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QDPSK Signal Transmission Performance with Postdetection Selection Diversity Reception in Land Mobile Radio

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Abstract—**Bit error rate (BER) performance of 16 ~ 128 kb/s Nyquist raised cosine filtered quaternary differential phase shift keying (RC-QDPSK) signal transmission is experimentally investigated. Two-branch postdetection selection diversity reception is employed. Measured results obtained by laboratory experiments are presented for the BER performance due to additive white Gaussian noise (AWGN), cochannel interference, and multipath channel delay spread. Field BER measurements are also conducted at a carrier frequency of 1.45 GHz in the Shinjuku area (in Tokyo), which is characterized by high-rise buildings and the Kofu area, which is surrounded by mountains. The results show that postdetection selection diversity is a simple, yet powerful technique to improve the BER performance in fading mobile radio channels.**

I. Introduction

BECAUSE of limited radio spectrum resources, bandwidth efficient modulation is required. Continuous phase modulation (or digital FM) has been extensively studied for the past decade for mobile radio applications. Recently, however, Nyquist raised cosine filtered quaternary differential phase shift keying (RC-QDPSK) has been attracting much attention [1]-[4], because its bandwidth is much narrower than that of digital FM.

Mobile radio channels are characterized by multipaths with different time delays created by signal reflection and diffraction from buildings and obstacles surrounding the mobile stations. Multipath fading is produced in these situations, and the received signal experiences rapid variations in its envelope and phase, thereby severely degrading transmission performance. For low bit rate transmissions, the errors due to additive white Gaussian noise (AWGN) and random FM noise are predominant (in this case, fading is called time selective fading). As the transmission bit rate increases, the effect of random FM noise decreases and the errors tend to be produced by time-varying intersymbol interference (ISI) from the multipath channel delay spread (in this case, the fading is called frequency selective fading). The average bit error rate (BER) due to delay spread cannot be reduced simply by increasing the transmission power, and thus the delay spread places an upper limit on the transmission bit rate. In cellular systems, the same radio frequency is reused at different cells, thus errors are also caused by cochannel interference. How effectively the frequency can be reused depends on the cochannel interference performance. Therefore, improving BER performance due to cochannel interference is also very important for cellular systems.

Diversity reception [5]-[9] is a powerful technique to reduce the impact of multipath fading. An attractive scheme for narrow-band modulation is postdetection diversity. There are three types of postdetection diversity [9]. The largest diversity gain is achieved with postdetection maximal-ratio combiner (MRC) diversity which weights the detector output of each branch in proportion to the squared value of the detector input envelope. Compared to selection diversity, the use of two-branch postdetection MRC diversity can increase diversity gain, in required average E_b/N_0 (signal energy per bit-to-noise power spectrum density ratio) and in required average signal-to-interference power ratio (SIR), by about 1.5 dB. It can also increase the tolerable root mean square (rms) delay spread by about 10% [9]. However, postdetection selection diversity is considered in this paper since it is the simplest and most practical scheme for mobile radio applications.[1]

Theoretical analysis has shown [9] that if the normalized rms delay spread (rms delay spread $\tau_{\rm rms}$/symbol duration T) is small, diversity reception can significantly minimize the BER degradation due to delay spread as well as minimizing the effect of AWGN, random FM noise, and cochannel interference. This paper is a follow-up study to [9], and experimentally investigates the BER performance of RC-QDPSK with two-branch postdetection selection diversity reception. Section II presents laboratory experimental results using a Rayleigh fading simulator. To investigate the BER performance in real fading environments, measurements were conducted in two typical areas, Shinjuku (in Tokyo), an urban area characterized by high-rise buildings and Kofu, a rural area surrounded by mountains. The field experimental results are presented in Section III.

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[1] For TDMA portable mobile radio, simple predetection selection diversity using a single receiver has already been proposed [6], [7]. Because of very slow fading, the received signal strength on each diversity antenna remains almost constant during a TDMA burst, and therefore, antenna selection just before reception of the TDMA burst can work similarly to predetection selection diversity.

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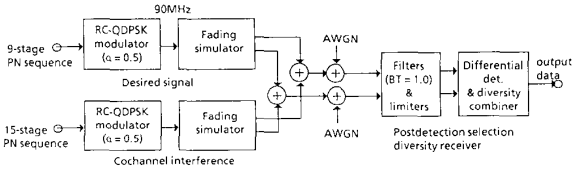


Fig. 1. Laboratory experiment block diagram.

