Title	Theoretical Analysis of Synergistic Effects Using Space Diversity Reception and Adaptive Equalization in Digital Radio Systems
Author(s)	Araki, Kojiro; Komaki, Shozo
Citation	IEICE Transactions on Communications. 1996, E79-B(4), p. 569-577
Version Type	VoR
URL	https://hdl.handle.net/11094/2880
rights	copyright©2008 IEICE
Note	

Osaka University Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

Osaka University

| PAPER |

Theoretical Analysis of Synergistic Effects Using Space Diversity Reception and Adaptive Equalization in Digital Radio Systems

Kojiro ARAKI[†] *and* Shozo KOMAKI[††], *Members*

SUMMARY   The synergistic effects obtained by adopting both space diversity reception and adaptive equalization play a very important role in circuit outage reduction. This paper quantitatively analyzes these synergistic effects when dispersive and flat fading occur simultaneously. Analytical results show that the synergistic effects are of the same magnitude as the adaptive equalizer improvement factor when only dispersive fading causes outage. The synergistic effects gradually disappear when noise is the predominant cause of outage.
key words: digital radio, composite fade margin, space diversity, equalizer, synergistic effect

1. Introduction

High capacity digital microwave radio relay systems using high level modulation are advantageous in achieving a high level of reliability and various trunk-link networks. One problem experienced in these digital radio relay systems is the decrease in receiving power due to fading. Another problem has been the bit errors caused by waveform distortion due to dispersive fading [1]-[3].

To overcome these problems, a number of correction techniques, such as space diversity reception (SD) and various types of adaptive equalizers (EQ) have been developed [4]-[6]. To determine circuit performance objective, it is important to estimate the degree of improvement in outage probabilities when these correction techniques are used.

The performance improvement achieved when the correction techniques of space diversity and adaptive equalization are used jointly is different from the sum of individual improvements, and such an effect is called the synergistic effect. Pertaining to this effect, field experiments and some investigations for various fading conditions such as amplitude and the delay time of interference rays, have been reported [7]-[10]. However, analytical investigation of only dispersive fading has been conducted [11].

The circuit design of digital microwave radio

relay systems using SD and EQ requires a method for estimating the degradation caused by noise and waveform distortion. In order to estimate waveform distortion and noise using the same measure, the influence from waveform distortion should be converted into an equivalent noise level.

This paper describes an analytical investigation of the synergistic effects using a frequency coefficient [12]. The calculations for circuit outage probability are based on the concepts of flat fade margin, the dispersive fade margin, and composite fade margin proposed by Rummler [8]. In order to calculate the dispersive fade margin, we use the concept of inband amplitude dispersion probability and allowable inband amplitude dispersion [2].

2. Method for Calculating the Synergistic Effect

The synergistic effect is defined as follows:

Synergistic effect ξ

$$= \frac{\left[\begin{array}{c}\text{Outage probability improvement} \\ \text{obtained by SD and EQ}\end{array}\right]}{\left[\begin{array}{c}\text{Outage probalility improve-} \\ \text{ment obtained by SD}\end{array}\right] \cdot \left[\begin{array}{c}\text{Outage probability improve-} \\ \text{ment obtained by EQ}\end{array}\right]} \quad (1)$$

A block diagram of the system studied is shown in Fig. 1. The procedure for estimating the synergistic effect is described below.

(1) The outage probability due to waveform distortion is calculated using the inband amplitude dispersion probability [12] and the allowable inband amplitude dispersion. These are related to the modulation scheme and equalizer performance. The dispersive fade margin is then calculated from this outage probability.

(2) The flat fade margin is calculated using a conventional method when noise is present.

(3) From procedures (1) and (2) above, the composite fade margin is calculated using Rummler's concept [8]. The outage probability due to dispersive fading and flat fading is then calculated.

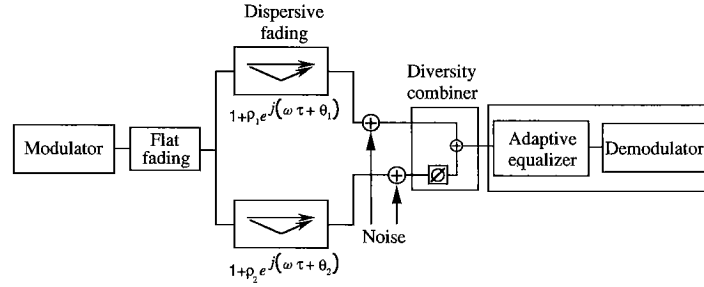(4) Procedures (1) through (3) are repeated four

Fig. 1 Analytical model.

times, i.e., for an unprotected system (modem alone), with SD, with EQ, and with both SD and EQ, to obtain four composite fade margins.

(5) The synergistic effect is calculated from these outage probabilities, using the four composite fade margins.

3. Improvement in Dispersive Fading

3. 1 Estimating the Outage from Linear Amplitude Dispersion

Signature and linear amplitude dispersion (LAD) are used to estimate outage probabilities when waveform distortion alone causes bit errors. As for the signature method, the regions where outage occurs are measured in relation to two variables, i.e., the amplitude dip frequency which originates from the delay time difference and the amplitude ratio of the interference rays. The outage probability is calculated from the likelihood of it falling into "signature."

On the other hand as for the LAD method, the probability that LAD exceeds the allowable value of the LAD is taken as the outage probability. This approach is based on the fact that the LAD distribution is closely related to the BER distribution [2]. The LAD can be expressed as the amplitude ratio between frequencies separated by Δf, and the effect of using space diversity can easily be calculated using an equation that includes a frequency correlation coefficient. In this paper, the LAD method is used to estimate the synergistic effect.

