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Performance Analysis of Optical Fiber Link for Microcellular Mobile Communication Systems

Hironori MIZUGUTI†, Toshiaki OKUNO†, *Associate Members*,
Shozo KOMAKI† *and* Norihiko MORINAGA†, *Members*

SUMMARY Recently, making good use of the advantages of optical fibers such as wide bandwidth and low loss, it has been investigated to apply optical fiber link to microcellular mobile communication systems. This system allows complex equipment to be located at microcell control station, and can simplify the equipment of microcell base stations compared with the conventional systems. In this paper, we analyze the performance of optical fiber link for microcellular mobile communication systems, taking radio link fading and optical link nonlinear distortions into consideration. From the calculated results, it is disclosed that the effect of both items does not generate the significant excess CNR degradation, and the correct CNR can be approximately calculated by using CNR of non-faded case. And it is also disclosed that the degradation of CNR due to optical link nonlinearity is slightly improved by taking adjacent channel signal fade into consideration.
key words: *microcell, radio communication, optical fiber, fading, nonlinearity*

1. Introduction

Because of a strong demand for people to communicate at any place, at any time, the number of subscribers to mobile communication systems are rapidly increasing. So it is necessary to provide systems to satisfy such a demand in future personal communication. To meet this situation, microcellular communication system has been investigated.

In this system, service areas are divided into many small zones called "microcell", the radius of which is reduced to several hundred meters, and one can reuse the same frequency as that used several distance away.

This system has such advantage as effective frequency utilization, and can accommodate a large number of subscribers. Furthermore, it can reduce the size of personal station, and can make the launch power smaller.

This system, however, has such disadvantages that a large number of base stations are required because the number of microcells rapidly increase according to the inverse of the square of the radius of microcells, and personal stations frequently move across microcells, so channel assignment or hand-off procedure is much complicated.

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† The authors are with the Faculty of Engineering, Osaka University, Suita-shi, 565 Japan.

For the solution to this problem, it is proposed to connect microcell base stations with a microcell control station using an optical fiber link, in which the frequency-division multiplexed microwave signals are transmitted as an intensity modulated optical signal.(1)–(5)

In this system, base stations have only a role to upconvert the radio frequency signal to optic signal or vice versa, so required equipment for base station is remarkably simplified compared with the conventional systems. Consequently, the cost of equipment of base station can be reduced and installation is easy to operate, and we can flexibly use the equipment of base stations for various type of new services because there is no need to replace the equipment of base stations even when new type of services are introduced.

Furthermore, since signals are transmitted to microcell control station in the form of the air interfaced RF signals, channel assignment and hand-off procedure are centralized, and each microcell can be considered as a branch of antenna, inter cell diversity technique could be easily introduced in this system.

This system consists of two fields of study, radio communication links and optical communication links. So the total system parameters, such as total link quality, should be derived taking both link's parameters into consideration simultaneously, one of the most important parameter is signal fading from the former, and nonlinear distortion that occurs by using a device such as laser diode from the latter.

In this paper, we analyze the performance of optical fiber link for microcellular mobile communication systems by means of computer simulation, taking signal fading and optical link nonlinear distortions into consideration.

2. System Configuration

This section summarizes the microcell optical communication system. Figure 1 shows the basic configuration of microcellular mobile communication systems using optical fiber link, schematically. At base stations, frequency-division multiplexed RF signals are combined as injection current and drive a laser diode directly. Intensity modulated optical signal is transmitted over optical fiber to microcell control station, where optical signal is directly detected using a device such as p-i-n photodiode, and bandpass filter is used to provide RF channel selection. After filtering, each RF signal is demodulated, separately, and finally it is connected to the public s itched telephone network.

In conventional sys.ems, channel frequencies are allocated at each base station to be used by various channel assignment schemes, so complex processing equipment such as modems or bandpass filters is required for each base station. The number of required equipment is determined by taking peak traffic per cell and grade of service into consideration, but the channels are not always used. Using subcarrier multiplexing technique, modems or bandpass filters are required only at microcell control station, so this system can reduce the number of surplus equipment.