II. Laboratory Experiments

A. Experiment Setup

The laboratory experiment block diagram is shown in Fig. 1. The input binary data are grouped into a two-bit symbol sequence and mapped to differential phase $\Delta\Phi$ of a QDPSK signal. There are two mapping rules for $\Delta\Phi$; $\Delta\Phi = \pm\pi/4, \pm 3\pi/4$ for symmetrical mapping and $\Delta\Phi = 0, \pm\pi/2, \pi$ for asymmetrical mapping. Both modulation schemes have similar BER performance (BER performance due to AWGN is identical for both modulation schemes). This experiment used asymmetrical mapping.

QDPSK signals can be demodulated by either differential detection or coherent detection with differential decoding. Coherent detection provides better BER performance than differential detection in very slow Rayleigh fading environments, however, the difference in required average E_b/N_0 is about 1 dB [10]. Differential detection is attractive for mobile radio applications because its BER performance is less affected by rapid random phase fluctuations in the received signal due to fast fading. Moreover, it eliminates the need for carrier recovery (this is extremely important for low bit rate TDMA mobile radio, because long preamble sequences for burst carrier recovery degrade the utilization efficiency of TDMA frames). In this experiment, differential detection was applied.

A 90 MHz RC-QDPSK signal with roll off factor $\alpha = 0.5$ was generated (Nyquist raised cosine transfer function of the transmission channel was realized by the transmitter filter alone), and then fed to a two-branch Rayleigh fading simulator. A nine-stage PN sequence was used as the transmitted data. The two faded signal outputs were the inputs to a two-branch postdetection selection diversity receiver employing differential detection and postdetection selection combining. Each of the two received signals was bandlimited by a Gaussian type predetection bandpass filter with $BT = 1$, where B is the 3 dB bandwidth and T is the symbol duration, and hard-limited for differential detection. The differential detector (DD), incorporating clock recovery and symbol decision functions, was implemented with digital signal processors. The DD output of the branch with the larger received signal envelope was selected.

To measure the cochannel interference performance, an RC-QDPSK ($\alpha = 0.5$) cochannel signal modulated with a 15-stage PN sequence was generated. Interference modulation timing was independent of desired signal modulation.

B. BER Performance due to AWGN and Cochannel Interference

The most practical arrangement of diversity antennas is to separate them spatially. If the antenna separation is too small, the fading signals are strongly correlated, and the diversity improvement degrades. Therefore, the average BER's were measured with the fading envelope correlation ρ_{env} between two antennas as a parameter for multiplicative Rayleigh fading.

Fig. 2 plots the measured average BER performance due to AWGN for 32 kb/s as a function of the average E_b/N_0. The maximum Doppler frequency f_D of the fading was 40 Hz (this corresponds to a vehicle speed of 24 km/h at 1.45 GHz). The diversity gain is defined as the reduced value of E_b/N_0 necessary to achieve a certain average BER. When $\rho_{\mathrm{env}} = 0$, the diversity gains at average BER $= 10^{-2}$ and 10^{-3} are 6.8 and 11 dB, respectively. As the value of ρ_{env} increases, the performance improvement with diversity reception decreases. When $\rho_{\mathrm{env}} = 0.5$, the reductions in diversity gain at average BER of 10^{-2} and 10^{-3} are 1.2 and 1.5 dB, respectively.

The cochannel interference performance is shown in Fig. 3, as a function of the average SIR. The BER performance due to cochannel interference is similar to that due to AWGN. This is because of Rayleigh fading, most errors are produced when the desired signal fades, irrespective of their cause. When $\rho_{\mathrm{env}} = 0$, diversity gains of 6.0 and 9.8 dB are obtained at average BER's of 10^{-2} and 10^{-3}, respectively. The values are about 1 dB smaller than those for fading plus AWGN channel. The degradations, due to correlation, in diversity gains at average BER's of 10^{-2} and 10^{-3}, are 0.8 and 1.2 dB, respectively, when $\rho_{\mathrm{env}} = 0.5$.

At large E_b/N_0 values, errors due to random FM noise are produced, and the BER's approach their floor values. However, measured BER with diversity reception is less than 10^{-5} even at $f_D = 100$ Hz. The effect of random FM noise decreases as the bit rate increases. Therefore, random FM noise is not important and is not considered hereafter.

At mobile stations, $\rho_{\mathrm{env}} = J_0^2(2\pi d/\lambda)$ [5], where d denotes antenna separation and λ denotes carrier wavelength. When $d = 0.18\ \lambda$ (3.7 cm at 1.45 GHz), $\rho_{\mathrm{env}} = 0.5$. Because of the cross coupling of the two antennas, an even smaller correlation can be obtained [11]. This suggests that a sufficiently low correlation can be achieved with close but separated antennas. In the following experiments, therefore, $\rho_{\mathrm{env}} = 0$ was used.

