Experimental evaluation of postdetection diversity reception of narrow-band digital FM signals in Rayleigh fading

著者	安達　文幸
journal or publication title	IEEE Transactions on Vehicular Technology
volume	38
number	4
page range	216-221
year	1989
URL	http://hdl.handle.net/10097/46479

doi: 10.1109/25.45484

Experimental Evaluation of Postdetection Diversity Reception of Narrow-Band Digital FM Signals in Rayleigh Fading

FUMIYUKI ADACHI, MEMBER, IEEE, AND KOJI OHNO, MEMBER, IEEE

Abstract—**Postdetection diversity is attractive for narrow-band digital FM signal reception because a cophasing function that may be difficult to realize in a fast Rayleigh fading environment, is not required. The combining scheme evaluated in this paper weighs each frequency detector (FD) output in proportion to the νth power of the received signal envelope of that branch. Maximum diversity improvement can be obtained when $\nu = 2$ (this combiner is referred to as postdetection maximal ratio combiner (MRC) in this paper). This paper presents experimental results of postdetection diversity reception in the Gaussian minimum shift keying (GMSK) signal transmission system. Diversity combining and FD-decision algorithms (decision feedback equalizer (DFE) and maximum likelihood sequence estimator (MLSE)) are performed by software on a computer using the data of the sampled FD output and received signal envelope obtained from a laboratory transmission system. It will be shown that the MRC can attain about a 1-dB larger diversity gain than the selection combiner (SC) when two-branch diversity is used. The degradations of two-branch diversity improvement caused by the differences between FD sensitivities and between received signal envelope detector gains are evaluated.**

I. Introduction

In DIGITAL mobile radio, a narrow-band digital FM modulation or continuous phase modulation (CPM) [1] is a promising modulation scheme because of its narrow-band power spectrum and constant envelope property (Gaussian minimum shift keying (GMSK) [2] and generalized tamed FM (GTFM) [3] are special cases of narrow-band digital FM). Although both coherent and noncoherent (differential and frequency) detection can be applied to the reception of narrow-band digital FM signals, frequency detection is of much greater interest because of its resistance to carrier frequency drift and also because carrier recovery is not required. However, the bit error rate (BER) performance with frequency detector (FD) reception is severely degraded by the increased intersymbol interference (ISI) due to premodulation filtering used in a narrow-band digital FM systems. Several improved decision schemes using decision feedback equalizer (DFE) [4], [5] and maximum likelihood sequence estimator (MLSE) [3], [6] have been investigated.

It is well known that signal transmissions for land mobile radio suffer from multipath Rayleigh fading, which severely degrades the BER performance. Diversity reception [7] is a powerful technique to reduce the impact of fading. Predetection diversity that coherently combines the received signals before demodulation may be difficult to implement because of fast phase variations in the received fading signal. Another reason for the preference of postdetection diversity is that if a predetection selection combiner (SC) is used, switching between two fading signals may cause an abrupt phase change that will produce bit errors. Postdetection diversity combines the detector outputs which are in phase; therefore, it requires no cophasing function, and can be applied to narrow-band digital FM systems. Recently, Adachi *et al.* [5], [8] predicted theoretically that when each FD output is weighted before combination in proportion to the square of the received signal envelope, the two branch postdetection diversity gain is only about 0.9 dB inferior to the predetection maximal-ratio combiner (MRC) and that about a 1.5-dB larger diversity gain than SC is possible.

This paper presents a follow-up study to [5] and [8] and emphasizes the experimental evaluation of postdetection diversity reception of narrow-band digital FM signals. Section II describes a postdetection diversity combining scheme that weights the detector outputs in proportion to the νth power of each received signal envelope and combines them before the decision operation. In Section III, the postdetection combining is applied to a GMSK transmission system and the average BER performance obtained by computer simulation using data on sampled FD outputs (eyes) and received signal envelopes are presented. MLSE and DFE are considered as decision schemes. How the value of ν affects the average BER is first investigated. Next, the BER performance of MRC ($\nu = 2$) is compared with that of SC.

Both the DFE and MLSE algorithms are based on the sum of the FD outputs of each branch weighted by the received signal envelope. Therefore, degradations of diversity improvement caused by differences between FD sensitivities and between received signal envelope detector gains are also evaluated for two-branch diversity reception.