Subcarrier multiplexing technique, however, has several disadvantages, one of the most important is the problem of optical source nonlinearity. This causes severe interchannel interference when several subcarriers are transmitted from a single source (See Fig. 2).

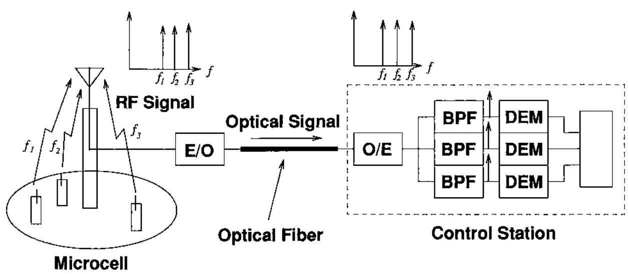

Fig. 1 Basic configuration of microcellular mobile communication system using optical fiber link.

In particular, the received signal level differences due to fading should be taken into consideration, and excess degradation in carrier-to-noise power ratio of the system will be expected, when a specific RF carrier suffers from fading.

3. Carrier-to-Noise Power Ratio of the System

The carrier-to-noise power ratio (CNR) of a subcarrier signal is given by following equation:[6]

$$\frac{C}{N}=\frac{\frac{1}{2}m^2 I_{ph}^2}{\{RIN\cdot I_{ph}^2+2\cdot e\cdot I_{ph}+\langle I_{th}^2\rangle\}\cdot BW+\sigma_{IM}^2} \tag{1}$$

where

m: optical modulation index (OMI),
I_{ph}: received dc photocurrent,
RIN: relative intensity noise of the laser,
$\langle I_{th}^2\rangle$: equivalent input noise current spectral density,
BW: signal bandwidth,
e: charge of the electron,
σ_{IM}^2: intermodulation noise,

and the first term of the denominator represents relative intensity noise of the laser diode, the second term is shot noise, the third term is thermal noise, and last term is the degradation due to intermodulation distor-

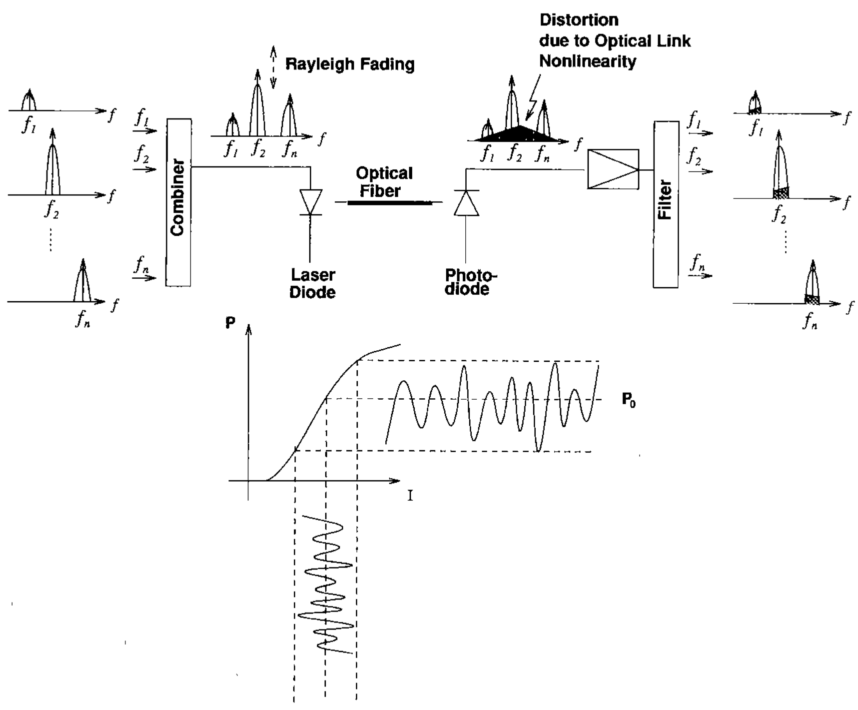

Fig. 2 System degradation due to optical source nonlinearity.

tion.