The received power distribution in a microwave link under duct-type fading follows a Gamma distribution. The density function of the Gamma distribution may be written as [13]

$$p(x) = \begin{cases} \dfrac{\beta^\lambda}{\Gamma(\lambda)} x^{\lambda-1} e^{-\beta x} : & x \geq 0 \\ 0 & : x < 0 \end{cases} \qquad (2)$$

where λ and β are parameters of the Gamma distribution and $\Gamma(\lambda)$ is defined as

$$\Gamma(a) = \int_0^\infty x^{a-1} e^{-x} dx \qquad (3)$$

The LAD "z" is defined as the amplitude ratio of two frequencies,

$$z = \frac{x(f_1)}{x(f_2)} \qquad (4)$$

where $x(f_1)$ and $x(f_2)$ are the received powers at frequencies f_1 and f_2 respectively and

$$f_1 - f_2 = \Delta f. \qquad (5)$$

Therefore, the density function $f(z)$ of LAD can be estimated from the density function of the ratio of the two Gamma variables $p(x(f_1))$ and $p(x(f_2))$ which are correlated by factor $\rho_{\Delta f}$ known as the frequency correlation coefficient [12]. It can be shown that

$$f(z) = \frac{\Gamma(2\lambda)(\beta_1\beta_2)^\lambda z^{\lambda-1}(\beta_1+\beta_2 z)(1-\rho_{\Delta f})^\lambda}{\Gamma(\lambda)^2((\beta_1+\beta_2 z)^2 - 4\rho_{\Delta f}\beta_1\beta_2 z)^{\lambda+1/2}} \qquad (6)$$

where β_1 and β_2 are scale parameters. The cumulative probability function of Eq. (6) is as follows [13]:

$$p(z \leq Z) = \int_0^z f(z)\,dz : z \geq 1$$

$$= \frac{\Gamma(2\lambda)}{\Gamma(\lambda)^2} \cdot \int_0^{\sin^2\frac{\theta}{2}} u^{\lambda-1}(1-u)^{\lambda-1} du \qquad (7)$$

where

$$\tan\theta = \sqrt{\frac{4\beta_1\beta_2(1-\rho_{\Delta f})Z}{(\beta_1-\beta_2 Z)^2}} \qquad (8)$$

Using Eqs. (7) and (8), and after some lengthy manipulation, it can be shown that for the particular case $\lambda=1$ and $\beta_1=\beta_2$, i.e., single reception [12],

$$p(z \leq Z) = \begin{cases} \dfrac{1}{2}\left[1 - \dfrac{1-Z}{\sqrt{(1+Z)^2 - 4\rho_{\Delta f}Z}}\right] & : Z < 1 \\[3mm] \dfrac{1}{2} & : Z = 1 \\[3mm] \dfrac{1}{2}\left[1 + \dfrac{1-Z}{\sqrt{(1+Z)^2 - 4\rho_{\Delta f}Z}}\right] & : Z > 1 \end{cases} \qquad (9)$$

Fig. 2 Synergistic effect under dispersive fading.

Fig. 3 Improvement due to SD under dispersive fading.
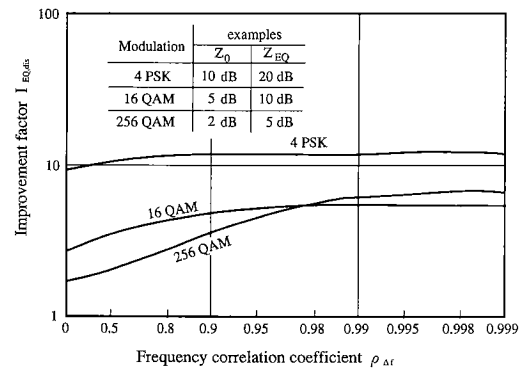
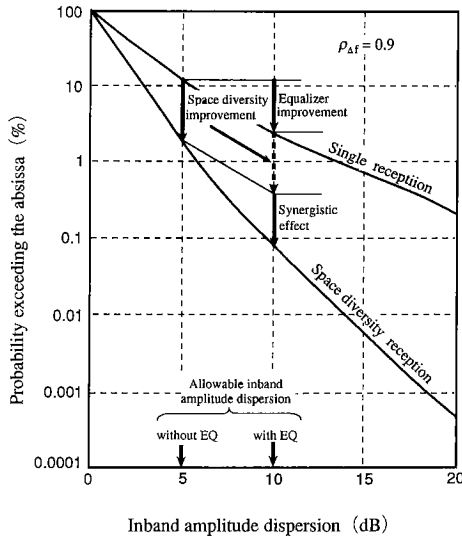Fig. 4 Improvement due to EQ under dispersive fading.

Assuming equal probabilities of positive and negative slopes, the outage probability $OP_{0,dis}(Z)$ due to inband amplitude dispersion can be expressed as

$$OP_{0,dis}(Z) = 2\alpha(Z), \tag{10}$$

where $\alpha(Z)$ is

$$\alpha(Z) = \frac{1}{2}\left(1 + \frac{1-Z}{\sqrt{(1+Z)^2 - 4\rho_{\Delta f}Z}}\right). \tag{11}$$

The concept of a joint density for the Gamma distribution may be applied to space diversity reception. Here we assume that the space diversity reception uses an equal gain pre-detection combining scheme as shown in Fig. 1. When the parameters are $\lambda=2$, $\beta_1=\beta_2$, and with a small value for the correlation coefficient for diversity branches ρ_s, the outage probability of $OP_{SD,dis}(Z)$ can be derived from Eq.(7) as

$$OP_{SD,dis}(Z) = 6(\alpha(Z))^2 - 4(\alpha(Z))^3. \tag{12}$$

Figure 2 shows an example of the results calculated from Eqs.(10) and (12) when $\rho_{\Delta f}=0.9$.