C. BER Performance due to Delay Spread

It has been shown [9] that if the normalized delay spread $\tau_{\mathrm{rms}}/T \ll 1$, the BER performance strongly depends on the value of τ_{rms}/T, and the delay profile has no importance. Hence, the fading simulator adopted a double-spike delay profile with equal power (when delay time difference between two paths is τ seconds, rms delay spread $\tau_{\mathrm{rms}} = \tau/2$). Average BER versus average E_b/N_0 at 32 kb/s with τ_{rms} as a parameter is shown in Fig. 4. It is observed that the BER's have floor values at large E_b/N_0 values because of the intersymbol interference produced by the delay spread. When $\tau_{\mathrm{rms}} = 4\ \mu$s, the error floor is about 10^{-2} without diversity reception. Diversity reception can reduce the error floor by about one order of magnitude.

To clearly see how diversity reception reduces the effects

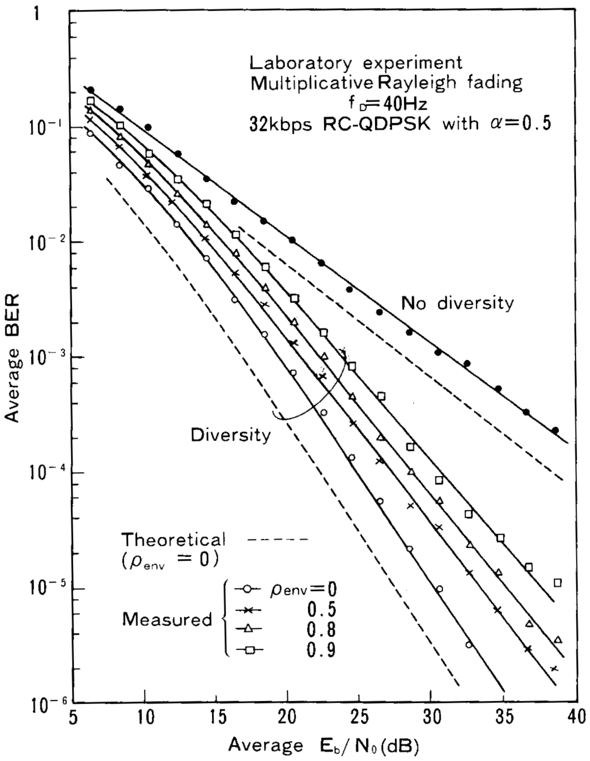


Fig. 2. Average BER performance due to AWGN. 32 kb/s.

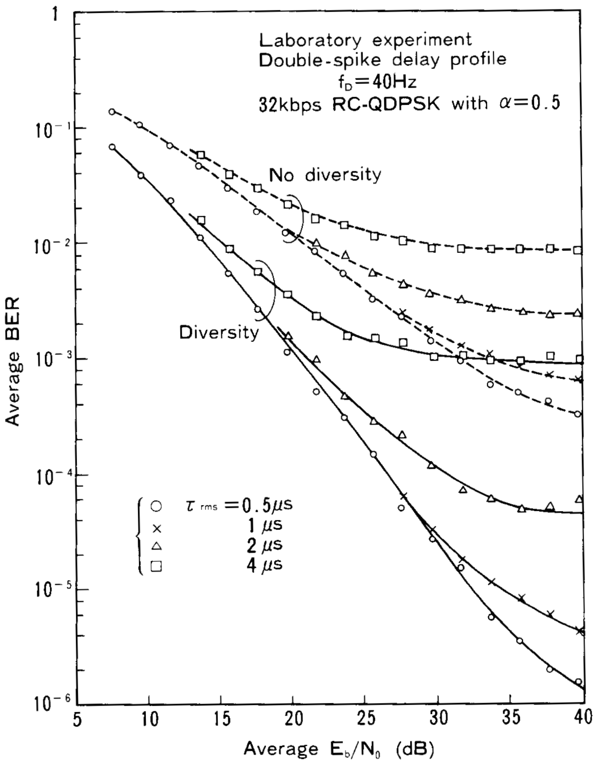


Fig. 4. Average BER performance with rms delay spread as a parameter. 32 kb/s.