Intermodulation distortion is caused when multiplexed signals are transmitted through a nonlinear device such as a laser diode. As the second-order products fall outside of the occupied frequency bands and can be filtered out by the harmonic rejection filter, it is not necessary to be taken into consideration. Higher order products are few in number and are at low level, making their contribution almost negligible.[7] So we take only third-order intermodulation distortion into account.

The light output of the laser, with one modulating channel, may be written as

$$P=P_0[1+m\cos\omega t] \tag{2}$$

where

P: instantaneous light output,
P_0: average light output.

Optical power is directly detected, and the received photocurrent is

$$i_{ph}=\eta P=\eta P_0[1+m\cos\omega t]. \quad (\eta\text{: detector sensitivity}) \tag{3}$$

Received dc photocurrent is

$$I_{ph}=\eta P_0. \tag{4}$$

Signal current is

$$i_s=\eta P_0 m\cos\omega t=I_{ph}m\cos\omega t. \tag{5}$$

We assume the nonlinearity of the light output versus injection current as

$$P=P_0[1+a_1I+a_2I^2+a_3I^3+\cdots] \tag{6}$$

and assume to transmit three unmodulated carriers, their frequencies are ω_1, ω_2, ω_3 (equally spaced), optical modulation indices are m_1, m_2, m_3, respectively.

In this case:

$$\begin{aligned}P=P_0[1&+m_1\cos\omega_1t+m_2\cos\omega_2t+m_3\cos\omega_3t\\&+a_2(m_1\cos\omega_1t+m_2\cos\omega_2t+m_3\cos\omega_3t)^2\\&+a_3(m_1\cos\omega_1t+m_2\cos\omega_2t+m_3\cos\omega_3t)^3\\&+\cdots].\end{aligned} \tag{7}$$

Among many terms obtained by expanding the Eq.(7), the signal power with respect to carrier frequency ω_2 is

$$C=\frac{1}{2}m_2^2I_{ph}^2. \tag{8}$$

The third-order intermodulation distortion that falls into carrier frequency $\omega_2(=\omega_1-\omega_2+\omega_3)$ is generated by the I^3 term in Eq.(7):

$$\begin{aligned}&a_3(m_1\cos\omega_1t+m_2\cos\omega_2t+m_3\cos\omega_3t)^3\\&=a_3[m_1^3\cos^3\omega_1t+m_2^3\cos^3\omega_2t+m_3^3\cos^3\omega_3t\\&+\frac{3}{4}m_1^2m_2\{\cos(2\omega_1+\omega_2)t+\cos(2\omega_1-\omega_2)t\}\\&+\frac{3}{4}m_1^2m_3\{\cos(2\omega_1+\omega_3)t+\cos(2\omega_1-\omega_3)t\}\\&+\frac{3}{4}m_2^2m_3\{\cos(2\omega_2+\omega_3)t+\cos(2\omega_2-\omega_3)t\}\\&+\frac{3}{4}m_1m_2^2\{\cos(\omega_1+2\omega_2)t+\cos(\omega_1-2\omega_2)t\}\\&+\frac{3}{4}m_1m_3^2\{\cos(\omega_1+2\omega_3)t+\cos(\omega_1-2\omega_3)t\}\\&+\frac{3}{4}m_2m_3^2\{\cos(\omega_2+2\omega_3)t+\cos(\omega_2-2\omega_3)t\}\\&+\frac{3}{2}m_1m_2m_3\{\cos(\omega_1+\omega_2+\omega_3)t\\&+\cos(\omega_1+\omega_2-\omega_3)t+\cos(\omega_1-\omega_2+\omega_3)t\\&+\cos(\omega_1-\omega_2-\omega_3)t\}].\end{aligned} \tag{9}$$