3.2 Space Diversity Improvement

The outage improvement factor $I_{SD,dis}$ when using space diversity is defined as

$$I_{SD,dis} \equiv OP_{0,dis}/OP_{SD,dis}. \tag{13}$$

As mentioned above, the outage probability can be estimated from the LAD distribution. Accordingly, the values become

$$OP_{SD,dis} = OP_{SD,dis}(Z=Z_0) = 6\alpha_0^2 - 4\alpha_0^3. \tag{14}$$

Here α_0 is given by $\alpha(Z_0)$ where Z_0 is the threshold or allowable LAD which corresponds to the outage. Examples of Z_0 are shown in the table in Fig. 3.
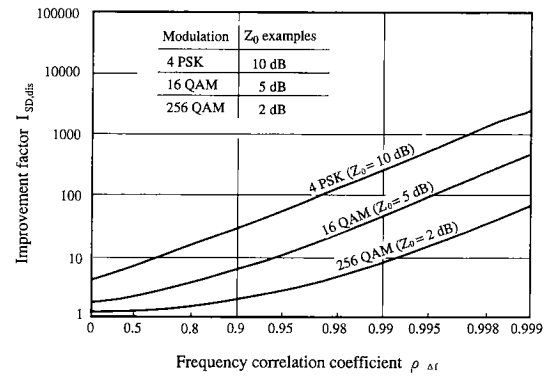
The $I_{SD,dis}$ achieved with space diversity reception can thus be expressed as

$$I_{SD,dis} = 1/(3\alpha_0 - 2\alpha_0^2) \tag{15}$$

The results calculated for $I_{SD,dis}$ as a function of frequency correlation coefficient $\rho_{\Delta f}$ are presented in Fig. 3.

3.3 Adaptive Equalizer Improvement

The degree of improvement achieved using adaptive equalizers is defined as

$$I_{EQ,dis} \equiv OP_{0,dis}/OP_{EQ,dis}. \tag{16}$$

Here, $OP_{EQ,dis}$ is the outage probability when only adaptive equalizers are used. $OP_{EQ,dis}$ can be expressed as

$$OP_{EQ,dis} = OP_{0,dis}(Z=Z_{EQ}) = 2\alpha_{EQ}. \tag{17}$$

Here, α_{EQ} is given by $\alpha(Z_{EQ})$, where Z_{EQ} is the threshold or allowable LAD when the adaptive equalizers, such as a variable resonance equalizer and an automatic transversal equalizer [6], are used. Some examples of Z_{EQ} are shown in the table in Fig. 4. The outage improvement factor $I_{EQ,dis}$ can be thus be expressed as
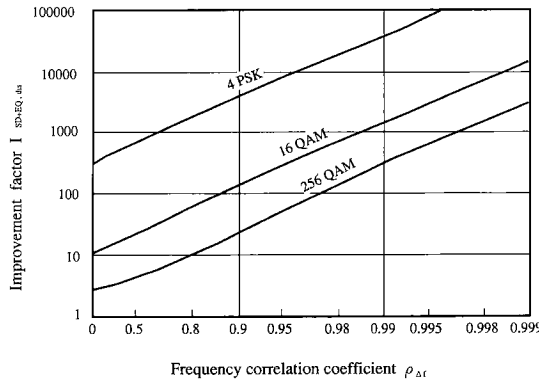
Fig. 5   Improvement due to SD and EQ under dispersive fading.

Fig. 6   Improvement due to SD under flat fading.

$$I_{EQ,dis} = a_0/a_{EQ}. \tag{18}$$

A plot of $I_{EQ,dis}$ vs. $\rho_{\Delta f}$ is shown in Fig. 4. Predictably, the equalizer improvement decreases for multilevel modulation schemes.

3. 4   Improvement Achieved Using Both Space Diversity and Adaptive Equalizers

When space diversity and adaptive equalizers are used together, the outage probability $OP_{SD+EQ,dis}$, can be expressed as

$$OP_{SD+EQ,dis} = OP_{SD,dis}(Z = Z_{EQ}) = 6a_{EQ}{}^2 - 4a_{EQ}{}^3. \tag{19}$$

The improvement factor $I_{SD+EQ,dis}$, can thus be expressed as

$$I_{SD+EQ,dis} = OP_{0,dis}/OP_{SD+EQ,dis}$$
$$= 2a_0/(6a_{EQ}{}^2 - 4a_{EQ}{}^3). \tag{20}$$

An example of the improvement factor in the outage probability is shown in Fig. 5. In the case of 16 QAM, when $Z_0 = 5$ dB, $Z_{EQ} = 10$ dB and $\rho_{\Delta f} = 0.9$, $I_{SD+EQ,dis}$ is found to be 150. As compared with the improvement of $I_{SD,dis} = 8$ with only space diversity and $I_{EQ,dis} = 4.5$ when adaptive equalizers are used alone, the combined use of space diversity and adaptive equalizers results in a much larger improvement than the product of the individual improvements. The larger improvement is attributed to the synergistic effect.

