation:

$$p_e(\gamma) = \frac{1}{2} erfc\left(\sqrt{\frac{\gamma}{2}}\right) \tag{10}$$

From eqs. (7)-(10), the average BER for MRC is expressed as

$$\overline{P_e} = \frac{1}{2} - \frac{1}{2(\lambda_1 - \lambda_2)}\left(\frac{\lambda_1}{\sqrt{\frac{2}{\lambda_1} + 1}} - \frac{\lambda_2}{\sqrt{\frac{2}{\lambda_2} + 1}}\right) \tag{11}$$

Figure 2 shows the average BER for SC and MRC with the correlation and the median value ratio as parameters. The diversity gain with respect to BER is defined by the following equation:

$$G_{div} = \frac{\Gamma_{div}}{\Gamma_{sngl}} \tag{12}$$

where $\Gamma_{sngl}$ is the average CNR at the prescribed BER, e.g. $10^{-3}$, when the signals are received by the single branch which has the greater CNR of the two branches. $\Gamma_{div}$ is the average CNR in case of diversity reception. From Fig. 2, the diversity gains at a BER of $10^{-3}$ are found to be 11.8 dB for SC and 12.9 dB for MRC under uncorrelated and equal median value condition; i.e. $\rho_e = 0$ and $r = 0$ dB. In addition, Fig. 2 suggests that the diversity gain decreases significantly when there is difference in median value between branches even in the case of small correlation coefficient.

### 3.3 DIVERSITY ANTENNA GAIN

By calculating $\rho_e$ and $r$, the average BER is calculated from eq. (3) and the diversity gain can be obtained from eq. (12). Now, we define a figure $F_{div}$, which includes all effects associated with MEG, unequal median value and correlation coefficient, by the following equation:

$$\begin{aligned} F_{div} &= G_{ew} \cdot G_{div} \qquad (r_m \le 1) \\ &= G_{ep} \cdot G_{div} \qquad (r_m > 1) \end{aligned} \qquad (13)$$

By using this figure, a direct comparison between the performance of diversity antennas with different MEG and correlation characteristics can be done. In Table I, a diversity antenna *A* has a low correlation and a small MEG whereas a diversity antenna *B* has a high correlation and a large MEG, which may be a possible situation in a handset diversity antenna, and it is difficult to know which has a better performance from the view point of system requirement.

Figure 3 shows the average BER vs. relative average incident wave power $P_t / P_0$, in which $P_0$ is the total incident wave power at a place where the mobile terminal is located when the average BER becomes $10^{-3}$ assuming that the branch #1 of the diversity antenna *A* is used as single receiving antenna, and $P_t$ is an arbitrary average incident wave power.

In Fig. 3, the two straight lines denoted "Non-div." represent the characteristics when received by the branch #1 of the diversity antenna *A* or *B*. Since the MEG of branch #1 of the diversity antenna *B* is 2 dB greater than that of the diversity antenna *A*, the same BER can be obtained at a 2 dB lower average incident wave power level in the case of diversity antenna *B* in comparison with the diversity antenna *A*. As explained in this manner, an evaluation of the BER characteristics which include the antenna gain characteristics can be done easily by considering the average incident wave power as a parameter.

When the selective combining diversity reception is applied to the diversity antenna *A* or *B*, the diversity gains at an average BER of $10^{-3}$ are 9.3 dB and 9.9 dB, and thus the figures $F_{div}$ are calculated to be 6.3 dBi and 8.9 dBi respectively, as shown in Fig. 3. This indicates that the diversity antenna *B* provides an average BER of $10^{-3}$ at a place where the average incident wave power is lower by 2.6 dB in level than that for the diversity antenna *A*. This incident wave power reduction agrees with reduction in transmitting power or in antenna gain of a base station required for achieving the same average BER of $10^{-3}$. As can be seen from this explanation, the figure $F_{div}$ corresponds to the effective performance (diversity effect + antenna gain) of a handset diversity antenna in a multiple radio wave environment, and thus we call the figure $F_{div}$ the Diversity Antenna Gain (DAG). By using the DAG, the direct performance comparison between diversity antennas with different MEGs and correlations can be done from the view point of the system requirement, and thus the DAG is particularly useful in antenna design.

**Table I Performance of the diversity antennas.**

| | Diversity Antenna *A* | Diversity Antenna *B* |
|---|---|---|
| **CORRELATION** | **0.2** | **0.6** |
| **MEG (Branch#1)** | **-3 dBi** | **-1 dBi** |
| **MEG (Branch#2)** | **-7 dBi** | **-1 dBi** |