Hence, third-order intermodulation distortion which falls into carrier ω_2 is

$$I=\frac{1}{2}\left(\frac{3}{2}a_3m_1m_2m_3\right)^2I_{ph}^2. \tag{10}$$

Therefore, the carrier-to-intermodulation power ratio (CIR) is

$$\frac{C}{I}=\frac{\frac{1}{2}m_2^2I_{ph}^2}{\frac{1}{2}\left(\frac{3}{2}a_3m_1m_2m_3\right)^2I_{ph}^2}. \tag{11}$$

The Eq.(11) shows that signal power is proportional to m^2, while the third-order intermodulation distortion is proportional to m^6. Totally, the CIR is proportional to $1/m^4$, which means that when optical modulation index m is relatively small and degradation due to intermodulation distortion is negligible, the major source which gives the limitation to CNR is thermal noise, and CNR can be improved as the value of m is greater. In contrast, when the value of m is relatively large, intermodulation distortion is dominant, and CNR is degraded mainly due to intermodulation distortion. So we can find optimum modulation index that maximize the received CNR.

Figure 3 shows the numerical result of calculating total CNR in the case of $m_1=m_2=m_3=m$. Parameters are as follows.

laser output power: -3.0 [dBm]
fiber loss (including connectors): 2.0 [dB]
detector sensitivity: 0.8 [A/W]
relative intensity noise of the laser: -152 [dB/Hz]
equivalent input noise current spectral density:
20 [pA/$\sqrt{\text{Hz}}$]
band width: 300 [kHz]
third order coefficient a_3: 10^{-2}

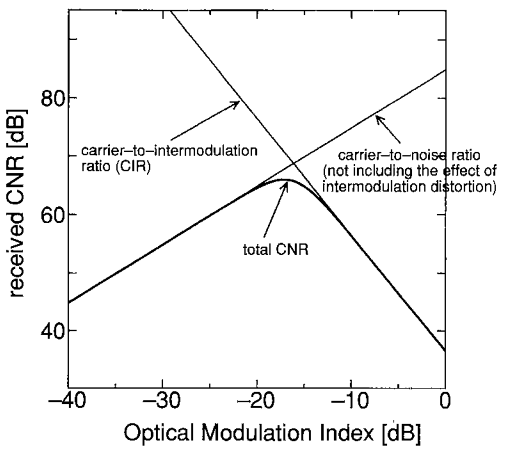

Fig. 3 Received signal carrier-to-noise ratio (CNR) taking intermodulation distortion into account.

In this case, we can obtain the optimum optical modulation index m_{opt}, mathematically. The result is:

$$m_{opt} = -17.1\ [\text{dB}],$$

$$(\text{CNR})_{max} = 66.0\ [\text{dB}].$$

When modulating the laser diode with many carriers, the calculations are a little more complicated, but the procedure of calculation is the same as the case of three carriers.

4. The Effect of Fading on CNR

In a mobile radio environment, the magnitude of the received signal will frequently vary over distances. This rapid variation of the received signal due to the multipath propagation is known as fading. In most cases, when measured over distances of a few tens of wavelength, the received signal envelope has been found to have a Rayleigh probability density function. The mean level of the received signal envelope, averaged over many Rayleigh fading cycles, also varies, but much less rapidly than Rayleigh fading. The slower variation is due to the shadowing caused by objects in the path of the radio signal. When measured over distances of several hundred wavelengths, this shadowing has been found to have an approximately lognormal probability density function.

In this paper, we evaluate how transmission quality of optical fiber link is degraded, when the RF signals which suffer from fading in the radio link are combined to drive a laser diode. It is assumed that Rayleigh fading is the cause of received signal variation to simplify the calculation.