4.   Improvement in Flat Fading

4. 1   Outage Probability Due to Thermal Noise

The probability of outage due to noise can be calculated from the probability that received power level X becomes smaller than the threshold received-power level, x. The received power distribution during fading is given by the following formulae for single recep-
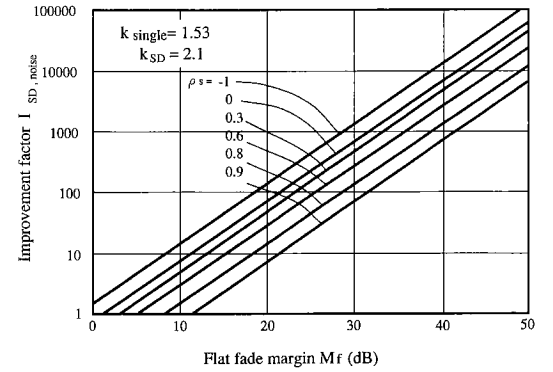
tion and space diversity reception [14].

$$p(X < x) \cong k_{single} \cdot 10^{-x/10}$$

: single reception $\tag{21}$

$$p(X < x) \cong k_{SD}/(1 - \rho_s) \cdot 10^{-x/5}$$

: space diversity reception. $\tag{22}$

Here, ρ_s is the correlation coefficient for diversity branches and k_{single} and k_{SD} are the coefficients for the increase due to long term fluctuations of single and space diversity reception respectively.

For the flat fade margin, Mf, the outage probability $OP_{0,noise}$ due to noise for single reception can be expressed as

$$OP_{0,noise} = k_{single} \cdot 10^{-Mf/10}. \tag{23}$$

Furthermore, the flat fade margin Mf, for space diversity reception is treated in the same way as for single reception.

$$OP_{SD,noise} = k_{SD}/(1 - \rho_s) \cdot 10^{-Mf/5} \tag{24}$$

4. 2   Space Diversity Improvement in Outage Probability Due to Noise

From Eqs. (23) and (24) the improvement factor for space diversity $I_{SD,noise}$, is obtained as

$$I_{SD,noise} = \frac{OP_{0,noise}}{OP_{SD,noise}} = \frac{k_{single} \cdot (1 - \rho_s)}{k_{SD}} \cdot 10^{Mf/10}. \tag{25}$$

The calculated results are presented in Fig. 6.

5.   Improvement under Simultaneous Dispersive Fading and Flat Fading

5. 1   Outage Probability

When waveform distortion and noise are simultaneously present, the outage probability is higher than when each element is present alone. It can be seen that the

influence of waveform distortion on the outage probability becomes more pronounced as Mf increases. At this point, let us determine the effect that waveform distortion and noise both have on composite fade margin CFM as follows [8],

$$10^{-\frac{CFM}{10}}=10^{-\frac{Mf}{10}}+10^{-\frac{Mf,dis}{10}}.\qquad(26)$$

We extended this concept to space diversity reception regardless of whether equalizers are used or not.

5.2 Unprotected Circuit

The equivalent deterioration in C/N ratio due to waveform distortion in the case of single reception is obtained from Eq.(10).

$$OP_{0,dis}=2\alpha_0\qquad(27)$$

Using Eq.(23), replacing flat fading with dispersive fading yields,

$$10^{-\frac{Mf,dis}{10}}=2\alpha_0/k_{single}.\qquad(28)$$

Accordingly, if Eq.(26) represents the CMF due to noise and waveform distortion, then the outage probability for unprotected circuit $OP_{0,total}$ is

$$
\begin{aligned}
OP_{0,total}&=k_{single}\cdot 10^{-\frac{CFM}{10}}\\
&=k_{single}\cdot (10^{-\frac{Mf}{10}}+10^{-\frac{Mf,dis}{10}})\\
&=k_{single}\cdot 10^{-\frac{Mf}{10}}+2\alpha_0.
\end{aligned}\qquad(29)
$$

5.3 Improvement in Space Diversity

For space diversity reception the equivalent flat fade margin Mf,dis, due to waveform distortion is found using Eqs.(12) and (24),

$$\frac{k_{SD}}{1-\rho_s}\cdot 10^{-\frac{Mf,dis}{5}}=6\alpha_0{}^2-4\alpha_0{}^3,\qquad(30)$$

which yields the following formula,

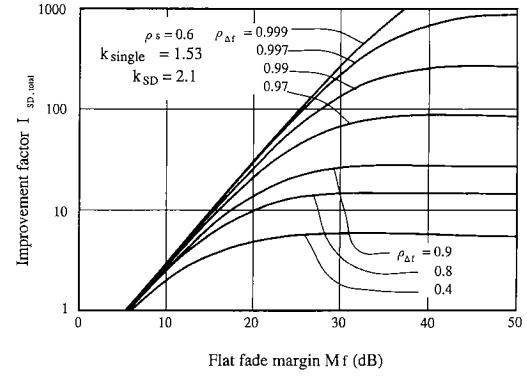$$10^{-\frac{Mf,dis}{5}}=\frac{1-\rho_s}{k_{SD}}(6\alpha_0^2-4\alpha_0^3).\qquad(31)$$

Accordingly, CFM is found to be

$$
\begin{aligned}
10^{-\frac{CFM}{5}}&=10^{-\frac{Mf}{5}}+10^{-\frac{Mf,dis}{5}}\\
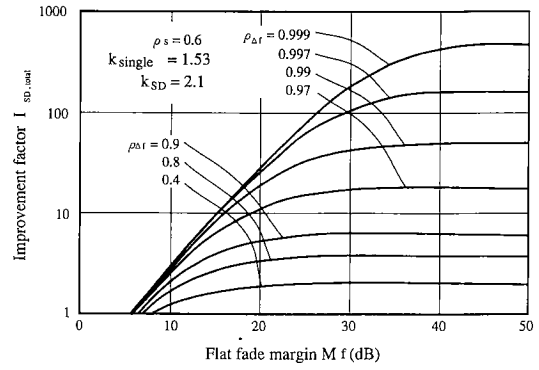&=10^{-\frac{Mf}{5}}+\frac{1-\rho_s}{k_{SD}}(6\alpha_0^2-4\alpha_0^3).
\end{aligned}\qquad(32)
$$