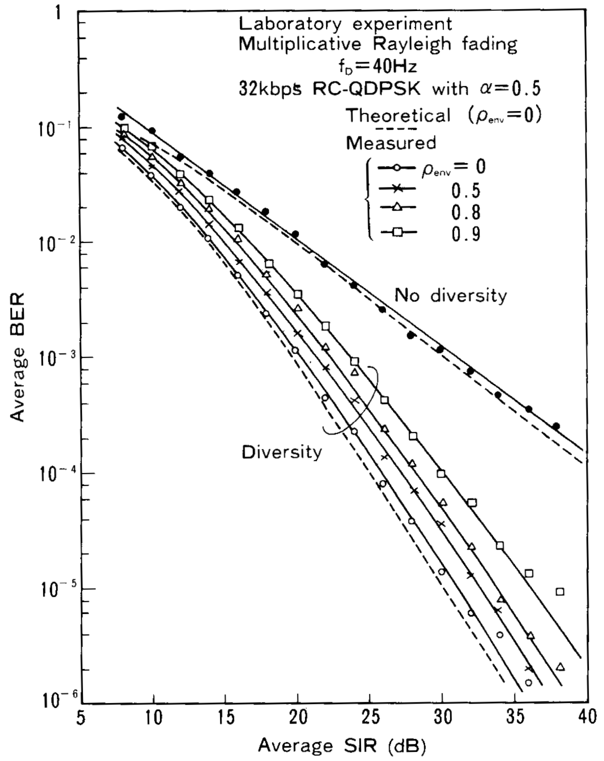


Fig. 3. Average BER performance due to cochannel interference. 32 kb/s.

of delay spread, measured average BER versus normalized rms delay spread for 32 and 64 kb/s is plotted in Fig. 5. The use of diversity can enlarge the tolerable rms delay spread necessary to achieve a certain average BER. If an average BER of 10^{-3} is required for 32 kb/s, diversity reception can increase the tolerable rms delay spread to $\tau_{\mathrm{rms}} = 4.2$ μs ($\tau_{\mathrm{rms}}/T = 6.7 \times 10^{-2}$) from 1.4 μs ($\tau_{\mathrm{rms}}/T = 2.2 \times 10^{-2}$) without diversity.

D. Comparison with Theoretical Results

BER performance of RC-QDPSK with postdetection diversity reception when $\rho_{\mathrm{env}} = 0$ was analyzed in [9] assuming very slow Rayleigh fading ($f_D \rightarrow 0$ Hz). It is assumed here that cochannel interference is also an RC-QDPSK signal, and its modulation timing is independent of the desired signal modulation. For calculation of average BER due to delay spread, a double-spike delay profile was assumed since the profile shape has negligible impact if $\tau_{\mathrm{rms}}/T < 0.1$.

The theoretical BER performances due to AWGN and cochannel interference are shown as dotted lines in Figs. 2 and 3, respectively. The measured BER performance due to AWGN is about 2.2 dB degraded from the theoretical performance at BER = 10^{-2}; however, measured diversity gains are the same as the theoretical values. The measured performance with cochannel interference is in good agreement with the theory.

Theoretical curves for average BER due to delay spread

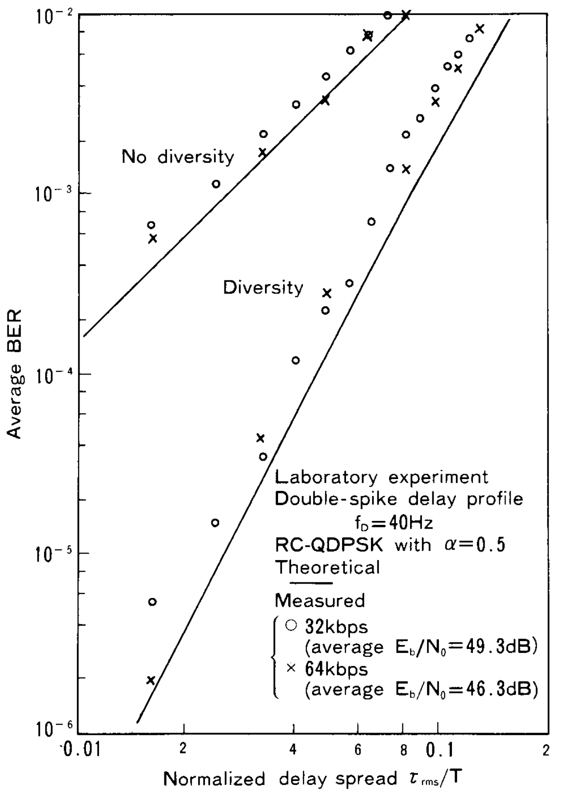


Fig. 5. Average BER due to delay spread.

are shown as solid lines in Fig. 5. Although the measured values are slightly higher than the calculated curves, good agreement is seen. This suggests that if the rms delay spread in the real fading environments is measured, then the average BER due to delay spread can be estimated.