In the upstream optical link (from personal station to control station), we transmit unmodulated carrier

$$s(t) = A\cos\omega t. \tag{12}$$

Over Rayleigh fading channel, received signal $x(t)$ at base station is written as

$$x(t) = r(t)\cos(\omega t + \theta(t)) \tag{13}$$

where $r(t)$ and $\theta(t)$ are random processes, that have following probability distribution

$$p(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right), \tag{14}$$

$$p(\theta) = \frac{1}{2\pi}. \tag{15}$$

Therefore, optical modulation index m, which is proportional to the amplitude of the signal r, can be regarded as random variable with the same statistics as r, and can be characterized following equation

$$p(m) = \frac{m}{\sigma^2}\exp\left(-\frac{m^2}{2\sigma^2}\right). \tag{16}$$

When three carriers are transmitted, each carrier propagates through a different path from each other, and the fadings of these paths are mutually independent. So we assume that the optical modulation indices m_1, m_2, m_3 are mutually independent random variables which have the following statistics, respectively.

$$p(m_i) = \frac{m_i}{\sigma^2}\exp\left(-\frac{m_i^2}{2\sigma^2}\right) \qquad (i=1, 2, 3). \tag{17}$$

Consequently, received carrier-to-noise ratio, which is the function of $m_i (i=1, 2, 3)$ as represented in Eq. (18), is time-variant, and its characteristic must be treated statistically.

$$\frac{C}{N} = \frac{\frac{1}{2}m_2^2 I_{ph}^2}{\{RIN \cdot I_{ph}^2 + 2\cdot e\cdot I_{ph} + \langle I_{th}^2\rangle\}\cdot BW + \frac{1}{2}\left(\frac{3}{2}a_3 m_1 m_2 m_3\right)^2 I_{ph}^2} \tag{18}$$

In numerical evaluation of this random variable, we generate the random variable m_1, m_2, m_3 with about 35 dB dynamic range, and we take the following two situations into account.

4.1 Fast Fading

The term, fast fading, means the case where the rapidity of fading (characterized by maximum doppler frequency f_d) is fast compared with signaling interval T_s (See Fig. 4). In this case, we adequately evaluate CNR by means of average value. Result of the simulation calculation with respect to 3-carriers system is shown in Fig. 5.

Figure 5 shows that the mean value of m, which is associated with the mean value of received signal power, has the optimum value that maximizes the mean value of CNR, similarly to the case of non-faded

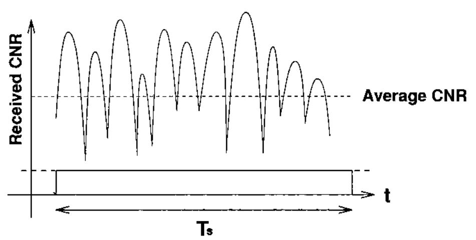

Fig. 4 Fast fading.

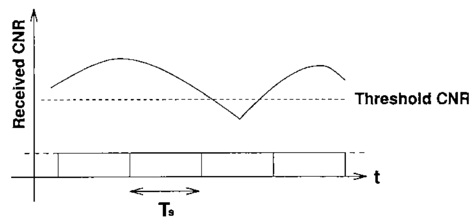

Fig. 6 Slow fading.

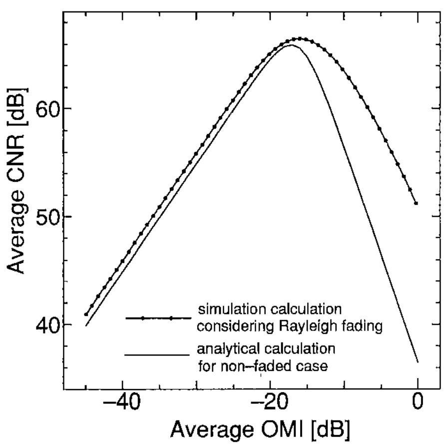

Fig. 5 The effect of signal fading on average CNR (3-carrier system).