II. Postdetection Diversity Combining

Fig. 1 shows a block diagram of narrow-band binary digital FM signal reception with postdetection diversity combining. A transmitted signal with carrier angular frequency ω_c can be represented as $s(t) = \mathrm{Re}[A \exp j\{\omega_c + \phi(t)\}]$, where $\phi(t)$ is the modulating phase given by

$$\phi(t) = \pi h \sum_{n=-\infty}^{\infty} a_n \int_{-\infty}^{t} g(t - nT)\, dt \tag{1}$$

Manuscript received
The authors are with the NTT Radio Communication Systems Laboratories, 1-2356 Take, Yokosuka-shi, Kanagawa-ken, 238-03, Japan.
IEEE Log Number 8933131.

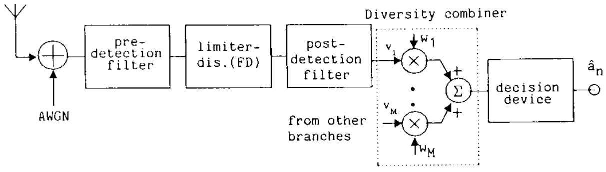


Fig. 1. Block diagram of narrow-band binary digital FM signal reception with postdetection diversity combining.

with $a_n = \pm 1$ being the nonreturn-to-zero (NRZ) data, h the modulation index, and T the bit duration. $g(t)$ is the frequency pulse response. In the case of GMSK, $h = 0.5$ and

$$g(t) = \frac{1}{2T}\left[\operatorname{erf}\left(\beta\left(\frac{t}{T}+0.5\right)\right) - \operatorname{erf}\left(\beta\left(\frac{t}{T}-0.5\right)\right)\right] \tag{2}$$

where erf(x) is the error function, $\beta = \pi B_b T\sqrt{2/\ln 2}$ and B_b is the premodulation filter 3-dB bandwidth. We assume a multiplicative fading and a predetection filter that is wide enough to prevent severe received signal distortion. The FD (a limiter–discriminator followed by a postdetection filter is assumed) delivers the instantaneous angular frequency deviation of the received signal plus additive white Gaussian noise (AWGN). The FD output of the mth branch can be represented as

$$v_m(t) = \pi h \sum_{n=-\infty}^{\infty} a_n G(t - nT) + \text{noise term} \tag{3}$$

where $G(t)$ is the response of the transmission channel including both predetection and postdetection filters to $g(t)$. When an l-bit integrate-and-dump (I&D) postdetection filtering is used, $G(t)$ becomes

$$G(t) = \int_{-lT/2}^{+lT/2} g(t-\tau)\,d\tau. \tag{4}$$

When the received signal fades, the FD output $v_m(t)$ is corrupted by noise due to AWGN. Therefore, it seems that little can be gained by simply combining all FD outputs. It is necessary to weight each FD output before combining so that the contribution of a noisy branch to the combiner output can be reduced. Letting $R_m(t)$ be the received signal envelope of the mth branch,

$$w_m(t) = \frac{R_m^{\nu}(t)}{\sum_{m=1}^{M} R_m^{\nu}(t)} \tag{5}$$

can be used as the weighting factor. $w_m(t)$ has been normalized so that the combiner output has the same eye level as in the no diversity case. The combiner output, fed to a decision device employing MLSE or DFE, is therefore represented as

$$v(t) = \sum_{m=1}^{M} w_m(t) v_m(t). \tag{6}$$

SC is a special case where the weighting factor is unity for the FD output associated with the largest signal envelope and zero for all other branches.

Using the normalized weighting factor of (5), the combiner output has a form identical to (3) except for the noise term that is now the sum of weighted noises from each FD. Therefore, this implies that improved decision schemes such as DFE and MLSE, can also be applied to postdetection diversity reception without any modification. The DFE and MLSE decision algorithms will be briefly reviewed before presenting the experimental results in Section III.