III. Field Experiments

The field experiments used a 1.45 GHz carrier frequency. An up- (down-) frequency convertor was employed at the base (and mobile) station to allow the use of a 90 MHz RC-QDPSK modulator (diversity receiver employing differential detection and postdetection selection combining). A 1.45 GHz RC-QDPSK signal with $\alpha = 0.5$ at bit rates ranging from 16 to 128 kb/s was transmitted from a corner-reflector antenna.

Two test areas were chosen. One is the Shinjuku area in Tokyo, characterized by high-rise buildings, and the other is the Kofu area, which is surrounded by mountains. Fig. 6 shows the test routes for BER measurements. Along any test route, the short-term rms delay spread (measured over, say, 100 m) varies because of variations in gross terrain characteristics. In the Shinjuku area, the rms delay spread is relatively small; the median value of rms delay spread along the test route is about 0.84 μs [12]. In the Kofu area, long-delayed waves reflected by the mountains are sometimes received, so the median value of rms delay spread along the test route is about 1.8 μs [12].

A test vehicle was driven at a speed of around 20 km/h around both routes. Two whip antennas separated by two carrier wavelengths were mounted on top of the vehicle for diversity reception. The separation used was large enough to achieve low envelope correlations. The received signal strengths at the two antennas were measured by signal strength measuring receivers. The average BER's and median signal strengths measured over 5-s intervals (corresponding to a distance of 150 carrier wavelengths at a vehicle speed of 20 km/h) were digitally stored for later processing.

Fig. 7 shows typical variations in the received median E_b/N_0 and the 5-s average BER along the test route in the Kofu area. The solid line shows the BER's with diversity, and the dotted line shows the BER's without diversity. The measured E_b/N_0 and BER's varied with vehicle movement. Diversity clearly improves BER performance. On average, as the median E_b/N_0 increases, the average BER decreases; however, even at the same E_b/N_0 value, measured BER's were scattered possibly because of variations in the fast fading characteristics (although Rayleigh is typical). The cumulative probability distribution of measured 5-s average BERs was calculated, and an example is shown in Fig. 8 for 32 kb/s at median E_b/N_0 values of 10, 15, and 20 dB. The median BER value (under which falls 50% of the measured average BER's) at median $E_b/N_0 = 15$ dB is 3×10^{-3} with diversity reception, while the corresponding value is 2×10^{-2} without diversity.

To evaluate BER performance, the values of median BER gathered over a complete test route were calculated with 2 dB increments in the median E_b/N_0. The results are shown in Fig. 9. For 16 kb/s transmission, the required median E_b/N_0 for a median BER of 10^{-2} with diversity is about 12 dB, which is almost equal to the laboratory experimental results (in Rayleigh fading, median E_b/N_0 value = average E_b/N_0 value minus 1.6 dB). As the bit rate increases to 32/64/128 kb/s, errors tend to be caused by delay spread and BER's approach floor values. In the Kofu area, the BER performance is more severely degraded than in the Shinkuju area because of the larger rms delay spreads; the measured BER values in the Kofu area have larger floor values than those in the Shinjuku area. In the case of 128 kb/s, the required median E_b/N_0 value with diversity at BER = 10^{-2} increases by about 6 dB, while in the Shinjuku area the increase is about 2 dB. To show the dependence of the BER floor value on the bit rate, the median BER values at $E_b/N_0 = 40 \sim 50$ dB were calculated and are shown in Fig. 10.

For comparison, theoretical BER curves were also calculated. The average BER due to delay spread can be determined by the normalized rms delay spread (τ_{rms}/T). Therefore, for a given rms delay spread τ_{rms}, the average BER can be calculated as a function of bit rate. In the calculation, double-spike delay profiles with $\tau_{\mathrm{rms}} = 0.84$ μs in the Shinjuku area and 1.8 μs in the Kofu area are assumed. The calculated results are shown in Fig. 10 as dotted lines for the Kofu area and as solid lines for the Shinjuku area. It can be clearly seen that diversity reception can reduce significantly the effects of delay spread which allows the transmission bit rate to be increased.