Thus, the outage probability $OP_{SD,total}$ is expressed as

$$
\begin{aligned}
OP_{SD,total}&=k_{SD}/(1-\rho_s)\cdot 10^{-\frac{CFM}{5}}\\
&=\frac{k_{SD}}{1-\rho_s}10^{-\frac{Mf}{5}}+(6\alpha_0^2-4\alpha_0^3).
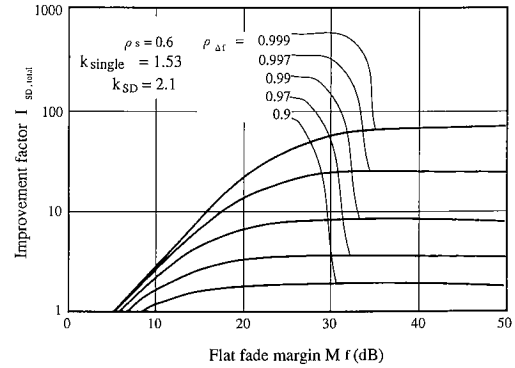\end{aligned}\qquad(33)
$$

The improvement coefficient $I_{SD,total}$, resulting from

(a) 4 PSK

(b) 16 QAM

(c) 256 QAM

Fig. 7 Improvement due to SD under both dispersive fading and flat fading.

space diversity is obtained from the following expression:

$$
\begin{aligned}
I_{SD,total}&\equiv OP_{0,total}/OP_{SD,total}\\
&=\frac{k_{single}\cdot 10^{-\frac{Mf}{10}}+2\alpha_0}{\frac{k_{SD}}{1-\rho_s}10^{-\frac{Mf}{5}}+(6\alpha_0^2-4\alpha_0^3)}
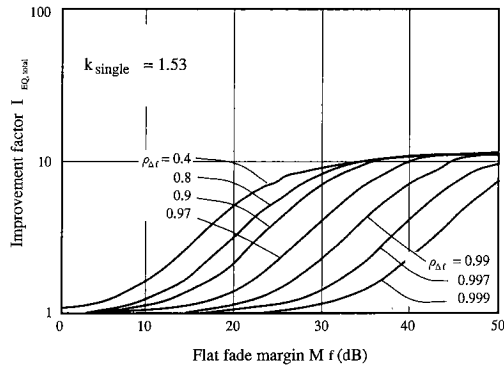\end{aligned}\qquad(34)
$$

Calculation examples for 4 PSK, 16 QAM, and 256 QAM are shown in Figs. 7(a)-(c) with the frequency correlation coefficient $\rho_{\Delta f}$ as the parameter. From these figures it can be seen that

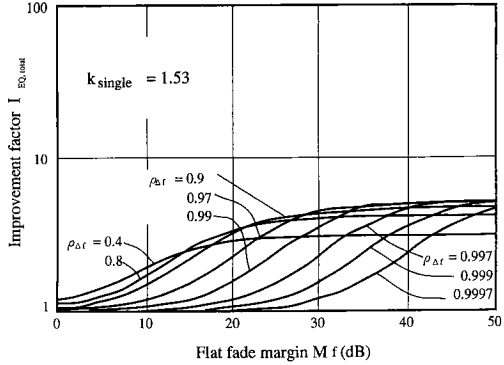(1) space diversity results in a significant improve-

ment in a modulation system which has a large allow-able LAD,

(2) with constant frequency correlation coefficient $\rho_{\Delta f}$ as the flat fade margin increases, the degree of improvement curve saturates,
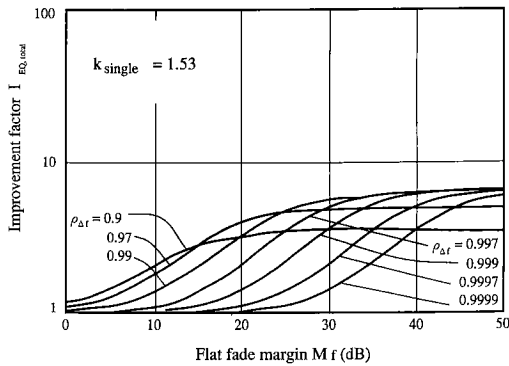
(3) with a smaller frequency correlation coefficient, there is less improvement, and improvement tends to level off faster in relation to the increasing flat fade margin.
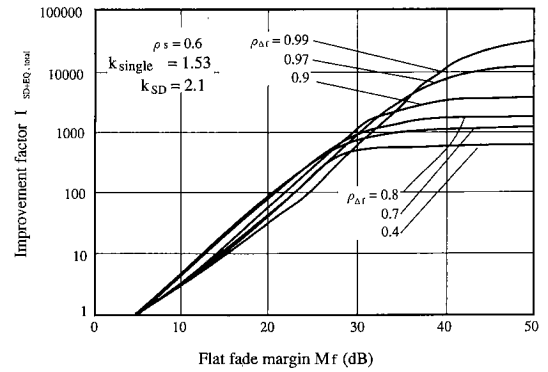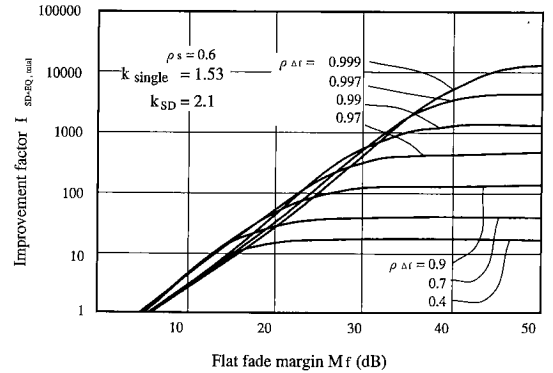
5.4 Equalizer Improvement