A. DFE Decision Algorithm

We assume that the nth data a_n is to be detected without loss of generality. The sampling time is assumed to be taken at $t_n = (n + \alpha)T$, where α is the appropriate sampling time offset that produces the minimum BER and is $-1/2 \leqq \alpha \leqq 0$. The combiner output is given by

$$v_n = v(t_n) = a_n \pi h G_\alpha + \pi h \sum_{k=-\infty,\neq 0}^{\infty} a_{n-k} G_{k+\alpha} + \text{weighted sum of noises}. \tag{7}$$

The second term of (7) is ISI from the past and future bits. A K-bit DFE is considered. It cancels the ISI from the past bits a_{n-k} $(k = 1, 2, \cdots, K)$ using the previous decision result $\hat{a}_{n-k}$ and subtracting $\eta_{n-k} = \hat{a}_{n-k}\pi h G_{k+\alpha}$ (where $G_{k+\alpha} = G((k+\alpha)T)$) from the combiner output prior to the decision on a_n. If all $\hat{a}_{n-k}$ are correct, then the perfect cancellation of the ISI from the past K bits is possible. The decision is based on the polarity of

$$v_n' = v_n - \pi h \sum_{k=1}^{K} \hat{a}_{n-k} G_{k+\alpha}, \tag{8}$$

and $\hat{a}_n = 1$ if $v_n' \geqq 0$ and -1 if $v_n' < 0$. The 2-bit DFE proposed by Hirono *et al.* [4] uses 2-bit I&D postdetection filtering with $\alpha = -1/2$ (thus the integration period is from $t = (n - 3/2)T$ to $(n + 1/2)T$).

B. MLSE Decision Algorithm

When the combiner output is sampled at $t_n = (n - 1/2)T$, we obtain

$$v_n = (a_n + a_{n-1})\pi h G_{1/2} + \pi h \sum_{k=-\infty,\neq 0,1}^{\infty} a_{n-k} G_{k-1/2} + \text{weighted sum of noises}, \tag{9}$$

which is a three-level eye that depends on the consecutive two bits, a_n and a_{n-1}. This correlative property is effectively used in Chung's MLSE decision algorithm [3], which is based on the assumption of white Gaussian noise and no ISI. However, click noise appears at the FD output and furthermore ISI exists in the case of GMSK. Although Chung's MLSE is not a real one in the strict sense, it significantly improves BER performance. The following three parameters U, V, and W_n are introduced [3]:

$$U = W_n + v_{n+1} - A$$

$$V = W_n + v_{n+1} + A \tag{10}$$

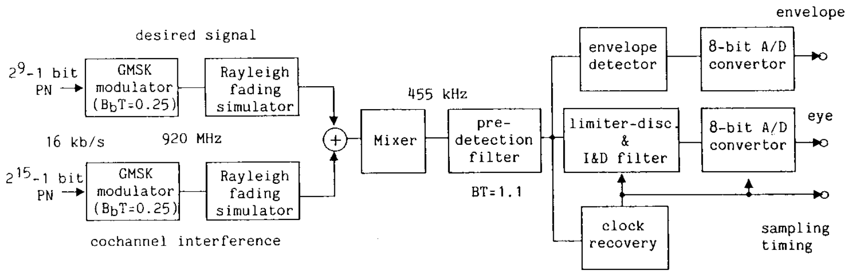


Fig. 2. Laboratory experiment block diagram (single branch).

where $A = \pi h G_{1/2}$. The decision rule is $\hat{a}_n = 1$ if $U \geqq 0$ and -1 if $V < 0$. If neither $U \geqq 0$ or $V < 0$, a definite decision is not possible, and it is necessary to store both binary sequences in output shift registers until the condition where either $U \geqq 0$ or $V < 0$ occurs. Finally, W_{n+1} is updated using the present decision result:

$$W_{n+1} = \begin{cases} v_{n+1} - A, & \text{if } U \geqq 0 (\hat{a}_n = 1) \\ v_{n+1} + A, & \text{if } V < 0 (\hat{a}_n = -1) \\ -W_n, & \text{if } U < 0 \text{ and } V \geqq 0. \end{cases} \tag{11}$$

Adachi and Parsons [8] investigated theoretically how the values of ν affect the BER and found that the BER can be minimized (or the diversity gain can be maximized) by choosing $\nu = 2$. This combiner was referred to as postdetection MRC [8]. The diversity gain of two-branch postdetection MRC approaches that of predetection MRC with a loss of about 0.9 dB in average signal energy per bit-to-noise power spectrum density ratio (E_b/N_0) when applied to MSK signal reception. This small difference in diversity gain between predetection and postdetection diversity can also be preserved for narrow-band digital FM signal reception [5]. The most attractive feature of postdetection diversity is that it requires no cophasing function to combine all FD outputs, thus its implementation is simpler. So far, postdetection SC has been extensively investigated for mobile radio use because of its simplicity [9]–[11]. However, comparison of postdetection MRC and SC predicted that [8] about a 1.5-dB larger diversity gain than SC can be obtained with $M = 2$ (two-branch diversity). This fact encourages us to apply postdetection MRC.