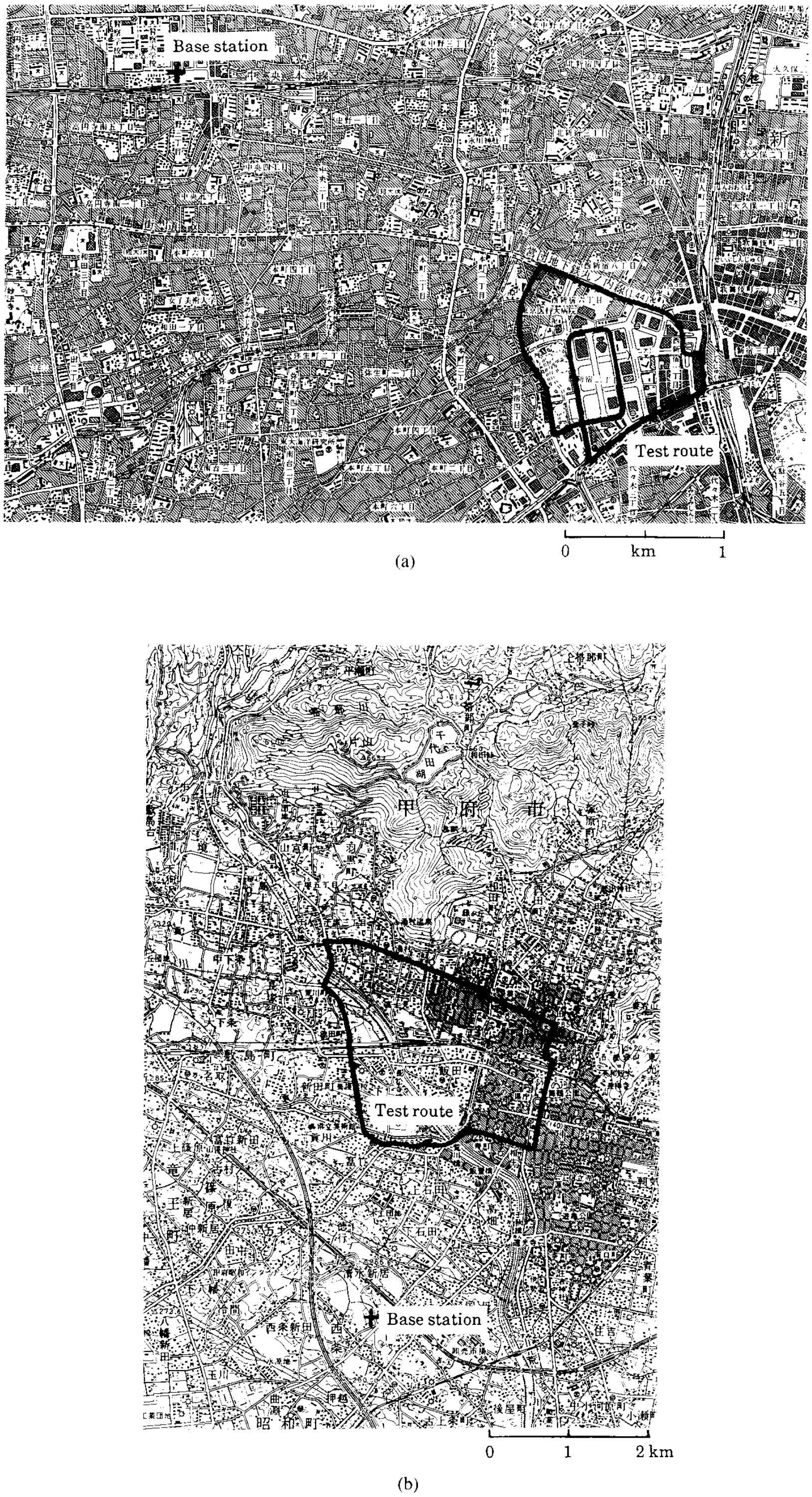


Fig. 6. Maps showing test routes. (a) Shinjuku area. (b) Kofu area.

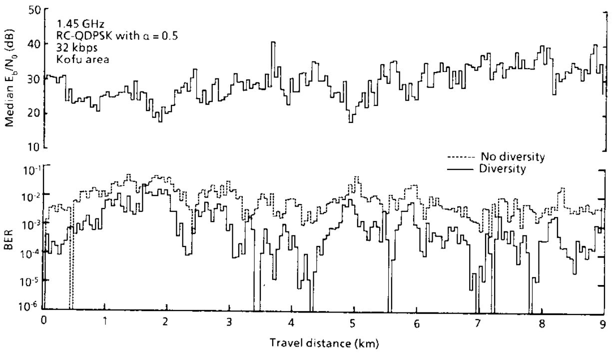


Fig. 7. Received median E_b/N_0 and 5-s average BER's along the test route in the Kofu area.