The outage probability for single reception when equalizers of $OP_{EQ,total}$, are used can be estimated easily from Eqs. (28) and (29).

$$OP_{EQ,total} = k_{single} \cdot 10^{-\frac{CFM}{10}}$$

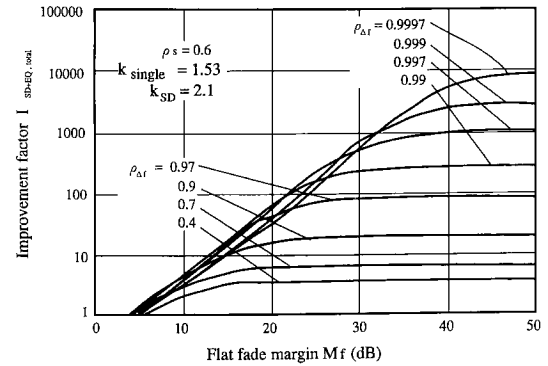$$= k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_{EQ} \quad (35)$$

Accordingly, the improvement coefficient with

(a) 4 PSK

(b) 16 QAM

(c) 256 QAM

Fig. 8 Improvement due to EQ under both dispersive fading and flat fading.

(a) 4 PSK

(b) 16 QAM

(c) 256 QAM

Fig. 9 Improvement due to SD and EQ under both dispersive fading and flat fading.

equalizers $I_{EQ,total}$, is expressed as follows.

$$I_{EQ,total} \equiv OP_{0,total}/OP_{EQ,total}$$

$$= \frac{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_0}{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_{EQ}}$$

$$= 1 + \frac{2(\alpha_0 - \alpha_{EQ})}{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_{EQ}} \quad (36)$$

From the calculation examples shown in Figs. 8(a)-(c), it is understood that:
(1) the degree of improvement increases with a larger allowable LAD, and
(2) when Mf is large, the degree of improvement curve saturates.

5. 5 Improvement Achieved Using Space Diversity and Equalizers in Combination

When both space diversity and equalizers are used, the outage probability $OP_{SD+EQ,total}$, is derived from Eq. (33).

$$OP_{SD+EQ,total} = \frac{k_{SD}}{1-\rho_s} 10^{-\frac{Mf}{5}} + (6\alpha_{EQ}^2 - 4\alpha_{EQ}^3) \quad (37)$$

Accordingly, the value of the improvement factor $I_{SD+EQ,total}$, is obtained from the following formula.

$$I_{SD+EQ,total} \equiv OP_{0,total}/OP_{SD+EQ,total}$$

$$= \frac{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_0}{\frac{k_{SD}}{1-\rho_s} 10^{-\frac{Mf}{5}} + (6\alpha_{EQ}^2 - 4\alpha_{EQ}^3)} \quad (38)$$

Calculation examples are presented in Figs. 9(a)-(c). They show the same tendencies as those in Sects. 5.2, 5.3, and 5.4.

6. Synergistic Effect Due to Space Diversity and Equalizers

6. 1 Synergistic Effect with Dispersive Fade

The coefficient ξ_{dis}, which shows the synergistic effect obtained using both space diversity and adaptive equalizers, is defined by the following expression.

$$\xi_{dis} \equiv I_{SD+EQ,dis}/(I_{SD,dis} \cdot I_{EQ,dis}) \quad (39)$$

This definition makes it possible to estimate the combined improvement, $I_{SD+EQ,dis}$, by $\xi_{dis} \cdot I_{SD,dis} \cdot I_{EQ,dis}$. This calculation is easy to perform because the combined improvement can be estimated using the degree of improvement obtained when each technique is employed separately. From Eqs.(15), (18) and (20), ξ_{dis} is given by [11]

$$\xi_{dis} = (3\alpha_0 - 2\alpha_0^2)/(3\alpha_{EQ} - 2\alpha_{EQ}^2). \quad (40)$$

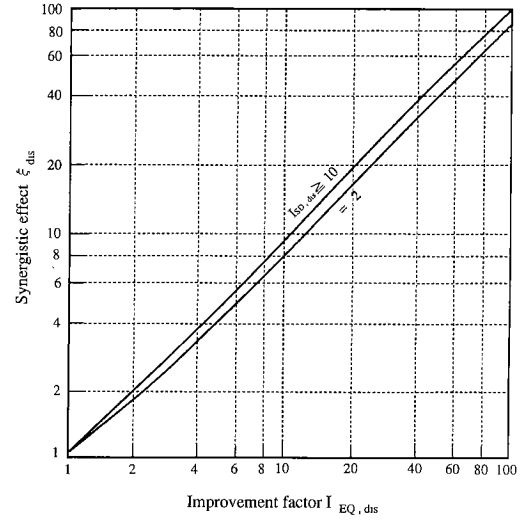Further, by using only $I_{SD,dis}$ and $I_{EQ,dis}$ in Eqs.

Fig. 10 Synergistic effect under dispersive fading.