III. EXPERIMENTS

We applied postdetection diversity using MRC and SC to a GMSK transmission system in multiplicative Rayleigh fading environments. In cellular mobile radio systems, the same radio channels are reused for spatially separated cells, in order to efficiently use the limited radio spectrum resources efficiently. The smaller the cell size becomes, the more the transmission performance is governed by cochannel interference. Hence the improvement in BER performance in the cochannel interference limited channel is as important as that in the AWGN channel. Therefore, both channels were considered in the experiments.

The DFE decision algorithm considered here was the 1-bit type [5]. The two output shift registers used for MLSE were 16 bits each.

A. Experimental Procedure

The laboratory experiment block diagram for single branch case is shown in Fig. 2. A 16-kbit/s $(2^9 - 1)$-bit PN sequence was used as the transmitted data. A generated 920-MHz GMSK signal with $h = 0.5$ and $B_bT = 0.25$ was fed into a fading simulator to produce a multiplicative Rayleigh fading signal with a maximum Doppler frequency of 40 Hz (this corresponds to a vehicle speed of about 47 km/h). The cochannel interference signal (GMSK with $B_bT = 0.25$) was generated using a $(2^{15} - 1)$-bit PN sequence and fed to another Rayleigh fading simulator. The desired signal and cochannel interference signal were combined to form the input to the GMSK-FD receiver. The receiver had a predetection filter with a 3-dB bandwidth of 17 kHz ($BT = 1.1$) at an IF stage of 455 kHz and a limiter–discriminator followed by a 1-bit I&D postdetection filter.

Postdetection diversity combining with DFE and MLSE decision algorithms described in Section II was performed by software on the computer to allow a valid evaluation of BER performance. For this, the I&D filter output (eye) and the received signal envelope were converted into digital format using two 8-bit A/D convertors and sampled eye and envelope data were stored in memory. The maximum number of diversity branches considered in the experiment was four. Data for each diversity branch were collected using a single branch over a time interval of 32 periods of the $(2^9 - 1)$-bit PN sequence; the numbers of sampled eyes and associated envelopes were 16,352 each. The time interval between obtaining the data for each diversity branch was larger than 32 PN sequence periods and thus sufficiently large to make the fading of one branch independent of the others.

We used a sampling timing offset $\alpha = -0.25$ for 1-bit DFE (found to be optimum through experiments). The A/D range for eye conversion was $\pm 1.5\ \pi$ rad and 50 dB for the received signal envelope.

B. Results

First, the way in which the value of ν affects the average BER was investigated for 1-bit DFE. The value of w_m were first calculated using the stored received signal envelope and then the sampled eyes were weighted to allow combination according to (6). The dependence of the average BER on the value of ν for two-branch diversity ($M = 2$) is shown in Fig. 3 for various average E_b/N_0. It can be seen that, as ν increases, the average BER decreases, but it almost remains

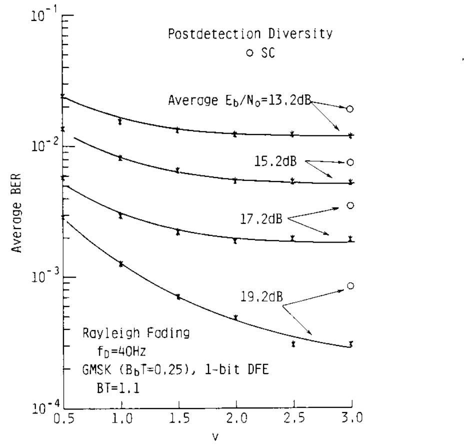


Fig. 3. Dependence of average BER on v for 1-bit DFE, $M = 2$.