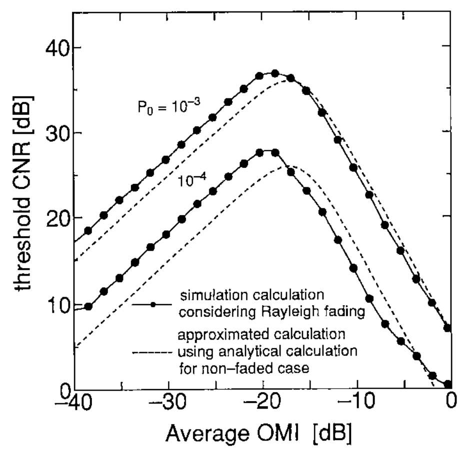

Fig. 7 The effect of signal fading on CNR that gives a specified outage probability P_0.

signal. As to third-order intermodulation distortion, when signals suffer from fading, average CNR is a little better. The reason of this is explained as follows: the third-order intermodulation distortion is the products of three different RF signals, and the effect of this is significant only if the signal levels of three different carriers are simultaneously large, but such a case is rare. On the other hand, desired signal level randomly varies according to the Rayleigh distribution. Consequently, the event that CIR is improved compared with the case of constant optical modulation index frequently occurs, and so far as we measure the system degradation by means of average value, total CNR seems to be improved.

The obtained optimum value of m and achievable average CNR (denoted as $(\mathrm{CNR})_{Ave}$) by simulation method are as follows:

$$m_{opt} = -16.0 \ [\mathrm{dB}],$$

$$(\mathrm{CNR})_{Ave} = 66.5 \ [\mathrm{dB}].$$

This numerical result shows that CNR is not degraded in the average point of view and achievable CNR is nearly equal to that in the case of not taking fading into consideration (the difference between them is only within 1 dB), while mean value of optical modulation index m is greater than that in the case of not taking fading into consideration by about 1 dB. This means that, when taking signal fading into consideration, we can make the average value of optical modulation index a little greater than that of non-faded case to avoid degradation of CNR due to fading.

4.2 Slow Fading

The term, slow fading, means the case where the rapidity of fading is slow compared with signaling interval (Fig. 6). In this case, we measure the system degradation due to fading by means of a statistical measure of outage probability, which is the probability of failing to achieve required CNR. From this outage probability, we can estimate the bit error rate performance. Result of simulation calculation is shown in Fig. 7.

Figure 7 shows that CNR that gives a specified outage probability P_0 decrease by about 10 dB as the value of P_0 increase tenfold, but as long as the mean level of the received signal envelope is sufficiently large not to suffer from degradation due to third-order intermodulation distortion, CNR that gives a specified P_0 is sufficiently large. For numerical example, if we want to achieve the outage probability $P_0 = 10^{-4}$, CNR that gives such an outage probability is over 25 dB, while the average optical modulation index m is a little smaller than that of non-faded case.

In Fig. 7, approximately calculated value (denoted as $(\mathrm{CNR})_{app}$) according to the following Eq. (19) is also shown to be compared with the value of simulation calculation for the case of fading.

$$(\mathrm{CNR})_{app}=(\mathrm{CNR})_{non-faded}+10\log_{10}P_0 \qquad (19)$$

In Eq. (19), $(\mathrm{CNR})_{non-faded}$ stands for the achievable maximum value of CNR discussed in Sect. 3. Calculated results in Fig. 7 shows that the relation in Eq. (19) is valid for $P_0=10^{-1}\sim10^{-4}$, and it is considerable that the equation is valid for other P_0. This result shows that we can apply the Eq. (19) to estimate threshold CNR P_0 in the case of taking both signal fading and intermodulation distortion consideration simultaneously.