(15), and (18), (39) can be rewritten as

$$\xi_{dis} = I_{EQ,dis}/\left\{1 + \frac{1}{8} \cdot \frac{I_{SD,dis}}{I_{EQ,dis}} \cdot (I_{EQ,dis} - 1)\right.$$

$$\left. \cdot \left(3 - \sqrt{9 - \frac{8}{I_{SD,dis}}}\right)^2\right\}. \quad (41)$$

The calculation results are presented in Fig. 10. From this figure, it is clear that the synergistic effect nearly equals the degree of improvement obtained by the adaptive equalizers. For instance, assuming that $Z_0 = 5$ dB, $Z_{EQ} = 10$ dB, and $\rho_{af} = 0.8$, then $I_{SD,dis} = 3.6$, $I_{EQ,dis} = 4.2$, and $I_{SD+EQ,dis} = 60$, from Figs. 3, 4, and 5. It is obvious that $I_{SD+EQ,dis} > I_{SD,dis} \cdot I_{EQ,dis}$. The synergistic effect of 4.0 ($= 60/(3.6 \times 4.2)$) is found to exist, which is almost identical to ξ_{dis}.

These results clarify the following points.
(1) The synergistic effect depends on the LAD gradient difference between the single reception and diversity reception as shown in Fig. 2, and the synergistic effect becomes larger when the LAD gradient difference becomes larger.
(2) The synergistic effect is dependent on Z_{EQ}, which shows the performance of the adaptive equalizers. The larger the Z_{EQ} value, the greater the effect.
(3) For space diversity reception, the synergistic effect has the same value as the degree of improvement obtained with the adaptive equalizers. Therefore, the combined effect obtained when both techniques are used is given by the expression,

$$I_{SD+EQ,dis} = I_{SD,dis} \cdot (I_{EQ,dis})^2. \quad (42)$$

6. 2 Synergistic Effect in Flat Fading

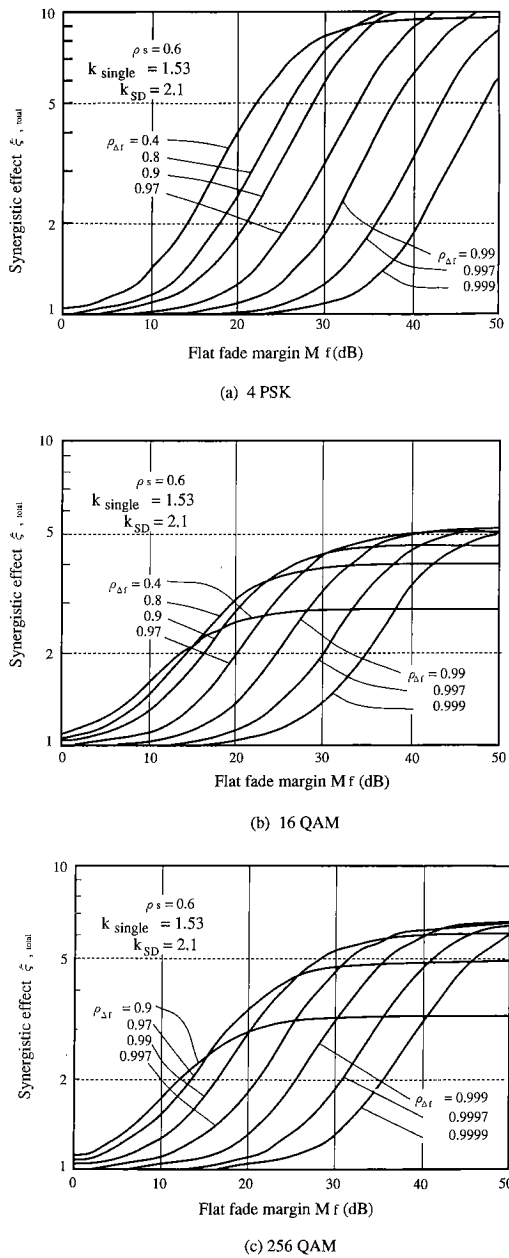Since adaptive equalizers do not result in any improvement in noise, the synergistic effect is predictably unity.

(a) 4 PSK

(b) 16 QAM

(c) 256 QAM

Fig. 11 Synergistic effects under both dispersive fading and flat fading.

The synergistic effect ξ_{noise}, is expressed as

$$\xi_{noise} = \frac{I_{SD+EQ,noise}}{I_{SD,noise} \cdot I_{EQ,noise}}$$

$$= I_{SD,noise} / I_{SD,noise}$$

$$= 1. \tag{43}$$

6.3 Synergistic Effect in Dispersive Fading and Flat Fading

From Eqs. (34), (36), and (38), the synergistic effect with both dispersive fading and flat fading ξ_{total}, is given by,

$$\xi_{total} = I_{SD+EQ,total} / \left(I_{SD,total} \cdot I_{EQ,total} \right)$$

$$= \frac{\dfrac{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_0}{\dfrac{1-\rho_s}{k_{SD}} 10^{-\frac{Mf}{5}} + \left(6\alpha_{EQ}{}^2 - 4\alpha_{EQ}{}^3 \right)}}{\dfrac{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_0}{\dfrac{1-\rho_s}{k_{SD}} 10^{-\frac{Mf}{5}} + \left(6\alpha_0{}^2 - 4\alpha_0{}^3 \right)}} \tag{44}$$

$$\cdot \left(1 + \frac{2\left(\alpha_0 - \alpha_{EQ} \right)}{k_{single} \cdot 10^{-\frac{Mf}{10}} + 2\alpha_{EQ}} \right)$$

Calculation examples are shown in Figs. 11 (a)-(c).

7. Experimental Results

An experiment was conducted to verify the foregoing calculation results. In order to compare the outage probability values of various reception methods, a fading simulator based on a two-ray model was used. The fading simulator can generate the same fading pattern repeatedly. The space diversity reception scheme is equal gain pre-detection combining, and the adaptive equalizer is a variable resonance type. External noise was applied for the purpose of establishing the flat fade margin. A 16 QAM signal with a roll-off rate of 50% was used with an Mf of 26 dB and a $\rho_{\Delta f}$ of 0.85. The obtained results are presented in Table 1 with theoretical results.