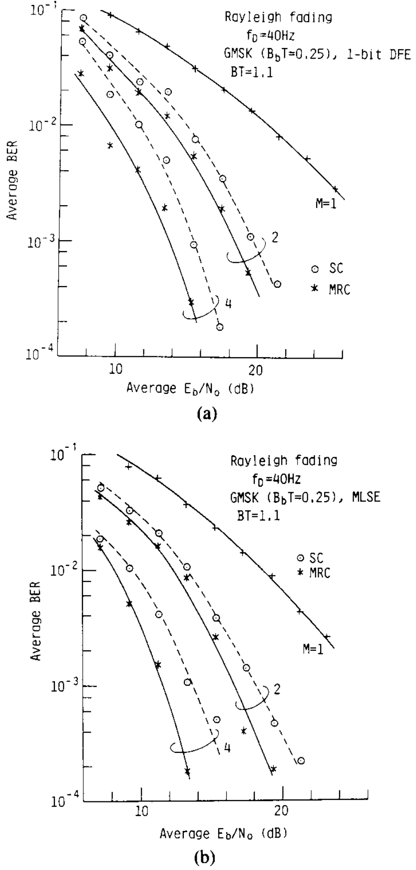


Fig. 4. Average BER performance as function of average E_b/N_0. (a) 1-bit DFE. (b) MLSE.

constant above $\nu = 2$ (MRC). This is consistent with the analysis given in [8]. For comparison, the BER's achieved by postdetection SC are plotted in the figure for the same E_b/N_0 values. As expected, MRC can achieve smaller average BERs than SC. In the subsequent experiments, both MRC and SC were used.

Fig. 4(a) and (b) show the average BER performance as a function of average E_b/N_0 for $M = 1$ (without diversity), 2 and 4 for 1-bit DFE and MLSE, respectively. It can be seen that when $M = 2$, MRC achieves a BER of 10^{-2} with about 6–7 dB less average E_b/N_0 than the no diversity case. This is about a 1-dB larger diversity gain than with SC. It was observed that as M increases, the difference between MRC and SC diversity gains tends to become larger. When $M = 4$, the diversity gain of MRC is about 10 dB at a BER of 10^{-2} which is about 2 dB larger than with SC. The average BER performance as a function of average signal-to-interference ratio (SIR) is shown in Fig. 5. The diversity gain improvement of MRC over SC is observed as in AWGN channels.

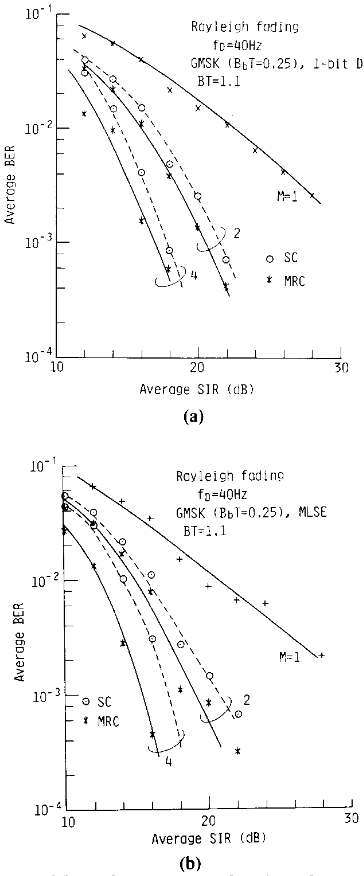


Fig. 5. Average BER performance as a function of average SIR. (a) 1-bit DFE. (b) MLSE.

Figs. 4 and 5 prove that postdetection MRC can be applied to narrow-band digital FM systems in order to yield larger diversity gains than is possible with SC. The only requirement is to weight all the FD outputs with the squared received signal envelope and combine them before input to the decision device.

Comparison of the performance achievable with the use of DFE and MLSE decision algorithms is interesting. Although Chung's MLSE is not a real one, it has been found to provide about 1 dB superior performance at a BER of 10^{-2} in both AWGN and cochannel interference limited channels. The lower performance of DFE compared with MLSE is attributed to the fact that ISI from the future bits remains uncanceled.