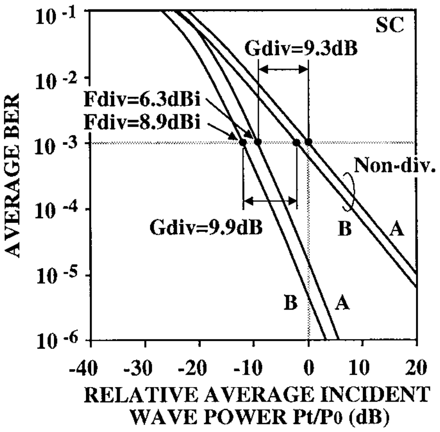

**Fig. 3 Comparison of the diversity antennas.**

## 4. ANALYTICAL RESULTS

Figure 4 shows the diversity gain and the DAG characteristics as a function of head-to-radio distance *D* with average BER as parameters. In the figures, $m_V$ and $m_H$ are the mean elevation angles and $\sigma_V$ and $\sigma_H$ are the standard deviations of incident waves, which were chosen in the same manner in the literature [1]. The analysis was made for average BERs of $10^{-1}$, $10^{-2}$ and $10^{-3}$ since the threshold BER to maintain the prescribed transmission quality exists near BER of $10^{-2}$ in the PDC system. Figure 5 shows the correlation and MEG characteristics in the same propagation environment as in Fig. 4.

Figure 4(a) shows that when the handset approaches a head ($D$ = 0.5cm) a diversity gain over 10dB at a BER of $10^{-3}$ is obtained and the diversity gain decreases gradually as *D* increases. As shown in Fig. 5(a), $\rho_e$ remains an almost constant value of 0.2 regardless of *D* under the conditions assumed in Fig. 4. As for the MEG in

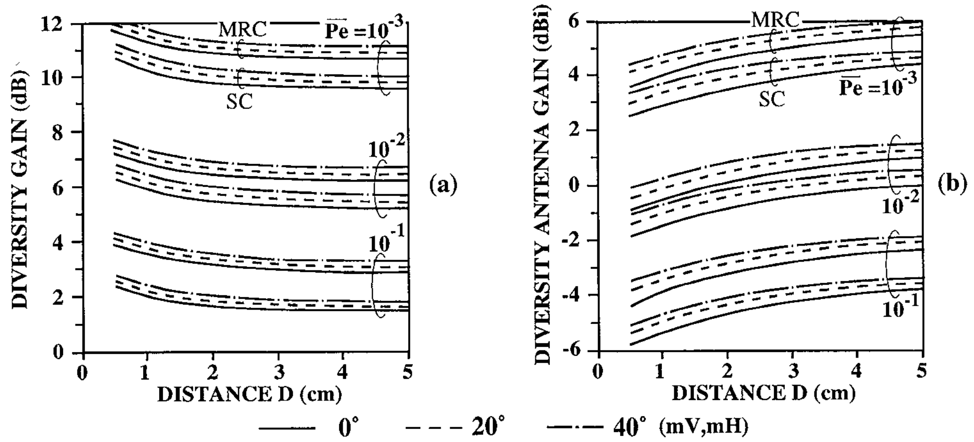

**Fig. 4 Distance *D* vs. (a) diversity gain and (b) DAG (XPR=6dB, σV=σH=40°, Lw=λ/4).**

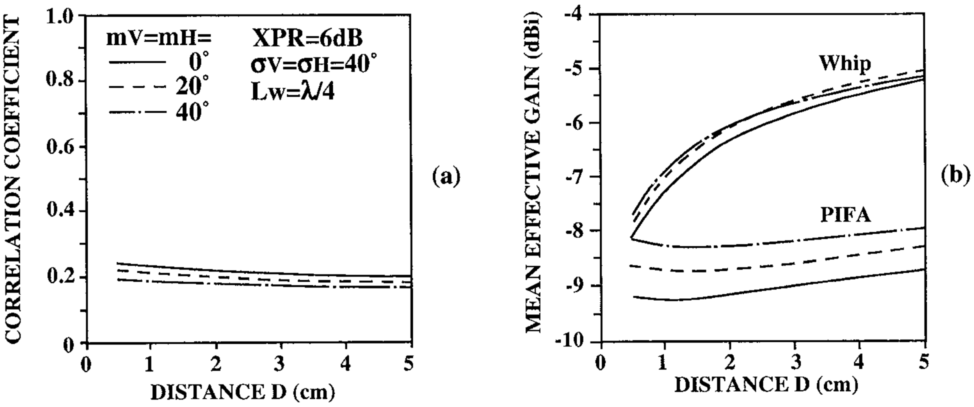

**Fig. 5 Distance *D* vs. (a) correlation coefficient and (b) MEG**

Fig. 5(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. From this, an increase in *D* gives rise to a decrease in the median value ratio *r* between the diversity branches, which in turn leads to a degradation of the diversity gain shown in Fig. 4(a). In contrast, Fig. 4(b) shows that the DAG increases with increasing *D*, which means that higher system gains are obtained, due to an increase in MEG of the whip antenna. For example, when D=0.5 cm the DAG decreases by 1dB compared with the case of D=2 cm. This DAG reduction directly indicates an increase in transmission power of a base station required for maintaining the same BER. Described in this manner, by using the DAG the effective performance of the diversity antenna from the view point of system criterion can be estimated.

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