5. The Relationship between Performance and Number of Carriers

In the previous section, for the sake of simplicity, we evaluate carrier-to-noise power ratio under the restricted condition that three radio frequency carriers are transmitted. In practice, many more RF signals will be used when users are concentrated in a specific cell, and nonlinearity of laser diode degrades the quality of optical fiber link significantly. Generally, the carrier which is in the middle of frequency band suffers from most severe third-order intermodulation distortion. In this section, we describe the relationship between the number of carriers transmitted and degradation of CNR with respect to the carrier which resides in the middle of frequency band.

5.1 The Number of Carrier versus Average CNR

Figure 8 shows the relationship between the mean value of optical modulation index and average value of CNR. In the figure, the analytically calculated value for non-faded case is also shown to be compared with the result of simulation calculation for the case of taking fading into consideration. The average value of CNR decreases as the number of carriers increases, and system dynamic range decreases. This relationship between the achievable maximum $(\mathrm{CNR})_{Ave}$ and the number of carriers n is shown in Fig. 9. In general, the number of third-order intermodulation products (three tone) which fall into the rth carrier among equally spaced n carriers is expressed in the following equation,[4]

$$N_{IM3}=\frac{r(n-r+1)}{2}+\frac{(n-3)^2-5}{4}-\frac{\{1-(-1)^n\}(-1)^{n+r}}{2}. \qquad (20)$$

In Fig. 9, we observe that, when taking signal fading into consideration, achievable maximum $(\mathrm{CNR})_{Ave}$ decreases approximately according to n^2, (in dB, according to $-20\log_{10}n$) similarly to the non-faded case. That is, achievable maximum $(\mathrm{CNR})_{Ave}$ decreases by 6 dB if the number of carriers increases twice.

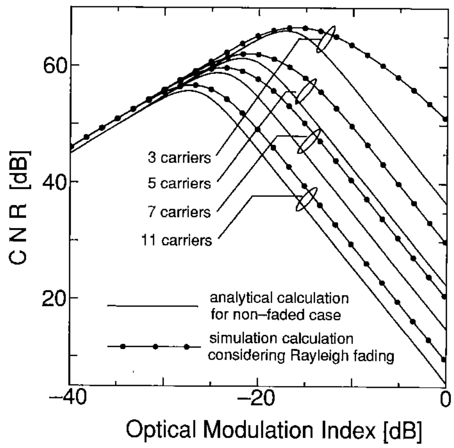

Fig. 8 Average CNR versus average optical modulation index (OMI).

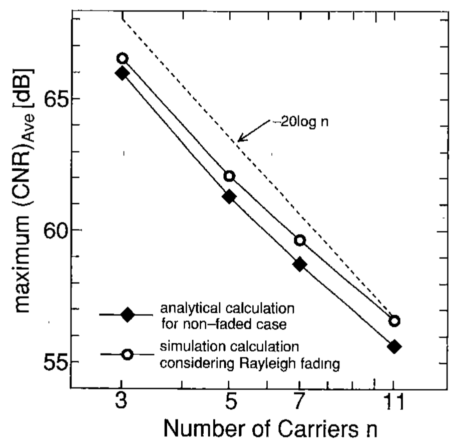

Fig. 9 Maximum value of average CNR versus the number of carriers.

5.2 The Number of Carrier versus Outage Probability

Figure 10 shows the relationship between the number of carriers and maximum achievable value of required CNR (denoted as $(\mathrm{CNR})_{out}$) corresponding to the parameter of outage probability P_0. The dotted line shows the threshold CNR which is approximately calculated from the analytical calculation for non-faded case shown in Fig. 5. In this case, threshold CNR decreases by about 10 dB from the average value as outage probability P_0 decreases to one tenth. The difference between these two values is not much significant, this shows that the characteristic of CNR including the effect of both signal fading and intermodulation distortion simultaneously is similar to that of taking only signal fading into account.