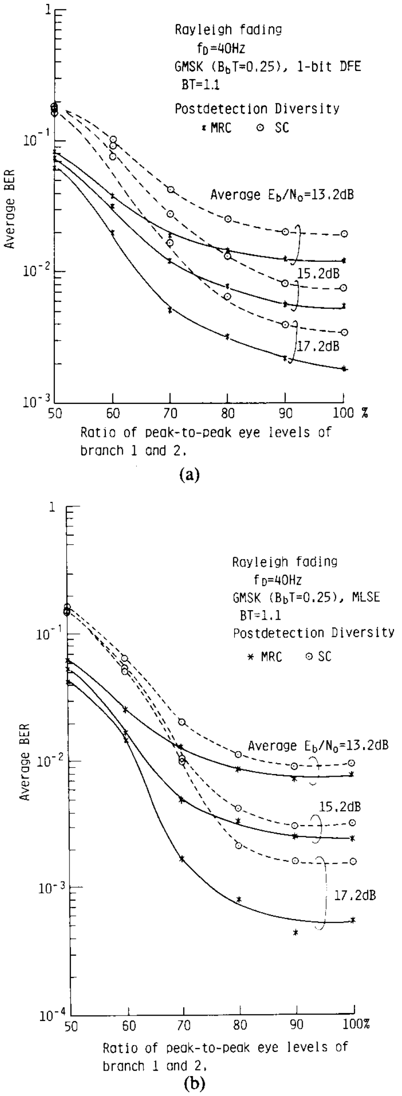


Fig. 6. Degradation due to difference between FD sensitivities. $M = 2$. (a) 1-bit DFE. (b) MLSE.

From the implementation point of view, however, the DFE decision algorithm is much simpler [5] than the MLSE decision algorithm and thus has a practical advantage over MLSE.

We have so far assumed identical FDs and identical received signal envelope detectors for all diversity branches. However, in practical receivers, there may be differences between demodulator sensitivities (or peak-to-peak eye levels without noise) and between envelope detector gains. Because both the DFE and MLSE decision algorithms are based on the sum of the weighted eye levels of each branch, those differences may degrade diversity improvements. Figs. 6 and 7 show the measured results for 1-bit DFE and MLSE when $M = 2$. It can be seen that MRC and SC experience similar degradation, however, MRC is still superior to SC. About 20-percent difference between FD sensitivities and about 2 dB difference between envelope detector gains are acceptable for both decision algorithms.

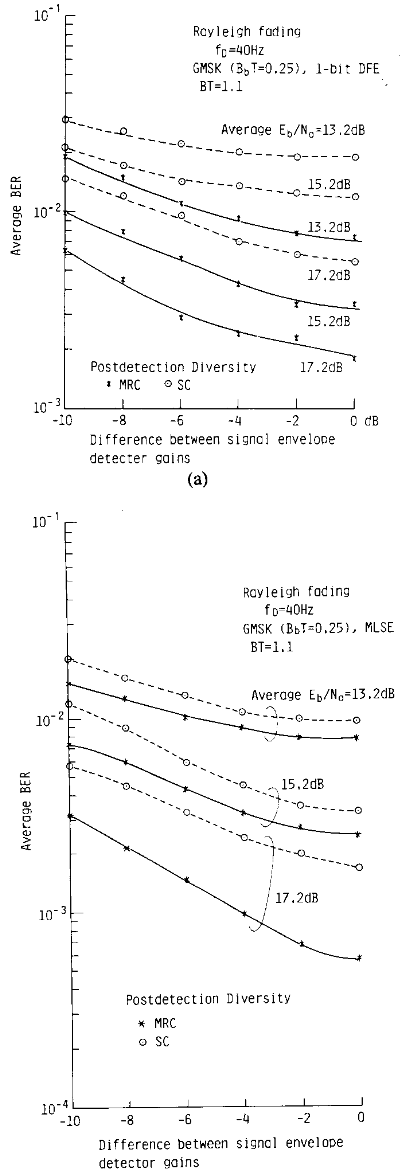


Fig. 7. Degradation due to difference between received signal envelope detector gains. $M = 2$. (a) 1-bit DFE. (b) MLSE.

IV. CONCLUSION

This paper has presented the experimental evaluation of postdetection diversity reception in narrow-band digital FM (GMSK) transmission system in multiplicative Rayleigh fading environments. As diversity combiners, both SC and MRC require the channel information of each diversity branch. The SC compares the values of the received signal envelopes and selects only the FD output of the branch having the maximum envelope. On the other hand, the MRC weights all FD outputs with the squared value of the envelope before combining them. Although the MRC algorithm adds some complexity to the combiner, diversity gains larger than those of the SC can be obtained because all FD outputs are effectively used. It has been experimentally shown that the MRC can attain about a 1-dB larger diversity gain than the SC when two-branch diversity is used. This improvement is in close agreement with the predicted value [5], [8].

In the experiment, postdetection diversity combining with improved decision algorithms was performed on a computer using the stored data of sampled eyes and received signal envelopes. This suggests the possibility that postdetection diversity combining and the decision algorithms (either DFE or MLSE) can be implemented in a single digital signal processor.