Table 1 Comparison of experimental and theoretical results.

Reception	Theoretical		Experimental	
	Outage probability (%)	Improvement factor	Outage probability (%)	Improvement factor
Unprotected	15.0	—	15.8	—
With SD	3.2	4.6	7.1	2.19
With EQ	3.9	3.8	4.1	3.8
With SD and EQ	0.2	68.1	0.36	40.8
Synergistic effect ξ	3.8		4.9	

$Mf = 26$ dB $\rho_{\Delta f} = 0.85$

The improvement factor for space diversity was smaller than the theoretical value, and thus, the synergistic effect was larger. However, the values show good agreement for the most part.

8. Conclusion

Synergistic effects have been defined and analyzed theoretically. From this analysis, the following conclusions have been obtained.

(1) Synergistic effects arise from the slope differences of the inband amplitude dispersion cumulative probability curves which are obtained with and without diversity reception.

(2) The synergistic effect is larger than unity.

(3) Synergistic effects were quantitatively clarified for dispersive fading with flat fading as well as for dispersive fading only.

(4) In the case of dispersive fading, the value of the synergistic effect is the same as the outage probability improvement factor obtained using only adaptive equalizers.

(5) In the case of dispersive fading with flat fading, the synergistic effects gradually decrease as the noise level increases.

(6) When the noise level is high, the synergistic effects disappear.

These results are applicable to various types of modulation methods, combiners, and equalizers, when the values of allowable inband amplitude dispersion with/without using an adaptive equalizer, and flat fading margin, etc. are known.

Acknowledgments

References

[1] L. J. Greenstein and M. Shafi, "Outage calculation methods for microwave digital radio," IEEE Commun. Magazine, vol. 25, no. 2 , p. 30, Feb. 1987.

[2] S. Komaki, I. Horikawa, K. Morita, and Y. Okamoto, "Characteristics of a high capacity 16 QAM digital radio system in multipath fading," IEEE Trans. Commun., vol. COM-27, no. 12, pp. 1854-1861, 1979.

[3] T. S. Giuffrida, "Measurements of the effects of propagation on digital radio systems equipped with spacediversity and adaptive equalization," IEEE ICC'79, 48.1, 1979.

[4] S. Komaki, K. Tajima, and Y. Okamoto, "A minimum dispersion combiner for high capacity digital microwave radio," IEEE Trans. Commun., vol. COM-32, no. 4, pp. 419-428, April 1984.

[5] P. Hartmann and B. Bynum, "Adaptive equalization for a digital microwave radio systems," IEEE ICC'80, 8.5, 1980.

[6] M. Araki, K. Tajima, and H. Matsue, "Correction techniques for multipath fading in 4/5/6L-D1 digital micro-

wave radio system," Review of the Electrical Commun. Labs. (NTT), vol. 30, no. 5, pp. 873-882, 1982.

[7] A. J. Giger and W. T. Barnett, "Effects on multipath propagation on digital radio," IEEE Trans. Commun., vol. COM-29, no. 9, pp. 1345-1352, 1981.

[8] W. D. Rummler, "A comparison of calculated and observed performance of digital radio in the presence of interference," IEEE Trans. Commun., vol. COM-30, no. 7, pp. 1693-1700, 1982.

[9] L. G. Greenstein and Y. S. Yeh, "A simulation study of space diversity and adaptive equalization in microwave digital radio," AT&T Tech. J., vol. 64, no. 4, pp. 907-935, 1985.

[10] O. Andrisano, "The combined effects of noise and multipath propagation in multilevel PSK radio links," IEEE Trans. Commun., vol. COM-32, no. 4, pp. 411-418, April 1984.

[11] K. Tajima, S. Komaki, and Y. Okamoto, "Outage probability of a digital microwave radio equipped with space diversity and adaptive equalizer," IEICE Trans., vol. J66-B, no. 5, pp. 583-590, 1983.

[12] S. Sakagami and Y. Hosoya, "Some experimental results on in-band linear amplitude dispersion," IEEE Trans. Commun., vol. COM-30, no. 8, pp. 1875-1888, 1982.

[13] I. Higuti and K. Morita, "Diversity effects of propagation characteristics during multipath fading in microwave links," Review of the Electrical Commun. Labs. (NTT), vol. 30, no. 3, pp. 544-551, 1982.

[14] A. Vigants, "The number of fades in space-diversity reception," B.S.T.J., 49.7, pp. 1513-1530, 1970.

Kojiro Araki was born in Nagano, Japan, in 1952. He received his B.S. degree from Shinsyu University, Nagano, Japan, in 1975. In 1975 He joined the NTT Radio Communication Labs., where he was engaged in research and development of digital microwave radio systems, and quasi-millimeter wave subscriber radio systems. He has been working on radio over fiber communications. He is now a Senior Research Engineer of NTT Wireless Systems Laboratories.

Shozo Komaki was born in Osaka, Japan, in 1947. He received B.E., M.E. and Dr. Eng degrees in Electrical Communication Engineering from Osaka University, in 1970, 1972 and 1983 respectively. In 1972, he joined the NTT Radio Communication Labs., where he was engaged in repeater development for a 20-GHz digital radio system, 16-QAM and 256-QAM systems. From 1990, he moved to Osaka University, and engaging in the research on radio and optical communication systems. He is currently a Professor of Osaka University, Faculty of Engineering. Dr. Komaki is a senior member of IEEE, and a member of the Institute of Television Engineers of Japan (ITE). He was awarded the Paper Award and the Achievement Award of IEICE, Japan in 1977 and 1994 respectively.