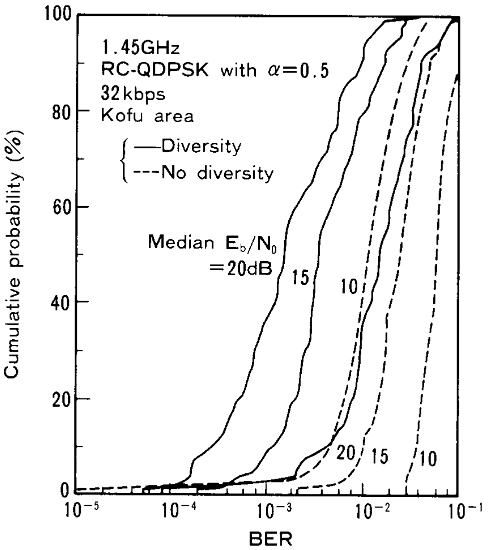
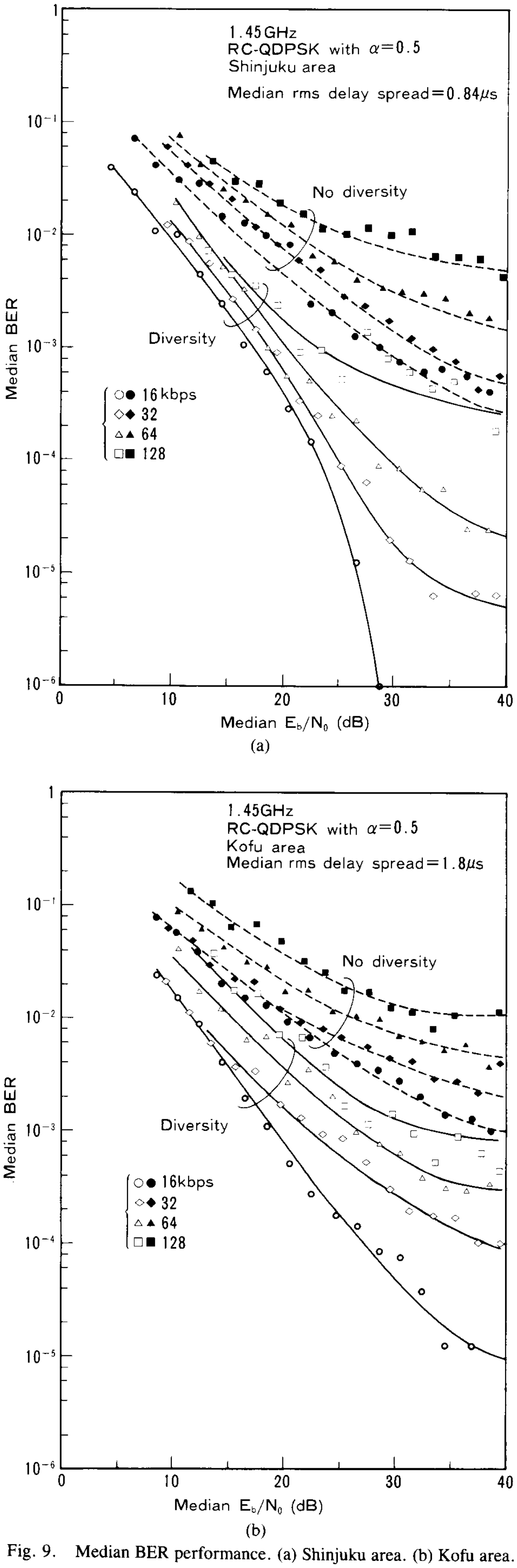


Fig. 8. Cumulative distribution of measured 5-s average BER's at median E_b/N_0 = 10, 15, and 20 dB.



(a)

(b)

Fig. 9. Median BER performance. (a) Shinjuku area. (b) Kofu area.

IV. Conclusion

This paper presented the measured BER performance of a 16 ~ 128 kb/s RC-QDPSK signal transmission scheme using diversity reception for mobile radio channels. Laboratory and field measurements have shown that two-branch postdetection selection diversity reception can significantly improve BER performance.