Figure 10 also shows that, similarly to the measure of average value, CNR that gives a specified outage probability decreases as the number of carriers increases, and for numerical example, the probability to fail to achieve CNR of 15 dB is 10^{-4} in the 11-

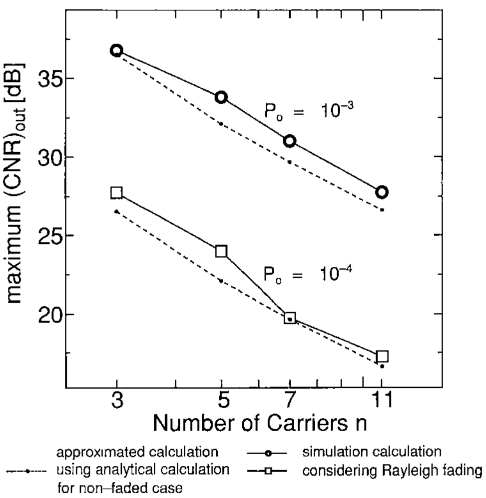

Fig. 10 CNR that gives a specified outage probability P_0 versus the number of carriers.

carriers system.

Under the condition of Rayleigh fading, numerical results shows that the effect of fading is not much significant in both cases of slow and fast fading, and in the system design, we can consider that the link parameter is not less than the analytical calculation of non-faded case for fast fading. Moreover, about 1 dB CNR improvement can be obtainable if we introduce the larger amount of optical modulation index. But optical source nonlinearity limits the number of carriers which can be accommodated per microcell, and we must take this into consideration in the system design.

6. Conclusion

We discussed the quality of transmission in the microcellular optical communication system with numerical evaluation, taking both signal fading and distortion due to nonlinearity. The results are:

1. In the system design, we must take the degradation due to both radio link and optical link, that is, signal fading and nonlinear distortion, into consideration.
2. By numerical evaluation using simulation method, there is not much difference (within the range of 1 dB) between non-faded case and faded case with respect to the measure of average value.
3. The number of carriers which drive a single laser diode (that is, the number of carriers which is allowed to be used per microcell) is limited due to the nonlinearity of a laser diode, and this may restrict the size of microcell.

From obtained results, we can say microcellular optical communication system is suitable for implementation of the future networks.

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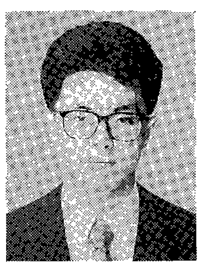
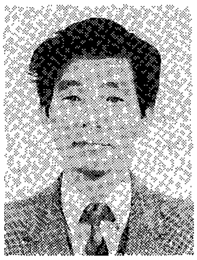


Hironori Mizuguti was born in Toyama, Japan on October 4, 1968. He received the B.E. degree in Electrical Communication Engineering from Osaka University, in 1991. He is currently pursuing the M.E. degree at Osaka University. He is mainly engaged in research on digital radio communication systems.

Toshiaki Okuno was born in Kanazawa, Japan on April 8, 1969. He received the B.E. degree in Electrical Communication Engineering from Osaka University, in 1992. He is currently pursuing the M.E. degree at Osaka University. He is mainly engaged in research on digital radio communication systems.



Shozo Komaki was born in Osaka, Japan in 1947. He received the B.E., M. E. and D.E. 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 has moved to Osaka University, Faculty of Engineering, and engaging in the research on radio and optical communication systems. He is currently a professor of Osaka University. Dr. Komaki is a member of IEEE, and the Institute of Television Engineers of Japan. He was awarded the Paper Award by IECE of Japan in 1977 and the NTT President Award in 1983.

Norihiko Morinaga was born in Nishinomiya, Japan, on June 6, 1939. He received the B.E. degree in electrical engineering from Shizuoka University, Shizuoka, Japan, in 1963, and M.E. and Ph.D. degrees from Osaka University, Osaka, Japan, in 1965 and 1968 respectively. He is currently a Professor in the Department of Communication Engineering at Osaka University, working in the area of radio, mobile, satellite and optical communication systems, and EMC. Dr. Morinaga is a member of the IEEE and the Institute of Television Engineers of Japan.