Postdetection diversity described in this paper is also applicable to other narrow-band modulation schemes such as GTFM and Nyquist pulse shaped PSK. Postdetection diversity analyzed for DPSK [7, ch. 6], and [12] is equivalent to the postdetection MRC of this paper.

REFERENCES

[1] J. B. Anderson, T. Aulin, and C. E. Sundberg, *Digital Phase Modulation*. New York: Plenum, 1986.

[2] K. Murota and K. Hirade, "GMSK modulation for digital mobile radio telephony," *IEEE Trans. Commun.*, vol. COM-29, pp. 1044-1056, July 1981.

[3] K. S. Chung, "Generalized tamed frequency modulation and its application for mobile radio communications," *IEEE J. Sel. Areas Commun.*, vol. SAC-2, pp. 103-113, July 1984.

[4] M. Hirono, T. Miki, and K. Murota, "Multilevel decision method for band-limited digital FM with limiter-discriminator detection," *IEEE J. Sel. Areas Commun.*, vol. SAC-2, pp. 498-506, July 1984.

[5] F. Adachi and K. Ohno, "Performance analysis of GMSK frequency detection with decision feedback equalisation in digital land mobile radio," *Proc. Inst. Elec. Eng.*, pt. F, vol. 135, pp. 199-207, June 1988.

[6] K. Ohno and F. Adachi, "Application of MLSE to GMSK signal reception using frequency demodulator," *Electron. Lett.*, vol. 24, pp. 1539-1540, Dec. 1988.

[7] W. C. Jakes, Jr., Ed., *Microwave Mobile Communications*. New York: Wiley, 1974.

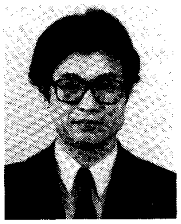
[8] F. Adachi and J. D. Parsons, "Unified analysis of postdetection diversity for binary digital FM mobile radio," *IEEE Trans. Veh. Technol.*, vol. 37, pp. 189-198, Nov. 1988.

[9] F. Adachi, "Postdetection selection diversity effects on digital FDM land mobile radio," *IEEE Trans. Veh. Technol.*, vol. VT-31, pp. 166-172, Nov. 1982.

[10] T. Miki and M. Hata, "Performance of 16 kbits/s GMSK transmission with postdetection selection diversity in land mobile radio," *IEEE J. Sel. Areas Commun.*, vol. SAC-2, pp. 512-517, July 1984.

[11] K. S. Chung, "Discriminator-MLSE detection of a GTFM signal in the presence of fast Rayleigh fading," *IEEE Trans. Commun.*, vol. COM-35, pp. 1374-1476, Dec. 1987.

[12] H. Voelcker, "Phase-shift-keying in fading channels," *Proc. Inst. Elec. Eng.*, pt. B, vol. 197, pp. 31-38, Jan. 1960.



Fumiyuki Adachi (M'79) graduated from Tohoku University, Japan, in 1973, and received the Ph.D. degree in 1984.

Since 1973 he has been with the Nippon Telegraph & Telephone Corporation (NTT) Laboratories in Japan, where he has carried out various analytical and experimental studies concerning diversity techniques in fading digital FM. He has also been concerned with the studies of man-made radio noise, voice transmission quality, syllabic compander effects, statistical estimation of the signal strength in Rayleigh fading. Currently, he is responsible for the research on digital transmission techniques including modulation/demodulation, diversity reception and error control, and on random access protocols for cellular digital land mobile radio. During the academic year of 1984/1985, he was U.K. SERC Visiting Research Fellow at the Department of Electrical Engineering and Electronics of Liverpool University, U.K.

Dr. Adachi was awarded the IEEE Vehicular Technology Society 1980 Paper of the Year Award. He is a member of Institute of Electronics, Information and Communication Engineers of Japan.

Koji Ohno (M'83) was born in Gifu, Japan, in 1958. He received the B.S. and M.S. degrees from Nagoya Institute of Technology, Nagoya, Japan, in 1981 and 1983, respectively.

In 1983 he joined NTT Laboratories. He has been engaged in the research and development of digital mobile radio communication systems. He is now a Research Engineer, NTT Radio Communication Systems Laboratories.

Mr. Ohno is a member of the Institute of Electronics and Communication Engineers of Japan.