When slightly separated diversity antennas are used, diversity improvements reduce; however, the laboratory experiments have shown that an antenna spacing of around 0.2 carrier wavelengths can be used at the mobile station. The BER performances under frequency selective multipath fading were measured using a Rayleigh fading simulator with a double-spike delay profile. Diversity reception can enlarge the tolerable rms delay spread necessary to achieve a certain average BER. If an average BER of 10^{-3} is required, the tolerable rms delay spread normalized by symbol duration is 7×10^{-2} with diversity and 2.2×10^{-2} without diversity. Therefore, a roughly threefold increase in the tolerable rms delay spread is obtained for the given bit rate. Con-

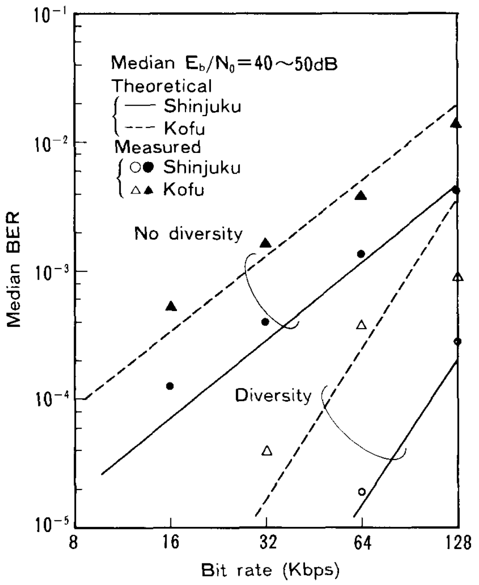


Fig. 10. Dependence of floor values of measured 5-s average BER on the bit rate.

versely a threefold increase in the bit rate is possible for a given rms delay spread. As described in [9], diversity reception can effectively work if $\tau_{\rm rms}/T < 0.2 \sim 0.3$. As the rms delay spread becomes larger than this, diversity improvement diminish and thus, an equalizer is required instead of diversity reception.

Field BER measurements in two typical areas (high-rise building area and mountainous area) were conducted. The results proved the effectiveness of two-branch selection diversity reception for QDPSK signal transmissions in real fading environments.

Currently, digital cellular systems using a 3-channel TDMA access scheme are under development in North America and Japan. QDPSK with symmetrical mapping (or, $\pi/4$-shift QDPSK) will be employed as the modulation scheme. The BER performance with symmetrical mapping is similar to that with asymmetrical mapping [9]. Because of relatively slow bit rates, i.e., 42 kb/s for the Japanese TDMA cellular system and 48.6 kb/s for the North American system, diversity reception can significantly reduce the impact of delay spread.

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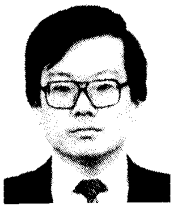

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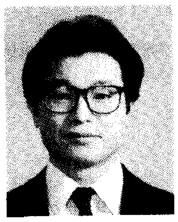

Fumiyuki Adachi (M'79-SM'90) graduated from Tohoku University, Japan, in 1973 and received the Dr. Eng. degree from the same University in 1984.

Since 1973 he has been with the Nippon Telegraph & Telephone Corporation (NTT) Laboratories, where his major activities included analytical and experimental works on diversity techniques for digital mobile radio communications. He was also concerned with man-made radio noise, syllabic compander for improving analog voice transmission quality, and statistical estimation of the signal strength in mobile radio. Besides above activities, he contributed to the development of Japanese analog cellular system with medium capacity. He is now a Research Group Leader for Mobile Communication Signal Processing at NTT Radio Communication Systems Laboratories, and is currently responsible for the development of transmission techniques including modulation/demodulation, diversity reception and error control, and on random access protocols for TDMA cellular mobile radio. During the academic year of 1984/1985, he was a U.K. SERC Visiting Research Fellow at the Department of Electrical Engineering and Electronics of Liverpool University.

Dr. Adachi authored chapters in two books, *Fundamentals of Mobile Communications*, Y. Okumura and M. Shinji, Eds., (in Japanese) (IEICE, Japan, 1986) and *Mobile Communications*, M. Shinji, Ed., (in Japanese) (Maruzen Publishing Co., 1989). He was a co-organizer/chairman of technical sessions for mobile/portable radio communications at the IEEE GCOM'86-89. He also chaired mobile radio technical sessions at IEEE VTC'88, '90, and '91 and Singapore ICCS'88. He was a member of IEEE Communications Society Asian Pacific Committee from 1986 to 1989. Since 1989 he has been Treasurer of IEEE Vehicular Technology Society Tokyo Chapter. He was awarded the 1980 and 1990 IEEE Vehicular Technology Society Paper of the Year Award. He is a member of the Institute of Electronics, Information, and Communication Engineers of Japan.